An investigation of the socio-economic, technical and appliance related factors affecting high electrical energy demand in UK homes

by

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Abstract

Electricity consumption from domestic buildings represented 35% of total UK electricity consumption in 2012, and since 1970, the UK domestic sector has experienced a general year on year rise in electricity use of around 1%. The UK government has made energy demand reduction in domestic buildings an essential part of their drive to lower CO_2 emissions in order to mitigate the risks of global climate change.

The amount of electricity used in individual UK homes varies considerably. A large range, as well as highly skewed distribution of electricity consumption, exists for the UK domestic sector and, whilst there is an absolute lower bound to electricity demand, there is no effective upper bound, with the upper quartile of electrical energy users consuming much more than the lower. Previous UK energy research has identified that high electricity consuming homes not only use more electricity, compared with others, but appear to be consuming even more electricity over time. Furthermore, there is additional evidence which shows that high consuming dwellings also have a greater potential to make energy savings than those who consume less. Given the immediate need for reduction of CO_2 emissions, these previous observations have substantial implications and it has been suggested that future UK energy policy might focus on reducing the demand of high electricity consumers in order to reduce overall CO_2 emissions. Therefore, understanding what drives high usage in domestic buildings is essential to support informed decisions.

This thesis asserts that to improve knowledge and understanding of the factors affecting high electrical energy consumption in UK domestic buildings, it is necessary to combine an analysis of the occupants' socio-economic characteristics, dwelling technical characteristics and appliance related aspects, with detailed monitoring of the ownership, power demand and occupants' use of electrical appliances. This thesis contains two main complementary studies: firstly, using a sample of 315 UK homes, the influence of socio-economic, technical and appliance related characteristics on the probability of a household being a high electrical energy consumer was investigated (Odds ratio analysis). Secondly, detailed appliance monitoring data was collected from 27 UK homes to establish the contributions of appliance ownership, power demand and use to high electrical energy demand (Appliance Electricity Use Survey).

The current research found similar skewed electricity distributions towards high electricity consumers for both the 315 and 27 home cohorts. Conflicting results were however obtained from the two household samples with regard to whether high electricity consumers are increasing electrical energy demand over time. The results of the odds ratio analysis and Appliance Electricity Use Survey suggest that high electricity consumption in domestic buildings is related to a combination of the socio-economic characteristics of the building occupants, technical characteristics of the dwelling and the ownership, power demand and use of electrical appliances. The study identifies the specific appliances and power modes which should be targeted to reduce the electricity consumption of high consuming dwellings. For each appliance power mode the research establishes whether the power demand and/or occupants' usage needs to be addressed in order to achieve energy savings.

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Contents

Abstract i

Acknowledgements iii

Contents iv

List of Acronyms xii

List of Figures xv

List of Tables xviii

List of Equations xxii

Chapter 1 1

Introduction 1

1.1 Introduction 1

1.2 Thesis overview 1

1.3 Climate change: the fundamental driver of carbon dioxide emission reduction 4

1.4 The UK Government's policy response to climate change 5

1.5 Energy use and carbon dioxide emissions from the UK housing stock 7

1.6 UK domestic electricity use 9

1.7 The skewed distribution of UK domestic electricity use and high electrical energy consumers 13

1.8 Aim and objectives 15

1.9 Thesis structure 16

Chapter 2 18

Literature Review 1: The socio-economic, technical and appliance related characteristics affecting electricity use in domestic buildings 18

2.1 Introduction 18

2.2 Previous studies investigating the factors affecting domestic electricity consumption 19

2.3 Socio-economic factors that influence domestic electricity consumption 28

2.3.1 Number of occupants 28

2.3.2 Family composition 30
2.3.3 Age of household representative person 32
2.3.4 Employment status of household representative person 33
2.3.5 Education level of household representative person 33
2.3.6 Socio-economic classification of household representative person 34
2.3.7 Tenure type 34
2.3.8 Household income 35
2.3.9 Disposal income 37
2.4 Technical factors that influence domestic electricity consumption 40
2.4.1 Dwelling type 40
2.4.2 Period dwelling was built 41
2.4.3 Number of rooms 42
2.4.4 Number of bedrooms 43
2.4.5 Number of floors 43
2.4.6 Floor area 44
2.4.7 Presence of electric space heating, ventilation and air-conditioning systems 45
2.4.8 Presence of electric hot water heating systems 46
2.4.9 Presence of low-energy lighting 46
2.5 Appliance factors that influence domestic electricity consumption 49
2.5.1 Ownership of appliances 49
2.5.2 Usage of the appliances 54
2.5.3 Power demand of appliances 54
2.6 Chapter 2: Summary 61

Chapter 3 62

Literature review 2: A review of appliance electricity monitoring studies in domestic buildings 62

3.1 Introduction 62
3.2 Overview of appliance electricity consumption monitoring in domestic buildings. 63
3.3 Previous and ongoing electrical end-use monitoring studies 67
3.4 Chapter 3: Summary 82

Chapter 4 .... **84**

Research methodology **84**

4.1 Introduction 84

4.2 Research design: a mixed methods approach 84

4.3 Data collection 89

4.3.1 Ethics 89

4.3.2 Risk assessment 90

4.4 The 4M Living in Leicester household survey 90

4.5 The 4M Living in Leicester electricity meter reading follow up 91

4.6 The 4M energy supplier annual electricity use follow up 92

4.7 The 4M Living in Leicester appliance survey follow up 93

4.8 The Appliance Electricity Use Survey 94

4.8.1 The AEUS sampling approach and recruitment procedure 94

4.8.2 The AEUS study households 95

4.8.3 The AEUS whole house and appliance level electricity monitoring 102

4.8.4 The AEUS electricity meter reading 112

4.8.5 The AEUS administered domestic appliance ownership survey 115

4.8.6 The AEUS unstructured interview 115

4.9 Data processing 118

4.9.1 The 4M Living in Leicester household survey data 118

4.9.2 The 4M Living in Leicester electricity meter reading follow up data 119

4.9.3 The 4M energy supplier annual electricity use data 120

4.9.4 The 4M Living in Leicester appliance survey follow up data 121

4.9.5 The Appliance Electricity Use Survey 121

4.10 Data analysis 124

4.10.1 Research question Q1: Does a sample of UK households demonstrate that large variations in electrical energy demand exist between homes? 124

4.10.2 Research question Q2: Is the electricity consumption of a sample of UK households with high electrical energy demand increasing over time? 125

4.10.3 Research question Q3: Which socio-economic, technical and appliance factors contribute to high electrical energy demand in a sample of UK households? 129

4.10.4 Research question Q4: To what extent do the ownership, power demand and use of different domestic appliances contribute to high electrical energy demand in a sample of UK households? ... 133

4.11 Chapter 4: Summary ... 148

Chapter 5 ... 149

Results: Variations in annual electricity use and changes in demand over time .. 149

5.1 Introduction ... 149

5.2 Electricity use of the L315 and L27 cohorts ... 150

5.2.1 Annual electricity consumption distribution for the L315 cohort ... 150

5.2.2 Annual electricity consumption distribution for the L27 cohort ... 152

5.2.3 Representativeness of the L315 and L27 electricity distributions ... 152

5.3 Changes in electricity use over time ... 156

5.3.1 Changes in the electrical demand of the L315 cohort from 2007 to 2009 .. 157

5.3.2 Changes in the electrical demand of the L27 cohort from 2007 to 2011 158

5.3.3 Changes in the electrical demand of individual dwellings in the L27 cohort from 2007 to 2011 and the occupants stated explanations ... 160

5.4 Uncertainty in results presented in Chapter 5 ... 166

5.5 Chapter 5: Summary ... 168

Chapter 6 ... 169

Results: The socio-economic, technical and appliance drivers of high electrical energy use ... 169

6.1 Introduction ... 169

6.2 Factors contributing to high electricity consumption amongst the L315 cohort .. 169

6.3 Odds ratios for socio-economic characteristics ... 180

6.4 Odds ratios for technical characteristics ... 181

6.5 Odds ratios for appliance characteristics ... 183

6.6 Uncertainty in results presented in Chapter 6 ... 188

6.7 Chapter 6: Summary ... 188

Chapter 7 ... 190

Results: Variations in appliance electricity consumption, ownership, power demand and use ... 190

7.1 Introduction ... 190

7.2 Variations in annual appliance electricity consumptions between electrical demand groups ... 191
7.2.1 Variations in annual electricity consumption on office equipment and infotainment appliances ... 192
7.2.2 Variations in annual electricity consumption on non-fixed lighting ... 197
7.2.3 Variations in annual electricity consumption on HVAC appliances ... 197
7.2.4 Variations in annual electricity consumption on transportation appliances. 198
7.2.5 Variations in annual electricity consumption on catering appliances ... 199
7.2.6 Variations in annual electricity consumption on washing appliances ... 201
7.2.7 Variations in annual electricity consumption on laundry appliances ... 202
7.2.8 Variations in annual electricity consumption on building and outdoors maintenance appliances ... 203
7.2.9 Variations in annual electricity consumption on hygiene, beauty and leisure appliances ... 204
7.2.10 Summary of variations in annual appliance electricity consumption ... 205
7.3 Variations in ownership of domestic appliances between electrical demand groups ... 206
7.3.1 Variations in the ownership of domestic appliances by appliance category 206
7.3.2 Variations in the ownership of office equipment and infotainment appliances 208
7.3.3 Variations in the ownership of non-fixed lighting appliances ... 212
7.3.4 Variations in the ownership of HVAC appliances ... 213
7.3.5 Variations in the ownership of transportation appliances ... 213
7.3.6 Variations in the ownership of catering appliances ... 214
7.3.7 Variations in the ownership of washing appliances ... 217
7.3.8 Variations in the ownership of laundry appliances ... 217
7.3.9 Variations in the ownership of building and outdoors maintenance appliances ... 218
7.3.10 Variations in the ownership of hygiene, beauty and leisure appliances ... 219
7.3.11 Summary of variations in ownership of domestic appliances ... 220
7.4 Variations in power demands of domestic appliances between electrical demand groups ... 221
7.4.1 Variations in power demands of office equipment and infotainment appliances ... 222
7.4.2 Variations in power demands of non-fixed lighting appliances ... 226

7.4.3 Variations in power demands of HVAC appliances 227
7.4.4 Variations in power demands of transportation appliances 227
7.4.5 Variations in power demands of catering appliances 228
7.4.6 Variations in power demands of washing appliances 231
7.4.7 Variations in power demands of laundry appliances 231
7.4.8 Variations in power demands of building and outdoors maintenance appliances 233
7.4.9 Variations in power demands of hygiene, beauty and leisure appliances 234
7.4.10 Summary of variations in power demands of domestic appliances 235
7.5 Variations in daily use of domestic appliances between electrical demand groups 237
7.5.1 Variations in daily use of office equipment and infotainment appliances 237
7.5.2 Variations in daily use of non-fixed lighting appliances 243
7.5.3 Variations in daily use of HVAC appliances 243
7.5.4 Variations in daily use of transportation appliances 244
7.5.5 Variations in daily use of catering appliances 245
7.5.6 Variations in daily use of washing appliances 248
7.5.7 Variations in daily use of laundry appliances 249
7.5.8 Variations in daily use of building and outdoors maintenance appliances 250
7.5.9 Variations in daily use of hygiene, beauty and leisure appliances 251
7.5.10 Summary of variations in daily use of domestic appliances 252
7.6 Uncertainty in results presented in Chapter 7 254
7.7 Chapter 7: Summary 255

Chapter 8 257

Discussion 257

8.1 Introduction 257
8.2 Discussion 1: The skewed electricity distribution and changes in demand over time 257
8.3 Discussion 2: The socio-economic, technical and appliance related factors contributing to high electrical energy demand 263
8.3.1 Socio-economic characteristics 263
8.3.2 Technical characteristics 269
8.3.3 Appliance characteristics 273

8.4 Discussion 3: The contributions of ownership, power demand and usage of domestic appliances to high electrical energy demand 285
8.4.1 Office equipment and infotainment appliances 286
8.4.2 Non-fixed lighting appliances 288
8.4.3 HVAC appliances 289
8.4.4 Transportation appliances 290
8.4.5 Catering appliances 290
8.4.6 Washing appliances 291
8.4.7 Laundry appliances 291
8.4.8 Building and outdoors maintenance appliances 292
8.4.9 Hygiene, beauty and leisure appliances 293
8.4.10 Overview of the contributions of ownership, power demand and usage of domestic appliances to high electrical energy demand 293
8.5 Facilitating energy saving from high electrical energy demand households 299
8.5.1 Scope of energy saving recommendations 299
8.5.2 Technical opportunities to reduce electricity use and CO_2 emissions from high electrical energy demand households 300
8.5.3 Behavioural opportunities to reduce electricity use and CO2 emissions from high electrical energy demand households 303

Chapter 9 306

Conclusions 306

9.1 Introduction 306
9.2 Main findings 306
9.2.1 Variations in electricity consumption of UK homes and changes in demand overtime 306
9.2.2 The socio-economic, technical and appliance related factors contributing to high electrical energy demand in UK homes 308
9.2.3 Opportunities to reduce high electrical energy demand in UK homes 309
9.3 Contributions to knowledge 312
9.4 Limitations 312
9.5 Further work 314
9.5.1 Further work using the existing dataset 314
9.5.2 Further work for the wider research community 315

References **317**

Appendices **336**

Appendix A 4M Domestic appliance survey 337

Appendix B AEUS recruitment letter and acceptance form 341

Appendix C AEUS participant information pack 344

Appendix D AEUS installation form 351

List of Acronyms

4M	Measurement, Modelling, Mapping and Management
AC	Alternating Current
AEUS	Appliance Electricity Use Survey
Amp	Ampere
AMC	Analytical Methods Committee
AMS	Appliance Monitoring System
ANOVA	Analysis Of Variance
BMRDA	Bombay Metropolitan Regional Development Authority
BRE	Building Research Establishment
BSI	British Standards Institution
CaRB	Carbon Reduction in Buildings
CCC	Committee on Climate Change
CCL	Climate Change Levy
CD	Compact Disk
CDA	Conditional Demand Model
CDEM	Community Domestic Energy Model
CERT	Carbon Emission Reduction Target
CESP	Community Energy Saving Programme
CFL	Compact Fluorescent Lamp
CI	Confidence Interval
cm	Centimetre
CO_2	Carbon dioxide
CRT	Cathode Ray Tube
CT	Current Transformer
DCLG	Department for Communities and Local Government
DECC	Department of Energy & Climate Change
Defra	Department for Environment, Food and Rural Affairs
DOE	US Department of Energy
DSDNI	Department for Social Development Northern Ireland
DSL	Digital Subscriber Line
DTI	Department of Trade and Industry
DVD	Digital Versatile Disk
EC	European Commission
EEC	Energy Efficiency Commitment
EES	Energy Efficient Strategies
EHCS	English House Condition Survey

EPSRC	UK Engineering and Physical Sciences research Council
EST	Energy Saving Trust
EU	European Union
EUP	Eco-design of Energy-using Products
FIT	Feed-In Tariffs
GDP	Gross domestic product
HEED	Homes Energy Efficiency Database
HRP	Household Representative Person
HVAC	Heating, Ventilation, and Air Conditioning
Hz	Hertz
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IESD	Institute of Energy and Sustainable Development
IPCC	Intergovernmental Panel on Climate Change
ICT	Information Communication Technologies
IT	Information Technology
kB	Kilobit
kB FRAM	Kilobit Ferroelectric Random Access Memory
kVARh	Kilo Volt Amperes Reactive hour
kW	Kilowatt
kWh	Kilowatt hour
kWhpa	Kilowatt hour per annum
L27	Leicester 27 households
L315	Leicester 315 households
LCD	Liquid Crystal Display
LED	Light-Emitting Diode
LIL	Living in Leicester
m^2	Square meter
Max	Maximum
MEPS	Minimum Energy Performance Standards
Min	Minimum
MPAN	Meter Point Administration Number
Mt	Megatonne
NatCen	National Centre for Social Research
NHER	National Homes Energy Rating
ºC	Degree Celsius
OECD	Organisation for Economic Co-operation and Development
Ofgem	Office of Gas and Electricity Markets
ONS	Office for National Statistics
OR	Odds Ratio
pa	Per annum
PAT	Portable Appliance Testing

PC	Personal Computer
PhD	Doctor of Philosophy
ppm	Parts per million
RECS	End-Use Residential Energy Consumption Survey
RHI	Renewable Heat Incentive
RO	Renewables Obligation
SME	Small and Medium Enterprise
SMP	Smart Meter Plug
STB	Set Top Box
TV	Television
TWh	Terawatt hour
UK	United Kingdom
UNFCCC	United Nations Framework Convention on Climate Change
US	United States
USB	Universal Serial Bus
V	Voltage
VCR	Video Cassette Recorder
W	Watt
Yr	Year

List of Figures

Figure 1-1 Final UK energy consumption by sector 2011 (TWh, Total 1,710 TWh) (DECC 2013a) 8

Figure 1-2 Domestic electricity consumption from 1970 to 2009. Building Research Establishment Housing Model for Energy Studies (1970-2008) (DECC 2013a), Cambridge Housing Model (2008 onwards) (Hughes 2011) 10

Figure 1-3 Domestic electricity consumption by end-use in 2011 (Zimmermann et al. 2012) 11

Figure 1-4 Percentage change in UK domestic energy use from 1970 to 2012 (DECC 2013b) 12

Figure 1-5 Distribution of UK domestic electricity use in 2007 (DECC 2011) 13

Figure 4-1 Explanatory mixed methods research design (Creswell & Plano Clark 2007) 84

Figure 4-2 Overview of the thesis research process 88

Figure 4-3 Current clamp logger: Plogg with external 100 Amp current transformer (Energy Optimizers 2010) 104

Figure 4-4 Current clamp logger: SPCmini (Elcomponent 2010a) 105

Figure 4-5 Plogg Smart Meter Plug (Energy Optimizers 2010) 107

Figure 4-6 Monitoring schematic of the AMS and whole house measurement 109

Figure 4-7 Load profile from calibration test 111

Figure 4-8 Example column chart of the variations in annual electricity consumption for household 134081 between 2007 and 2011 117

Figure 4-9 Example data in the 4M LIL household survey database 118

Figure 4-10 Example AMS and whole house data in combined Excel work sheet for household 146061 122

Figure 4-11 Irregular power consumption values identified and removed for a toaster.. 123

Figure 4-12 Power mode thresholds for an example television 138

Figure 4-13 Attributing measured power loads to specific power modes for a television139

Figure 4-14 Example screen shot of the data columns used to calculate the annual electricity consumption of a television in each power mode 140

Figure 4-15 Example screen shot of the process of calculating the average annual electricity consumptions of televisions in each power mode for the electrical demand groups 141

Figure 4-16 Example screen shot of the data columns used to calculate the average power demands of a television 144

Figure 4-17 Example screen shot of the process of calculating the average power demand of televisions in each power mode for the electrical demand groups 145

Figure 4-18 Example screen shot of the data columns used to calculate the average daily use of a television 147

Figure 5-1 The annual electricity consumptions of the L315 households ranked from smallest to largest in 2009 151

Figure 5-2 The annual electricity consumptions of the L27 households ranked from smallest to largest in 2011-2012 152

Figure 5-3 Comparison of the L315, L27 and Great Britain distributions of domestic electricity consumption 153

Figure 5-4 Year-on-year change in mean electrical consumption for each electrical demand group for the L315 cohort from 2007 to 2009 157

Figure 5-5 Year-on-year change in mean electrical consumption for each electrical demand group for the L27 cohort from 2007 to 2011 159

Figure 5-6 Year-on-year change in annual electricity use for each L27 household from 2007 to 2011 161

Figure 7-1 Appliance ownership rates by appliance category 207

Figure 7-2 Appliance ownership rates in the office equipment and infotainment category211

Figure 7-3 Appliance ownership rates in the non-fixed lighting category 212

Figure 7-4 Appliance ownership rates in the HVAC category.. 213

Figure 7-5 Appliance ownership rates in the transportation category............................ 214

Figure 7-6 Appliance ownership rates in the catering category..................................... 216

Figure 7-7 Appliance ownership rates in the washing category 217

Figure 7-8 Appliance ownership rates in the laundry category 218

Figure 7-9 Appliance ownership rates in the building and outdoors maintenance category219

Figure 7-10 Appliance ownership rates in the hygiene, beauty and leisure category 220

List of Tables

Table 2-1 Summary of the effects of socio-economic factors on electricity consumption in domestic buildings studied in the literature 38

Table 2-2 Summary of the effects of technical factors on electricity consumption in domestic buildings reported in the literature 47

Table 2-3 Summary of the effects of appliance factors on electricity consumption in domestic buildings reported in the literature 56

Table 3-1 Summary of the previous and ongoing end-use monitoring studies in domestic buildings 78

Table 4-1 Data required for the thesis research questions 85

Table 4-2 Description of the research methods used in the current research 86

Table 4-3 Summary of the key socio-economic characteristics of the 27 AEUS households 98

Table 4-4 Summary of the key technical characteristics of the 27 AEUS households ... 100

Table 4-5 Summary of the Plogg with external 100 Amp current transformer specifications (Energy Optimizers 2010) 104

Table 4-6 Summary of the SPCmini specifications (Elcomponent 2010b) 106

Table 4-7 Summary of the Plogg SMP specifications (Energy Optimizers 2010) 109

Table 4-8 Average power measurements for SMPs and SPC Pro for power loads tested in calibration test 112

Table 4-9 Specific meter reading dates for the 27 AEUS households 114

Table 4-10 Comparison of the L315 electrical demand groups with those in previously reported studies 127

Table 4-11 Template analysis process 129

Table 4-12 Odds ratio example for presence of children 131

Table 4-13 Modified appliance taxonomy used in the data analysis 135

Table 4-14 Definitions of appliance power modes (International Standby Power Data Project 2008) 136

Table 4-15 Definitions of additional active power modes 137

Table 4-16 Example Excel formulas used to calculate the annual electricity consumption of a television in active, passive standby and off standby modes 140

Table 4-17 Example Excel formulas used to calculate the average power demands of a television in active, passive standby and off standby modes 143

Table 4-18 Example Excel formulas used to calculate the average daily use of a television in active, passive standby, off standby modes and unplugged 146

Table 5-1 Comparison of the main characteristics of the L315 and L27 cohorts with previously reported studies 155

Table 5-2 Year-on-year changes in annual electrical consumption for each home in the L27 cohort from 2007 to 2011, including missing data 162

Table 5-3 Factors that the occupants of the L27 households believed were responsible for significant increases or decreases in the annual electricity consumption of their homes 166

Table 6-1 Odds ratio results for the socio-economic, technical and appliance characteristics affecting high electricity consumption 170

Table 7-1 Mean annual electricity consumptions on office equipment and infotainment appliances by power mode and electrical demand group 193

Table 7-2 Mean annual electricity consumptions on non-fixed lighting appliances by power mode and electrical demand group 197

Table 7-3 Mean annual electricity consumptions on HVAC appliances category by power mode and electrical demand group 198

Table 7-4 Mean annual electricity consumptions on transportation appliances by power mode and electrical demand group 199

Table 7-5 Mean annual electricity consumptions on catering appliances by power mode and electrical demand group 200

Table 7-6 Mean annual electricity consumption on washing appliances by power mode and electrical demand group 202

Table 7-7 Mean annual electricity consumptions on laundry appliances by power mode and electrical demand group 202

Table 7-8 Mean annual electricity consumptions on building and outdoors maintenance appliances by power mode and electrical demand group 203

Table 7-9 Mean annual electricity consumptions on hygiene, beauty and leisure appliances by power mode and electrical demand group 204

Table 7-10 Summary of appliances types that high electrical energy demand households have a higher ownership rate than low and medium electricity consumers 221

Table 7-11 Mean appliance power demands in the office equipment and infotainment category by power mode and electrical demand group.................................. 224

Table 7-12 Mean appliance power demands in the non-fixed lighting category by power mode and electrical demand group 227

Table 7-13 Mean appliance power demands in the HVAC category by power mode and electrical demand group 227

Table 7-14 Mean appliance power demands in the transportation category by power mode and electrical demand group 228

Table 7-15 Mean appliance power demands in the catering category by power mode and electrical demand group 229

Table 7-16 Mean appliance power demands in the washing category by power mode and electrical demand group 231

Table 7-17 Mean appliance power demands in the laundry category by power mode and electrical demand group 232

Table 7-18 Mean appliance power demands in the building and outdoors maintenance category by power mode and electrical demand group.................................. 233

Table 7-19 Mean appliance power demands in the hygiene, beauty and leisure category by power mode and electrical demand group... 234

Table 7-20 Summary of appliance power modes which had the greatest power demand when owned by high electricity consumers 235

Table 7-21 Mean appliance daily use in the office equipment and infotainment category by power mode and electrical demand group... 239

Table 7-22 Mean appliance daily use in the non-fixed lighting category by power mode and electrical demand group 243

Table 7-23 Mean appliance daily use in the HVAC category by power mode and electrical demand group... 244

Table 7-24 Mean appliance daily use in the transportation category by power mode and electrical demand group 244

Table 7-25 Mean appliance daily use in the catering category by power mode and electrical demand group 246

Table 7-26 Mean appliance daily use in the washing category by power mode and electrical demand group 248

Table 7-27 Mean appliance daily use in the laundry category by power mode and electrical demand group 250

Table 7-28 Mean appliance daily use in the building and outdoors maintenance category by power mode and electrical demand group..... 251

Table 7-29 Mean appliance daily use in the hygiene, beauty and leisure category by power mode and electrical demand group 252

Table 7-30 Summary of appliance power modes which had the longest daily use when owned by high electricity consumers..... 253

Table 8-1 Summary of key findings: Research questions 1 and 2 262

Table 8-2 Summary of key findings: Research question 3 283

Table 8-3 Summary of key findings: Research question 4 296

List of Equations

Equation 4-1 Annual electricity consumption of dwelling ……………………………….... 118

Equation 4-2 Example of the odds ratio calculation for the presence of children …….. 129

Equation 4-3 Example of the 95% CI for the presence of children ……………………... 130

Equation 4-4 Total average annual appliance electricity consumption for power mode for electrical demand group ……………………………………………..……... 137

Equation 4-5 Average percentage of appliance ownership rate for appliance type for electrical demand group ……………………………………………….…….. 140

Equation 4-6 Total average appliance power demand for power mode for appliance type ……………………………………………………………………..… 142

Equation 4-7 Average daily use of appliance type for electrical demand group ……… 144

Chapter 1

Introduction

1.1 Introduction

This chapter begins with an outline of this thesis (section 1.2). An overview of climate change and its potential impacts are then described (section 1.3), followed by a summary of the UK Government's policy response (section 1.4). The importance of reducing the energy demand of the UK domestic sector to achieve the Government's CO_2 emission reduction targets is established (section 1.5), and the growth in UK domestic electricity consumption associated with increased ownership and use of appliances is developed (section 1.6). An examination of the skewed distribution of domestic electricity use towards high electrical energy consumers is then undertaken (section 1.7). The aim and objectives of the research are defined (section 1.8) and finally, the structure of the thesis is outlined (section 1.9).

1.2 Thesis overview

This thesis documents research undertaken to improve knowledge and understanding of the socio-economic, technical and appliance related factors affecting high electrical energy consumption in UK domestic buildings. The socio-economic factors refer to the characteristics of the occupants residing in a home (e.g. number of occupants, presence of children, annual household income); the technical factors describe the characteristics of the dwelling (e.g. dwelling type, number of bedrooms, heating system type); and the appliance factors specify the ownership level, power demand and use of electrical appliances in the home.

Electricity consumption from domestic properties represented 35% of total UK electricity consumption in 2012, and since 1970, the UK domestic sector has experienced a general year on year rise in electricity use of around 1% (DECC 2012). The amount of electricity used in individual UK homes varies considerably. A large range, as well as highly skewed distribution of electricity consumption, exists for the UK domestic sector and, whilst there is an absolute lower bound to electricity demand, there is no effective upper bound, with the upper quartile of electrical energy users consuming much more than the lower (Zimmermann et al. 2012; DECC 2011; BRE 2008). Previous UK energy research has identified that high electricity consuming homes not only use more electricity, compared with others, but appear to be consuming even more electricity over time (Summerfield et al. 2010; Firth et al. 2008; Summerfield et al. 2007).

There is additional evidence which shows that high consuming dwellings also have a greater potential to make energy savings than those who consume less. McLoughlin et al. (2012) asked a sample of 3,334 households in Ireland to quantify by how much they believed they could reduce electricity use by changing their behaviour. Participant's responses showed a strong positive correlation with increasing electricity use, whereby households with higher electricity consumption believed they could make greater electricity savings, suggesting that larger electricity consumers are more wasteful. A sensitivity study of the CDEM model by (Firth et al. 2010) showed that whilst larger detached properties consume more energy they are also more responsive to energy efficiency measures. Firth et al. (2008) found that the high electricity consuming group in a study of 72 UK domestic buildings used a greater proportion of annual electricity use in continuous and standby modes (24%), compared with the low (19%) and medium consuming groups (15%). The electricity used in the continuous and standby mode by the high consuming group also increased between year 1 and year 2 of the study.

Given the immediate need for reduction of CO_2 emissions, these previous observations have substantial implications and it has been suggested that future UK energy policy might focus on reducing the demand of high electricity consumers in order to reduce overall CO_2 emissions (McLoughlin et al. 2012; Summerfield et al. 2010; Firth et al. 2010; Lomas 2010; Firth et al. 2008; Summerfield et al. 2007). Therefore, understanding what drives high usage in domestic buildings is essential to support informed decisions.

Internationally, existing research investigating the significance of background socio-economic, technical and appliance related factors on the total electricity consumption of residential buildings (e.g. Kavousian et al. 2013; McLoughlin et al. 2012; Bartusch et al. 2012; Ndiaye & Gabriel 2011) have provided insights into the drivers of high electricity consumption. However, at present, little research has been undertaken to understand the underlying socio-economic, technical and appliance related factors driving high electrical energy demand in UK homes. Therefore a significant gap in knowledge exists.

It has been suggested that potentially only 30-40% of the variation in household electricity consumption can be explained by the occupants' socio-economic characteristics and the technical aspects of the dwelling, and the remaining variation relates to differences in the occupants' behaviour (Gram-Hanssen et al. 2004). As appliances account for a significant proportion of a household's electricity use (greater than 50% (EST 2012)), variations in the ownership, power demand and patterns of use (i.e. occupants' behaviour influences the appliances duration of use) of electrical appliances should determine the differences in overall electricity consumption observed between dwellings. Previous studies have monitored the electricity consumption of domestic appliances (Coleman et al. 2012; Zimmermann et al. 2012; Zimmermann 2009; Firth et al. 2008) but the results obtained do not provide sufficient detail about how the three factors of ownership, power and use, affect high electricity consumption in residential buildings.

This thesis asserts that to improve knowledge and understanding of the factors affecting high electrical energy consumption in UK domestic buildings, it is necessary to combine an analysis of the occupants' socio-economic characteristics, dwelling technical characteristics and appliance related aspects, with detailed monitoring of the ownership, power demand and occupants' use of electrical appliances. Therefore, this research contains two main complimentary studies: firstly, using a sample of 315 UK homes, the influence of socio-economic, technical and appliance related characteristics on the probability of a household being a high electrical energy consumer was investigated. Secondly, detailed appliance monitoring data was collected from 27 UK homes to establish the contributions of appliance ownership, power demand and use to high electrical energy demand.

It is expected that the research reported in this thesis will contribute to the current body of knowledge by providing: (i) an understanding of which socio-economic, technical and appliance related factors affect high electrical energy consumption in UK homes; (ii) evidence based recommendations for reducing the electricity use of high electrical energy consumers in the UK domestic sector; (iii) electricity consumption and power demand data for the majority of domestic appliance types; (iv) accurate patterns of appliance use data.

This research was undertaken as part of a larger research project called 4M: 'Measurement, Modelling, Mapping and Management 4M: an Evidence Based Methodology for Understanding and Shrinking the Urban Carbon Footprint'. The four year project began in March 2008 and was supported by the UK Engineering and Physical Sciences research Council (EPSRC) through grant EP/F007604/1. The 4M consortium had 5 UK partners: Loughborough University (lead), De Montfort University, Newcastle University, the University of Sheffield, and the University of Leeds. The overall aim of the 4M project was to investigate the carbon sources and sinks for the City of Leicester, UK. This PhD research was designed to complement the results of the 4M project.

1.3 Climate change: the fundamental driver of carbon dioxide emission reduction

Climate change is one of the greatest challenges facing the world today, with serious and global consequences for the environment (IPCC 2007a), human health (IPCC 2007b; McMichael et al. 2006), and the economy (Stern 2006). Overwhelming scientific evidence has demonstrated that over the past century there has been a trend towards increasing global average temperatures primarily in response to the release of greenhouse gases from human activities. The global average temperature has increased by nearly 0.8ºC since the late 19th century (IPCC 2007a) and nine out of the fifteen warmest years on record for England have been in the last 15 years (Jenkins et al. 2007). Evidence collated by the Intergovernmental Panel on Climate Change (IPCC) shows that the global average temperature increases are very likely (greater than 90%) to result from rising concentrations of greenhouse gases in the atmosphere caused by human activities (IPCC 2007a).

Carbon dioxide (CO_2) is considered the main greenhouse gas contributing to anthropogenic climate change (IPCC 2007a). The primary greenhouse gases in the Earth's atmosphere are water vapour, carbon dioxide, methane, nitrous oxide, and ozone. The primary source of the increased atmospheric concentration of CO_2 is the result of the combustion of fossil fuels, such as coal, natural gas and crude oil. The atmospheric concentration of CO_2 has increased from a pre-industrial value of about 280 ppm to 379pmm in 2005 (IPCC 2007a). Greenhouse gases, like CO_2, absorb solar radiation reemitted from the Earth’s surface and release this energy into the atmosphere. This results in solar heat being retained within the Earth’s atmosphere which consequently increases atmospheric temperature (Boyle et al. 2003). The science underpinning climate change is however not without controversy, and some gaps still remain in our understanding (Schiermeier 2010). The primary focus of the debate now relates to the fraction of climate change caused by anthropogenic emissions (Mastrandrea & Schneider 2004; Lee et al. 2006), the extent of the impacts, and what responses are required to halt or even reverse these impacts (Hasselmann et al. 2003; Karl & Trenberth 2003).

The consequence of anthropogenic climate change is that the Earth’s climatic systems are being altered and the Earth’s biosphere is at risk from the negative environmental effects of a more hostile climate and rising temperatures (IPCC 2007b). The possible effects of climate change include continued changes in weather patterns, rising sea levels, increased frequency and intensity of extreme weather events (e.g. droughts and floods), and changes to biodiversity and agriculture (IPCC 2007b). The UK Climate Projections 2009 suggest that the UK is likely to experience warmer wetter winters (Murphy et al. 2010), hotter drier summers, and more frequent extreme weather events.

Sea levels are also projected to rise around the UK and estimates (taking into account land movement) show a projected rise around London of 36 cm by 2080 under a medium emissions scenario (Lowe et al. 2009).

However, due to the inertia of the climate system, whereby global temperatures lag behind the emissions of greenhouse gases, actions taken now to cut emissions would not slow the rate of rise of global temperature until at least 2040 (IPCC 2007b). It is predicted that global average temperatures are likely to increase between 1.1 and 6.4ºC by 2100 (compared to the 1980-1999 average) depending on which emissions pathway the world follows for the rest of the century (IPCC 2007b).

The serious potential impacts have elevated the position of climate change on the political agenda and it is accepted that strong international action is required to reduce anthropogenic CO_2 emissions (UNFCCC 2008). The UK, along with the EU-15 countries as a whole, committed to reducing emissions by 8%, on average, over the 2008-2012 period, compared with 1990 levels at the inception of the Kyoto Protocol (Bowen & Rydge 2011). The EU has also legally committed to a 20% reduction of greenhouse gas emissions by 2020, relative to 1990 levels. This emission-reduction target has recently been raised to 25% although the legally binding 20% target has not been amended. It is envisaged that the target could rise further to 30% should other developed countries also commit to similar reduction levels (EC 2009). The UK government has developed a complex set of measures and policies from around the year 2000 to deliver the extensive CO_2 emission reductions required.

1.4 The UK Government's policy response to climate change

The UK government has a strong domestic policy framework for addressing the challenges of climate change, which is setting a useful international example (Bowen & Rydge 2011). The UK is amongst the most prominent developed countries encouraging international action on climate change. The UK has strongly supported international climate change negotiations through the United Nations Framework Convention on Climate Change (UNFCCC) and the European Union. In 2005, the UK government commissioned the prominent Stern Review on the economics of climate change, which pushed climate change to the centre of the political agenda both nationally and in many other OECD countries (Stern 2006).

The current core underpinning of UK policy is the 2008 Climate Change Act, which established legally binding targets for reductions in UK CO_2 emissions of 80% by 2050 from 1990 levels (HM Government 2008). A medium-term reduction target of 34% by 2020 was also adopted. The Act created an independent body, the Committee on Climate

Change (CCC), to recommend carbon budgets, assess progress towards the long-term emission reduction target, and provide general advice to government on climate change policies (CCC 2008).

UK government policies addressing climate change are however wide-ranging with the earliest policy established in 2000. The 2000 and updated 2006 Climate Change Programme set policies to reduce CO_2 emissions by 15-18%, and greenhouse gas emissions by 23-25% below 1990 levels by 2010 (HM Government 2006). The 2001 Climate Change Levy (CCL) introduced a tax on non-domestic energy use by industry and the public sector (HM Revenues and Customs 2001). The 2002 Renewables Obligation (RO) required electricity end-suppliers to purchase a fraction of their annual electricity supply from producers using specific renewable technologies (HM Government 2002). The 2008 Carbon Emission Reduction Target (CERT) and 2009 Community Energy Saving Programme (CESP), which replaced the 2002 Energy Efficiency Commitment (EEC), required energy suppliers to achieve a reduction of 293 million tonnes of CO_2 by the end of 2012 through implementing substantial and robust household energy saving measures, such as insulation. A proportion of these upgrades had to target those most vulnerable to fuel poverty and those living in the most deprived areas of Great Britain (Ofgem 2013a; Ofgem 2013b).

The 2007 Code for Sustainable Homes established minimum performance standards for the design and construction of homes. All new homes from 2008 are required to be rated against the code and government funded social housing from 2010 must comply with Level 3: a 25% improvement in energy efficiency over 2006 building regulations (DCLG 2010). Building Regulations Part L set energy efficiency standards for new-build homes in England and Wales (HM Government 2010a; HM Government 2010b; HM Government 2010c; HM Government 2010d). In addition, Energy Performance Certificates (EPS) have been introduced in 2008, which provide an energy efficiency rating for buildings, from A being the most energy efficient and G being the least. A certificate is required when a building is built, sold or rented (DCLG 2012).

Furthermore, the UK government has offered financial incentives through the 2010 Feed-In Tariffs (FITs) to households, businesses and communities that generate electricity through small-scale low-carbon technologies (Ofgem 2010). The 2012 Renewable Heat Incentive (RHI) provides financial support for the installation of a wide range of renewable heating technologies in the domestic and non-domestic sectors (Ofgem 2011). Most recently, the 2013 Green Deal was launched which provides an innovative financing mechanism that allows both the domestic and non-domestic sectors to pay for energy efficiency improvements through the savings achieved on future energy bills (DECC 2010a).

In addition to combating climate change and the associated environmental impacts, the UK Government acknowledges that a transition towards a lower carbon society will also benefit the country's energy security (DECC 2009). The UK's overreliance on imported energy has made the UK economy vulnerable to energy supply disruption from international disputes, accidents or terrorism and has resulted in energy supply becoming a potential political tool. Therefore, energy demand reduction is considered an essential part of national security (DTI 2007). The UK government is now assessing the main risks and opportunities for the UK, arising from climate change (HM Government 2012) and establishing adaption plans that will help to reduce adverse consequences and take advantage of new opportunities (Defra 2010).

1.5 Energy use and carbon dioxide emissions from the UK housing stock

The energy used in homes accounts for more than a quarter of the UK's energy use and CO_2 emissions (Figure 1-1). CO_2 emissions and the use of energy from a fossil source are currently inseparable as almost all energy arising from fossil sources will result in increased CO_2 emissions. CO_2 is the most important greenhouse gas arising from the domestic sector and the most closely related to energy use in homes (DECC 2012). Whilst, the energy consumed by housing has increased by 5% from 429 TWh in 1970 to 452 TWh in 2011, equalling an average increase of 0.1% per year, the resulting CO_2 emissions have fallen from 182 Mt to 126 Mt over the same time period, despite the number of UK homes increasing by 50% and occupants expectations of thermal comfort and appliance use becoming more energy intensive (DECC 2012). The reductions in CO_2 have primarily come from the development of gas-fired rather than coal-fired power stations, as well as better insulation in homes and more efficient space and water heating systems.

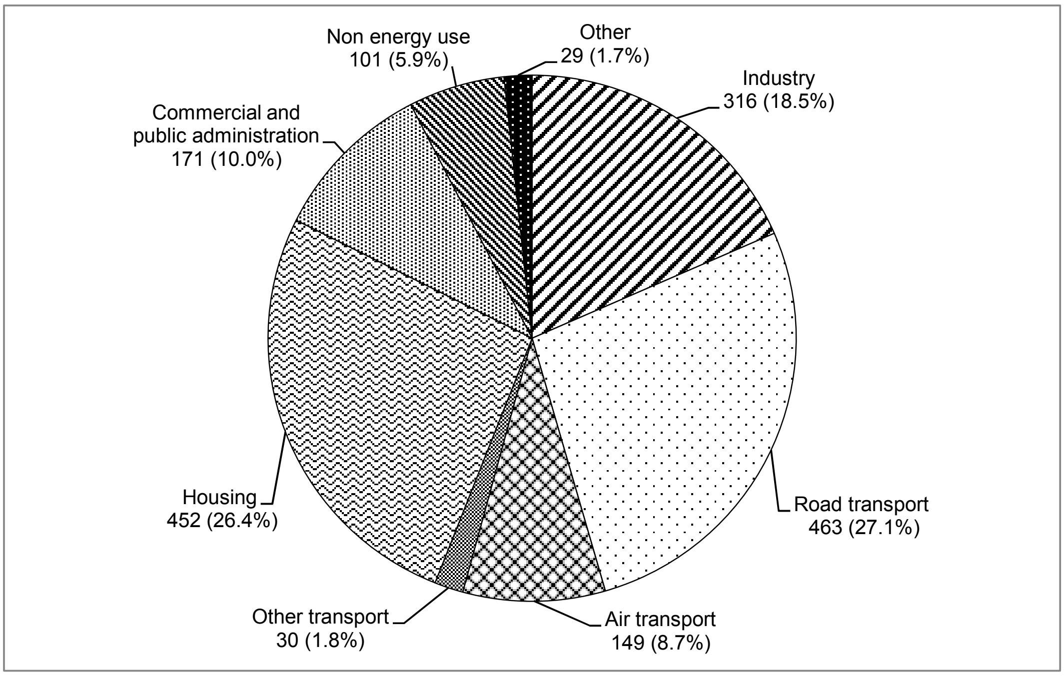


Figure 1-1 Final UK energy consumption by sector 2011 (TWh, Total 1,710 TWh) (DECC 2013a)

Due to the significant percentage of energy used by the existing UK housing stock, domestic buildings are a key target for government energy policy. It is important to note that the UK's housing stock changes very slowly, fewer than 180,000 new homes are built each year, and far fewer homes are demolished (ONS 2009; DSDNI 2011; Boardman 2003; Boardman et al. 2005; Boardman 2007), therefore addressing the current building stock is paramount. Previous research has shown that existing housing also represents a major opportunity to cut energy use and CO_2 emissions (Ürge-Vorsatz et al. 2007; Firth & Lomas 2009; Johnston et al. 2005; Roberts 2008).

Policy-makers have now realised that without significant reductions in the energy demand, and significant increases in the energy efficiency of the domestic sector, it will be impossible to achieve the long-term objective of an 80% reduction in CO_2 emissions by 2050 (Lomas 2010; Oreszczyn & Lowe 2010). In response, the Committee on Climate Change (CCC) has established a carbon reduction timeline for the domestic sector, which includes a reduction of 15-18 Mt of CO_2 by 2020, representing a cut in residential emissions of around 11.5-13.8%, with additional periodic reduction targets scheduled to 2050 (CCC 2008).

To achieve the government's ambitious CO_2 reduction target, policy and actions addressing the residential sector will require a combination of technical measures to improve the building stock (e.g. insulation) and social interventions to influence attitudes and behaviours towards the use of energy (Lomas 2010). The 2013 Green Deal is the current primary mechanism to encourage the installation of technical measures (DECC 2010a); however there is an emerging body of research which has observed that many technical improvements do not deliver the level of energy and CO_2 savings expected (Kelly et al. 2012; Sunikka-Blank & Galvin 2012). Amongst the possible explanations for this phenomenon are the poor quality of installation by contractors (Guerra-Santin et al. 2013), as well as the concept of “rebound” or “takeback” (Ouyang et al. 2010; Sorrell & Dimitropoulos 2008; Chitnis et al. 2012), where the installation of a technical measure may lead to changes in occupant behaviour, for example the installation of insulation may result in more extensive heating to a higher internal temperature.

Energy use in domestic buildings is simply the occupants’ need for energy services, such as light, comfort and entertainment, but the amount of energy required to meet these energy services results from a complex series of interlinked and interacting economic, technical, social and behavioural factors. Therefore, to support informed decisions about how to reduce energy use and CO_2 emissions from the housing sector, it is essential to investigate these complex driving factors and understand how occupants use energy in their homes. With this goal in mind, this thesis investigates the factors affecting electricity use in UK domestic buildings, with an emphasis on those homes which are high electrical energy consumers.

1.6 UK domestic electricity use

Since 1970, the UK domestic sector has experienced a general year on year rise in electricity use of around 1% (Figure 1-2). Electricity consumption from domestic properties represented 35% of total UK electricity consumption in 2012, equating to approximately 114 TWh (DECC 2012). Electricity’s share of overall household energy use has also increased from a fifth in 1970 to almost a quarter in 2009. This expansion has been attributed to increased ownership and use of electrical appliances, and more recently due to continued growth of electric space heating associated with a rise in the number of flats (DECC 2012).

An electrical appliance in this thesis is defined as any device that has a plug and requires the building occupants to connect it to the mains power supply via a socket. It therefore does not include fixed electric space and water heating systems or lighting, but does include portable HVAC systems and non-fixed lighting, such as lamps.

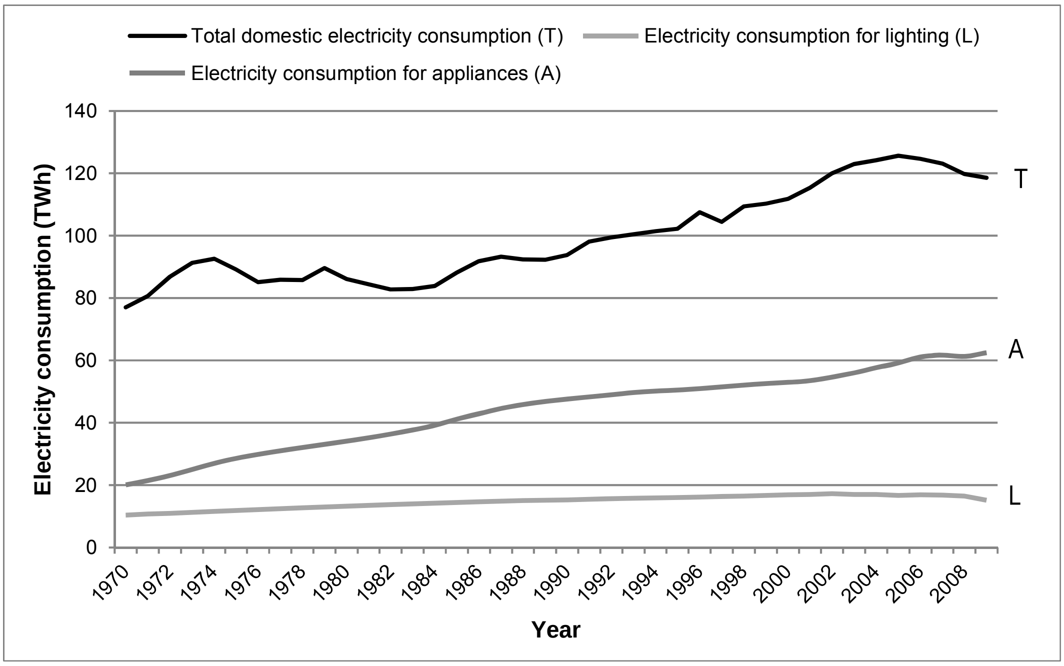


Figure 1-2 Domestic electricity consumption from 1970 to 2009. Building Research Establishment Housing Model for Energy Studies (1970-2008) (DECC 2013a), Cambridge Housing Model (2008 onwards) (Hughes 2011)

Traditionally, as space and water heating account for the highest proportion of energy consumption in the UK, around 82% in 2012 (DECC 2013b), these end-uses have been the primary target for energy efficiency measures as they have been considered to have the most potential to make significant energy and CO_2 emission reductions. However, in recent years, there has been growing concern about domestic electricity consumption, particularly due to the increased electricity use associated with the operation of domestic appliances (DECC 2012; EST 2012).

This concern is for three main reasons; firstly, electricity use currently emits almost three times as much CO_2 per kWh than the equivalent for gas. Natural gas, the primary fuel type for 80% of UK heating systems used for space and water heating (DCLG 2006), produces around 0.20 kg CO_2/kWh compared with 0.50 kg CO_2/kWh for electricity (Defra 2009a). Therefore in terms of CO_2 emissions electricity use has increased importance. Secondly, the price of electricity per kWh is more than three times higher than the price of gas (DECC 2012), so for the individual household, particularly now at a time of economic downturn, electricity accounts for a significant portion of their energy bill. Thirdly, electricity's proportion of UK domestic energy use is going to increase further as a consequence of shrinking energy consumption for space heating, due to improved thermal efficiency of the housing stock as a result of the increased installation of energy efficiency measures.

Primarily, the electricity supplied to UK homes is used to power lighting and appliances, with the exception of those homes with electric space or water heating. Figure 1-3 illustrates how electricity consumption is disaggregated in the average UK home (Zimmermann et al. 2012). It can be seen that lighting and appliances combined, identified with an asterisk (*), account for more than half of the total electricity consumed.

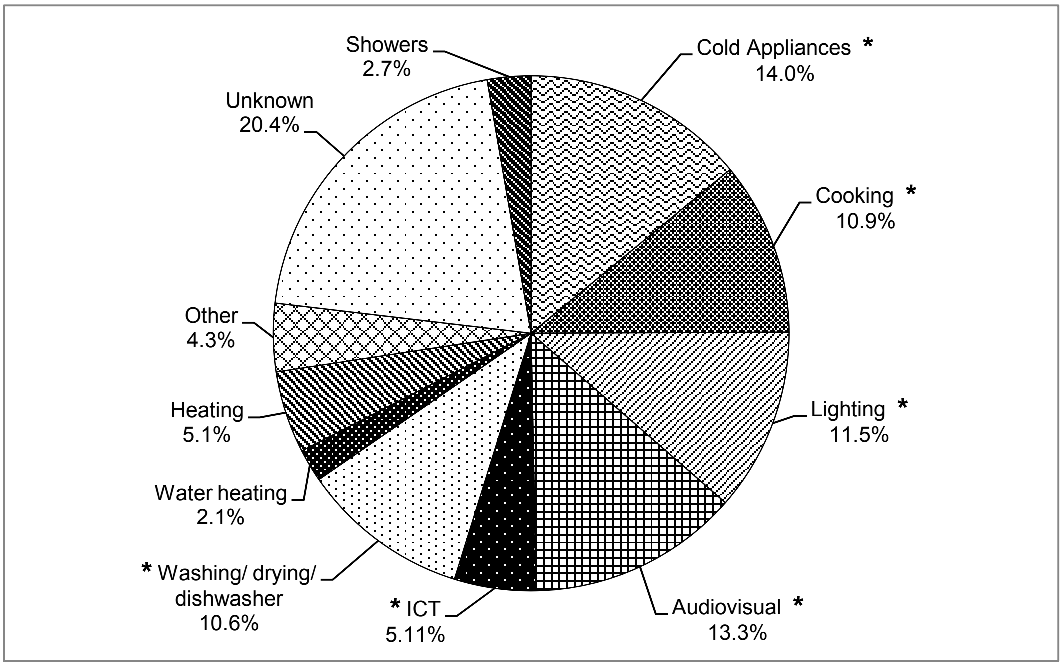


Figure 1-3 Domestic electricity consumption by end-use in 2011 (Zimmermann et al. 2012)

The electricity used for lighting in residential buildings has however been in decline since 2002, falling from 17.3 TWh to 15.2 TWh in 2009 (DECC 2012). This has been attributed to the removal of incandescent bulbs from the market and the Carbon Emissions Reduction Target (CERT) providing free low energy bulbs to homes. It has been suggested that potential reductions have however been mitigated by an increase in light fittings, particularly in kitchens and bathrooms (DECC 2012). The long-term trends in electricity consumption for lighting (Figure 1-2) however, show quite a different picture, as the annual electricity use for lighting has actually increased by nearly 50% from 1970 to 2009, growing year on year until 2002.

The increase in electricity consumption for appliance use over the same period of time has been even more dramatic, increasing 211% from 1970 to 2009 (Figure 1-2), equalling an annual growth of nearly 3% per year (DECC 2012). This has resulted in appliances' share of total domestic energy use increasing from less than 5% in 1970 to 12.5% in 2009. This large growth has been associated with three contributing factors: an increased ownership of domestic appliances in homes; increased use of appliances; and a greater use of cold appliances to store food (DECC 2012). These contributing factors are linked with wider societal changes, such as increased living standards, increased life expectancy, lifestyle changes, automation of jobs previously done by hand, higher disposable incomes, and increases in smaller and fragmented households (DECC 2012; Boardman et al. 2005; Herring 1995).

The increase in electricity used for both lighting and appliances has made this energy end-use the fastest growing in the UK domestic sector. Figure 1-4 shows this trend using data of UK domestic energy consumption by end-use from 1970 to 2012 (DECC 2013b). The growth in electricity consumption for appliance use is also widely anticipated to continue in the coming years (EST 2011; IEA 2009; EST 2006). This thesis investigates the variations in appliance electricity consumption, as dictated by the differences in ownership, power demand and use between high electrical energy consumers and low and medium electricity consumers.

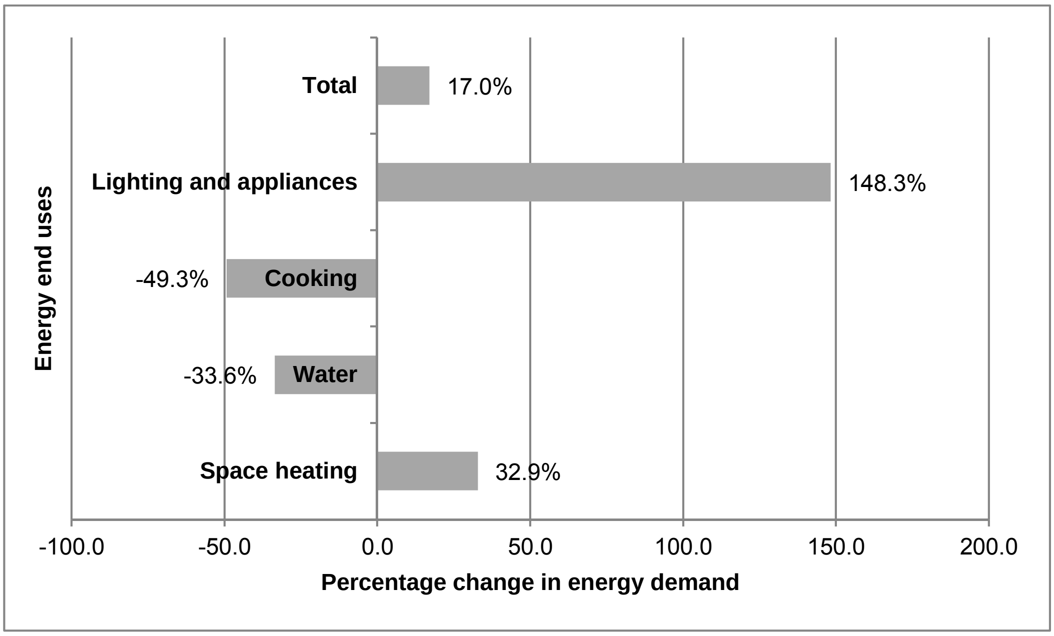


Figure 1-4 Percentage change in UK domestic energy use from 1970 to 2012 (DECC 2013b)

1.7 The skewed distribution of UK domestic electricity use and high electrical energy consumers

The amount of electricity used in individual UK homes varies considerably (Figure 1-5). A large range, as well as highly skewed distribution of electricity consumption exists for the UK domestic sector. Whilst there is an absolute lower bound to electricity demand there is no effective upper bound, with the upper quartile of electrical energy users consuming much more than the lower. By analysing households with an annual electricity consumption of up to 25,000 kWh (DECC 2011), a representation of the disproportionate domestic electricity use is evident; with 1.1% of the homes consuming 5% of the total electricity supplied to the whole domestic sector.

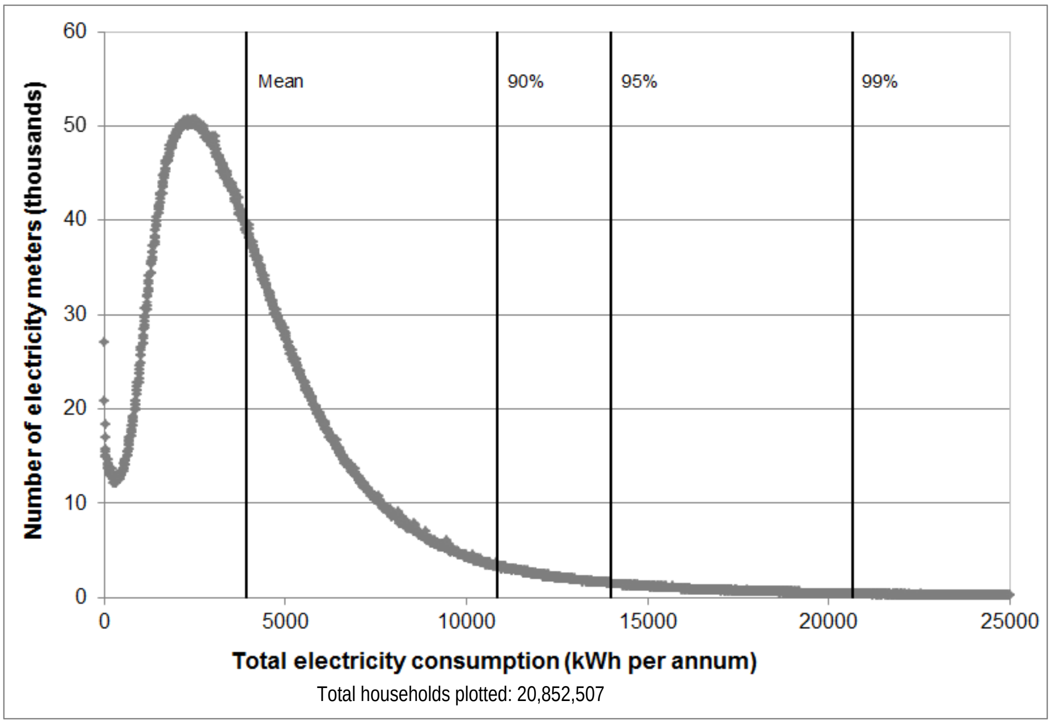


Figure 1-5 Distribution of UK domestic electricity use in 2007 (DECC 2011)

Unequal domestic electricity consumption has also been observed by the Building Research Establishment (BRE 2008), who analysed the metering data of the 7,370 households in England, that were part of the English House Condition Survey (EHCS) in 2001. The highest consuming 0.8% of the dwellings used over 5% of the total electricity.

Zimmermann et al. (2012) whilst monitoring the electrical power and energy consumption of 251 homes in England from May 2010 to July 2011 identified a wide range of annual electricity consumptions between the dwellings ranging from around 600 kWh to around

17,000 kWh per annum. The large variations in electricity use were evident regardless of whether electrically heated dwellings were included and whether the total annual electricity consumptions were normalised for floor area or number of occupants. The electricity demands of the dwellings were also found to vary greatly within house types (e.g. detached, semi-detached, etc.) and family compositions (household with children, single pensioner, etc.).

During a follow-up study of 36 UK 'low-energy' dwellings in Milton Keynes between 2005 and 2007, Summerfield et al. (2010) identified both the skewed distribution towards high consuming dwellings, but even more importantly that the skew is increasing over time. Those dwellings which were classified as high consumers in the original study in 1990 had disproportionately increased their electrical demand by the mid-2000's, whereas no significant change in usage was seen amongst those in the low and middle groups. The dwellings were grouped into thirds based on their total energy consumption in 1990 and were referred to as the low (n = 12), middle (n = 12) and high (n = 12) energy groups, and remained in the same groups for the subsequent follow-up analysis. The electricity consumption of the high consuming group rose by 72% from 13.8 kWh per day (equivalent, if representative, to 5,037 kWh pa) to 23.7 kWh per day (equivalent to 8,651 kWh pa) during the 17 years.

Previously, Summerfield et al. (2007), had observed similar trends amongst 14 of the dwellings in Milton Keynes. The dwellings that were initially monitored for energy use between 1989 and 1991 had increased electricity consumption by 31.6% in the period 2005-2006, with the largest increases amongst those households which were originally classified as high energy consumers in 1990. The same method of splitting the dwellings into three groups of one third each was used, although the high group in this case contained one less household (n = 4) than the low and middle energy groups. The high group's electricity usage increased by 75% to 28.3 kWh per day (equivalent to 10,330 kWh pa), and had 50% higher energy intensity at 172Wh/m^2 of total floor area. Moreover, the high group used more electricity than both the low and middle groups combined.

The uneven, as well as increasingly skewed demand for electricity was also recognised by Firth et al. (2008) during a two year electricity monitoring study of 72 UK households. The annual total electricity consumption of the social housing ranged from 902 kWh to 7,743 kWh. The dwellings were classified into low, medium, and high energy groups, based on their consumption in the first year of monitoring. Again, the dwellings were split into thirds with each energy group containing 24 households. At the end of the second year, those dwellings in the low energy group increased their total average consumption by 11%, the middle group decreased slightly (-0.7%), and the high group increased by 5.1% (4,841 kWh to 5,088 kWh).

Firth et al. (2008) established that the high and low energy using households were responsible for the overall increase in electricity consumption, which was through the increased electricity consumption of appliances that were continuously on (such as, burglar alarms, modems and telephones), in standby mode (such as TVs and other 'infotainment' equipment) or active (i.e. being used).

Given the immediate need for reduction of CO_2 emissions, these previous observations have substantial implications for energy policy. As high electricity consumers not only use more electricity, compared with others, but appear to be consuming even more electricity over time, it has been suggested that future UK energy policy might focus on reducing the demand of high electricity consumers in order to reduce overall CO_2 emissions (Summerfield et al. 2010; Lomas 2010; Firth et al. 2010; Firth et al. 2008; Summerfield et al. 2007). Therefore, understanding what drives high usage in domestic buildings is important to support decisions about how to reduce energy use and CO_2 emissions from this user group. The work reported in this thesis investigates the influence that socio-economic, technical and appliance related characteristics have on the likelihood of being a high electrical energy user, as well as a detailed analysis of the contributions of ownership, power demand and use of domestic appliances to high electrical energy demand.

1.8 Aim and objectives

This thesis presents an investigation of the socio-economic, technical and appliance related factors driving high electrical energy consumption in UK homes. This thesis has two main avenues of enquiry: a study of how the background socio-economic, technical and appliance related characteristics of UK homes affect the probability of a household being a high electrical energy consumer and a detailed appliance electricity monitoring study of the contributions of ownership, power demand and use of domestic appliances to high electrical energy demand. The overarching aim of this exploratory study is to:

Improve knowledge and understanding of the socio-economic, technical and appliance related factors affecting high electrical energy consumption in UK homes, with a particular focus on appliance electricity consumption.

To achieve this aim, the following research objectives were identified:

1. *Explore the variations in electricity consumption of a sample of UK homes and examine their change in electricity demand over time.*
2. *Identify the underlying socio-economic, technical and appliance related characteristics that affect the likelihood that a household will be a high electrical energy consumer in a sample of UK homes.*

3. *Establish the contributions of appliance ownership, power demand and use to high electrical energy demand in a sample of UK homes.*

4. *Provide recommendations to support policy aimed at reducing electricity use and CO_2 emissions from high electrical energy consuming homes in the UK.*

1.9 Thesis structure

This thesis has nine chapters. The chapters that follow this introduction are outlined below.

Chapter 2. Literature review 1: The socio-economic, technical and appliance related characteristics affecting electricity use in domestic buildings

Presents a review of the socio-economic, technical and appliance related characteristics that previous studies have identified that affect electricity use in domestic buildings. The review includes specific recognition of the factors that previous authors have linked to high electrical energy demand.

Chapter 3. Literature review 2: A review of appliance electricity monitoring studies in domestic buildings

Provides a review of previous and current appliance electricity monitoring studies in domestic buildings. The review provides the current state-of-the-art in appliance electricity monitoring, focusing on the specifications of the studies (i.e. the monitoring systems employed, the monitoring duration, logging interval used, appliances monitored, etc.).

Chapter 4. Research methodology

Outlines the methodology applied in this thesis to meet the aim and objectives of this thesis and to answer the research questions. This includes descriptions of the research design and research methods used, as well as the methods of data collection. This is followed by an account of the stages of data processing and methods of data analysis.

Chapter 5. Results: Variations in annual electricity use and changes in demand over time

Presents results of the annual electricity use and changes in demand over time of two samples of UK homes. The purpose of this chapter is to establish whether a skewed distribution of electricity consumption was evident amongst this thesis' samples of UK dwellings and to provide further evidence as to whether high electrical energy users are increasing their demand over time.

Chapter 6. Results: The socio-economic, technical and appliance drivers of high electrical energy use

Presents results of an odds ratio analysis of how the background socio-economic, technical and appliance related characteristics of UK homes affect the probability of a household being a high electrical energy consumer.

Chapter 7. Results: Variations in appliance electricity consumption, ownership, power demand and use

Presents results of a detailed appliance electricity monitoring study, highlighting variations in electricity consumption on a broad range of domestic appliance types between low, medium and high electricity consumers. The variations in appliance ownership, power demand and use between the electrical demand groups are investigated to explain the evident differences in the appliance electricity consumptions of the groups.

Chapter 8. Discussion

Discusses the current research findings with respect to previous research and describes potential implications for policy aimed at reducing energy use and CO_2 emissions from high electrical energy consumers in the UK.

Chapter 9. Conclusions

Presents a summary of key findings from the research and a discussion of the contributions to knowledge. Limitations of the current research are highlighted and potential areas of future research identified.

Chapter 2

Literature Review 1: The socio-economic, technical and appliance related characteristics affecting electricity use in domestic buildings

2.1 Introduction

This chapter presents a literature review undertaken to examine existing research that has investigated the key factors that influence domestic electricity consumption. According to previous research, electricity consumption in residential buildings is affected by: (i) socio-economic factors; (ii) technical factors; and (iii) appliance related factors. It is therefore necessary to understand these factors and their impact on the electricity use of high electrical energy demand dwellings.

The review focuses on the socio-economic, technical and appliance related factors that explain variations in the electricity consumption of domestic buildings. It begins with a review of previous studies aimed at identifying and assessing relationships between these factors and the electricity use of both UK and international residential buildings (section 2.2). It continues with a review of the socio-economic, technical and appliance related factors mentioned in the previous studies (section 2.3 to 2.5). The factors are reviewed separately, stating whether a significant effect (positive or negative) or no effect on domestic electricity use was identified by previous researchers. Finally, the findings of the review are summarised (section 2.6). This review highlights the current gaps in knowledge and establishes the need to better understand the underlying factors affecting domestic electricity consumption in UK, specifically for high electrical energy consuming homes.

2.2 Previous studies investigating the factors affecting domestic electricity consumption

A number of studies have been conducted in both the UK and globally to investigate the socio-economic, technical and appliance related factors that influence electricity consumption in residential buildings (Zhou & Teng 2013; Bedir et al. 2013; Blázquez et al. 2013; Carlson et al. 2013; Hamilton et al. 2013; Kavousian et al. 2013; Wyatt 2013; Bartusch et al. 2012; Brounen et al. 2012; Carter et al. 2012; McLoughlin et al. 2012; Sanquist et al. 2012; Ndiaye & Gabriel 2011; Wiesmann et al. 2011; Leahy & Lyons 2010; Baker & Rylatt 2008; Druckman & Jackson 2008; Louw et al. 2008; Yohanis et al. 2008; Santamouris et al. 2007; Summerfield et al. 2007; Tso & Yau 2007; Bartiaux & Gram-Hanssen 2005; Genjo et al. 2005; Gram-Hanssen et al. 2004; Filippini & Pachauri 2004; Larsen & Nesbakken 2004; Parker 2003; Halvorsen & Larsen 2001; Tiwari 2000; Haas et al. 1998; Nielsen 1993; Munley et al. 1990; Cramer et al. 1985; Parti & Parti 1980).

Previous studies examining the factors affecting the electricity consumption of residential buildings have been undertaken using either a top-down (e.g. Blázquez et al. 2013) or bottom-up approach (e.g. Bedir et al. 2013; McLoughlin et al. 2012; Sanquist et al. 2012; Baker & Rylatt 2008; Tso & Yau 2007). A top-down approach is used in studies which consider the national level and aim to attribute the electricity consumption of the housing stock to the characteristics of the dwellings (Grandjean et al. 2012). A bottom-up approach is used in studies based at the individual dwelling level aimed at establishing relationships between household characteristics and electricity use, which are then extrapolated to the entire housing stock (McLoughlin et al. 2012). A combination of the top-down and bottom-up approaches are used in Wiesmann et al. (2011) and Druckman & Jackson (2008).

Statistical/regression and econometric methods are the most commonly implemented to investigate the influence of socio-economic, technical and appliance related factors on domestic electricity consumption. The statistical/regression method can be considered both a top-down and a bottom-up method of analysis and is particularly useful for analysing large datasets. Examples of statistical/regression studies are Kavousian et al. (2013), Brounen et al. (2012), Sanquist et al. (2012), Baker & Rylatt (2008), Bartiaux & Gram-Hanssen (2005), and Tiwari (2000). A variant of the statistical/regression approach is the econometric method based on a Conditional Demand Model (CDA) first developed by Parti & Parti (1980). This method, following a top-down approach, is used to forecast electrical energy demand as a function of macro-economic variables. Previous econometric studies include Zhou & Teng (2013), Blázquez et al. (2013), Larsen & Nesbakken (2004), Filippini & Pachauri (2004), and Parti & Parti (1980).

Depending on the approach and method used, research studies in this area typically require a large amount of data. This data can vary in detail and can be collected at a national or individual dwelling level. National studies based on a top-down approach use aggregated data (e.g. national energy statistics, gross domestic product (GDP), and population figures). Dwelling level studies based on a bottom-up approach use data at a high level of detail (e.g. individual technical characteristics of dwellings, socio-economic characteristics of occupants, domestic appliance information).

Different data collection methods have been used in previous studies, including personal interviews (Tso & Yau 2007; Gram-Hanssen et al. 2004), phone surveys (Ndiaye & Gabriel 2011), electricity meter readings provided by energy providers (Wyatt 2013; Bartusch et al. 2012; Bartiaux & Gram-Hanssen 2005), household electricity monitoring, including sub-metering of appliances (Kavousian et al. 2013; McLoughlin et al. 2012; Ndiaye & Gabriel 2011; Yohanis et al. 2008; Gram-Hanssen et al. 2004; Parker 2003), questionnaires (Kavousian et al. 2013; Bartusch et al. 2012; Baker & Rylatt 2008; Genjo et al. 2005; Gram-Hanssen et al. 2004), energy audits (Ndiaye & Gabriel 2011), national household surveys (Wyatt 2013; McLoughlin et al. 2012; Sanquist et al. 2012; Yohanis et al. 2008; Gram-Hanssen et al. 2004), and gathering information from utility bills (Sanquist et al. 2012; Genjo et al. 2005).

Several previous studies have analysed extensive national energy surveys collected at a dwelling level. This includes Wyatt (2013), Hamilton et al. (2013), and Druckman & Jackson (2008) in the UK; McLoughlin et al. (2012) and Leahy & Lyons (2010) in Ireland; Sanquist et al. (2012) and Carlson et al. (2013) in the USA; Gram-Hanssen et al. (2004) and Nielsen (1993) in Denmark; Brounen et al. (2012) in the Netherlands; Wiesmann et al. (2011) in Portugal; Blázquez et al. (2013) in Spain; Lam (1998) in China; and Tiwari (2000) in India.

In the UK, large datasets of domestic electricity consumption tend to be collected by government agencies and energy utilities (DECC 2013a; DECC 2013b; EST 2012; DECC 2011; EST 2011). These datasets provide information regarding residential electricity consumption at a national level and have been used in a number of studies seeking to understand the socio-economic, technical and appliance related factors that influence household electricity consumption.

Wyatt (2013) undertook a statistical analysis to examine the drivers of domestic electricity consumption in relation to the technical characteristics of the dwellings and socio-economic characteristics of the occupants in 3,528,100 English households. Annual electricity consumption data from 2004 to 2008 was provided by UK energy suppliers. Modelled data for the property attributes and socio-economic characteristics of occupants were supplied by Experian.

Hamilton et al. (2013) conducted an analysis on approximately 13 million homes in the UK included in the Homes Energy Efficiency Database (HEED), along with annual metered gas and electricity use for the period 2004 to 2007. The study examined the influence of dwelling characteristics and tenure type on domestic energy demand.

Following a mixed methods approach, Druckman & Jackson (2008) sought to understand how residential energy use is related to the socio-economic characteristics of UK households at three different levels: (a) national level; (b) specific small geographical areas; and (c) 'typical' types of households. For electricity consumption at the national level, the analysis used a national dataset for 2004 and 2005 to explore the relationship of domestic electrical energy use with income and household composition. At the lower levels, the study also observed the relationship of domestic electricity use with type of dwelling, tenure, household composition and rural/urban location.

Outside the UK, McLoughlin et al. (2012) examined the influence of dwelling and occupant characteristics on domestic electricity consumption in Ireland. The study analysed data obtained from a smart metering survey of a representative sample of approximately 4,200 dwellings. The study collected the electricity consumption of the households at half hourly internals for a 6 month period. In addition, detailed socio-economic and technical characteristics of each home were recorded. A multiple linear regression model was applied to total electricity consumption, maximum demand, load factor and time of use of maximum electricity demand for the different socio-economic and technical variables.

Furthermore, Leahy & Lyons (2010) applied an ordinary linear least squares regression using the Irish Household Budget Survey (2004-2005), which contains data regarding 6,884 private households in Ireland. Using estimates of the amount of energy used by households from previous energy bills, the authors identified the determinants of energy use while controlling for household characteristics and the ownership of domestic appliances.

Based on a sample of US households, Carlson et al. (2013) analysed how many and which domestic appliances contribute to household electricity use reported in the End-Use Residential Energy Consumption Survey (RECS) completed in the USA in 2001 and 2005. The survey contained data of 4,382 houses.

In addition, Sanquist et al. (2012) applied a multivariate statistical approach to investigate the influence of lifestyle factors on residential electricity consumption in the USA. The study used data collected by the national household energy survey conducted by the US Energy Information Administration in 2001 and 2005. The survey included data regarding the physical characteristics of the dwellings, household demographic characteristics, appliance information (such as age, size and use), fuel types and energy consumption.

Annual electricity bills were provided by 2,690 in the 2001 survey and 2,165 households in the 2005 survey. Five of the sixteen variables analysed were found to have a significant influence on the total electrical energy demand, accounting for more than 40% of the variance in electricity consumption.

In Denmark, Gram-Hanssen et al. (2004) studied the impact of socio-economic background variables on household electrical energy use, taking into account the practices of the families' everyday life in Denmark. The study was based on the combination of two different sets of data: (i) a dataset of over 50,000 households coupling electricity use with socio-economic data of the household members (obtained from the Danish personal data net), and data on the buildings (from the Danish national building data net); (ii) a dataset created as part of the European Project EURECO of 100 households with electricity consumption collected every 10 minutes during one month in either 1999 or 2000 for each appliance and most lamps. A detailed analysis of the use of appliances was combined with socio-economic and building data collected using a questionnaire and with qualitative interviews on everyday life and electricity use in 10 households. The results revealed the significant influence of some of the background variables and concluded that background variables can only describe 30-40% of the variation in household electricity consumption.

Previously, Nielsen (1993) analysed the results of a research project undertaken by the Danish Ministry of Energy on electricity saving in the domestic sector. Using a multiple regression analysis, the study assessed the influence of number of children and adults, dwelling size, household income and stock of electrical appliances on annual electricity consumption in approximately 1,500 households in Denmark in 1992. Results revealed that 64% of electricity consumption can be attributed to the number of adults in the house, the number of children, appliance consumption and the total floor area.

Brounen et al. (2012) conducted an analysis on a sample of more than 300,000 homes in the Netherlands aimed at quantifying the extent to which electricity use is determined by the technical specifications of the dwelling compared with the demographic characteristics of the residents. The technical and socio-demographic data (collected in 2008 and 2009) and annual electricity consumption (collected in 2007) of each household was provided by the Bureau of Statistics in the Netherlands.

Using both a top-down and bottom-up approach, Wiesmann et al. (2011) undertook an econometric study of Portuguese residential electricity consumption with a focus on the influence of household and dwelling characteristics. The study also estimated the relationship between dwelling and household characteristics on per capita residential electricity consumption. Two different databases were used for the analysis: top-down data at municipality level for 2001, and bottom-up data from a Portuguese consumer expenditure survey collected in 2005 and 2006 which included 7,925 households in the Portuguese mainland.

Following a top-down approach, Blázquez et al. (2013) undertook an empirical analysis of residential electricity demand in 47 Spanish provinces for the period 2000 to 2008. The study aimed to establish the characteristics affecting Spanish residential electricity use, specifically, electricity price, income, and weather conditions.

Lam (1998) performed regression and correlation analyses to investigate the relationships between domestic electricity consumption and economic variables and climatic factors in Hong Kong, China. The study used economic and energy data for the 23 year period from 1971 to 1993.

Tiwari (2000) developed a regression model using a household survey undertaken in 1987–1988 by the Bombay Metropolitan Regional Development Authority (BMRDA), which included a total of 6,358 dwellings in Bombay, India. The study analysed the influence of technical and socio-economic factors on electricity consumption.

Other previous studies have analysed data collected in smaller samples of households but instead have more disaggregated and detailed information available (Kavousian et al. 2013; Bartusch et al. 2012; Ndiaye & Gabriel 2011; Baker & Rylatt 2008; Santamouris et al. 2007; Summerfield et al. 2007; Tso & Yau 2007; Bartiaux & Gram-Hanssen 2005).

Kavousian et al. (2013) studied structural and behavioural determinants of residential electricity consumption by developing a regression model. The electricity consumption and socio-economic and technical characteristics of 952 households in the USA were analysed in the study. Electricity consumption was collected by smart meters at a 10 minutely interval over 238 days in 2010. The data collection also included an online survey of household data, including climate and location, building characteristics, appliance stock, demographics, and occupants' behaviour.

Bartusch et al. (2012) applied statistical analysis to assess the variance in annual electricity consumption of Swedish single-family homes, as well as to estimate the impact of household and building characteristics. 595 households from three geographically separated areas in Central Sweden were included in the study. The analyses were based on hourly electricity meter readings of the individual households, which were subsequently used to estimate their annual electricity consumption. These data were provided by the local distribution system operators. Household and building features were collected by questionnaire survey.

Ndiaye & Gabriel (2011) used data collected in 270 dwellings in Oshawa (Ontario, Canada) to generate regression models of the electricity consumption of the city's residential dwellings. Data regarding the socio-economic and technical characteristics of the households were collected by phone surveys and energy audits. Electricity consumption data was gathered during one year by smart meters installed in the dwellings. The final model obtained in the study explained 75% of the variance in electricity consumption.

Baker & Rylatt (2008) used multiple regression to determine the strength of the relationships and identify the most statistically significant indicators of differences in electricity consumption in 148 households in the cities of Leicester (48 terraces) and Sheffield (52 detached and 48 semi-detached dwellings). The study was based on a dataset collected by means of a questionnaire survey in 2005, supported by annual gas and electricity meter data obtain from the energy suppliers and floor-area estimates derived from a GIS.

Santamouris et al. (2007) studied the relationship between family income and annual expenditure on electricity for 945 households located in Athens, Greece, in 2004. Data were collected through interviews with family members and inspections of each building. The sample was divided into seven income groups and a detailed analysis of the influence of family income on electricity demand, annual electricity cost per person, and annual electricity cost per unit of area was undertaken.

Summerfield et al. (2007) undertook a follow-up study in 2005–2006 of 15 low-energy dwellings in Milton Keynes, UK, that were originally monitored for energy consumption from 1989 to 1991. The results from both periods were compared by classifying the dwellings into three groups of low, middle, and high-energy users. In 2005–2006, it was found that the high group had consumed more energy than the other two groups combined and its electricity usage had risen by 75%. The study investigated the effects of floor area, income and number of occupants on the increase in electricity use.

Tso & Yau (2007) applied three modelling techniques for the prediction of electrical energy consumption (regression analysis, decision tree and neural networks) on a dataset of 1,516 households in Hong Kong, China. Data was collected by means of a two-phase survey carried out in the summer and winter of 1999–2000 (Tso & Yau 2003). During an in home interview, household characteristics, dwelling type and appliance ownership and efficiency data was collected. A diary was then used to record usage patterns of selected major appliances every half-hour for one week.

Bartiaux & Gram-Hanssen (2005) extended the research developed by Gram-Hanssen et al. (2004) to Belgium and compared household electricity consumption (excluding heating) in both Denmark and Belgium on the basis of survey data, national statistics and consumption data provided by the utilities. The database of approximately 50,000 households in Denmark (Gram-Hanssen et al. 2004) and data from nearly 500 households in Belgium collected in 2004 were used in the analysis. The study aimed to understand which social, cultural and technical factors influence the level of household electricity consumption. The study also looked at whether ownership or use of appliances explained the greater electricity consumption in Belgium compared with Denmark. The results revealed that background variables can explain 30-40% of the variation in Danish electricity consumption, whereas the Belgian data could only explain 10-30% of the variation. Moreover, the analysis showed that the number and use of appliances better explain which households consume most electricity rather than the energy efficiency of the appliances.

The influence of the socio-economic, technical and appliance related factors on specific electrical end-uses have also been the focus of extensive research (Bedir et al. 2013; Yohanis et al. 2008; Genjo et al. 2005; Parker 2003; Cramer et al. 1985).

Bedir et al. (2013) focused on electricity consumption for lighting and appliances in Dutch dwellings. The study was based on a dataset of 304 households in the Netherlands, which covered household characteristics, individual characteristics, economic characteristics, occupancy (number of people and duration of occupation in each room), dwelling characteristics, appliance use and lighting devices. The data were collected by questionnaires in winter 2008. Three regression models were built for the direct and indirect determinants: the first was based on the total duration of use of appliances (direct) and dwelling and room occupancy (indirect); the second was based on the number of lights and household appliances (direct) and the characteristics of the dwelling (indirect), and the third was based on the total duration of use of appliances (direct) and the characteristics of the dwelling (indirect).

Yohanis et al. (2008) studied the effect of occupancy and dwelling characteristics on domestic electric use in 27 representative dwellings in Northern Ireland. For this study, electricity measurements of lighting, kitchen and entertainment appliances were taken using a half-hour load meter installed in series with the normal utility meter in each home. The duration of the study was 20 months (between December 2003 and February 2004). The socio-economic and technical data was collected by a detailed survey with householders.

Genjo et al. (2005) performed a multivariate analysis to evaluate the relationship between end-use electricity consumption on lighting and appliances and influencing factors in 238 Japanese households. Electricity consumption data was obtained from the household’s electricity bills and a questionnaire survey was conducted to collect data on household characteristics and ownership of electric appliances. Sixty-seven appliances were included in the analysis, which were classified in the categories cooking (18 appliances), cooling and space heating (13), audio visual and information (14), household and sanitation (12) and others (10). The final regression model explained 60% of electricity consumption from lighting and appliances.

Parker (2003) undertook a monitoring study of both total electricity consumption as well as a number of end-uses in 171 residences in Central Florida, USA, in 1999. The data collected was analysed applying a linear regression to study the effect of socio-economic and technical characteristics on electricity consumption in a hot climate. Data was collected on a fifteen minutely basis on several end-uses, including space cooling (accounting for 33% of the electricity consumption by end-use in the sample of the study), heating (7%), water heating (13%), range and cooking (2%), clothes drying (5%), and swimming pools (7%) electricity use. The electricity consumption of "other" appliances (accounting for a 34%) such as lighting, refrigerator, ceiling fan, and plug loads were subtracted from the total. It is important to note that this study was carried out in a hot climate where electricity is commonly used to heat and cool homes, something which is not replicated in more temperate climates such as the United Kingdom and Ireland (McLoughlin et al. 2012).

Cramer et al. (1985) analysed the summer electricity consumption for appliances and air conditioning use in 192 dwellings in California, USA, in 1981. By means of a linear regression analysis, which included appliance ownership, frequency of use, location in the dwelling, published average efficiencies, and estimated seasonality factors, the study concluded that the appliance and air conditioning related factors were able to explain 51% of the variance in summer electricity consumption. Moreover, the results revealed that social factors were able to explain 34% of the variance in summer electricity consumption. The combined model of engineering and social determinants was able to explain 58% of the variance in summer electricity consumption.

While previous studies have primarily used a statistical/regression analysis, others have applied an econometric method. This method was first developed by Parti & Parti (1980) using a Conditional Demand Model (CDA). Parti & Parti (1980) analysed monthly electricity bills of 5,286 households in San Diego, USA, against appliance ownership figures and demographic variables. The electricity demand was disaggregated into 16 different end-uses.

Haas et al. (1998) applied a cross-section analysis on a sample of about 500 households in Austria. Monthly electricity bills were regressed against economic (both income and electricity price), and social-demographic parameters to assess the impact of these factors on the electrical energy demand for appliances.

Munley et al. (1990) focused on the factors that influence domestic electricity consumption for appliance use of multi-family, renter-occupied households. During a 12 month period (1978-1979), the electricity consumption of 44 households in Washington D.C., USA, was metered and recorded.

Halvorsen & Larsen (2001) applied an econometric analysis on data from Norway's Annual Survey of Consumer Expenditure and tax statistics for the period 1976 to 1993 to identify the factors determining residential electricity consumption in Norway. The data set (of an annual net sample of between 900 and 1,400 households) contained information about the household's expenditure on electricity, income and other household characteristics and appliance ownership.

Larsen & Nesbakken (2004) also applied an econometric conditional demand model to estimate domestic electricity consumption for different end-uses. The study used data for appliance ownership, demographic and economic variables collected from 1,453 households in Norway during a 1990 energy survey. The electricity consumption of each household was obtained from the utility supplier or from a home survey.

Filippini & Pachauri (2004) developed three electricity demand functions using disaggregated level survey data for about 30,000 households in India to understand the extent to which household characteristics influence variations observed in households' electricity demand.

Louw et al. (2008) studied the determinants of electricity demand for 92 newly electrified low-income households in a rural site in South Africa. Using an econometric regression model, metered electricity consumption data, socio-economic survey data and appliance ownership data collected in 2001 and 2002 were analysed to determine the drivers of electricity consumption within these households.

Carter et al. (2012) estimated an electricity demand function using survey data of a sample of 130 Barbadian households in 1997. The survey was conducted by home interview and collected information about the electricity consumed by households, dwelling characteristics, appliance stock and demographic data. Each household's metered energy consumption data were sourced directly from the electric utility. The model accounted for 85% of the cross-sectional variation in electricity consumption.

Zhou & Teng (2013) used annual urban household survey data of 5,980 households located in 17 cities in south west China from 2007 to 2009 to estimate the income and price elasticities of residential electricity demand, along with the effects of socio-demographic and dwelling related variables. The empirical results were estimated by an ordinary least squares model.

2.3 Socio-economic factors that influence domestic electricity consumption

The studies outlined in the previous section have identified a range of socio-economic factors that affect the electricity consumption of domestic buildings. These factors can be classified as: (i) number of occupants; (ii) family composition, including presence of children, presence of teenagers, number of adults, and presence of elderly people (over 65 years old); (iii) age of household responsible person; (iv) employment status of household responsible person; (v) education level of household responsible person; (vi) socio-economic classification of household responsible person; (vii) tenure type; (viii) household income; and (ix) disposal income.

The following subsections provide a synthesis of the socio-economic factors identified in the literature, citing those authors that have observed a significant effect on domestic electricity use as well as those that have not. A summary of the socio-economic factors affecting domestic electricity consumption is provided in Table 2-1.

2.3.1 Number of occupants

The effect of number of occupants on the electricity consumption in residential buildings has been extensively studied. Previous research has concluded that there is a significant positive relationship between the household size and domestic electricity use, suggesting that as the number of people living in a dwelling increases, the more electricity that is used (Zhou & Teng 2013; Kavousian et al. 2013; Brounen et al. 2012; Ndiaye & Gabriel 2011; Leahy & Lyons 2010; Baker & Rylatt 2008; Druckman & Jackson 2008; Yohanis et al. 2008; Summerfield et al. 2007; Tso & Yau 2003; Bartiaux & Gram-Hanssen 2005; Genjo et al. 2005; Gram-Hanssen et al. 2004; Parker 2003; Halvorsen & Larsen 2001; Tiwari 2000; Lam 1998; Haas 1997).

Leahy & Lyons (2010) established that households occupied by only one person consume significantly less electricity than households with two or more occupants, calculating that a one person household uses approximately 14.5 kWh less electricity per week than a two person household. Yohanis et al. (2008) examined the average daily annual electricity consumption per unit floor area for dwellings occupied by one, two, three or four or more occupants and established that households with four or more occupants consume the largest amount of electricity and there is a small difference between the consumption in households with two or three occupants. In addition, Tiwari (2000) recognised that a five-member family would have 23% more electricity expenditure compared to a two-member family. The study also quantified the effect of an additional household member on electricity consumption and concluded that it increases use by 7.7%. Similarly, Zhou & Teng (2013) found an increase of 8% for every additional family member. In comparison, Brounen et al. (2012) established that an additional occupant in the household increases electricity use by about 21%.

Other authors have focused on the effect of household size and dwelling type on the electricity consumption. Bartiaux & Gram-Hanssen (2005) and Gram-Hanssen et al. (2004) determined that the number of people living in Danish households was the single most significant explanation for electricity consumption and established that the effect of household size was similar for three types of dwelling (detached, semi-detached and apartment). In Belgium, the number of occupants made a significant difference both for detached and semi-detached houses, but not in apartments (Bartiaux & Gram-Hanssen 2005). Correspondingly, Baker & Rylatt (2008) found this effect to be stronger in terrace and detached houses in the UK.

The effect of number of occupants on particular electrical end-uses has also been considered in the literature. Parker (2003) studied the electricity demand for hot water heating and concluded that the number of occupants has the strongest influence on variation of electricity consumption for hot water heating. Moreover, Genjo et al. (2005) and Haas (1997) determined that number of occupants significantly influences the electricity consumption for lighting and appliances. In particular, Genjo et al. (2005) calculated that electric consumption for lighting and appliances would increase 230 kWh per person with the growth of household size.

Contrary to previous studies, Filippini & Pachauri (2004) determined that household size has a negative correlation with electrical energy consumption in domestic buildings in India, suggesting that houses with a large number of members (greater than 6) have lower electricity consumption than those which have fewer members.

Other authors have concluded that the effect of household size on electricity demand is insignificant (Bartusch et al. 2012; Carter et al. 2012; Louw et al. 2008). Louw et al. (2008) established that the number of household members does not affect the electricity consumption for newly electrified low-income African households, as most of the electrical end-uses of household members are shared simultaneously between occupants (e.g. cooking or watching TV). Bartusch et al. (2012) studied the effect of the number of household members on the annual electricity consumption per square meter of heated living space and concluded that there is no significant variance in those households using an electric heating system.

In addition to the effect of household size on total electricity consumption of residential buildings, several studies have also looked at the correlation between per capita electricity use and size of household. For example, Druckman & Jackson (2008) found that per capita electrical energy use was negatively correlated to household size, suggesting that a household with more people is generally more efficient in terms of per capita energy use, demonstrating the economies of scale that are achieved by a larger household. Yohanis et al. (2008) also studied the electricity consumption per unit floor area per occupant and, on this basis, established that electricity consumption per person decreases as the number of occupants increases, this effect is more significant in large dwellings, as the number of occupants per dwelling get smaller. Similarly, Kavousian et al. (2013) found a non-linear relationship between household electricity consumption and number of occupants, leading to the conclusion that larger households have higher total electricity consumption but lower per capita consumption. Similar results were found by Zhou & Teng (2013), Blázquez et al. (2013), Wiesmann et al. (2011), Bartiaux & Gram-Hanssen (2005), and Gram-Hanssen et al. (2004).

2.3.2 Family composition

A significant effect of family composition (i.e. presence of children, teenagers, adults and elderly people) on electricity consumption in residential buildings has been widely acknowledged in the literature (Wyatt 2013; Brounen et al. 2012; Bartusch et al. 2012; McLoughlin et al. 2012; Wiesmann et al. 2011; Leahy & Lyons 2010; Bartiaux & Gram-Hanssen 2005; Gram-Hanssen et al. 2004; Nielsen 1993; Cramer et al. 1985). On the contrary, other studies have reported no significant effect on electricity demand (Bedir et al. 2013; Leahy & Lyons 2010; Bartiaux & Gram-Hanssen 2005; Cramer et al. 1985).

The presence of children and its influence on electricity consumption has been proved to be significant by McLoughlin et al. (2012), who determined that adults living with children consume considerably more electricity than those living alone or with other adults. Brounen et al. (2012) revealed that households with children consume almost one-fifth more electricity than families without children, and this effect becomes stronger when the age of the children increases. The authors believe that this is due to the fact that older children watch more television, use personal computers, and are frequent users of gaming devices. Similar results were published in Wiesmann et al. (2011) and Nielsen (1993).

Contrary to previous studies, Gram-Hanssen et al. (2004) and Bartiaux & Gram-Hanssen (2005) revealed that the presence of one or more small children (0-9 years old) in a household has a negative effect on consumption, indicating that the presence of children decreases mean electricity consumption. This effect was found to be significant in the Danish household sample in Gram-Hanssen et al. (2004) and Bartiaux & Gram-Hanssen (2005), but not significant in the Belgian households in Bartiaux & Gram-Hanssen (2005). Cramer et al. (1985) found that the presence of children under 3 does not have any significant influence, but children greater than 3 years old have a significant effect on electricity consumption. A non-significant effect of the presence of children on electricity demand was also reported by Bedir et al. (2013) and Leahy & Lyons (2010), indicating that there is no significant difference between the electricity use in households occupied by families with children and households comprised of adults only.

The impact of presence of teenagers has also been reported in different studies. Bartiaux & Gram-Hanssen (2005) and Gram-Hanssen et al. (2004) revealed that presence of teenagers (13 -19 year olds) is a significant explanatory variable of domestic electricity consumption and has a positive effect on consumption, meaning that mean electricity consumption is significantly higher in households with teenagers. This effect was found to be significant in Danish households (Bartiaux & Gram-Hanssen 2005; Gram-Hanssen et al. 2004), but not significant in Belgian households (Bartiaux & Gram-Hanssen 2005). Cramer et al. (1985) established that the presence of teenagers significantly increases summer electricity demand. Additionally, Bartusch et al. (2012) found a significant variance in annual electricity consumption per square metre of heated living space for families with teenagers in households using an electric space heating system.

Furthermore, Wyatt (2013) and Nielsen (1993) stated that there is a positive relationship between the number of adults residing in a dwelling and the amount of electricity consumed.

Leahy & Lyons (2010) determined that single parent households use significantly more electricity than two parent households. The results suggested that a one parent household uses 9.11 kWh more electricity per week than a two parent household.

Moreover, Bartusch et al. (2012) established that there is a significant variance in annual electricity consumption per square meter of heated living space in households occupied by adult couples using electric space heating systems.

Bedir et al. (2013) and Cramer et al. (1985) recognised that the presence of elderly people over 65 in a household has no significant effect on domestic electricity demand. In addition, Brounen et al. (2012) determined that elderly households consume about two to four per cent less electricity than middle-aged married couples, it was suggested that although the elderly may spend more time at home, they seem to have fewer energy-consuming appliances.

Brounen et al. (2012) extended the analysis of family composition and determined that per capita electricity use is significantly lower in dwellings occupied by female or non-native households. According to the authors, this might be due to an unobserved wealth effect. Gram-Hanssen et al. (2004) found that the citizenship of a family affected the annual electricity consumption of semi-detached houses, with non-western citizens using on average 800 kWh per year less than Danish or Western citizens.

2.3.3 Age of household representative person

According to Yohanis et al. (2008), the household responsible person (HRP) dictates a household's behaviour and consequently has an influence on electricity consumption. For this reason, the HRP's age and its effect on domestic electricity consumption has been the focus of a number of previous studies, which have reported very similar effects for different age ranges. In general, the literature suggests that there is a significant effect between the HRP age and electricity consumption and that consumption is higher in those households where the HRP age is approximately in the range of 50 and 65 years old. For households with a HRP under 50 years old and older than 65 years old the electricity consumption is consistently reported to be lower.

In particular, Leahy & Lyons (2010) indicated that HRPs between 45 and 64 years old use significantly more electricity than HRPs in the range of 35 - 44 years old. However, as the age of the HRP increases past 64, electricity use significantly decreases. Equal results were reported by Yohanis et al. (2008), who found that households occupied by a HRP in the range of 50 - 65 years old consume the largest amount of electricity during the day and households with HRPs older than 65 years old use the smallest amount. The authors believe that this is because the 50 - 65 years bracket includes those with higher household incomes, bigger houses and a broad range of appliances. Correspondingly, McLoughlin et al. (2012) found that electricity consumption for younger HRPs (aged between 18 and 35 years old) was significantly lower when compared to the other two age categories, 36 - 55 and 56 plus. In this case, the authors believe that this could be attributed to middle aged HRPs having more children living at home (thus having a higher number of occupants) and increased occupancy patterns (i.e. dwelling occupants at home for longer periods of the day). Consistent with pervious authors, Kavousian et al. (2013) revealed that HRPs older than 55 and between 19 and 35 have lower electricity consumption. The authors suggest that the older household members tend to be more conscious about the way they use electricity, and also tend to use less electric gadgets, whereas, household members between 19 and 35 are more likely to have a full-time job and are therefore less at home. Filippini & Pachauri (2004) found that houses with a younger HRP (less than 45 years old) have lower electricity consumption than those which have older household heads. The significant effect of HRP age on electricity consumption was also acknowledged by Bedir et al. (2013) and Tiwari (2000).

Differing from previous studies, Zhou & Teng (2013) established that HRPs older than 50 years consume approximately 3% more electricity consumption than other HRP age ranges. The authors argued that the electricity consumption of old households is relatively higher because old people generally stay at home longer than young people.

While the significant influence of HRP age has been widely reported, Bartiaux & Gram-Hanssen (2005) did not find any correlation between the age of the oldest person in the household and electrical energy use in either Denmark or Belgium.

2.3.4 Employment status of household representative person

The effect of the HRP's employment status on domestic electricity demand has consistently been reported as insignificant (McLoughlin et al. 2012; Leahy & Lyons 2010; Baker & Rylatt 2008; Yohanis et al. 2008; Cramer et al. 1985). Yohanis et al. (2008) did not find any significant effect of the HRP's employment status on electricity consumption but observed that homes that were occupied during the day by unemployed or retired people had generally smaller electricity consumptions than homes unoccupied during the day. On the contrary, Baker & Rylatt (2008) established that people regularly working from home consume more electricity and concluded that this variable is a strong indicator of differences in electricity consumption.

Differing from previous studies, Bedir et al. (2013) determined a significant effect of the occupation of the household responsible person on electricity use.

2.3.5 Education level of household representative person

Differing effects of the HRP's education level on domestic electricity demand have been reported in the literature. Gram-Hanssen et al. (2004) observed that mean domestic electricity consumption decreases significantly with the level of education in Denmark, whereby, households occupied by family members with a long education appear to use significantly less electricity than households occupied by family members with no further education than primary school. Households with no further education than primary school use on average over 200 kWh per year more than households with high education. On the contrary, Zhou & Teng (2013) determined that families with higher education have higher electricity consumption. According to the authors, the difference in household electricity consumption among different education groups is more evident between households whose heads have educational backgrounds of primary school or below and above primary school.

According to Bedir et al. (2013), McLoughlin et al. (2012), and Leahy & Lyons (2010) education level does not significantly affect electricity use.

2.3.6 Socio-economic classification of household representative person

While the social group of the HRP has been observed to have a significant effect on electricity demand by both McLoughlin et al. (2012) and Cramer et al. (1985), Leahy & Lyons (2010) reported that the socio-economic status does not significantly affect electricity use.

Specifically, McLoughlin et al. (2012) and Cramer et al. (1985) revealed that the HRP's social class had a negative effect on total electricity consumption when compared against higher professionals, suggesting that higher professionals are inclined to consume more electricity than lower professionals with the former tending to live in larger dwellings and have a greater number of electrical appliances, suggesting a possible income effect.

2.3.7 Tenure type

Different significant and non-significant effects of tenure type on the electricity consumption of residential buildings have been reported in the literature. While some studies have observed a significantly higher consumption in privately owned houses (Hamilton et al. 2013; Wyatt 2013; Wiesmann et al. 2011; Yohanis et al. 2008), others have reported a significantly higher demand in rented dwellings (Ndiaye & Gabriel 2011). Other studies have concluded that all tenure types have no significant effect on electricity use (Bedir et al. 2013; Kavousian et al. 2013; Leahy & Lyons 2010; Tso & Yau 2007).

Yohanis et al. (2008) established an impact of private ownership on electricity use. According to the authors, houses that are privately owned show a significantly higher electricity demand profile than rented homes. They believe that this effect is due to the fact that in Northern Ireland the majority of social housing is rented by lower income families from the Northern Ireland Housing Executive. Similarly, Wyatt (2013) observed that council housing and housing association homes had the lowest average consumption for electricity at 3,737 kWh, and owner-occupied households had the highest at 4,607 kWh, whilst, privately rented homes were in the middle at 4,047 kWh. The author mentions that tenure is likely to be correlated with wealth and that rented properties are generally smaller than privately owned dwellings. Hamilton et al. (2013) determined that owner occupied dwellings use 25% more electricity than rented houses. The results also establish that electricity demand in private rental dwellings have a very similar demand to social rentals. Wiesmann et al. (2011) also concluded that houses that are privately owned consume significantly more electricity than rented homes.

Contrary to previous studies, Ndiaye & Gabriel (2011) also identified that tenure type has a significant influence on electrical energy demand but, in this case, a higher electricity consumption was observed in rented rather than owned houses. The authors believe that this effect is due to the fact that, often, rented homes have all utilities included in the rent, so renters do not necessary pay the extra cost associated with excessive electricity consumption and thereby have less incentive to save energy.

2.3.8 Household income

The relationship between household income and electrical energy consumption has been the subject of extensive research. A large number of studies have concluded that electrical energy consumption increases with income (Zhou & Teng 2013; Bedir et al. 2013; Carlson et al. 2013; Wyatt 2013; Wiesmann et al. 2011; Louw et al. 2008; Yohanis et al. 2008; Santamouris et al. 2007; Summerfield et al. 2007; Bartiaux & Gram-Hanssen 2005; Genjo et al. 2005; Gram-Hanssen et al. 2004; Halvorsen & Larsen 2001; Tiwari 2000; Lam 1998; Haas 1997; Cramer et al. 1985; Parti & Parti 1980).

In particular, Yohanis et al. (2008) determined that households with large incomes (over £30,000 per annum) use 2.5 times more electricity on average in the evenings compared with low-income households (less than £10,000 per annum). The authors explain this effect arguing that larger income households commonly have a greater number of occupants and larger homes, as well as diverse type and range of electric appliances. Similarly, Wyatt (2013) found that the electricity consumption of the highest income group (more than £75,000 per annum) was 1.9 times higher than the lowest income group (less than £10,000 per annum). In addition, Santamouris et al. (2007) found an almost linear relationship between the annual expenditure on electricity and the family income, whereby the expenditure on electricity of high income families was 1.6 times higher than low income families.

Genjo et al. (2005) also determined that electrical energy consumption increases linearly with annual income. In this case, the authors specifically studied the influence of income on the electricity consumption for lighting and appliance use and found a significant relationship and estimated that electricity consumption for lighting and appliances increases 350 kWh for every $27,000 increase in annual household income.

In addition, Gram-Hanssen et al. (2004) and Bartiaux & Gram-Hanssen (2005) observed the effect of income on electricity use in different dwelling types in Denmark and established that household income was the variable with the second largest explanatory power for electricity consumption in residential buildings. This variable was found to be significant for three dwelling types (detached, semi-detached and apartment). A comparative analysis undertaken by Bartiaux & Gram-Hanssen (2005) revealed that in Belgium, net-income is the only variable always significant for the three dwelling types.

Santamouris et al. (2007) analysed the annual electricity cost per unit of floor area by income group and determined that the high income group (more than €100,000 per annum) pays almost 38% more electricity per square meter than the low income group (less than €9,000 per annum). The authors stated that this increased cost may be explained by the considerably higher installed power and use of electrical appliances and equipment in households of the richest groups. This was also stated by Carlson et al. (2013) and Haas (1997), who determined that higher income households generally consume more electricity due to a higher ownership of appliances. In addition, Santamouris et al. (2007) examined the annual electricity cost per person by income group. In this case, the results showed a U-shaped figure and a difference between the poorest and richest group of 6% annual electricity cost per person by income group. Wiesmann et al. (2011) also studied the electricity consumption per capita by income and established that an increase in income results in a higher per capita electricity consumption. Santamouris et al. (2007) also calculated the annual electricity cost per unit of floor area and person and revealed that the lower the income, the higher the cost of electricity per person and unit floor area. The results determined that people with a low income pay almost 67% more per person and square metre than those with a high income.

Other studies have also identified a statistically significant effect of household income on electricity consumption, but determined that electricity demand rises relatively little with income, suggesting that electricity consumption in low and high income households does not differ much because electricity is considered a necessity good in both groups. For example, Zhou & Teng (2013) established that an increase of 1% in household income results in an increase of only 0.14 % in household electricity consumption. Equally, Halvorsen & Larsen (2001) found that when income changes by 1%, electricity consumption changes by about 0.13% on average.

Whilst many previous studies have concluded that domestic electricity demand is positively correlated with income, other authors have not identified any significant relationship (Kavousian et al. 2013; Carter et al. 2012; Sanquist et al. 2012; Tso & Yau 2007; Filippini & Pachauri 2004). Specifically, Sanquist et al. (2012) suggested that income is not a particularly good predictor of electrical energy consumption as it adds less than 1% to the prediction of electricity use. Carter et al. (2012) added that the effect of income on electricity demand may be better predicted by the rate of appliance purchasing (number and efficiency). Kavousian et al. (2013) did not observe any statistical effect of income on electricity consumption and argued that this could be explained by the similar socio-economic status of the household sample of the study.

2.3.9 Disposal income

The effect of disposal income on the electricity demand of residential buildings has been consistently reported as significant and positive, indicating that electricity demand increases with increased disposal income of the household (Blázquez et al. 2013; Brounen et al. 2012; Leahy & Lyons 2010; Druckman & Jackson 2008).

In particular, Leahy & Lyons (2010) indicated that as the log of household disposable income increases by one unit, electricity use increases by 3.67 kWh per week. Similarly, Brounen et al. (2012) found that a 1% increase in disposable income is associated with an 11% increase in household electricity use.

Table 2-1 Summary of the effects of socio-economic factors on electricity consumption in domestic buildings studied in the literature

Factors	Total number of citations	Significant positive effect on domestic electricity consumption	Significant negative effect on domestic electricity consumption	No effect on domestic electricity consumption
Number of occupants	22	18 (Zhou & Teng 2013), (Kavousian et al. 2013), (Brounen et al. 2012), (Ndiaye & Gabriel 2011), (Leahy & Lyons 2010), (Baker & Rylatt 2008), (Druckman & Jackson 2008), (Yohanis et al. 2008), (Summerfield et al. 2007), (Tso & Yau 2007), (Bartiaux & Gram-Hanssen 2005), (Genjo et al. 2005), (Gram-Hanssen et al. 2004), (Parker 2003), (Halvorsen & Larsen 2001), (Tiwari 2000), (Lam 1998), (Haas 1997)	1 (Filippini & Pachauri 2004)	3 (Bartusch et al. 2012), (Carter et al. 2012), (Louw et al. 2008)
Family composition				
Presence of children	11	5 (Brounen et al. 2012), (McLoughlin et al. 2012), (Wiesmann et al. 2011), (Nielsen 1993), (Cramer et al. 1985)	2 (Bartiaux & Gram-Hanssen 2005), (Gram-Hanssen et al. 2004)	4 (Bedir et al. 2013), (Leahy & Lyons 2010), (Bartiaux & Gram-Hanssen 2005), (Cramer et al. 1985)
Presence of teenagers	5	4 (Bartusch et al. 2012), (Bartiaux & Gram-Hanssen 2005), (Gram-Hanssen et al. 2004), (Cramer et al. 1985)	0	1 (Bartiaux & Gram-Hanssen 2005)
Number of adults	4	4 (Wyatt 2013), (Bartusch et al. 2012), (Leahy & Lyons 2010), (Nielsen 1993)	0	0
Presence of elderly people (over 65 years old)	3	0	1 (Brounen et al. 2012)	2 (Bedir et al. 2013), (Cramer et al. 1985)
Age of household responsible person	9	8 (Zhou & Teng 2013), (Bedir et al. 2013), (Kavousian et al. 2013), (McLoughlin et al. 2012), (Leahy & Lyons 2010), (Yohanis et al. 2008), (Filippini & Pachauri 2004), (Tiwari 2000)		1 (Bartiaux & Gram-Hanssen 2005)

Factors	Total number of citations	Significant positive effect on domestic electricity consumption	Significant negative effect on domestic electricity consumption	No effect on domestic electricity consumption
Employment status of household responsible person	6	1 (Bedir et al. 2013)		5 (McLoughlin et al. 2012), (Leahy & Lyons 2010), (Baker & Rylatt 2008), (Yohanis et al. 2008), (Cramer et al. 1985)
Education level of household responsible person	5	1 (Zhou & Teng 2013)	1 (Gram-Hanssen et al. 2004)	3 (Bedir et al. 2013), (McLoughlin et al. 2012), (Leahy & Lyons 2010)
Socio-economic classification of household responsible person	3	2 (McLoughlin et al. 2012), (Cramer et al. 1985)	0	1 (Leahy & Lyons 2010)
Tenure type	9	5 (Hamilton et al. 2013), (Wyatt 2013), (Ndiaye & Gabriel 2011), (Wiesmann et al. 2011), (Yohanis et al. 2008)		4 (Bedir et al. 2013), (Kavousian et al. 2013), (Leahy & Lyons 2010), (Tso & Yau 2007)
Household income	23	18 (Zhou & Teng 2013), (Bedir et al. 2013), (Carlson et al. 2013), (Wyatt 2013), (Wiesmann et al. 2011), (Louw et al. 2008), (Yohanis et al. 2008), (Santamouris et al. 2007), (Summerfield et al. 2007), (Bartiaux & Gram-Hanssen 2005), (Genjo et al. 2005), (Gram-Hanssen et al. 2004), (Halvorsen & Larsen 2001), (Tiwari 2000), (Lam 1998), (Haas 1997), (Cramer et al. 1985), (Parti & Parti 1980)	0	5 (Kavousian et al. 2013), (Carter et al. 2012), (Sanquist et al. 2012), (Tso & Yau 2007), (Filippini & Pachauri 2004)
Disposal income	4	4 (Blázquez et al. 2013), (Brounen et al. 2012), (Leahy & Lyons 2010), (Druckman & Jackson 2008)	0	0

2.4 Technical factors that influence domestic electricity consumption

Several technical factors related to the dwelling characteristics have also been studied in the literature. These factors are: (i) dwelling type; (ii) dwelling age; (iii) number of rooms; (iv) number of bedrooms; (v) number of floors; (vi) total floor area; (vii) use of HVAC systems, including electric space heating, air-conditioning and mechanical ventilation; (viii) use of electric water heating systems, including ownership of an electric water heating system and number of showers and baths per week; and (ix) use of low-energy lighting.

The following subsection provides an overview of the technical factors reported in the literature which have a significant or insignificant effect on domestic electricity demand. Table 2-2 provides a summary of the factors and presents the studies where these factors have been cited in the literature.

2.4.1 Dwelling type

The relationship between dwelling type and electrical energy consumption in residential buildings has been the subject of extensive research. A large number of studies have concluded that, in general, electrical energy consumption increases with the level of detachment of the dwelling, suggesting that detached houses consume more electricity than semi-detached houses, and these consume more than terrace houses and apartments (Bedir et al. 2013; Hamilton et al. 2013; Wyatt 2013; Brounen et al. 2012; McLoughlin et al. 2012; Wiesmann et al. 2011; Leahy & Lyons 2010; Yohanis et al. 2008; Bartiaux & Gram-Hanssen 2005; Gram-Hanssen et al. 2004; Larsen & Nesbakken 2004; Tiwari 2000).

In particular, Leahy & Lyons (2010) identified that semi-detached, terrace houses and apartments use significantly less electricity than detached houses. According to the study, semi-detached and terrace houses use 5.61 kWh less electricity per week than detached houses, and apartments 10.1 kWh less electricity per week than detached houses. Gram-Hanssen et al. (2004) and Bartiaux & Gram-Hanssen (2005) also observed a higher average consumption in detached houses than semi-detached houses and apartments in both Denmark and Belgium and determined that detached houses consume approximately double the amount of electricity per year than apartments. Similarly, Halvorsen & Larsen (2001) established that living in a block of flats significantly influences household electricity demand and estimated that electricity consumption is reduced by about 2,800 kWh per year compared to other households. Wyatt (2013) established that, on average, detached houses are responsible for significantly higher consumption than other dwelling types, purpose-built flats and mid-terrace houses consume the least electricity, and bungalows, semi-detached and end-of-terrace houses are fairly similar in terms of electricity consumption levels. Similar results were also reported by Bedir et al. (2013), Hamilton et al. (2013), Brounen et al. (2012), Wiesmann et al. (2011), Yohanis et al. (2008), Larsen & Nesbakken (2004), and Tiwari (2000).

In general, the literature suggests that the influence of dwelling type on electricity consumption is related to the differences in floor area between dwelling types (Wyatt 2013; Brounen et al. 2012; McLoughlin et al. 2012). However, Yohanis et al. (2008) looked at the monthly electricity consumption normalised by floor area for different types of dwellings and the results indicated a similar variation in the average consumption for each type of house (between 2.5 and 5.0 kWh m^{-2}). The profile of the building occupants has also been identified as a possible reason for variations in electricity use between dwelling types, in particular, Wyatt (2013) found that bungalows had a low electricity consumption, despite being detached, and relates this effect to the fact that bungalows are more often occupied by elderly residents that perhaps have reduced electricity demands than family residents. Similar results were found by Firth et al. (2010).

Kavousian et al. (2013) and Baker & Rylatt (2008) did not observe any significant correlation between electricity consumption and dwelling type.

2.4.2 Period dwelling was built

Previous studies have observed higher domestic electricity consumptions in newer houses, which has commonly been attributed to the penetration of air conditioning and other high-consumption appliances (Chong 2012; Halvorsen & Larsen 2001). Other studies have observed the opposite, reporting a decrease in household electricity consumption for newer houses, associating the pattern to improved insulation and use of more efficient appliances, lighting and air conditioning (Wyatt 2013; Bartusch et al. 2012; Brounen et al. 2012; Wiesmann et al. 2011; Leahy & Lyons 2010; Baker & Rylatt 2008; Genjo et al. 2005; Parker 2003; Tiwari 2000). A non-significant effect was also reported by Kavousian et al. (2013), Hamilton et al. (2013) and Tso & Yau (2007).

Wiesmann et al. (2011) found that dwelling age was a statistically significant predictor of electricity use with a negative influence on total electrical energy demand, suggesting that newer buildings consume significantly less electricity than older houses. Leahy & Lyons (2010) observed that homes built before 1918 use significantly more electricity per week (5.34 kWh) than those built between 1918 and 1960, due to increased heat loss associated with less insulation and use of electric heating and power showers instead of gas central heating. Homes built later than 2000 used significantly less electricity than dwellings built in the period 1918-1960. Similar results were reported by Parker (2003). Parker (2003) concluded that older homes have greater electrical energy use for both space heating and cooling and revealed that older houses in the study were often less well insulated and had less efficient equipment, which could explain the effect. Brounen et al. (2012) observed that houses built in the periods 1980 - 1990 and 1990 - 2000 consume 3.7% and 1.3% more electricity than houses built later than 2001. Contrary to previous studies, the authors attribute the negative relationship between property age and electricity consumption to the wealth of the occupants and the availability of more energy-efficient appliances in modern homes. A negative correlation was also found by Genjo et al. (2005) between dwelling age and the electricity consumed by lighting and appliances. A significant and negative correlation between dwelling age and electricity demand of residential buildings was also reported by Wyatt (2013), Bartusch et al. (2012), Baker & Rylatt (2008), and Tiwari (2000).

Differing from other research, Chong (2012) determined that dwelling age is positively correlated with electricity consumption, suggesting that electricity consumption is higher in newer rather than older dwellings. In particular, the study found that new buildings (1970-2000) have a statistically significant higher electricity consumption than old buildings (pre 1970) in a region of Southern California. The authors comment that although newer buildings are subject to stricter building energy codes, they are larger and more likely have air conditioning due to the climatic conditions in California. Halvorsen & Larsen (2001) also found that electricity consumption declines with the age of the dwelling, suggesting newer dwellings consume more electricity than older ones. This finding was attributed to a higher wiring capacity in newly built houses and the greater use of equipment.

Contradicting other studies that report either a significant positive or significant negative influence on electrical energy demand, other authors have concluded that the effect of dwelling age is insignificant (Hamilton et al. 2013; Kavousian et al. 2013; Tso & Yau 2007). Hamilton et al. (2013) determined that there is no dwelling age effect on electricity consumption. Electricity use appeared to be very similar in old and new dwellings, with a slight increase in newer dwellings. Kavousian et al. (2013) attributes the insignificant effect to the fact that the physical conditions of the buildings in the sample of the study had been maintained through time, possibly due to the enforcement of building regulations. However, the results suggest that houses that were built before 1975 on average consumed less electricity than the houses that were built between 1993 and 2003. According to the authors, a potential explanation for this trend is the increased penetration of air conditioning and other high consumption appliances in newer houses.

2.4.3 Number of rooms

A significant positive relationship between the numbers of rooms and electricity consumption in domestic buildings has been reported in the literature, which suggests that as the number of rooms increases, more electricity is used (Bedir et al. 2013; Leahy & Lyons 2010; Baker & Rylatt 2008; Tiwari 2000). Leahy & Lyons (2010) determined that dwellings with only one or two rooms use significantly less electricity than five room houses. Similarly, Bedir et al. (2013) found that the number of rooms, and in particular the number of study/hobby rooms were significantly positively correlated with electricity consumption. Tiwari (2000) observed that an additional room in the house can lead to 11% more electricity expenditure.

On the contrary, Brounen et al. (2012) determined that an additional room decreases electricity consumption by 0.5%.

Differing from previous results, Wiesmann et al. (2011) determined that the number of rooms per dwelling has no significant effect on electrical energy demand.

2.4.4 Number of bedrooms

Previous research has reported that there is a significant and positive relationship between the number of bedrooms and domestic electricity consumption (Hamilton et al. 2013; Carter et al. 2012; McLoughlin et al. 2012; Baker & Rylatt 2008; Yohanis et al. 2008). Whereby, an increase in the number of bedrooms results in an increase in household electrical energy demand.

In particular, McLoughlin et al. (2012) established that for each additional bedroom, total electricity consumption on average increases 349 kWh over a six month period. In addition, Hamilton et al. (2013) found that electricity demand increases linearly from 1 to 4 bedrooms and that the increase from 4 to more than 5 bedrooms is 12%. Yohanis et al. (2008) observed that load peaks of five bedroom households are over three times more than those of two bedroom households. The authors explain the influence of number of bedrooms and electricity use by arguing that households with more bedrooms have more appliances and a larger consumption of electricity for lighting.

Contrary to previous studies, Bedir et al. (2013) revealed that the number of bedrooms has a negative impact on electricity consumption, attributed to the fact that a bedroom is normally used only in the evening, at night and early in the morning for a short while and do not contain a lot of electrical appliances, compared with other types of rooms in the house.

2.4.5 Number of floors

Bartusch et al. (2012) determined that the number of stories does not represent any statistically significant variance in annual electricity consumption per square meter of living space within different household groupings according to heating system.

2.4.6 Floor area

The significant influence of the floor area of a dwelling on domestic electricity consumption has been widely reported in the literature. Previous research consistently suggests that dwellings with a larger floor area have higher electricity consumption.

Bartiaux & Gram-Hanssen (2005) and Gram-Hanssen et al. (2004) observed that total floor area was the variable with the third largest explanatory power for electricity consumption in residential buildings in Denmark. Similar results were found by Baker & Rylatt (2008) in a UK-based study. This variable was found to be significant for three dwelling types (detached, semi-detached and apartment). In Belgium, the floor area was only significant for detached houses (Bartiaux & Gram-Hanssen 2005). Nielsen (1993) quantified the relationship between floor area and electricity consumption and established that when the dwelling size increases 1%, the electricity consumption rises 0.61%. Similarly, Zhou & Teng (2013), observed that a 1% increase in dwelling size results in a 0.1% increase in household electricity consumption. Filippini & Pachauri (2004) studied the electricity consumption of urban Indian households and established that a 1% increase in the number of feet squared results in a 0.2% increase in household electricity consumption.

Comparable results are observed in Carlson et al. (2013), Hamilton et al. (2013), Kavousian et al. (2013), Wyatt (2013), Wiesmann et al. (2011), Yohanis et al. (2008), Summerfield et al. (2007), and Halvorsen & Larsen (2001).

The influence of floor area on electricity consumption has been commonly related to the demand for space heating and cooling. For example, Zhou & Teng (2013) stated that dwelling size positively affects household electricity consumption, because larger houses need more electrical cooling in the summer, and heating in the winter. Tso & Yau (2007) established that floor area is statistically significant in relation to summer domestic electric consumption due to cooling systems but not in winter period. Similarly, Parker (2003) observed the influence of floor area on space heating and space cooling electricity use and concluded that larger homes have greater electrical energy use and demand for both space heating and cooling. Bartusch et al. (2012) also determined that there is an influence of the size of the heated living space area on annual electricity consumption. In particular, the results suggest that this influence is stronger in households whose main heating system is an electric boiler and weakest in those whose main heating system is a combined electric and non-electric boiler. Similar results were reported by Larsen & Nesbakken (2004).

Contrary to previous studies, Bedir et al. (2013) and Genjo et al. (2005) concluded that domestic electricity demand is not significantly correlated with dwelling floor area. In particular, Genjo et al. (2005) determined that total floor area had a very small influence on the electricity consumption for lighting and appliances. Bedir et al. (2013) believe that this insignificant effect can be explained by the similar architectural characteristics between dwellings in the sample studied.

2.4.7 Presence of electric space heating, ventilation and air-conditioning systems

The effect of the use of electric space heating, ventilation and air-conditioning on electrical energy demand in domestic buildings has been addressed in a number of previous studies.

Several authors have studied the influence of different space heating systems on total household electricity consumption (Bedir et al. 2013; Kavousian et al. 2013; Bartusch et al. 2012; Ndiaye & Gabriel 2011; Leahy & Lyons 2010; Baker & Rylatt 2008; Larsen & Nesbakken 2004; Halvorsen & Larsen 2001). The results consistently agree that there is a significant and positive effect of the use of an electric space heating system on electricity use. Larsen & Nesbakken (2004) estimated the difference in electricity consumption for households with portable electric heaters, electric under floor heating and electric central heating with other households and found that all have a significant impact on electricity consumption. The results revealed that households with portable electric heaters and/or electric under floor heating use 3,700 kWh more electricity than households without such a system. Differing from previous studies, McLoughlin et al. (2012) found that space heating type had no significant influence on electricity consumption. However, the authors believe that these conflicting results are due to a very low penetration of electric heating (less than 3%) in the household sample in Ireland.

The significant and positive effect of air conditioning on electrical energy demand in residential buildings has been consistently reported by earlier studies primarily based in locations with a hot summers, such as the South-East of Canada (Ndiaye & Gabriel 2011), hot climatic zones in the USA (Sanquist et al. 2012; Cramer et al. 1985), south west China (Zhou & Teng 2013), and Hong Kong (Tso & Yau 2007). In particular, Tso & Yau (2007) observed that air conditioning consumes on average 59% of the electricity in a typical household in Hong Kong during the summer. On the contrary, Kavousian et al. (2013) did not find any correlation between electricity consumption and the number of air conditioning systems in California, USA.

Bedir et al. (2013) found that mechanical or balanced ventilation is not a significant predictor of electricity consumption.

2.4.8 Presence of electric hot water heating systems

Several studies have observed a significant influence of the use of electric hot water heating systems on the electrical energy demand of residential buildings (Kavousian et al. 2013; McLoughlin et al. 2012; Ndiaye & Gabriel 2011; Leahy & Lyons 2010; Baker & Rylatt 2008; Tso & Yau 2007; Larsen & Nesbakken 2004). Consistently, the results suggest that the use of electric water heating is positively correlated with electrical energy demand. In particular, Larsen & Nesbakken (2004) identified a significant relationship between electricity consumption and the use of an electric hot water heating system. The authors concluded that electricity consumption is 2,684 kWh higher for the households taking showers and 1,014 kWh higher for households taking baths which are heated using an electric water heater compared with other households.

Other authors have also observed a statistically significant correlation between the number of showers per week heated using an electric hot water heating system and domestic electricity demand (Bedir et al. 2013; Baker & Rylatt 2008). Bedir et al. (2013) added that there is also a significant correlation between electricity consumption and the number of baths per week heated using an electric hot water heating system, as well as the duration of each shower.

2.4.9 Presence of low-energy lighting

While Bedir et al. (2013) and Kavousian et al. (2013) concluded that the use of energy-efficient lights is correlated with lower electrical energy consumption, Bartiaux & Gram-Hanssen (2005) determined that there is no significant correlation between having low-energy lights and electricity consumption.

Table 2-2 Summary of the effects of technical factors on electricity consumption in domestic buildings reported in the literature

Factors	Total number of citations	Significant positive effect on domestic electricity consumption	Significant negative effect on domestic electricity consumption	No effect on domestic electricity consumption
Dwelling type	14	12 (Bedir et al. 2013), (Hamilton et al. 2013), (Wyatt 2013), (Brounen et al. 2012), (McLoughlin et al. 2012), (Wiesmann et al. 2011), (Leahy & Lyons 2010), (Yohanis et al. 2008), (Bartiaux & Gram-Hanssen 2005), (Gram-Hanssen et al. 2004), (Larsen & Nesbakken 2004), (Tiwari 2000)		2 (Kavousian et al. 2013), (Baker & Rylatt 2008)
Dwelling age	14	2 (Chong 2012), (Halvorsen & Larsen 2001)	9 (Wyatt 2013), (Bartusch et al. 2012), (Brounen et al. 2012), (Wiesmann et al. 2011), (Leahy & Lyons 2010), (Baker & Rylatt 2008), (Genjo et al. 2005), (Parker 2003), (Tiwari 2000)	3 (Hamilton et al. 2013), (Kavousian et al. 2013), (Tso & Yau 2007)
Number of rooms	6	4 (Bedir et al. 2013), (Leahy & Lyons 2010), (Baker & Rylatt 2008), (Tiwari 2000)	1 (Brounen et al. 2012)	1 (Wiesmann et al. 2011)
Number of bedrooms	6	5 (Hamilton et al. 2013), (Carter et al. 2012), (McLoughlin et al. 2012), (Baker & Rylatt 2008), (Yohanis et al. 2008)	1 (Bedir et al. 2013)	0
Number of floors	1	0	0	1 (Bartusch et al. 2012)
Total floor area	20	18 (Zhou & Teng 2013), (Carlson et al. 2013), (Hamilton et al. 2013), (Kavousian et al. 2013), (Wyatt 2013), (Bartusch et al. 2012), (Wiesmann et al. 2011), (Baker & Rylatt 2008), (Yohanis et al. 2008), (Summerfield et al. 2007), (Tso & Yau 2007), (Bartiaux & Gram-Hanssen 2005), (Filippini & Pachauri 2004), (Gram-Hanssen et al. 2004), (Larsen & Nesbakken 2004), (Parker 2003),	0	2 (Bedir et al. 2013), (Genjo et al. 2005)

Factors	Total number of citations	Significant positive effect on domestic electricity consumption	Significant negative effect on domestic electricity consumption	No effect on domestic electricity consumption
		(Halvorsen & Larsen 2001), (Nielsen 1993)		
Use of HVAC systems				
Presence of electric space heating system	9	8 (Bedir et al. 2013), (Kavousian et al. 2013), (Bartusch et al. 2012), (Ndiaye & Gabriel 2011), (Leahy & Lyons 2010), (Baker & Rylatt 2008), (Larsen & Nesbakken 2004), (Halvorsen & Larsen 2001)	0	1 (McLoughlin et al. 2012)
Presence of air-conditioning	5	4 (Sanquist et al. 2012), (Ndiaye & Gabriel 2011), (Tso & Yau 2007), (Cramer et al. 1985)	0	1 (Kavousian et al. 2013)
Presence of mechanical ventilation	1	0	0	1 (Bedir et al. 2013)
Use of electric water heating system				
Presence of an electric water heating system	7	7 (Kavousian et al. 2013), (McLoughlin et al. 2012), (Ndiaye & Gabriel 2011), (Leahy & Lyons 2010), (Baker & Rylatt 2008), (Tso & Yau 2007), (Larsen & Nesbakken 2004)	0	0
Number of showers and bath per week	2	2 (Bedir et al. 2013), (Baker & Rylatt 2008)	0	0
Presence of low-energy lighting	3	0	2 (Bedir et al. 2013), (Kavousian et al. 2013)	1 (Bartiaux & Gram-Hanssen 2005)

2.5 Appliance factors that influence domestic electricity consumption

It has been observed in the literature that electrical appliances make a very significant contribution to a household's electricity consumption. This impact not only relates to the ownership rate of each type of appliance, but also to the power demand and frequency of use.

The following subsection presents the appliance related factors: (i) ownership of appliances; (ii) use of appliances; and (iii) power demand of appliances. Each type of appliance mentioned in previous studies is included in the review, indicating whether its influence on domestic electricity consumption is significant. The appliance related factors are summarised in Table 2-3.

2.5.1 Ownership of appliances

The relationship between appliance ownership (i.e. the number and type of appliances owned by households), and electricity consumption has been the subject of extensive research.

A significant and positive effect of the total number of appliances owned on domestic electricity demand has been acknowledged by several authors. Halvorsen & Larsen (2001) established that, in general, electricity consumption rises with the stock of electrical appliances and that this stock of appliances has a relatively large impact on electricity consumption. In particular, Nielsen (1993) determined that a 1% increase in appliance ownership, results in a 0.35% rise in electricity consumption. Similarly, Genjo et al. (2005) observed that the electric consumption for lighting and appliances increases on average 62 kWh for every additional appliance owned. Moreover, Carlson et al. (2013) concluded that 12 specific appliances types can explain up to 80% of a household's electricity consumption and between 3 and 5 appliance types describe 50% of household electricity use. According to Bedir et al. (2013), number of appliances explains 21% of the variance in electricity consumption between dwellings. In addition, Cramer et al. (1985) observed that the location of the appliances in a dwelling is also a significant contributing factor. Wiesmann et al. (2011) and Tiwari (2000) also reported a significant influence of the number of appliances on electricity use.

The significant influence of the ownership of specific types of appliances on domestic electricity use has also been studied in detail. This relates to the ownership of (i) office IT appliances, (ii) entertainment appliances, (iii) HVAC appliances, (iv) major cooking appliances, (v) minor cooking appliances, (vi) preservation and cooling appliances, (vii) washing appliances, (viii) laundry appliances, (ix) building maintenance appliances, and (x) hygiene and leisure appliances.

The significant effect of the ownership of IT appliances such as desktop computers and laptops on electricity consumption has been acknowledged by Zhou & Teng (2013), McLoughlin et al. (2012), Baker & Rylatt (2008) and Bartiaux & Gram-Hanssen (2005). In particular, Zhou & Teng (2013) determined that households that own a computer consume approximately 10% more electricity compared with those without a computer. McLoughlin et al. (2012) concluded that computers (both desktop and laptop) had a significant effect on electricity use. Desktop computers were found to be the third largest contributors to electricity consumption, behind dishwashers and tumble dryers. Moreover, Baker & Rylatt (2008) established that the number of PCs in use have the strongest correlation with total electricity consumption compared to other home appliances. However, Leahy & Lyons (2010) observed that the ownership of a home computer was not a statistically significant predictor of electricity use.

In relation to the ownership of entertainment appliances, several authors have observed a significant influence of the ownership of appliances such as a television, portable television, video player/recorder, video console and CD player on the electrical energy demand of residential buildings. Regarding the effect of the ownership of televisions, several studies consistently agree that households owning a TV have significantly higher electricity consumption than those without (Kavousian et al. 2013; McLoughlin et al. 2012; Baker & Rylatt 2008; Bartiaux & Gram-Hanssen 2005; Genjo et al. 2005; Larsen & Nesbakken 2004; Parti & Parti 1980). Specifically, Larsen & Nesbakken (2004) estimated that the effect of having a TV as 1,301 kWh per year. Electricity consumption has also been estimated as significantly higher in households owning a video player/recorder (Bartiaux & Gram-Hanssen 2005; Larsen & Nesbakken 2004) and a video console (Kavousian et al. 2013; McLoughlin et al. 2012; Baker & Rylatt 2008). However, little effect of the ownership of a portable television and CD player on household electricity usage has been observed (Leahy & Lyons 2010).

The significant effect of the use of electric space heating, air-conditioning and ventilation systems has been widely mentioned in the literature (Section 2.4.7). However, apart from portable electric heaters which were found to be significant in Baker & Rylatt (2008) and Larsen & Nesbakken (2004), very little or no influence of the ownership of smaller HVAC appliances such as desk or wall fans or dehumidifiers on domestic electric demand has been observed (Carter et al. 2012; Tso & Yau 2007).

The effect of major cooking appliances, such as electric oven and range hood, has also been researched. A significant and positive effect of the ownership and use of electric cooking on domestic electricity demand has been reported by McLoughlin et al. (2012), Leahy & Lyons (2010), Halvorsen & Larsen (2001), and Parti & Parti (1980) suggesting that households which cook with electric have a higher electricity consumption than those households using other fuel types. It is worthwhile mentioning that Halvorsen & Larsen (2001) observed that the purchase of a new electric oven results in a reduction in electricity consumption, possibly due to the replacement of an old inefficient appliance for a more energy efficient one. Differing from previous studies, Parker (2003) determined that the energy use of electric ovens (existing in 93% of homes of the sample) was very low, likely reflecting the increasing prevalence for dining out and non-cooked breakfast foods in the USA. Similarly, Kavousian et al. (2013) and Carter et al. (2012) did not find any correlation between electricity consumption and the use of electric stoves for cooking. In relation to the ownership of a range hood, a significant influence on electricity use was established by Tso & Yau (2007).

Only a few minor cooking appliances and their effect on household electricity demand have been studied in the literature. In particular, Leahy & Lyons (2010) and Tso & Yau (2007) established that the ownership of a microwave and a kettle have no influence on the variance in electricity use of domestic buildings.

Extensive research has been undertaken aimed at exploring the influence of ownership of preservation and cooling appliances, including refrigerators, fridge-freezers and chest freezers (Zhou & Teng 2013; Kavousian et al. 2013; Carter et al. 2012; McLoughlin et al. 2012; Leahy & Lyons 2010; Bartiaux & Gram-Hanssen 2005; Genjo et al. 2005; Gram-Hanssen et al. 2004; Larsen & Nesbakken 2004; Halvorsen & Larsen 2001; Parti & Parti 1980). The significant effect of the ownership of refrigerators on electricity demand has been consistently acknowledged (Zhou & Teng 2013; Kavousian et al. 2013; Bartiaux & Gram-Hanssen 2005; Gram-Hanssen et al. 2004; Larsen & Nesbakken 2004; Halvorsen & Larsen 2001; Parti & Parti 1980), as one of the most important predictors of electricity demand compared to other appliances. According to Zhou & Teng (2013), households with a refrigerator have an electricity consumption 22.2% higher than that of households without a refrigerator. Contrary to previous authors, Carter et al. (2012) and Leahy & Lyons (2010) did not observe any significant relationship between the ownership of refrigerators and electricity use. Apart from the effect of ownership, Genjo et al. (2005) also determined that the size of the refrigerator owned has a significant influential effect on the electricity consumption for appliances and lighting.

Regarding the ownership of a fridge-freezer, Leahy & Lyons (2010) found that electricity consumption is significantly higher in households owning a fridge-freezer compared to those without. In particular, the study revealed that households with a fridge-freezer use between 5 and 6 kWh more electricity per week (6 - 7% of their weekly electricity use).

Several studies have also acknowledged the impact of having a chest freezer on electricity demand (Kavousian et al. 2013; McLoughlin et al. 2012; Leahy & Lyons 2010; Parti & Parti 1980). Leahy & Lyons (2010) concluded that the effect of having a chest freezer is stronger than having a fridge-freezer, accounting for over 9 kWh more electricity per week.

Halvorsen & Larsen (2001) studied the effect of both owning a freezer and purchasing a new freezer and revealed that the purchase of a new freezer results in a reduction in electricity consumption, due to the acquisition of more energy efficient appliances. However, no significant effects of purchasing or owning a freezer were found. Carter et al. (2012) also concluded that the ownership of a freezer is not a good predictor of electricity consumption.

The ownership of washing appliances (i.e. dishwasher and dish-dryer), and its impact on electricity demand has been the focus of extensive research (Kavousian et al. 2013; McLoughlin et al. 2012; Leahy & Lyons 2010; Bartiaux & Gram-Hanssen 2005; Genjo et al. 2005; Gram-Hanssen et al. 2004; Larsen & Nesbakken 2004; Halvorsen & Larsen 2001; Parti & Parti 1980). Apart from Kavousian et al. (2013), who did not find any significant influence, all other authors consistently agreed on the significant relationship between the ownership of a dishwasher and increased electricity demand. McLoughlin et al. (2012) determined that, with a household penetration of 67%, dishwashers were the largest contributors to electricity consumption. In addition, Leahy & Lyons (2010) established that having a dishwasher increases electricity consumption by over 9 kWh per week. Similarly, Larsen & Nesbakken (2004) added that those households with a dishwasher use 2,015 kWh more electricity per year than households that do not have such an appliance. Moreover, Genjo et al. (2005) found that the ownership of a dish-dryer also influences domestic electricity demand.

Several authors have also explored the influence of the ownership of laundry appliances, including washing machine, tumble-dryer and iron, on domestic electricity demand (Kavousian et al. 2013; Carter et al. 2012; McLoughlin et al. 2012; Leahy & Lyons 2010; Tso & Yau 2007; Bartiaux & Gram-Hanssen 2005; Genjo et al. 2005; Gram-Hanssen et al. 2004; Larsen & Nesbakken 2004; Parker 2003; Halvorsen & Larsen 2001; Parti & Parti 1980). While the significant contribution of the ownership of a washing machine has been acknowledged by Carter et al. (2012), Larsen & Nesbakken (2004), and Halvorsen & Larsen (2001), other studies have reported little or no effect (Leahy & Lyons 2010; Tso & Yau 2007). Specifically, Larsen & Nesbakken (2004) established that those households with a washing machine use 2,099 kWh more electricity per year than households that do not have such appliance. Moreover, Halvorsen & Larsen (2001) not only found a significant effect of the ownership of a washing machine but also a significant relationship between the purchasing of a new washing machine and electricity consumption. In particular, the authors found that the purchase of a washing machine results in an increased electricity use. Apart from the effect of ownership, Genjo et al. (2005) also determined that the size of the washing machine owned is a significant influential factor on the electricity consumption for appliances and lighting.

The high impact of the ownership of a tumble dryer on electrical energy demand has been the focus of extensive research (McLoughlin et al. 2012; Leahy & Lyons 2010; Bartiaux & Gram-Hanssen 2005; Gram-Hanssen et al. 2004; Larsen & Nesbakken 2004; Parker 2003; Parti & Parti 1980). In particular, Leahy & Lyons (2010) established that households owning a tumble dryer consume over 9 kWh more electricity per week than those without the appliance. Similarly, Larsen & Nesbakken (2004) found that households with a tumble dryer use 2,338 kWh more electricity per year than households that do not own one. Parker (2003) and McLoughlin et al. (2012) added that, with a household penetration of 90% and 68% respectively, the ownership of a tumble dryer was one of the three largest contributors to electricity consumption. Differing from previous studies, Kavousian et al. (2013), Carter et al. (2012), and Tso & Yau (2007) did not find any correlation between electricity consumption and the number of tumble dryers owned.

Regarding the ownership of an iron and its influence on electricity use, Louw et al. (2008) found a significant and positive relationship in newly electrified low-income African households.

In relation to the ownership of building maintenance appliances, Leahy & Lyons (2010) and Genjo et al. (2005) agreed on the significant effect of the ownership of a vacuum cleaner on domestic electrical energy demand. In particular, Leahy & Lyons (2010) found that households with a vacuum cleaner use between 5 and 6 kWh more electricity per week (6 - 7% of their weekly electricity use) than households that do not have such appliance. In addition, McLoughlin et al. (2012) concluded that water pumps (used in residential areas with low water pressure) have a significant impact on high electrical energy demand.

Other studies have also looked at the influence of the ownership of specific hygiene and leisure appliances. Generally, the choice of appliances studied and the results obtained are highly influenced by the cultural and climatic aspects of the country where the research is based. For example, Genjo et al. (2005) concluded that the number of electric toilet seats is a highly influential factor on domestic electricity demand in Japan. In addition, Parker (2003) and Kavousian et al. (2013), both US-based studies, found a significant effect of the use of swimming pool pumps and spas on household electricity use. Moreover, Larsen & Nesbakken (2004), whose study was located in Norway, estimated that electricity consumption was significantly higher for households with a sauna than those without.

2.5.2 Usage of the appliances

According to Zhou & Teng (2013), the number of appliances only partially reflects the effects of electrical appliances on household electricity consumption. It is also necessary to consider the frequency of appliance use and running power. Bedir et al. (2013) established that the duration of use of appliances (including IT, entertainment, HVAC, washing and laundry appliances) explains 37% of the variance in electricity consumption between domestic buildings. However, little research has been undertaken on assessing the influence of the use of appliances on the total electrical energy demand of residential buildings (Bedir et al. 2013; Sanquist et al. 2012; Bartiaux & Gram-Hanssen 2005; Cramer et al. 1985).

In relation to the use of IT appliances, Sanquist et al. (2012) determined a strong correlation between the use of a desktop computer and the annual electrical energy demand of households. The study suggests that the use of IT appliances in a household may be a manifestation of higher disposable income.

The use of entertainment appliances, and in particular the use of a TV, has also been studied in the literature. According to Sanquist et al. (2012), there is a significant effect between the use of a TV and domestic electricity use. The authors observed that this impact is higher on larger households which tend to own and use more televisions.

Bedir et al. (2013) also determined that the duration of use of extra ventilation appliances, such as desk fan, does not have a significant influence on electricity consumption.

A significant positive correlation between the duration and frequency of use of washing appliances (i.e. dishwasher), and electricity demand has been reported in Bedir et al. (2013) and Bartiaux & Gram-Hanssen (2005).

The same authors (Bedir et al. 2013; Sanquist et al. 2012; Bartiaux & Gram-Hanssen 2005) have also reported a significant influence of the use of laundry appliances, both washing machines and tumble dryers, on domestic electricity demand. Sanquist et al. (2012) adds that there is a modest relationship between the number of household members and the use of laundry equipment, as larger households would have more frequent laundering needs. In addition, Bedir et al. (2013) reported a significant correlation between the number of hot (90 ^{o}C) and cold washes (30 ^{o}C) and total electricity use.

2.5.3 Power demand of appliances

The effect of the power demand of domestic appliances on total electricity consumption of residential buildings has had little previous research attention. From the few studies that have observed the effect of appliance power demand, Cramer et al. (1985) concluded that appliance efficiency (i.e. lower power demand) contributed significantly to a reduction in summer electrical energy consumption. Conversely, Bartiaux & Gram-Hanssen (2005) found that having a low-energy refrigerator or freezer is not significantly correlated with a lower level of electricity consumption. In addition, Kavousian et al. (2013) established that households purchasing energy-efficient Energy Star appliances and air conditioners have higher levels of daily minimum consumption, after adjusting for all other variables, meaning these dwellings have a higher overall electrical energy demand. The authors attribute this finding to the "rebound effect", where an increase in the efficiency of appliances results in increased use, hence an increase in overall energy consumption.

Table 2-3 Summary of the effects of appliance factors on electricity consumption in domestic buildings reported in the literature

Factors	Total number of citations	Significant positive effect on domestic electricity consumption	Significant negative effect on domestic electricity consumption	No effect on domestic electricity consumption
Total number of appliances	8	8 (Bedir et al. 2013), (Carlson et al. 2013), (Wiesmann et al. 2011), (Genjo et al. 2005), (Halvorsen & Larsen 2001), (Tiwari 2000), (Nielsen 1993), (Cramer et al. 1985)	0	0
Ownership of office IT appliances				
Desktop computer	5	4 (Zhou & Teng 2013), (McLoughlin et al. 2012), (Baker & Rylatt 2008), (Bartiaux & Gram-Hanssen 2005)	0	1 (Leahy & Lyons 2010)
Laptop	1	1 (McLoughlin et al. 2012)	0	0
Ownership of entertainment appliances				
TV	7	7 (Kavousian et al. 2013), (McLoughlin et al. 2012), (Baker & Rylatt 2008), (Bartiaux & Gram-Hanssen 2005), (Genjo et al. 2005), (Larsen & Nesbakken 2004), (Parti & Parti 1980)	0	0
Portable TV	1	0	0	1 (Leahy & Lyons 2010)
Video player/recorder	3	2 (Bartiaux & Gram-Hanssen 2005), (Larsen & Nesbakken 2004)	0	1 (Leahy & Lyons 2010)

Factors	Total number of citations	Significant positive effect on domestic electricity consumption	Significant negative effect on domestic electricity consumption	No effect on domestic electricity consumption
Video console	3	3 (Kavousian et al. 2013), (McLoughlin et al. 2012), (Baker & Rylatt 2008)	0	0
CD player	1	0	0	1 (Leahy & Lyons 2010)
Ownership of HVAC appliances				
Desk fan	2	0	0	2 (Carter et al. 2012), (Tso & Yau 2007)
Dehumidifier	1	0	0	1 (Tso & Yau 2007)
Portable electric-heaters	1	1 (Baker & Rylatt 2008)	0	0
Ownership of major cooking appliances				
Electric oven	7	4 (McLoughlin et al. 2012), (Leahy & Lyons 2010), (Halvorsen & Larsen 2001), (Parti & Parti 1980)	0	3 (Kavousian et al. 2013), (Carter et al. 2012), (Parker 2003)
Range hood	1	1 (Tso & Yau 2007)	0	0
Ownership of minor cooking appliances				
Microwave	1	0	0	1 (Leahy & Lyons 2010)
Kettle	1	0	0	1 (Tso & Yau 2007)

Factors	Total number of citations	Significant positive effect on domestic electricity consumption	Significant negative effect on domestic electricity consumption	No effect on domestic electricity consumption
Ownership of preservation and cooling appliances				
Refrigerator	9	7 (Zhou & Teng 2013), (Kavousian et al. 2013), (Bartiaux & Gram-Hanssen 2005), (Gram-Hanssen et al. 2004), (Larsen & Nesbakken 2004), (Halvorsen & Larsen 2001), (Parti & Parti 1980)	0	2 (Carter et al. 2012), (Leahy & Lyons 2010)
Size of refrigerator	1	1 (Genjo et al. 2005)	0	0
Fridge-freezer	1	1 (Leahy & Lyons 2010)	0	0
Chest freezer	6	4 (Kavousian et al. 2013), (McLoughlin et al. 2012), (Leahy & Lyons 2010), (Parti & Parti 1980)	0	2 (Carter et al. 2012), (Halvorsen & Larsen 2001)
Ownership of washing appliances				
Dishwasher	9	8 (McLoughlin et al. 2012), (Leahy & Lyons 2010), (Bartiaux & Gram-Hanssen 2005), (Genjo et al. 2005), (Gram-Hanssen et al. 2004), (Larsen & Nesbakken 2004), (Halvorsen & Larsen 2001), (Parti & Parti 1980)	0	1 (Kavousian et al. 2013)
Dish-dryer	1	1 (Genjo et al. 2005)	0	0
Ownership of laundry appliances				
Washing machine	5	3 (Carter et al. 2012), (Larsen & Nesbakken 2004), (Halvorsen & Larsen 2001)	0	2 (Leahy & Lyons 2010), (Tso & Yau 2007)

Factors	Total number of citations	Significant positive effect on domestic electricity consumption	Significant negative effect on domestic electricity consumption	No effect on domestic electricity consumption
Size of washing machine	1	1 (Genjo et al. 2005)	0	0
Tumble-dryer	10	7 (McLoughlin et al. 2012), (Leahy & Lyons 2010), (Bartiaux & Gram-Hanssen 2005), (Gram-Hanssen et al. 2004), (Larsen & Nesbakken 2004), (Parker 2003), (Parti & Parti 1980)		3 (Kavousian et al. 2013), (Carter et al. 2012), (Tso & Yau 2007)
Iron	1	1 (Louw et al. 2008)	0	0
Ownership of building maintenance appliances				
Vacuum cleaner	2	2 (Leahy & Lyons 2010), (Genjo et al. 2005)	0	0
Water pump	1	1 (McLoughlin et al. 2012)	0	0
Ownership of hygiene and leisure appliances				
Electric toilet seat	1	1 (Genjo et al. 2005)	0	0
Swimming pool pump and spa	1	2 (Kavousian et al. 2013), (Parker 2003)	0	0
Sauna	1	1 (Larsen & Nesbakken 2004)	0	0
Use of office IT appliances				
Desktop computer	1	1 (Sanquist et al. 2012)	0	0

Factors	Total number of citations	Significant positive effect on domestic electricity consumption	Significant negative effect on domestic electricity consumption	No effect on domestic electricity consumption
Use of entertainment appliances				
TV	1	1 (Sanquist et al. 2012)	0	0
Use of HVAC appliances				
Desk fan	1	0	0	1 (Bedir et al. 2013)
Use of washing appliances				
Dishwasher	2	2 (Bedir et al. 2013), (Bartiaux & Gram-Hanssen 2005)	0	0
Use of laundry appliances				
Washing machine	3	3 (Bedir et al. 2013), (Sanquist et al. 2012), (Bartiaux & Gram-Hanssen 2005)	0	0
Tumble dryer	3	3 (Bedir et al. 2013), (Sanquist et al. 2012), (Bartiaux & Gram-Hanssen 2005)	0	0
Number of hot (90 °C) and cold washes (30 °C)	1	1 (Bedir et al. 2013)	0	0
Power demand of appliances	3	1 (Kavousian et al. 2013)	1 (Cramer et al. 1985)	1 (Bartiaux & Gram-Hanssen 2005)

2.6 Chapter 2: Summary

This chapter has provided an overview of literature investigating the socio-economic, technical and appliance factors that influence domestic electricity consumption.

The review has shown that there are only limited contemporary studies concerning the factors that have an impact on UK domestic electrical energy demand. This deficit in knowledge could restrict both the implementation of effective UK energy policy and the ability to predict and plan for the future electricity consumption of the UK domestic sector.

The literature review has also identified that the previous studies in the UK and other countries have not always been able to reach a conclusive effect relating to the impact of socio-economic, technical and appliance factors on residential electricity consumption. Therefore, further research is required to develop our understanding of the effects of these factors.

The review has shown agreement on the correlations (significant positive/negative or insignificant) between domestic electricity use and the following socio-economic variables: number of occupants, presence of teenagers, number of adults, age of HRP, employment status of HRP, and disposal income. However, an inconclusive effect of the factors: presence of children, presence of elderly people (over 65 years old), education level of HRP, socio-economic classification of HRP, tenure type, and household income were identified (Table 2-1).

For the technical factors, consistent effects were reported by previous studies for the dwelling type, number of bedrooms, total floor area, use of electric space heating, use of air-conditioning, and ownership of an electric water heating system. Conversely mixed findings related to influence were obtained for dwelling age, number of rooms, number of floors, use of mechanical ventilation, number of showers and baths per week, and use of low-energy lighting (Table 2-2).

In addition, despite several studies acknowledging the high impact of electrical appliances on the electricity consumption of domestic buildings, only a few previous studies have analysed the effects of the ownership, usage and power demand of appliances on electricity consumption (Table 2-3). Therefore, correlations between electricity consumption and appliance related factors have not yet well been established.

Importantly, the review has revealed a lack of studies specifically focusing on the socio-economic, technical and appliance factors influencing high electrical energy consumption in domestic buildings as well as those providing an estimation of the changes in likelihood of a dwelling being a high electric consumer based on having certain characteristics.

Chapter 3

Literature review 2: A review of appliance electricity monitoring studies in domestic buildings

3.1 Introduction

This chapter presents a literature review undertaken to examine existing research on end-use electricity consumption in domestic buildings, focusing on detailed electrical appliance end-use monitoring studies. According to previous studies, the electrical energy consumption of residential buildings is affected by: (i) socio-economic factors; (ii) technical factors; and (iii) appliance factors, with the latter factor much less explored than the former ones. Appliance factors relate to the ownership of electrical appliances, their power demand characteristics and usage by building occupants.

The review focuses on current and previous research projects aimed at measuring detailed end-use electricity consumption data in both the UK and other countries. Firstly, a general overview of the state of the art is presented (section 3.2). Secondly, the studies are described chronologically, from the oldest to the most current. For each study, the number of households, the monitoring period, the number and type of appliances monitored, the logging interval and the monitoring technology used are presented (section 3.3). A comparison of the different monitoring studies is enabled through the provision of a summary table (Table 3-1). Finally, the findings of the review are provided (section 3.4). This review highlights the current gaps in knowledge and points towards the need to better understand the underlying appliance factors affecting domestic electricity consumption in UK.

3.2 Overview of appliance electricity consumption monitoring in domestic buildings

Previous research (See Chapter 2) has highlighted the importance of collecting detailed data of the ownership, power and use of electrical appliances in households in order to understand the relationship between the total electricity consumption of a dwelling and the appliance related factors, thereby permitting the design of effective energy demand reduction interventions. However, the variation in the type of electrical appliances owned and the occupant's semi random use of these, makes domestic electricity consumption difficult to accurately predict, particularly at short time steps such as an hour or less (Firth et al. 2008).

The relationship between appliance ownership, i.e. the number and type of appliances owned by households, and the total household electrical energy consumption has been the subject of extensive research (Bedir et al. 2013; Carlson et al. 2013; Wiesmann et al. 2011; Genjo et al. 2005; Halvorsen & Larsen 2001; Tiwari 2000; Nielsen 1993; Cramer et al. 1985). Other previous studies have also acknowledged the influence of occupant use of electrical appliances on the total electricity consumption of residential buildings (Bedir et al. 2013; Sanquist et al. 2012; Cramer et al. 1985). Only a few earlier studies have observed the effects of appliance power characteristics (Kavousian et al. 2013; Cramer et al. 1985). However, these previous studies normally report on the impact of electrical appliances on average annual or monthly electricity consumptions recorded by means of large scale surveys and do not provide sufficient detail for planning effective interventions such as the replacement of appliances or promoting behavioural change. Therefore, more detailed studies with smaller sample sizes are required to achieve a better understanding of appliance electricity consumption in households.

Energy monitoring studies can provide data on individual household electricity consumption and has been recognised as the only method to accurately record patterns of electricity consumption, free from the influence of self-report bias (Crosbie 2006; Lopes et al. 1997). Such studies generally take two approaches (Hart 1992): intrusive and non-intrusive monitoring.

According to Hart (1992), non-intrusive monitoring is defined as the estimation of individual appliance loads through the analysis of their total cumulative load. It consists of monitoring the whole house electricity load profile at a high resolution and identifying the effects of different appliance end-uses by means of mathematical algorithms. For example, Firth et al. (2008) undertook a monitoring study of the electricity consumption of a sample of 72 dwellings at five UK sites. Five-minutely average whole house power consumption measurements were recorded over a 2 year period which was later disaggregated into four appliance end-use categories: continuous, standby, cold and active appliances. Similarly, Newborough & Augood (1999) carried out a demand side management study which recorded one minutely electricity load profiles for 30 UK homes over periods of 1 to 4 weeks. The effects of different appliances on consumption levels were disaggregated form the total load profiles recorded. Despite having a lower economic cost, non-intrusive monitoring presents some limitations which relate to the inability to distinguish between two different appliances with the same real power consumption (Berges et al. 2008).

Conversely, Hart (1992) defines intrusive monitoring as approaches which make use of a number of sensors attached to each of the individual components of the electricity load. Therefore, appliance end-use electricity consumption monitoring refers to the installation of a system in which individual appliances are monitored directly using one smart meter plug per appliance in order to ensure that no other electrical loads contribute to the measurement. This approach provides accurate consumption data on individual appliances and the results are of sufficient detail to make energy efficiency recommendations (Firth et al. 2008). Moreover, by monitoring the appliance end-use electricity consumption directly, it is possible to clearly separate different uses of electricity, thus distinguishing between different appliances (Berges et al. 2008).

Appliance end-use monitoring normally requires a hybrid approach due to the variety and complexity of the appliances. For example, some of the largest energy consumers are either hard-wired (such as electric hot-water heaters) and others might use different plug styles than standard household appliances (Berges et al. 2008). Typically, the monitoring system consists of clamp-on meters and plug-in meters. Clamp-on meters are normally used to monitor those appliances which are hard-wired. They are installed by attaching a clamp around the electric live wire and the power is calculated by measuring the electromagnetic field generated by the flow of current through the wire. Those appliances that are plugged into a plug socket are commonly monitored by plug-in meters, which are installed by plugging the appliance into the meter, and plugging the meter into the mains circuit. They allow the meter to monitor and even control the flow of electricity between the mains circuit and the appliance. A detailed evaluation of strengths and weaknesses of the different methods for metering end-use demand is presented in Sæle & Feilberg (2012).

Due to technological innovation and cost cutting through market liberalisation, different appliance smart metering systems have become commercially available in the past few years (Sæle & Feilberg 2012). Consequently, there have been a growing number of notable monitoring campaigns in both the UK and abroad. These studies are being undertaken by utility companies, national energy agencies and research institutions to better understand how electricity is being used in the home.

Of the studies in the UK, it is worth mentioning the large scale monitoring campaigns carried out in 200 households as part of the ENLITEN project (2012-2016) (Lovett et al. 2013), 126 households participating in the DEHEMS project (2007-2013) (Sundramoorthy et al. 2012), 251 dwellings monitored by (Zimmermann et al. 2012) between 2010 and 2011, and 100 houses involved in the Electricity Association project between 1992 and 1996 (Wood & Newborough 2003). Other UK studies at a smaller scale, ranging from 4 to 36 households, include Coleman et al. (2012), Leach et al. (2012), LEEDR (2010), Padget et al. (2010), Yohanis et al. (2008), and Mansouri & Newborough (1999).

Similar research has also been undertaken in other European countries. For example, a comprehensive monitoring study was carried out as part of the REMODECE project (De Almeida et al. 2011; De Almeida et al. 2009) between 2006 and 2008 which involved the monitoring of 1200 households in 12 different European countries, including Bulgaria, Czech Republic, Hungary, Romania, Belgium, Denmark, France, Germany, Greece, Italy, Norway and Portugal. Similarly, 400 households in five European countries, comprising Denmark, Greece, Italy, Portugal and France, participated in the EURECO metering campaign from 2000 to 2001 (Sidler 2002). Another large study was undertaken in Sweden between 2005 and 2007, with the participation of 400 households (Zimmermann 2009). Other previous EU appliance monitoring projects can be traced back to the 1990s, such as the ECUEL metering campaign in 100 French dwellings in 1998 (Sidler et al. 2000; Sidler & Waide 1999), the EcoDrôme project which monitored 20 households in France between 1995 and 1997 (Sidler 1998a), the CIEL project which involved 114 French homes between 1995 and 1996 (Sidler 1996), and the NUTEK campaign where 66 houses in Sweden were monitored from 1991 to 1993 (NUTEK 1995). Internationally, it is worth mentioning the monitoring campaign undertaken by Parker (2003) in 171 houses in the USA in 1999 and the Household Energy End-use Project (HEEP) completed between 1999 and 2005 in 100 households in New Zealand (Isaacs et al. 2006).

The common objective of these studies has been to collect the most detailed data of electricity consumption by end-use possible. However, each of them had different purposes. End-use campaigns such as Leach et al. (2012), the EURECO project (Sidler 2002), Montreuil Vincennes Energy (ENERTECH 2000) and the EcoDrôme project (Sidler 1998a) aimed to assess potential energy reductions by replacing household appliances with the most energy efficient examples available on the market.

Other studies aimed to quantify the electrical energy consumption of appliances in standby, such Nakagami et al. (1999), the standby appliances monitoring study led by ENERTECH (ENERTECH, 2006), the Montreuil Vincennes Energy campaign (ENERTECH 2000), and the EURECO project (Sidler 2002). While previous studies sought to assess the energy consumed by standby appliances, Gudbjerg & Gram-

Hanssen (2006) also verified to what extent standby losses could be reduced by influencing users' behaviour or using specific equipment, such as auto-saver plugs for televisions.

Detailed monitoring data have also been used to communicate energy consumption information and influence occupants' habits and behaviours with respect to energy use. For example, Mansouri & Newborough (19998) monitored electrical cooking appliances and applied different information methods to change users' cooking habits. Similarly, ENLITEN (Lovett et al. 2013), DEHEMS (Sundramoorthy et al. 2012), ElDeK (Sæle & Feilberg 2012) and eDiana (Peltonen et al. 2010) monitoring campaigns measured the energy consumption of the main domestic appliances with the aim of increasing users' awareness of electricity consumption.

Other monitoring studies focused on identifying and cataloguing the range and quantity of electrical appliances owned, to understand their frequency and patterns of usage, as well as the different appliance power modes by collecting detailed data of the main domestic appliances' characteristics (Cosar Jorda 2013; Zimmermann et al. 2012; LEEDR 2010; Sidler 1996). Coleman et al. (2012) studied the electricity consumption of information, communication and entertainment (ICE) appliances and focused on identifying patterns of appliance use.

In addition, REMP campaign (REMP 2012) aimed to improve the energy efficiency of appliances and products.

Appliance monitoring research has also been carried out to assess the effect of the households' socio-economic, technical and appliance related characteristics, as well as the underlying drivers that determine occupants' purchasing behaviour and use, on total electricity consumption (Cosar Jorda 2013; LEEDR 2010; Zimmermann 2009; Bennich et al. 2009; Yohanis et al. 2008).

With the exception of the six longitudinal studies (Lovett et al. 2013; Yohanis et al. 2008; Gudbjerg & Gram-Hanssen 2006; Isaacs et al. 2006; Sidler 2004; Sidler 1998a) with monitoring durations ranging from eleven months to two years, previous end-use monitoring studies have tended towards short durations per home, ranging from one week up to a maximum of six months. Other campaigns have employed different monitoring durations for different groups of the research sample. For example, the UK Household Electricity Use Study (EST 2012; Zimmermann et al. 2012) monitored 225 homes for 1 month and 26 homes for 1 year, Zimmermann (2009) studied 360 homes for 1 month and 40 homes for 1 year in Sweden, and Mansouri & Newborough (1999) measured the energy consumption of a group of UK households for 12 months and the rest of the sample for a period of 16 weeks.

The logging interval, defined as the frequency at which energy consumption measurements are recorded, also varies between monitoring studies. With the desire to achieve detailed electricity consumption measurement, some studies have employed a minutely logging interval (Cosar Jorda 2013; Sæle & Feilberg 2012; REMP 2012; LEEDR 2010), 2 minutely interval (Zimmermann et al. 2012) and 5 minutely interval (Coleman et al. 2012) for appliance monitoring. Other appliance monitoring projects have demonstrated that an interval of 10 minutes is sufficient to be able to analyse most appliance cycles (De Almeida et al. 2008; Bennich & Persson 2006; Sidler 2002; Siddler 1998b; Lebot et al. 1997). Less frequent logging intervals, such as every 15 minutes (Nelson & Berrisford 2010; Parker 2003; Wood & Newborough 2003; Nakagami et al. 1999) and every 30 minutes (Yohanis et al. 2008) have also been employed for appliance monitoring.

3.3 Previous and ongoing electrical end-use monitoring studies

Several appliance monitoring studies have been conducted in both the UK and abroad to investigate appliance electricity consumption in residential buildings.

Between 1991 and 1992, the main domestic appliances in 66 Swedish homes were monitored for several months by NUTEK (the Swedish energy and environment agency) (NUTEK 1995). The total consumption of the wall socket outlets were monitored and detailed measurements of the individual appliances loads were taken using a wattmeter. Lighting was not monitored, but estimated based on the wall socket outlet total and information of the measured individual loads.

An electricity consumption monitoring study was undertaken between 1992 and 1996 in the UK, with the support of different English electricity suppliers. 100 UK dwellings participated in the study, which consisted of monitoring all domestic appliances at a 15 minutely interval during one month per household. Smart meters were used for the study (POEM metering system), which measured the electricity consumptions of up to 16 appliances within a home. Data was transferred from the appliance to a main local collector unit using radio waves. The data was then sent down the telephone line for analysis elsewhere, when the phone was not in use (Wood & Newborough 2003).

The CIEL campaign (1995-1996), led by ENERTECH, was one of the first European attempts to systematically examine the electricity consumption of the domestic appliance stock. The study took place in 114 households in France during one month in each dwelling (Sidler 1996). The electricity consumption and power of all domestic appliances (720 appliances in total), except lighting and cooking, were monitored every 10 minutes by means of individual electricity meters (DIACE). Data collected by the electricity meters were transferred from the measurement points to a collector device using a power-line carrier system. The collector had a built-in modem function, which allowed the contents of its memory to be downloaded regularly to a central data logger and a computer. In this case, the total electricity consumption of the household was not measured. The detailed study of each appliance type, together with a personal questionnaire, helped to formally understand, for the first time, the different appliance power modes, the standby mode consumption, the electricity consumption of individual appliances and the influence of user behaviour.

Following the CIEL campaign, the European funded project EcoDrome was carried out in France between 1995 and 1997 (Sidler 1998a). The EcoDrome project was also led by ENERTECH and aimed to assess the potential household savings by using more efficient appliances. Electricity consumption and power demand data of all the electrical appliances and lighting circuits in 20 French households was collected at a 10 minutely interval during one year. At the end of the first year, all the metered appliances were replaced with more efficient ones (Energy label Class A appliances), the light bulbs were replaced with Compact Fluorescent Light (CFL) bulbs, and the control circuit of the circulation pump of the heating system was also modified in those cases when the pump was not initially controlled by the ambient temperature thermostat. Electricity consumption and power demand data was recorded again for one additional year. Data was collected by means of the same DIACE individual electric meters used in the CIEL project. The data collected was used to precisely determine the characteristics of all the existing appliances, their yearly consumptions, as well as the load curve by detailing the weight of each end-use.

A follow-up monitoring campaign was undertaken between 1996 and 1997 by ENERTECH to compare the average electrical appliance consumptions of households in France and French Guyana. The same methodology applied in the CIEL and EcoDrome projects was used in 100 households in the French Guyana (Sidler 1998b). This time, all domestic appliances, except lighting, were monitored at 10 minutely intervals for one month using the DIACE individual electricity meters. At that time, it was the first study to measure the contribution of air conditioners and pumps of swimming pools to household electricity consumption. Both end-uses were very common in households in French Guyana and were found to be the two highest electrical end-uses of the whole monitoring study.

One year later, in 1998, the ECUEL project (Sidler et al. 2000; Sidler & Waide 1999) was carried out by ENERTECH in partnership with ADEME (The French National Energy and Environmental Agency), EDF (The French National Electricity Utility) and the CEC (Commission of the European Communities). The project aimed to quantify the electricity consumption of electric cooking, understand the effects of external conditions on the electricity consumption of cold appliances, and assess whether using a tumble-dryer could reduce the energy consumption for ironing. The end-use power demand and electrical energy consumption of cooking appliances, cold appliances and tumble-dryers of 100 French households was monitored for one month (Sidler 2001). The study centred on the analysis of a database containing metered data of 517 cases of 32 types of domestic electrical appliance covering the main forms of electric cooking, as well as auxiliary uses, such as coffee-makers and kettles. Identical to previous ENERTECH studies, the power demand and electrical energy consumption of each appliance was measured every 10 minutes over one month using the DIACE monitoring system.

Seeking to reduce the end-use electrical energy consumption of cooking by influencing users' behaviour with different energy consumption information methods, Mansouri & Newborough (1999) undertook a monitoring study of electrical cooking appliances in 36 UK homes between 1997 and 1998 (1.5 years). The household sample was split into four groups. Group 1 (the control group) was monitored across a period of 12 months, while the three other groups (associated with three different information communication methods) were monitored for a minimum period of 16 weeks (i.e. 8 weeks before and 8 weeks after introducing the energy consumption information to the household). The electrical power demand of the free-standing cooker (or oven and hob arrangement) was recorded by means of a current transformer fitted around the supply cable to the cooker. The electrical energy consumption was calculated and displayed on a screen at the point of use.

The energy consumption of 398 dwellings in New Zealand were monitored as part of the "Household Energy End-use Project (HEEP)" led by BRANZ (Isaacs et al. 2006). It aimed to understand how, where, when and why energy is used in New Zealand homes. The monitoring campaign began in 1997 and was completed in 2005. All energy consumptions (natural gas, electricity, solid fuel, solar water heaters, oil and LPG) were monitored on a 10 minutely basis for 11 months for each house. The electricity consumption monitoring was undertaken in 100 dwellings by means of a power line carrier system that monitored up to eight fixed electric circuits (e.g. lighting, stove) and up to eight remote uses (e.g. dishwasher, television) in combination with a standard revenue meter with a pulse output that fed into a datalogger. In addition to the stove, lights, and electric heaters, two or three further individual appliances were monitored in each house. These were randomly selected on a monthly basis in order to increase the number and variety of studied appliances with the limited monitoring sets.

Nakagami et al. (1999) studied the characteristics of appliances in standby, their consumption and total standby power consumption was related to the total electricity consumption of the dwellings. Thirty-six households in Japan participated in the study. The average electricity consumption of all appliances in the households was monitored every 15 minutes during several days using an individual electric meter plugged into the appliance. In total, 616 appliances were tested, which could be categorised into 56 different appliances types, and of these, 480 appliances or 46 appliance types were found to have standby electricity consumption. These were mainly audio visual equipment, shower, toilet, rice cooker and electric urn.

Similarly, between 1997 and 1999, a total of 1,280 French households participated in an appliance standby monitoring study led by ENERTECH (ENERTECH, 2006). However, in this case, only instant power was recorded, which was measured using a portable wattmeter. The main features of the appliances that were always or temporarily in stand-by mode were also noted.

Parker (2003) undertook a monitoring study of total electricity consumption as well as a number of end-uses in 171 dwellings in Central Florida, USA, in 1999. Power consumption was collected for several end-uses on a fifteen minute basis, including space cooling, heating, water heating, cooking, clothes drying, and swimming pools. The electricity consumption of other appliances such as lighting, refrigerator, ceiling fan, and plug loads were subtracted from the total.

In Montreuil (France), 359 social houses participated in a large monitoring campaign carried out by the local energy supplier Montreuil Vincennes Energy (ENERTECH 2000). The aim of the study was to undertake a very detailed analysis of the electricity end-uses in order to propose solutions resulting in a reduction of electricity consumption. The measurement campaign lasted for 5 months in total and each house was continually monitored for three months. Four measurements were recorded: (i) total consumption of cold appliances; (ii) power of all devices with a standby mode; (iii) power in all operating modes of the wall mounted appliances (e.g. emergency lighting or alarms); and (iv) total household power consumption over the period of observation, as well as total household electricity consumption over the previous year. Lighting consumption was not monitored but it was calculated from the total electricity consumption.

The EU project "Demand-side management: End-use metering campaign in 400 households of the European Community. Assessment of the Potential Electricity Savings (EURECO)" (Sidler 2002) took place between 2000 and 2001. It used a similar methodology and approach to the EcoDrome project (1995-1997); however, rather than replacing individual appliances for more efficient ones, the potential energy savings were assessed by comparing the consumption of the existing appliances in the EURECO homes with the most energy efficient models of similar capacity and function on the market at that moment in time. The project involved 400 dwellings in Denmark, Greece, Italy, and Portugal. One hundred households were monitored in each country during one month. In every house, the following appliances were monitored every ten minutes: household utility meter, all cold appliances (one plug meter for each one of them), all sources of light (one lamp-meter per control point), audiovisual sites (TV, VCR, decoders, demodulators, HiFi and sometimes individual antenna were monitored as a group), and washing machine. Occasionally, circulating pumps of the boilers, computer sites (central unit, screen and all the peripherals) and dishwasher were also monitored. The household total electricity consumption was recorded from the utility meter, individual appliance energy and power demand were monitored using DIACE individual electricity meters, the appliance standby electricity use was measured with a portable wattmeter, and the light sources were measured by means of lampmeters. Data collected by the DIACE electricity meters were transferred from the measurement points to a collector device using a power-line carrier system. The collector had a built-in modem function, which allowed the contents of its memory to be downloaded regularly to a central data logger and a computer, which gathered and processed the data from all the experimental sites. A detailed questionnaire was also used to assess participants' habits and to collect socio-economic data.

In 2003, ENERTECH undertook a lighting monitoring campaign (Sidler 2004) aimed at studying the lighting consumption of 100 households in France during one year. In each household, every light source and the mains were monitored, which allowed a very precise representation of electricity that was consumed for lighting. On average, 28.3 light bulbs were metered per household. A lampmeter especially designed for the study was installed in each light source and recorded the time for each switch on and switch off.

Between 2003 and 2004, Yohanis et al. (2008) undertook a detailed electricity consumption monitoring study in 27 representative dwellings in Northern Ireland (UK) for 20 months. It aimed was at assessing the effect of different socio-economic and technical characteristics of the dwelling, including the appliance ownership and size on total household electricity consumption. Direct domestic electricity measurements of lighting, kitchen and entertainment appliances were taken using a 30 minute load meter installed in series with the normal utility meter in each home. Each meter had a mobile telephone unit that enabled remote downloading of stored electricity data once every month. Remote access software was used to connect with the mobile units within the metering system and data was downloaded via modems.

Detailed metering of electricity consumption in 400 Swedish households was undertaken from September 2005 to June 2008 as part of the project entitled "End-use metering campaign in 400 households in Sweden, assessment of the potential electricity savings" led by ENERTECH and funded by the Swedish Energy Agency (Bennich et al. 2009; Zimmermann 2009; Bennich et al. 2006). Specifically, 40 households were measured for one year and the remaining 360 households were monitored for one month. In each house, all the main electrical appliances (e.g. cold appliances, washing machine, dishwasher, clothes-drier, TV, audio-visual, computer, microwave) were monitored at a time step of 10 minutes using Wattmeters connected in series with the appliances. Other end-uses such as space heating and water heating systems, were monitored directly from the main switchboard of the house. Moreover, lampmeters were used to measure the consumption of the light sources that draw a constant electrical power (incandescent bulbs, CFL, etc.). The lampmeter measured the time during which the light source was switched on and the power was measured separately during the meter installation. From these two measurements, the consumption of each light point in the households was determined. Wattmeters connected in series with the lamp were used to determine the consumption of the halogen lights, for which the power drawn was not constant. The analysis performed on the results also covered technical efficiency, characteristics of the appliances and lighting equipment, in terms of quantity as well as size, use of the appliances and lighting equipment, drivers that determine purchase and use, in terms of composition of households, age, revenues etc.

Between 2006 and 2008, a large-scale monitoring campaign supported by the Intelligent Energy for Europe Programme of the European community was undertaken in twelve European countries, including Belgium, Bulgaria, Czech Republic, Denmark, France, Germany, Greece, Hungary, Italy, Portugal, and Romania as part of the project "Residential Monitoring to Decrease Energy Use and Carbon Emissions in Europe (REMODECE)" (De Almeida et al. 2011; De Almeida et al. 2009). The project involved a total of 1,300 households. In each house, 10 electricity meters were used to monitor the major appliances or end-uses per household (cold appliances, washing machines, consumer electronics etc.). About 12,310 single appliances were measured in total, which were grouped into 24 end-uses groups. In addition, at least the 10 main light sources were monitored in each dwelling. The logging interval for the measurements was 10 minutely, collected over a period of about two weeks per household. The monitoring equipment consisted of (i) serial watt data loggers installed on the majority of appliances; (ii) wattmeter with amp clamp and pulse meter; (iii) lampmeter logger that required no connection to supply network (it recorded turning lighting on and off); and (iv) energy and power spot meter (measuring energy consumption, power, current and voltage). Data were transferred remotely by Internet router to PC.

Focusing on appliances in standby, Gudbjerg & Gram-Hanssen (2006) monitored 30 households in Denmark over a period of 2 years. The purpose of the project was to verify the extent standby losses in household consumption could be reduced through interventions with the household occupants (e.g. direct communication by means of posted leaflets or visits from an energy adviser) or by using specific technical equipment (e.g. auto-saver plugs for television and PC, remote control or time switch to socket outlet). Four data loggers where used in each house. Appliances types belonging to the same appliance category located in the same room were connected together in one channel of the data logger. For example, all the entertainment appliances of the living room were connected in one channel and all the office appliances in another channel. The data was logged with a time resolution of one hour.

Coleman et al. (2012) studied the electricity consumption of information, communication and entertainment (ICE) appliances to identify patterns of appliance use. Fourteen UK households took part in the study in 2009. The total electricity consumptions of the dwellings and the electricity consumption of over 220 individual ICE appliances were monitored for two weeks. Personal interviews with the household's occupants were also undertaken. The ICE appliances included in the study were classified in four broad categories: (i) video (e.g. televisions, STB, DVD, etc.); (ii) audio (e.g. Hi-Fi equipment, radios, etc.); (iii) computing (e.g. desktop computers, laptops, monitors, routers, printers, etc.); and (iv) telephony (cordless telephones, answer-phones). Mobile telephones and other small portable devices were excluded. The monitoring system consisted of a single channel current logger installed on the incoming electricity supply used to record the total electricity consumption of the households. In addition, individual appliances were monitored, at five minutely intervals, using twenty plug-in meters connected to a central data collection point (gateway), using the dwelling's mains cabling. Electricity consumption data, at a 1 Wh resolution, were transferred, on a daily basis, from the gateway to a central server via a GSM modem and were later managed in an SQL database.

The project "Electricity Demand Knowledge (ElDeK)" (Sæle & Feilberg 2012), funded by the Norwegian Research Council and the Norwegian Water Resources and Energy Directorate, took place in Norway from 2009 to 2012. It was aimed at increasing knowledge concerning household electricity demand, including both the total energy demand and power demand for different customer types and end-uses. Using the same monitoring systems used in the REMODECE project (2006-2008), the electricity end-use demand of 32 households was measured. In each house, the total electricity consumption was monitored every hour for one year and the different end-use demands at a one minute interval for 4 weeks. Between 5 and 10 end-uses were metered per household, including the washing machine, clothes dryer, dishwasher, cooker, fridge, freezer, lighting, TV, PC/laptop, electric space heating and electric water heating.

A small feasibility study of end-use monitoring in residential homes was carried out by Nelson & Berrisford (2010) in three houses in British Columbia (Canada) in 2009. Up to 40 appliances were monitored in each house. Each appliance was connected to a plug outlet monitoring and control device which recorded Watts, Wh, Vars, and Voltage at 15 minutely intervals. The recordings were transmitted from the meter devices, by Zigbee radio protocol, to a computer in the home, which worked as a gateway, and then emailed the researcher's computer for validation, editing and estimation, storage and aggregation. Total electricity consumption was also recorded every 15 minutes.

One of the most complete electricity monitoring campaigns undertaken in UK is the "Household Electricity Use Study" (EST 2012; Zimmermann et al. 2012), which was jointly commissioned by the Department for Environment, Food and Rural Affairs (Defra), the Department of Energy and Climate Change (DECC) and the Energy Saving Trust. The study monitored electrical appliances in a total of 251 owner-occupier households across England from 2010 to 2011. In particular, 26 of these households were monitored for a full year, whilst the remaining 225 were monitored for the duration of one month on a rolling basis throughout the trial period. The project was aimed at (i) identifying and cataloguing the range and quantity of electrically powered appliances, products and gadgets found in the typical home (classified in the categories entertainment, kitchen, heating and cooling, ICT, laundry, personal care and lighting appliances), (ii) understanding their frequency and patterns of usage, in particular their impact on peak electricity demand, (iii) monitoring the total electricity consumption of the home (every ten minutes) as well as individually monitoring the majority of appliances in the household (every two minutes), and (iv) collecting data about user habits for some appliance types. Several types of metering device were used during the monitoring campaign. As in Bennich et al. (2009) and Zimmermann (2009), the power of most of the individual appliances and groups of appliances were monitored using wattmeters connected in series with the appliances. In addition, space heating, water heating and cooking appliances were monitored directly from the consumer unit of the house. Data were stored in a computer and downloaded periodically by the researchers. In addition to the automatic monitoring systems, occupants were asked to complete simple diaries for some of the products that were monitored to identify the most common programme settings used so that the energy consumption of those programmes could be established in the monitored data.

In 2010, the Australian Federal Government commissioned a pilot project to test the equipment, methodologies, and the approaches required to capture detailed energy data in Australian homes. The pilot study was called "Residential Energy Monitoring Program (REMP)" (REMP 2012) and was carried out as part of the Equipment Energy Efficiency (E3) Program, which is a joint initiative of the Australian and New Zealand Governments aimed at improving the energy efficiency of appliances and products. The pilot project was conducted over three months and involved setting up a detailed monitoring program in five Melbourne households to help improve understanding of energy consumption in the residential sector by monitoring internal temperatures, various electrical circuits, gas, hot water and a number of appliances. Specifically, the electrical end-use monitoring equipment installed in each house consisted of: (i) separate monitoring at the switchboard for every electricity circuit (on average 12 circuits per house – some of which were dedicated to particular appliances); (ii) in-line metering of 24 major plug-in appliances and plug-in luminaires in each house; and (iii) light sensors for 12 hard-wired luminaires in each house. Data from the in-line meters and light sensors were collected via an internal Zigbee wireless network. All parameters (wireless and switchboard data) were collected at one minutely intervals and automatically uploaded to a server each hour via a GPRS modem. The approach did not require any routine visits to the house to collect data or check sensors and any equipment failure could be detected remotely.

Padget et al. (2010) carried out an exploratory study of the potential for a highly disaggregated household electrical energy use monitoring and feedback system. By means of energy sensors, the real time power demand (W) and the cumulative energy consumption (kWh) from individual electrical devices connected to power sockets was collected and monitored. The sensors were connected through a Zigbee mesh network which facilitated the transmission of the data stored on the sensors to a collector component. A Bluetooth communication system was also used in some cases. The monitoring system was tested in two different scenarios: offline, where the sensors stored the data in their internal memory and then manually downloaded; and online, where the data collected by the sensors was accessed by a collector and displayed in a web browser. For the offline scenario, twenty-two sensors were installed in 4 households in Bath (UK) for 4 weeks in 2009. The sensors were connected to different appliances, such as PC and peripherals, washing machine, electric kettle, television, microwave, and freezer. Power demand was collected at 10 minute intervals and stored in the sensors memory for the total duration of the monitoring study. The online scenario consisted of a short-term deployment in student housing on the University of Bath campus (UK) in 2010. Three appliances (toaster, microwave, and kettle) were instrumented with sensors in three communal student kitchens. Power demand was monitored and stored on the sensor every second and this data was accessed every 5 seconds by a collector and displayed on different types of displays.

In 2012, another small-scale exploratory study of the electricity consumption of cold and wet appliances was undertaken in five households in the UK (Leach et al. 2012). The main aim of the study was to explore the extent to which switching to more efficient modern cold and wet appliances could enable significant energy savings. The total duration of the study was four months which were split into monitoring phases of one month each. Four appliances in each household were monitored with an individual appliance monitor which, working in conjunction with the household total electricity consumption smart meter, recorded the electricity consumption of each appliance continuously throughout the study. A selection of the oldest monitored appliances were replaced approximately halfway through the study with brand new and more energy efficient models in order to quantify the energy savings and changes in user behaviour.

The European project “Embedded Systems for Energy Efficient Buildings (eDiana)” (2009-2012) (Peltonen et al. 2010) aimed to develop a platform which integrates intelligent embedded devices (sensors and actuators), installed in residential (mainly apartment buildings) and non-residential buildings for improving their energy efficiency. The platform enables the communication of the existing appliances, lighting and other HVAC systems at a household level and at the whole apartment building level. The platform can monitor the total building electricity consumption and provide data to define saving strategies when connecting the building to the electrical grid. Moreover, the platform makes the user aware of the electricity consumption and enable user-controlled policies for household devices (lighting, domestic electronics, etc.). The platform has been tested in two residential buildings in Eindhoven (Netherlands) and Helsinki (Finland). The results are not yet public.

The Digital Environment Home Energy Management System (DEHEMS) (2007-2013) is a European project looking at how technology can improve domestic energy efficiency (Sundramoorthy et al. 2012). The project aimed to develop and test a home energy management system (both gas and electricity) in residential buildings in 5 cities across Europe, which are Manchester, Birmingham and Bristol in the UK, and Plovdiv and Ivanovo in Bulgaria. The home electricity management system included different sensing technologies that provided electrical energy consumption information to the households. These were electrical mains circuit and individual appliance level sensors. The project initially tested the system in a total of 250 households, 126 across the UK and 124 in Bulgaria, for a period of six months from March 2009. A current transformer sensor coupled to a radio modem was clamped around the mains electricity circuit and current readings were taken approximately every 6 seconds. Moreover, plug sensors were attached to the appliances' plugs, which transmitted electricity measurements wirelessly via Zigbee to the DEHEMS Gateway. Up to 10 appliances were sensed in the Zigbee mesh. The gateway comprised a data collection mechanism and data aggregation function for processing data received from the sensors, and an external communication module to communicate with the DEHEMS server via the in-home broadband router. In addition, the project also tested the use of user interfaces such as PC-based website, a dedicated real-time energy display device and ubiquitous interfaces such as digital photo frames and mobile phones. Energy usage data was displayed in real-time and updated every 6 seconds.

Low-Effort Energy Demand Reduction (LEEDR) is an on-going project (2010-2014) led by Loughborough University and funded by the Engineering and Physical Sciences Research Council (EPSRC, UK) (Cosar Jorda 2013; LEEDR 2010). The project seeks to create a better understanding of how energy use is implicated in the rhythms and activities of everyday life by combining monitoring data with social-scientific analysis of the practices through which energy is consumed. Through the use of wireless monitoring equipment installed in the households which communicate with a central hub in the home using a Zigbee wireless network, the project will measure gas consumption, hot water use, and electrical consumption in 20 homes in the Midlands of the UK. Appliances, circuits and incoming mains are monitored at a frequency of 1 minute using smart plugs and CT devices.

Energy literacy through an intelligent home energy advisor (ENLITEN) (2012-2016) (Lovett et al. 2013) is an on-going project led by the University of Bath and funded by the Engineering and Physical Sciences Research Council (UK). It aims to reduce carbon emissions attributable to energy use within residential buildings by understanding and influencing occupants' habits and behaviours with respect to energy use. To do so, a whole building energy model will be developed, which will integrate a thermal model, a model of occupants' habits and requirements, and a disaggregated model of energy use in the dwelling. Focusing on the energy use model, the internal light level, real and reactive power of the appliances, different electric circuits and the main household electricity supply will be measured. The project seeks to use a minimal sensor set to collect the live data required for the whole building energy model. This data will be displayed by an interactive in-building tool to help occupants identify and break poor energy habits, form better ones and reduce energy demand and carbon emissions. This system is to be deployed in 200 homes for a period of 2 years in the city of Exeter (UK).

Table 3-1 presents a summary of the previous and ongoing end-use monitoring studies in domestic buildings.

Table 3-1 Summary of the previous and ongoing end-use monitoring studies in domestic buildings

Author(s)	**Year**	**Location**	**Number of homes**	**Duration per home**	**Main data**	**End-uses monitored**	**Frequency of end-use monitoring**	**Frequency of whole house logging**	**Downloading method**
Swedish energy and environment agency (NUTEK) (NUTEK 1995)	1991-1993	Sweden	66	Several months	Wh/day	Main appliances, except lighting	N/A (end value - beginning value)	Unknown	Manual to PC
Electricity Association (Wood & Newborough 2003)	1992-1996	UK	100	1 month	W	Main appliances (up to 16 appliances per home)	Every 15 minutes	Unknown	Telephone line
CIEL (Sidler 1996)	1995-1996	France	114	1 month	W, Wh	Main appliances, except lighting and cooking (total of 720 appliances)	Every 10 minutes	Not monitored	Power-line carrier system plus modem
EcoDrôme (Sidler 1998a)	1995-1997	France	20	2 years	W, Wh	Main appliances and lighting circuit	Every 10 minutes	Monitored but unknown frequency	Power-line carrier system plus modem
French Guiana (Sidler 1998b)	1996-1997	France and French Guiana	100	1 month	W, Wh	Main appliances, except lighting	Every 10 minutes	Unknown	Power-line carrier system plus modem
ECUEL (Sidler et al. 2000; Sidler & Waide 1999)	1998	France	100	1 month	W, Wh	Main electric cooking appliances (oven, kettle, coffee maker), cold appliances and tumble-dryers	Every 10 minutes	Unknown	Power-line carrier system plus modem
(Mansouri & Newborough 1999)	1997 - 1998	UK	36	12 months (control group) 16 weeks (experimental groups)	W, Wh	Main electric cooking appliances	Unknown	Unknown	Power-line
Household Energy End-use Project (HEEP) (Isaacs et al. 2006)	1999-2005	New Zealand	100	11 months	W, Wh	Stove, lights, electric heaters and individual appliances	Unknown	Every 10 minutes	Unknown

Author(s)	Year	Location	Number of homes	Duration per home	Main data	End-uses monitored	Frequency of end-use monitoring	Frequency of whole house logging	Downloading method
(Nakagami et al. 1999)		Japan	36	Several days	W	Main appliances, with particular interest on standby appliances	Every 15 minutes	Every 15 minutes	Unknown
Stand-by Power (ENERTECH, 2006)	1997-1999	France	1,280	Instant power measurement	W	All standby appliances	N/A	Not monitored	N/A
(Parker 2003)	1999	US	171	Unknown	W	Main appliances	Every 15 minutes	Unknown	Unknown
(ENERTECH 2000)	2000	France	359	3 months	W, Wh	Cold appliance, standby appliances and wall mounted appliances	Unknown	Monitored but unknown frequency	Unknown
Demand-side management: End-use metering campaign in 400 households of the European Community. Assessment of the Potential Electricity Savings (EURECO) (Sidler 2002)	2000-2001	Denmark, Greece, Italy, Portugal and France	400 (100 in each of the four first countries)	1 month	W, Wh	All appliances, including every light source	Every 10 minutes	Monitored but unknown frequency	Power-line carrier system plus modem
(Sidler 2004)	2003	France	100	12 months	W, Wh	Every light source	Every time the light switched on and off	Monitored but unknown frequency	Unknown
(Yohanis et al. 2008)	2003-2004	UK	27	20 months	W, Wh	Lighting, kitchen and entertainment appliances	Every 30 minutes	Unknown	Modem to a mobile phone
End-use metering campaign in 400 households in Sweden, assessment of the potential electricity savings (Bennich et al. 2009; Zimmermann 2009)	2005-2007	Sweden	400	1 month in 360 homes 12 months in 40 homes	W, Wh	Main appliances and lighting	Every 10 minutes	Monitored but unknown frequency	Stored on PC at home

Author(s)	Year	Location	Number of homes	Duration per home	Main data	End-uses monitored	Frequency of end-use monitoring	Frequency of whole house logging	Downloading method
Residential Monitoring to Decrease Energy Use and Carbon Emissions in Europe (REMODECE) (De Almeida et al. 2011; De Almeida et al. 2009)	2006-2008	Bulgaria, Czech Republic, Hungary, Romania, Belgium, Denmark, France, Germany, Greece, Italy, Norway, Portugal	1200 (100 in each country)	2 weeks - 1 month	W, Wh	Main appliances and light sources (average of 10 major appliances per house and at least 10 light sources)	Every 10 minutes	Every 10 minutes	Unknown
(Gudbjerg & Gram-Hanssen 2006)	2004-2006	Denmark	30	24 months	W	All standby appliances	Every 1 hour	Unknown	Unknown
(Coleman et al. 2012)	2009	UK	14	2 weeks	W, Wh	Information, communication and entertainment appliances (up to 20 appliances per house)	Every 5 minutes	Every 5 minutes	Internet
Electricity Demand Knowledge (ElDeK) (Sæle & Feilberg 2012)	2009-2013	Norway	32	12 months (total consumption) 4 weeks (appliances)	W, Wh	Main appliances (between 5 and 10 appliances per house)	Every 1 minute	Every 1 hour	Unknown
(Nelson & Berrisford 2010)	2009	Canada	3	Unknown	W, Wh, V	Main appliances (up to 40 appliances per house)	Every 15 minutes	Every 15 minutes	Zigbee radio and internet
Household Electricity Use Study (EST 2012, Zimmermann et al. 2012)	2010-2011	UK	251	1 month in 225 homes 12 months in 26 homes	W, Wh	Main appliances and lighting	Every 2 or 10 minutes	Monitored but unknown frequency	Stored on PC at home
Residential Energy Monitoring Program (REMP) (REMP 2012)	2010	Australia	5	3 months	W, Wh	Main plug-in appliances and light sources (up to 24 per house)	Every 1 minute	Every 1 minute	Zigbee radio and internet

Author(s)	Year	Location	Number of homes	Duration per home	Main data	End-uses monitored	Frequency of end-use monitoring	Frequency of whole house logging	Downloading method
(Padget et al. 2010)	2009-2010	UK	4 homes (offline scenario) 1 student housing (online scenario)	4 weeks	W, Wh	In offline scenario, main appliances (a total of 22 sensors) In online scenario, three appliances (toaster, microwave, and kettle)	Every 10 minutes (offline scenario) Every 5 seconds (online scenario)	Unknown	Manual (in offline scenario) Zigbee radio and internet (in online scenario)
(Leach et al. 2012)	2012	UK	5	1 month	W, Wh	Cold and wet appliances	Unknown	Monitored but unknown frequency	Unknown
Embedded Systems for Energy Efficient Buildings (eDiana) (Peltonen et al. 2010)	2009-2012	Netherlands and Finland	2 residential buildings	Unknown	W, Wh	Main appliances	Unknown	Monitored but unknown frequency	Unknown
Digital Environment Home Energy Management System (DEHEMS) (Sundramoorthy et al. 2012)	2007-2013	UK and Bulgaria	126 in UK 124 in Bulgaria	6 months	W, Wh	Main appliances (up to 10 appliances per house)	Every 6 seconds	Every 6 seconds	In-home broadband router
Low-Effort Energy Demand Reduction (LEEDR) (Cosar Jorda 2013; LEEDR 2010)	2010-2014	UK	20	Unknown	W, Wh	Main appliances	Every 1 minute	Every 1 minute	Zigbee radio and internet
Energy literacy through an intelligent home energy advisor (ENLITEN) (Lovett et al. 2013)	2012-2016	UK	200	24 months	W	Main appliances	Unknown	Monitored but unknown frequency	Unknown

3.4 Chapter 3: Summary

This chapter has provided an overview of literature regarding electrical appliance monitoring studies in domestic buildings.

The review has shown that the number of studies aiming to measure detailed end-use electricity consumption in households has increased in the UK and other countries in recent years due to a growing need to reduce domestic electricity consumption. In addition, several commercially available monitoring systems have now been developed that meet the needs of a successful end-use monitoring study: good accuracy, high reliability, moderate cost, high storage capacity, flexible communications, non-intrusive, powerful pre-processing of data, as well as being suitable for a large number of monitored end-uses.

Previous monitoring studies, both in UK and internationally, have significantly enhanced the understanding of end-use electricity consumption, by providing detailed data related to the number and type of appliances installed, how they are used and their technical characteristics (power demand). Unfortunately, these aspects have commonly been studied separately in line with varying project aims, either cataloguing domestic appliances, assessing standby consumption or identifying users' habits. Therefore, historically there has been little research studying the interrelations between appliance ownership, usage and power demand in households and their influence on the total electrical energy consumption of domestic buildings. Without this information, accurate estimates of total electricity consumption and specific energy efficiency recommendations cannot be made.

In addition, previous studies have limited the scope of monitoring campaigns to the measurement of the electricity consumption of the main domestic appliances only. Others have studied one specific appliance category (e.g. cooking appliances). The commonly stated reason for this limitation was a lack of equipment, but as a result, little remains known about the energy consumption, ownership, usage and power demands of the smaller domestic appliances (e.g. minor cooking, beauty and leisure appliances). Furthermore, only a limited number of previous studies have monitored both the total household electricity consumption and the consumptions of the appliance end-uses. Therefore, there remains a limited understanding of the contributions of individual appliances to total domestic electricity use.

Importantly, the review has also revealed a lack of monitoring studies focusing on the variations in appliance electricity consumption between specific consumption groups (i.e. low, medium and high electrical energy demand households), as well as the underlying appliance drivers of these variations in demand (i.e. ownership, usage and power demand of appliances). Therefore, a significant gap in knowledge remains for an appliance monitoring study focusing on high electrical energy demand in domestic buildings that will establish the appliances responsible, the underlying contributing factors and potential methods for demand reduction.

Chapter 4

Research methodology

4.1 Introduction

This chapter outlines the methodology applied to this study to meet the aim and objectives of this thesis defined in Chapter 1 and answer the research questions defined in this Chapter. This chapter begins with a description of the research design and the research methods used (section 4.2). The methods of data collection are then described (from section 4.3 to 4.8). This is followed by an account of the stages of data processing (sections 4.9). The methods of data analysis are then outlined (section 4.10). Finally, a brief chapter summary is presented (section 4.11).

4.2 Research design: a mixed methods approach

To investigate the socio-economic, technical and appliance drivers of high electricity consumption in UK domestic buildings, a mixed methods approach was adopted for the research design. The research design refers to “the plan of action that links the philosophical assumptions to specific methods” (Creswell & Plano Clark 2007). A mixed methods study comprises the collection of both quantitative and qualitative data. Creswell & Plano Clark (2007) proposed four mixed methods designs to structure the research design: triangulation design, embedded design, explanatory design and exploratory design. The current study is closely aligned with the explanatory design (Figure 4-1), in which quantitative data are used to identify a phenomenon, and qualitative data used to explore in greater detail (e.g. Gill et al. (2010), Wall & Crosbie (2009), Brandon & Lewis (1999)).

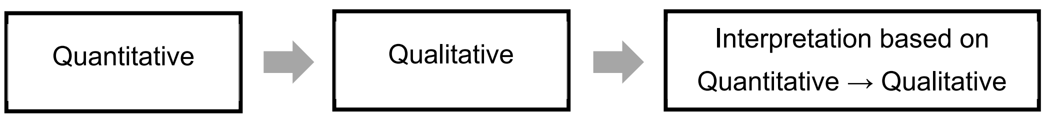


Figure 4-1 Explanatory mixed methods research design (Creswell & Plano Clark 2007)

Table 4-1 shows how the thesis' research questions have guided the choice of a mixed methods research design to generate both quantitative and qualitative data.

Table 4-1 Data required for the thesis research questions

Research questions	Research method	Data	Reason for use of research method
Q1. Does a sample of UK households demonstrate that large variations in electrical energy demand exist between homes?	Energy monitoring	Quantitative	To obtain accurate and objective measurements of the annual electricity consumptions of a sample of UK homes
Q2. Is the electricity consumption of a sample of UK households with high electrical energy demand increasing over time?	Energy monitoring Unstructured interview	Quantitative Qualitative	To obtain accurate and objective measurements of the changes in annual electricity consumptions of a sample of UK homes over time
Q3. Which socio-economic, technical and appliance factors contribute to high electrical energy demand in a sample of UK households?	Energy monitoring Self-reported survey Administered survey	Quantitative	To obtain accurate and objective measurements of the annual electricity consumptions of a sample of UK homes. To collect details of the occupants' socio-demographic data, technical characteristics of the dwellings and appliance related information.
Q4. To what extent do the ownership, power demand and use of different domestic appliances contribute to high electrical energy demand in a sample of UK households?	Energy monitoring Administered survey	Quantitative	To obtain accurate and objective measurements of the power demand and use of different domestic appliances in each power mode for a sample of UK homes. To collect domestic appliance ownership information.
Q5. What policy recommendations can be established from the research findings?	Study evaluation		

To answer this study's research questions a series of research methods, which are the techniques used to collect and analyse data (Silverman 2006), have been employed. They are summarised in Table 4-2. Crosbie (2006) provides a summary of the main research methods that have previously been used in household energy studies more widely.

Table 4-2 Description of the research methods used in the current research

Method	Description
Energy monitoring	Energy monitoring produces quantitative data by logging actual energy use, which can be used to better understand patterns of energy consumption as well as use and power demand of domestic appliances.
Self-reported survey	Principally used to generate quantitative data from large randomly selected samples that are suitable for statistical analysis (Creswell & Plano Clark 2007). Standardised closed questions are usually used to gain descriptive data (e.g. socio-demographics, technical building characteristics) or interpretive data (e.g. explanations of phenomena and correlations).
Administered survey	Similar to self-reported surveys, this method is largely used to collect quantitative data through standardised closed questions (Robson 2002); however the survey is delivered face-to-face by an interviewer to the participant.
Unstructured interviews	This method uses non-standardised, open-ended questions to generate qualitative data. Interviewees are encouraged to talk freely, in their own terms, about the research topic and the researcher is able to delve into issues as they arise (Robson 2002). Sample sizes are usually small (due to time and economic constraints), but offers the greatest opportunity to use probing questions to uncover, in depth, why a phenomenon occurred.

The research methods used in this study have been extensively applied in previous household energy research studies and each have advantages and disadvantages. Energy monitoring is the only method that can precisely record patterns of electricity consumption, which is not affected by self-report bias (Crosbie 2006; Lopes et al. 1997). As a result, to answer the thesis research questions Q1, Q2, Q3 and Q4, electricity meter reading and whole house and appliance level electricity monitoring was an essential method. However, energy monitoring alone could not provide the data necessary to understand why high electricity consumption occurs in domestic buildings. Consequently, a series of additional research methods were used, which together could answer the proposed thesis research questions.

Self-reported and administered surveys were employed as they have widely been used to investigate statistical relationships between energy consumption and socio-demographic , technical, and appliance variables in previous energy studies (e.g. Kavousian et al. 2013, Bartusch et al. 2012, Baker & Rylatt 2008, Genjo et al. 2005, Gram-Hanssen et al. 2004), which was a requirement of research question Q3. Self-reported surveys provide a fast and economic means to gain data representative of large populations. However, threats to validity include low response rates, misinterpretation of survey questions and self-report bias (Robson 2002). Administered surveys have the added advantage that the interviewer can clarify questions (i.e. reduce misinterpretation) and encourage interviewee participation and involvement (Robson 2002). However, data can be affected by interviewer bias and, as the survey is not anonymous, participants may be less open (Robson 2002).

In addition, unstructured interviews were used as they provided the opportunity to ask probing questions to the occupants of the dwellings about their perspectives on the reasons behind significant changes in the annual electricity consumption of their homes over time, which was used to answer research question Q2. Unstructured interviews provide a non-standardised, open-ended and in-depth means to collect data but are vulnerable to self-report bias (Crosbie 2006; Robson 2002).

The different research methods used to collect the data for this thesis were employed across a series of individual studies, as part of a larger research project called 4M: ‘Measurement, Modelling, Mapping and Management 4M: an Evidence Based Methodology for Understanding and Shrinking the Urban Carbon Footprint’. The four year project began in March 2008 and was supported by the UK Engineering and Physical Sciences Research Council (EPSRC) through grant EP/F007604/1. The 4M consortium had 5 UK partners: Loughborough University (lead), De Montfort University, Newcastle University, the University of Sheffield, and the University of Leeds.

Figure 4-2 provides an overview of the research process used for the thesis data collection, processing and analysis.

		Number of households	Period	Data Collection	Data Processing	Data analysis
PHASE 1	**4M LIL household survey**	575	March'09 – July'09	NatCen	Irvine & Fisher (DMU, 4M partner)	Jones (author)
PHASE 2	**4M LIL electricity meter reading**	436	March'09 – July'09	NatCen	Allison (Lboro University)	Jones (author)
		232	Oct'09 – March'10	Households self-reported		
		266	June'10 – July'10	4M researchers (Lboro University) Households self-reported		
	4M Energy supplier annual electricity use data	219	2007	Energy supplier	Rylatt (DMU, 4M partner)	Jones (author)
		218	2008			
	4M LIL appliance survey	240	Jan'10 - March'10	Households self-reported	Guo (Lboro University)	Jones (author)
	Appliance Electricity Use Survey (AEUS)	27	July'11 - May'12	Jones (author) (assisted by Guo)	Jones (author) (assisted by Guo)	Jones (author) (assisted by Guo)
	AEUS whole house and appliance level electricity monitoring	27	July'11 - Dec'11 (4 weeks period)	Jones (author)	Jones (author)	Jones (author)
	AEUS electricity meter reading	27	July'11 – Nov'11	Jones (author)	Jones (author)	Jones (author)
		27	August'11 - Dec'11	Jones (author)	Jones (author)	Jones (author)
		27	April'12 – May'12	Jones (author) Households self-reported	Jones (author)	Jones (author)
	AEUS domestic appliance ownership survey	27	July'11 – Nov'11	Jones (author)	Jones (author)	Jones (author)
	AEUS unstructured interview	27	August'11 – Dec'11	Jones (author) & Guo	Guo (Lboro University)	Jones (author)

Figure 4-2 Overview of the thesis research process

4.3 Data collection

As outlined in the previous section, both quantitative and qualitative data were collected during the research presented in this thesis. Quantitative data were collected by the use of energy monitoring, self-reported surveys and administered surveys. Qualitative data were collected by unstructured household interviews. These methods of data collection were applied during individual studies, as part of a larger research programme. The research methods used in both phases one and two of the thesis research process are outlined sequentially in the following sections. Firstly, the administered survey delivered during the 4M Living in Leicester (LIL) household survey is described in section 4.4. The energy monitoring undertaken during the 4M LIL electricity meter reading follow up is then explored (section 4.5). The process of obtaining previous energy monitoring data for the 4M LIL households from their energy suppliers is then outlined (section 4.6). The self-reported survey for the 4M LIL appliance survey follow up is presented in section 4.7. Finally, the Appliance Electricity Use Survey (AEUS) undertaken with a sub-set of the LIL households is described, which comprised the research methods of energy monitoring (whole house and appliance monitoring as well as electricity meter reading), an administered survey of appliance ownership and unstructured interviews with the building occupants (section 4.8).

4.3.1 Ethics

The ethical issues relating to this thesis fundamentally concern the households that participated in this research. The programme of research presented was covered by two separate ethical clearance applications; firstly the generic application for the larger 4M research programme that was obtained by Professor Kevin Lomas and secondly, the specific full ethical application for the Appliance Electricity Use Survey (AEUS) obtained by the current author (Jones). In line with Loughborough University policy, a full ethical clearance application was submitted to the University's Ethical Advisory Committee for the AEUS on the 15th November 2010. A clearance notification to proceed with the study was received on the 9th December 2010 subject to: a participant information sheet, invitation to participate letter and consent form being produced and copies provided to the Committee; that project researchers carried Loughborough University ID when visiting participants' homes; and that participants were made aware that the energy monitoring could affect electricity usage in their homes. Confirmation of full ethical approval was received on the 8th July 2011. 4M project participants were informed prior to their participation that any research outputs would ensure their identity remained anonymous and that they could withdraw from the study at any time. All personal data were kept confidential and stored securely at Loughborough University.

4.3.2 Risk assessment

The risks associated with this thesis concerned both the households that participated in the research as well as the 4M researchers involved. A series of separate School risk assessments and safe system of works for the individual studies of the research programme were submitted to the responsible person in the School of Civil and Building Engineering at Loughborough University. Specific approval for the AEUS was received on the 22nd June 2011. In addition, further advice was sought from the University's Insurance Officer regarding a requirement identified by the School risk assessment that every reasonable step was taken to minimise any risks to the participants and their households. To fulfil this requirement, in addition to completing the School risk assessment, researchers were required to produce a document for the participants outlining the safety instructions for the energy monitoring equipment as per the manufacturers operating guidelines; ensure that all monitoring equipment was PAT tested; and place a contact telephone number on the monitoring equipment for the householder to call if they felt there was a problem.

4.4 The 4M Living in Leicester household survey

The initial research phase from which data were used in this thesis was the 4M Living in Leicester (LIL) household survey. The 4M LIL household survey was a large-scale city-wide administered housing survey undertaken with a representative sample of Leicester households which aimed to investigate the relationships between household composition, socio-economic status, house type, appliance characteristics and the energy used in homes.

The 4M LIL household survey was undertaken by the National Centre for Social Research (NatCen) on behalf of the 4M researchers, the data processing was completed by Dr Katherine Irvine and Jill Fisher of the Institute of Energy and Sustainable Development (IESD) at De Montfort University.

Leicester was the case study city chosen by the 4M project consortium (Lomas et al. 2010), as it is geographically central in England, has a clearly identifiable city boundary and a City Council keen to understand energy and CO_2 emissions from city households. With a resident population of 280,000 in 2007, living in over 111,000 homes (ONS 2010), Leicester is the UK's 15th largest city and has households that cover a wide range of socio-economic categories. The most frequent housing types are semi-detached dwellings (37% of the city's housing stock) and terraces (35%), which proliferate towards the city centre along with flats (17%). The detached houses are found primarily in the suburbs (10%) (ONS 2010).

A face-to-face computerised questionnaire was administered in 575 homes (i.e. 0.5% of Leicester homes). These were randomly selected after stratifying by percentage of detached homes and percentage with no dependent children. The survey was devised by the 4M team based on the National Homes Energy Rating (NHER) with 4M additions and conducted on their behalf by the National Centre for Social Research (NatCen) between 17th March and 18th July 2009. NatCen's surveyors were trained with help from the 4M team and included individuals with Asian language skills (Leicester has a large Asian population). The survey lasted about 45 minutes and had at least 247 questions supported by 51 show cards. The responses of the interviewees were recorded directly onto a laptop and then downloaded, cleaned and organised in the 4M database. There were 1,411 anonymous and 157 confidential variables in the complete data set.

The 4M LIL household survey has provided the socio-economic, technical and some appliance data used to answer research question Q3. Specifically for this thesis, the survey captured the number of occupants, presence of children and teenagers, age of the Household Representative Person (HRP)[1], employment status of the HRP, education level of the HRP, the National Statistics Socio-economic classification of the HRP, tenure, annual household income, dwelling type, period dwelling was built, number of bedrooms and floors, total floor area, presence of electric space heating, presence of fixed electric heating, presence of portable electric heating, presence of electric water heating, presence of electric cooking, presence of electric showers and use of electric showers.

During the survey participants were asked whether they would be willing to partake in follow up studies as part of a programme of research. From the initial 575 households, varying numbers of households agreed to the different 4M follow up activities. In detail, 407 households gave consent for 4M researchers to collect repeat meter readings for their home, 241 agreed to allow access to previous energy data for their home from their energy supplier, 504 households were willing to fill in a self-reported appliance survey, and 508 were prepared to be part of a detailed electricity monitoring study with an interview.

4.5 The 4M Living in Leicester electricity meter reading follow up

Periodic electricity meter reading was undertaken with a sub-set of the 4M LIL households in phase two of the research process. Data collection was by manual reading of the household electricity meter during three periods defined as the 1st, 2nd and 3rd meter readings.

[1] The Household Representative Person is the individual that is taken to represent that household. This is usually taken as the eldest male within the household (ONS 2010).

The 1st meter reading was taken by NatCen during the 4M LIL household survey. 436 households agreed to provide this initial meter reading, however only 407 agreed to provide future readings and of those, readings were actually recorded in 398 homes. The date of the meter reading was assumed to be the date of the NatCen interview. The 1st meter readings were therefore taken between 17th March and 18th July 2009. NatCen recorded the meter readings using paper based forms and were incorporated in to the 4M database.

The 2nd meter reading was by a letter request followed by a reminder letter. The homeowners were responsible for self-reporting their electricity meter reading. 404 letters were sent out on 5th October 2009 and 203 reminders on 20th November 2009. In total, 232 replies were received between 7th October 2009 and 25th March 2010. The date of the meter reading was assumed to be the day before the reply was received, unless the reply stated otherwise. This data collection was undertaken by Dr David Allinson of the School of Civil and Building at Loughborough University.

The 3rd meter reading was by a home visit from 4M researchers followed by a letter request. Letters were sent out to 382 households on 17th May 2010, warning households that the 4M researchers would be visiting to take a meter reading. Home visits took place between 1st June and 21st June 2010. This resulted in 211 meters being read by the 4M researchers, 4 by telephone, 1 by letter and 1 by email. 13 households were found to have moved at this stage. A further letter was sent out on 6th July 2010, to 128 households asking for meter readings to be returned by post, telephone or email or an appointment made for a visit. A further 49 readings were obtained (1 visit, 2 telephone, 46 mail) giving a total of 266. This data collection was coordinated by Dr David Alllinson of the School of Civil and Building Engineering at Loughborough University. The author was involved in the in home meter reading.

The 4M LIL electricity meter reading follow up has provided the annual whole house electricity data for the 4M households for 2009, which was used to answer research questions Q1, Q2 and Q3.

4.6 The 4M energy supplier annual electricity use follow up

During the 4M LIL household survey, a request was made to the households to sign a mandate which would allow 4M researchers to access past annual whole house electricity use data from their energy supplier for their home. 241 households agreed to this form of energy monitoring. For these homes NatCen's surveyors recorded the electricity meter's 21-digit Meter Point Administration Number, also known as MPAN, Supply Number or S-

Number, which is a reference used in Great Britain to uniquely identify electricity supply points such as individual domestic residences.

Using the signed mandate and MPAN reference, Professor Mark Rylatt of the IESD at De Montfort University retrieved annual electricity use data for 219 households for 2007 and 218 households for 2008. The electricity consumption data obtained from the energy supplier was the total kWh that the homeowners were billed for in 2007 and 2008 and are likely based on a combination of actual and estimated meter readings.

The 2007 and 2008 whole house electricity use data from the energy supplier for the 4M households has been used to answer research question Q2.

4.7 The 4M Living in Leicester appliance survey follow up

A follow up self-reported survey regarding domestic appliance ownership and use was administered to a sub-set of the 4M LIL households in research phase two by Dr Liyan Guo of the School of Civil and Building Engineering at Loughborough University. 504 households had stated that they were willing to fill in a self-reported appliance survey as part of the on-going research programme. The appliance survey contained three sections, relating to the ownership of appliances; usage patterns for main appliances; as well as size and age of main appliances (Appendix A). The design of the survey was based on the Carbon Reduction in Buildings (CaRB) project appliance survey (Lomas et al. 2006) with 4M additions.

The domestic appliance survey was sent out by post to the households in January 2010, followed by a reminder in February to those that had not yet responded. In total, 240 of the households returned a completed survey by 9th March 2010, giving an overall response rate of 47.6%.

In this thesis, the 4M LIL appliance survey has provided the total number of appliances owned, number of IT, telephony, entertainment, HVAC, minor cooking, preservation and cooling, washing, laundry, building and outdoors maintenance and hygiene, beauty and leisure appliances owned, number of desktop and laptop computers owned, working hours per day for weekdays and weekend for the main desktop and laptop computer, number of televisions owned, main television type, working hours per day for weekdays and weekend for the main television, working hours per day for weekdays and weekend for electric oven and hob, ownership of refrigerators, fridge-freezers, upright freezers and chest freezers, ownership of a dishwasher, loads of dishwashing per week, temperature of dishwashing, ownership of washing machines, washer-dryers and tumble dryers, loads of clothes washing per week, temperature of clothes washing and loads of clothes drying in the summer and winter, which has been used to answer research question Q3.

4.8 The Appliance Electricity Use Survey

The Appliance Electricity Use Survey (AEUS) was comprised of four components: detailed whole house and appliance level electricity monitoring, electricity meter reading, an administered domestic appliance ownership survey, and an unstructured interview. These four elements are described in the following sub-sections. The detailed electricity monitoring study and interview has provided the data necessary to answer research questions Q1, Q2 and Q4. The data collection of the AEUS was undertaken by the author of the thesis (Jones) and was accompanied to participant households by Dr Liyan Guo.

4.8.1 The AEUS sampling approach and recruitment procedure

For the Appliance Electricity Use Survey, a random sampling approach was chosen because it is widely stated in the research methods literature as the most valid means of obtaining a representative sample (Creswell & Plano Clark 2007; Silverman 2006; Robson 2002; Wheater & Cook 2000; Tashakkori & Teddlie 1998; Henry 1990). Methods of probability sampling, such as random sampling, allow the probability that a participant will be included in a sample to be specified and thus the potential for sample bias to be assessed (Robson 2002). A random sampling approach has been used in many previous energy research studies (e.g. Coleman et al. (2012), De Almeida et al. (2011), Isaacs et al. (2006), Lomas et al. (2006)).

Two criteria were placed on participation in the AEUS at the recruitment stage. The first criterion specified that the household should be owner occupied. This was imposed due to the high monetary value of the monitoring equipment to be deployed in the homes and therefore it was essential that “trustworthy” and “permanent” households were recruited. Once this condition had been applied to the 508 potential households who had identified in the initial 4M LIL household survey that they were prepared to be part of the follow up, 430 potential households were still available. This sample was subsequently divided in two because a separate 4M follow up also required a share of the sample. Jill Fisher a 4M PhD researcher of the IESD at De Montfort University required a sample of households which had not been involved in other follow up activities. The second criteria required that the household should have an Internet connection, as Internet was required by the monitoring equipment to export data from the study households.

Recruitment of participant households was by a letter request (Appendix B). The letter provided a brief description of the follow up and asked households to express their interest in participating. The need of internet connection was also stated. Households that were interested were asked to complete the returning form and return it using the stamped addressed envelope provided. The returning form asked for a contact telephone number, email address, and a convenient time to call. On receipt of the returning form, a researcher would call the participant household to provide more details about the study, answer any questions, and arrange a time and date for a home visit to install the monitoring equipment.

Letters were sent out to 215 households on 22nd June 2011. A total of 79 replies were received between 24th June 2011 and 22nd July 2011; representing a response rate of 36.7%. Of these, 40 households responded that they were interested in partaking in the study and a further 39 were not interested. Nine of the households that replied that they were not interested also indicated that they would have participated but were unable to as their home did not have an Internet connection.

4.8.2 The AEUS study households

From the 40 households that responded that they were interested in participating in the AEUS, data from twenty-seven households were ultimately collected. Table 4-3 summarises the key socio-economic and Table 4-4 the key technical characteristics of the individual households.

Overall, the AEUS study cohort could be categorised into six different household types; 'pensioners' were the most common type, accounting for 29.63% of the AEUS sample. In comparison this household type describes 20.77% of homes in Leicester (L) and 23.81% in England and Wales (EW). This was followed by: 'married couples with dependent children' (25.93% AEUS, 20.10% L, 20.80% EW) and 'married couple with no children' (22.22% AEUS, 13.02% L, 17.72% EW). The remaining three household types composed 7.41% of the AEUS sample, these were 'one person' (18.81% L, 15.59% EW), 'lone parent with dependent children' (7.71% L, 5.88% EW) and 'other' (4.29% L, 3.62% EW) households. The 'other' household type in this study described a multi-generational family (i.e. grandparent, children and grandchildren all residing in a single dwelling) and two cohabiting sisters. It can be seen that the sample was over representative of pensioner, married couples with dependent children, married couples with no children and other households and under representative of one person homes both for Leicester and England and Wales. The percentage of lone parent with dependent children households was similar to that of Leicester as a whole. All other household types (e.g. student, lone parent with non-dependent children, etc.) were not represented in the AEUS.

The number of occupants in the AEUS cohort varied from single occupancy to six person households. Single occupant households accounted for 18.52% of the dwellings in the AEUS sample. Two occupant homes were the most common household size (44.44%). Three and four occupant homes were both 14.81% of the sample respectively. Furthermore, five and six occupant families were 3.70% of the cohort each.

In relation to the employment status of the AEUS cohort, the representation of households with a HRP employed part-time was similar to that in both Leicester, and England and Wales (11.11% AEUS, 10.45% L, 11.78% EW). Furthermore, in the AEUS sample, 33.33% of the households' HRPs were employed full-time (37.38% L, 40.55% EW), 40.74% were retired (10.84% L, 13.61% EW), 11.11% were permanently sick/disabled (6.45% L, 5.52% EW) and 3.70% were looking after the home/family (7.50% L, 6.51% EW). Clearly, the sample had a large over representation of households with a retired or permanently sick/disabled HRP. All other employment status' (e.g. unemployed, self-employed, student, etc.) were not represented in the AEUS.

Regarding the National Statistics Socio-economic classification of HRP, an identical percentage of the households HRPs worked in 'managerial or professional' and 'semi-routine or routine' occupations (25.93%). This was followed by 'intermediate' occupations (18.52%), 'small employers or own account workers' (14.81%) and 'lower supervisory or technical' occupations (3.70%). 11.11% of the households' HRPs did not answer this question in the 4M LIL household survey.

The annual household incomes of the AEUS households ranged from '£5,200 - £10,399' to '£75,000 to £79,999'. The two lowest income bands indicated by the occupants as their annual household incomes (£5,200 to £10,399 and £10,400 to £15,599) described the greatest proportion of the sample of homes (22.22% each). 11.11% of the dwellings had a household income between £15,600 - £20,799 and another 11.11% from £26,000 - £31,199. The percentage of the AEUS dwellings with an annual household income between £20,800 - £25,999, £31,200 - £36,399 and £36,400 - £41,599 were each 7.41%. The remaining households' incomes were from £41,600 - £46,799, £46,800 - £51,999 and £75,000 - £79,999 per annum, with individual bands accounting for 3.70%.

Concerning the technical characteristics of the AEUS cohort, the sample could be categorised into five dwelling types; 'semi-detached' were the most common type, accounting for 51.90% of the AEUS sample, which compares with 35.70% of homes in Leicester and 31.20% in England and Wales. This was followed by: 'terraced' (22.20% AEUS, 31.70% L, 24.50% EW) and 'detached' (18.50% AEUS, 10.60% L, 22.40% EW) dwellings. The remaining two dwelling types accounted for 3.70% of the sample, these were 'Purpose-built block of flats or tenement' (18.81% L, 15.59% EW) and 'Part of a converted or shared house' (3.0% L, 3.8% EW).

The floor areas of the AEUS households ranged from 42.30 m^2 to 154.42 m^2. The majority (77.77%) of the dwellings had a total floor area between 50 m^2 and 100 m^2. 18.52% of the homes had a floor area greater than 100 m^2 and 3.70% less than 50 m^2.

Regarding electric space heating, 7.41% of the AEUS cohort used night electric storage heaters as their primary source of heating, 14.81% of the dwellings had a fixed electric heater and more than half of the dwellings owned some type of portable electric heating (59.26%). Nationally, 8.48% of homes use electric as the main form of heating (DECC 2012)

With respect to electric water heating, 11.11% of the dwellings in the AEUS had an electric immersion heater.

Almost half of the AEUS dwellings had some type of electric cooking, 29.63% of the households had an electric oven only, 3.70% an electric hob only and 14.81% both an electric oven and hob. 51.85% of the dwellings had no form of electric cooking.

A large proportion of the AEUS sample had at least one electric shower in their home (62.96%).

In relation to the proportion of low-energy lighting installed in the AEUS dwellings, 40.74% of the homes had more than half of their lights installed with low-energy lamps; similarly, 37.04% had up to half of their lights that were low-energy. 7.41% of the households had no low-energy lighting at all, compared with 14.81% that had all lights fitted with low-energy lamps.

Table 4-3 Summary of the key socio-economic characteristics of the 27 AEUS households

Serial	Household type	Adults (>16)	Children (<16)	Employment status of HRP*	National Statistics Socio-economic classification of HRP*	Annual household income (£)
115061	One person (female, 35 years old)	1	0	In full-time paid employment	Managerial and professional occupations	£26,000 to £31,199
116011	Married couple, no children (62 and 62 years old)	2	0	In part-time paid employment	Small employers and own account workers	£46,800 to £51,999
116091	Married couple (48 and 46 years old), one dependent child (12 years old)	2	1	In part-time paid employment	Managerial and professional occupations	£20,800 to £25,999
116121	Married couple, no children (61 and 64 years old)	2	0	In full-time paid employment	Intermediate occupations	£15,600 to £20,799
116161	Married couple (32 and 32 years old), two dependent children (3 and 1 years old)	2	2	In full-time paid employment	Managerial and professional occupations	£75,000 to £79,999
117191	Married couple, no children (70 and 60 years old)	2	0	Retired from paid work	Managerial and professional occupations	£15,600 to £20,799
119041	Married couple (43 and 29 years old), four dependent children (12, 11, 8 and 2 years old)	2	4	In full-time paid employment	Lower supervisory and technical occupations	£31,200 to £36,399
119191	Married couple (47 and 44 years old), two dependent children (11 and 9 years old)	2	2	Permanently unable to work because of disability	Intermediate occupations	£41,600 to £46,799
119211	Married couple (43 and 44 years old), two dependent children (16 and 14 years old)	3	1	In full-time paid employment	Intermediate occupations	£20,800 to £25,999
121151	Married couple, no children (71 and 70 years old)	2	0	Retired from paid work	Semi-routine and routine occupations	£5,200 to £10,399
129141	Multi-generation household, widowed female (88 years old), separated female (52 years old) and non-dependent child (23 years old)	3	0	In full-time paid employment	Semi-routine and routine occupations	£31,200 to £36,399
130091	Married couple, no children (62 and 58 years old)	2	0	Retired from paid work	Semi-routine and routine occupations	£26,000 to £31,199
130101	Divorced female (45 years old), one non-dependent child (19 years old), one dependent child (14 years old)	2	1	In full-time paid employment	Managerial and professional occupations	£36,400 to £41,599

Serial	Household type	Adults (>16)	Children (<16)	Employment status of HRP*	National Statistics Socio-economic classification of HRP*	Annual household income (£)
132091	One person (male, 65 years old)	1	0	Retired from paid work	Managerial and professional occupations	£10,400 to £15,599
132111	One person (male, 78 years old)	1	0	Retired from paid work	Small employers and own account workers	£10,400 to £15,599
132261	Married couple, no children (69 and 66 years old)	2	0	Retired from paid work	Semi-routine and routine occupations	£10,400 to £15,599
134021	Married couple, no children (62 and 65 years old)	2	0	Retired from paid work	-	£5,200 to £10,399
134081	Married couple, no children (63 and 57 years old)	2	0	Permanently unable to work because of disability	Semi-routine and routine occupations	£15,600 to £20,799
134161	Divorced female (43 years old), two dependent children (15 and 13 years old)	1	2	In full-time paid employment	Intermediate occupations	£10,400 to £15,599
136211	One person (male, 82 years old)	1	0	Retired from paid work	-	£5,200 to £10,399
137161	Two related adults (female 55 years old, female 58 years old)	2	0	Looking after the family/home	Semi-routine and routine occupations	£5,200 to £10,399
139071	Married couple, no children (76 and 76 years old)	2	0	Retired from paid work	Small employers and own account workers	£10,400 to £15,599
139091	Married couple (40 and 44 years old), two dependent children (14 and 9 years old)	2	2	In full-time paid employment	Managerial and professional occupations	£26,000 to £31,199
143251	Married couple (49 and 46 years old), two non-dependent children (21 and 19 years old), one dependent child (17 years old)	5	0	In part-time paid employment	Small employers and own account workers	£36,400 to £41,599
144051	Married couple, no children (68 and 67 years old)	2	0	Retired from paid work	Semi-routine and routine occupations	£5,200 to £10,399
144151	Married couple, no children (62 and 46 years old)	2	0	Permanently unable to work because of disability	-	£5,200 to £10,399
146061	One person (female, 64 years old)	1	0	Retired from paid work	Intermediate occupations	£10,400 to £15,599

**Household Reference Person (HRP) is the highest income earner in the household*

Table 4-4 Summary of the key technical characteristics of the 27 AEUS households

Serial	Dwelling type	Total floor area (m^2)	Electric space heating	Fixed electric heating	Portable electric heating	Electric water heating	Electric cooking	Total number of electrical appliances owned	Electric showers	Low-energy lighting	Appliance monitoring period
115061	1900 converted house, ground floor level (1 bed)	42.30	No	No	Yes	No	No	23	Yes	Up to half the lights	15/07/2011 – 12/08/2011
116011	1905 mid-terrace, three floors (4 bed)	154.42	No	No	Yes	No	No	30	Yes	More than half of the lights	29/09/2011 – 28/10/2011
116091	1930 detached, two floors (5 bed)	113.00	No	No	Yes	No	No	33	No	More than half of the lights	28/07/2011 – 01/09/2011
116121	1972 flat, mid-floor level (2 bed)	61.00	Night electric storage heaters	Yes	No	Electric immersion heater	Electric oven, electric hob	21	Yes	More than half of the lights	11/07/2011 – 08/08/2011
116161	1938 semi-detached, two floors (3 bed)	98.20	No	No	Yes	No	Electric oven	32	Yes	More than half of the lights	30/08/2011 – 27/09/2011
117191	1963 semi-detached, one floor (2 bed)	81.00	No	Yes	No	No	Electric oven	41	No	More than half of the lights	23/08/2011 – 22/09/2011
119041	1935 semi-detached, two floors (3 bed)	92.28	No	No	Yes	No	No	18	No	More than half of the lights	13/10/2011 – 21/11/2011
119191	1887 mid-terrace, two floors (3 bed)	71.10	No	No	No	No	No	31	Yes	All lights	05/09/2011 – 04/10/2011
119211	1936 semi-detached	75.52	No	No	Yes	No	Electric oven, electric hob	36	Yes	More than half of the lights	06/10/2011 – 03/11/2011
121151	1937 semi-detached, two floors (3 bed)	89.11	No	No	No	No	No	30	Yes	Up to half the lights	27/07/2011 – 22/08/2011
129141	1960 semi-detached	80.68	No	No	No	No	Electric hob	25	Yes	More than half of the lights	26/10/2011 – 23/11/2011
130091	1933 semi-detached, two floors (3 bed)	122.10	No	No	Yes	No	Electric oven	31	No	None	31/08/2011 – 28/09/2011
130101	1960 mid-terrace, two floors (3 bed)	79.66	No	No	Yes	No	No	33	Yes	Up to half the lights	28/10/2011 – 23/11/2011
132091	1938 detached, two floors (3 bed)	73.40	No	No	Yes	No	Electric oven	24	No	More than half of the lights	05/09/2011 – 06/10/2011

Serial	Dwelling type	Total floor area (m^2)	Electric space heating	Fixed electric heating	Portable electric heating	Electric water heating	Electric cooking	Total number of electrical appliances owned	Electric showers	Low-energy lighting	Appliance monitoring period
132111	1961 semi-detached, two floors (3 bed)	73.20	No	No	No	No	Electric oven	22	No	Up to half the lights	25/07/2011 – 22/08/2011
132261	1979 mid-terrace, two floors (3 bed)	81.00	No	No	No	No	No	29	Yes	More than half of the lights	25/07/2011 – 24/08/2011
134021	1980 mid-terrace	78.60	No	No	No	No	No	21	Yes	None	08/11/2011 – 13/12/2011
134081	1984 semi-detached	69.52	No	No	No	No	Electric oven	24	Yes	Up to half the lights	28/09/2011 – 26/10/2011
134161	1990 detached	79.70	No	No	No	No	Electric oven, electric hob	31	No	Up to half the lights	23/08/2011 – 21/09/2011
136211	1897 mid-terrace, two floors (2 bed)	76.00	Night electric storage heaters	Yes	No	Electric immersion heater	No	19	No	All lights	08/08/2011 – 22/09/2011
137161	1933 semi-detached, two floors (3 bed)	82.84	No	No	No	No	No	26	Yes	Up to half the lights	12/10/2011 – 09/11/2011
139071	1970 semi-detached	78.12	No	No	Yes	No	Electric oven, electric hob	34	Yes	All lights	29/09/2011 – 27/10/2011
139091	1973 semi-detached, one and a half floors (3 bed)	114.95	No	No	No	No	No	12	No	Up to half the lights	08/11/2011 – 14/12/2011
143251	1930 semi-detached, one and a half floors (4 bed)	122.55	No	No	Yes	No	No	23	Yes	Up to half the lights	12/10/2011 – 09/11/2011
144051	1949 semi-detached	89.20	No	No	No	Electric immersion heater	No	35	Yes	All lights	26/07/2011 – 24/08/2011
144151	1975 detached, one floor (3 bed)	62.10	No	No	No	No	Electric oven	32	Yes	Up to half the lights	26/07/2011 – 24/08/2011
146061	2002 detached, one floor (2 bed)	56.60	No	Yes	No	No	Electric oven	28	No	More than half of the lights	30/08/2011 – 27/09/2011

4.8.3 The AEUS whole house and appliance level electricity monitoring

This section describes the collection of the quantitative data from the AEUS whole house and appliance electricity consumption monitoring. This was accomplished through the installation of two types of electricity monitoring equipment at each of the participant households: (i) a current clamp logger, which measured the whole house electricity consumption and (ii) an appliance monitoring system (AMS). Prior to describing the monitoring equipment, the justifications for the four week monitoring period and minutely logging interval are clarified.

4.8.3.1. Monitoring period

The monitoring period is defined as the overall time period over which electricity consumption data was collected in the participant households. Monitoring periods affect both the validity (Lopes et al. 1997) and limit the generalisation of results. A short monitoring period (e.g. weeks) is more likely to be effected by seasonal variation (e.g. more television watching in winter months) and infrequent influences on occupancy (e.g. school holidays, participant illness, sports events etc.). A long monitoring period (e.g. months and years) will, on the one hand provide more representative electricity consumption data for a household, but on the other hand, restrict the sample size due to the availability and cost of the monitoring equipment, as well as result in large, possibly unmanageable, quantities of data (Lopes et al. 1997).

The current research employed a minimum of four weeks monitoring. This period was deemed sufficient for a number of reasons: firstly, it matched the exploratory purpose of the research; secondly, a pilot study revealed that it was possible to identify consistent patterns of electricity consumption from this length of monitoring period; and thirdly, previous research has suggested that a monitoring period of a few weeks is sufficient for whole house and appliance monitoring studies (Zimmermann et al. 2012; Coleman et al. 2012; De Almeida et al. 2011; Padget et al. 2010; Bennich et al. 2009; Sidler 2002; Sidler et al. 2000). The REMODECE project used a two week monitoring period and extrapolated the data collected to produce average annual electricity consumption totals for domestic appliances (De Almeida et al. 2011; De Almeida et al. 2009). Participant households were asked before and after the energy monitoring whether the four week period was a regular representation of their everyday lives (i.e. no unusual influences on occupancy) and all 27 households confirmed that it was.

4.8.3.2. Logging interval

The logging interval is the frequency at which energy consumption measurements are recorded. It has been suggested that the choice should be sufficiently short to answer the research question but at the same time not generate unmanageable amounts of data (Lopes et al. 1997). The same authors recommended that an interval of between 5 and 10 minutes is sufficient to be able to analyse most appliance cycles (Lopes et al. 1997). Other energy monitoring projects have employed a minutely logging interval (Cosar Jorda 2013; Sæle & Feilberg 2012; REMP 2012; LEEDR 2010), 2 minutely interval (Zimmermann et al. 2012) and 5 minutely interval (Coleman et al. 2012), 10 minutely logging interval (De Almeida et al. 2008; Bennich & Persson 2006; Lebot et al. 1997; Siddler 1998; Sidler 2002), 15 minutely logging interval (Nelson & Berrisford 2010; Parker 2003; Wood & Newborough 2003; Nakagami et al. 1999), or 30 minutely logging interval (Yohanis et al. 2008). Guided by the suggestions of previous energy monitoring studies and the desire to achieve detailed electricity consumption measurements, the current research employed a minutely logging interval for both the whole house and appliance monitoring.

4.8.3.3. Whole house electricity monitoring

To measure the total household electrical demand during the monitoring period, one of two current clamp loggers were installed, depending on whether a mains power supply was available close to the electricity meter. Preferentially, the current clamp used was a *Plogg with external 100 Amp current transformer (CT)* single channel current logger (Figure 4-3). It was supplied by *Energy Optimizers Ltd and* operated together with the Appliance Monitoring System (AMS). The *Plogg with external CT* was essentially the same as those that were used to measure the appliances as part of the AMS, but had an external rather than internal CT. To install the logger, the *Plogg* was plugged into a nearby socket and the external CT clipped around the live phase of the dwelling's mains electricity supply. Table 4-5 shows the specification of the *Plogg with external CT* current clamp logger, which is a Class 1 metering device with an accuracy of +/- 1%.

Figure 4-3 Current clamp logger: Plogg with external 100 Amp current transformer (Energy Optimizers 2010)

Table 4-5 Summary of the Plogg with external 100 Amp current transformer specifications (Energy Optimizers 2010)

Specification: Plogg with external 100 Amp current transformer current clamp logger	
Connection	Single phase AC mains supply rated at nominal 230 V, 50 Hz via a socket
Measured parameters	Volts, Amps, reactive power, phase angle
Derived parameters	kW, kWh, kVARh
Accuracy	+/- 1%
Logging interval	1 minute to 1 month
Storage capacity	1 minute with 13 parameters (1,253 logs or 20.88 hours)
Memory	64kB FRAM
Software	Plogg Manager

The *Plogg with external CT* was setup to log the whole house electricity consumption measurements at 1 minutely intervals. The smart meter plug stored data regarding the date and time, average Watts, and kWh consumed over the minute. The *Plogg with external CT* had Zigbee wireless communications, which allowed it to mesh with the AMS. The data collected was exported in near real-time to the remote PC at Loughborough University using the same communications framework as the AMS shown later in Figure 4-6.

A significant benefit of using the *Plogg with external CT* compared with other potential systems that were available on the market at the time of data collection, was that the meter system chip contained within the loggers sampled the current and voltage at 2,500 times per second and averaged the electrical consumption over the 1 minute sampling interval. This provided a more accurate measurement of the whole house electricity consumption than simply taking a single measurement at the end of each minute. This method of sampling also ensured that no electricity consumption was missed and unrecorded.

The *Plogg with external CT* was also selected, because it provided a relatively low cost method to obtain accurate whole house electricity consumption data. In addition, the logger was deemed both relatively easy to use and install compared to other equipment available. The simple clip on current clamp also reduced installation time and health and safety issues associated with interfering with a live electricity supply directly. The main constraint to deploying the *Plogg with external CT* into all of the study households was the required availability of a mains power supply for operation.

In the event that a mains power supply was not available near a household's electricity meter, an *SPCmini* single channel current logger manufactured by *Elcomponent Ltd* was used (Figure 4-4) as the logger had its own battery power supply. Similarly, the *SPCmini* clipped around the live phase of the dwelling's mains electricity supply and was activated by pressing a button on the device. Table 4-6 shows the specification of the *SPCmini* logger, which is a Class 1 metering device with an accuracy of +/- 1%.

Figure 4-4 Current clamp logger: SPCmini (Elcomponent 2010a)

Table 4-6 Summary of the SPCmini specifications (Elcomponent 2010b)

Specification: SPCmini current clamp logger	
Connection	Single channel current logger
Measured parameters	Amps: 2 scales (autoranging) 20A, 200A, 500A
Derived parameters	kW, kWh, Cost
Accuracy	+/- 1% of measurement +/- 0.5% of scale
Logging interval	1 second to 30 minutes
Storage capacity	1 minute for 1 month (45,000 records)
Memory	Flash (non-volatile)
Software	PowerPackPro

The *SPCmini* was chosen as an alternative because, in addition to having a battery power supply, it also shared many of the core benefits of the *Plogg with external CT*. However, the *SPCmini* had two main disadvantages compared with the *Plogg with external CT*. Firstly, the logger measured current only and the electricity consumption data were consequently calculated at the end of the monitoring survey based on a static assumed supply voltage and power factor input during data download. Secondly, the logger was deployed as a stand-alone device with no network communications (i.e. it did not mesh with the AMS), meaning the data collected was not available until the logger was retrieved at the end of the monitoring period. Therefore, should any problem have occurred with the logger, it would only be identified once the data collection had terminated.

The *SPCmini* was setup to log the whole house electricity consumption measurements at one minutely intervals using the logger's dedicated utility software (*PowerPackPro*). The logger stored data regarding the date and time and current only. At this logging frequency and with two parameters logged, the internal memory could store a maximum of 2,184 hours (91 days) of data.

4.8.3.4. Appliance Monitoring System

The participant households' electricity consumption on domestic appliances was measured using a network of *Plogg S*mart Meter Plugs (SMPs), which logged each appliance's electricity consumption at the socket (Figure 4-5). The *Plogg* SMP was placed into a three pin mains socket and the domestic appliance plugged into it. At the time of the study, the *Plogg* SMP was promoted as the highest-quality, most fully functioned smart meter on the commercial market. The Appliance Monitoring System (AMS) which comprised a network of *Plogg* SMPs was developed by *Energy Optimizers*

Ltd, an SME that specialised in energy monitoring systems for both domestic and non-domestic buildings. The 4M project bought ten sets of the AMS (at the beginning of this PhD research) as it was simple to use and install, it provided the ability to check appliances electricity consumption in real-time via the Internet, monitor appliances over a long period of time, and even control the AMS over a network connection.

Figure 4-5 Plogg Smart Meter Plug (Energy Optimizers 2010)

The AMS deployed in each home comprised of three types of device: (i) a maximum of thirty Plogg SMPs; (ii) Plogg Zigbee USB dongle; (iii) local PC with Ethernet or Wifi Internet communications.

Figure 4-6 shows the overall monitoring schematic of the AMS and whole house measurement combined. The Plogg Zigbee USB dongle attached to a local PC was the coordinator of the AMS and controlled the transfer and storage of the electricity consumption data. The Plogg Zigbee USB dongle coordinated up to thirty Plogg SMPs and a Plogg with external 100 Amp CT in the houses where it was used. There was no technical limit on the number of SMPs that could form the AMS, thirty was the average appliance ownership identified during the 4M LIL appliance survey and was imposed due to financial constraints. The AMS operated on the Zigbee wireless mesh networking standard, which was both low-cost and low-power, making the technology suitable to be deployed in an energy monitoring application. The meshing function also provided high reliability and allowed more extensive ranges of SMPs to be installed in the homes.

The electricity consumption of an appliance was measured and stored on the SMP minutely. Every fifteen minutes the data stored on each SMP was accessed and transferred by the Plogg Zigbee USB dongle (the coordinator) to the local PC. Individual SMPs either communicated directly with the coordinator or formed a mesh network using the Zigbee protocol and communicated as a group. The AMS had its own devoted software (*Plogg Manager*), which was running on the local PC, which scheduled the data downloading from the SMPs, converted the data into Microsoft Excel spreadsheets and transferred a copy of the files to an export folder.

The copies of the *Microsoft Excel* spreadsheets stored in the export folder were then uploaded every fifteen minutes via Ethernet or Wifi connection to *Dropbox* (Dropbox 2011), an online storage database. The *Dropbox* database was synchronised with a remote PC at Loughborough University, which allowed the researcher to obtain new data every fifteen minutes for each home. The *Dropbox* platform also meant that data could be accessed anytime, from any location, using a device operating the software. An additional benefit of the setup was that the researcher could quickly identify that there was a problem with the AMS if no data was received from a particular dwelling and take appropriate action. The overall data transfer process automatically created three backup copies of the data, in different locations, reducing the likelihood of data loss.

The on board memory of the SMPs allowed for almost four days data storage at the minutely logging interval before data loss occurred, therefore if there was a problem with the AMS, identified by no data being received, the researcher had time to implement corrective actions. Unfortunately, a record of data transfer faults was not stored by the researcher but ultimately no data loss occurred. When a data transfer problem was identified in this study, it always related to the local PC in the participant households being turned off. The researcher telephoned the households directly and provided instructions to the occupants to turn the PC back on. Occupants were normally unaware that the PC was switched off. Checking data reception and the files received was a daily task for the researcher throughout the monitoring period of the AEUS.

To periodically check that the AMS was operating correctly and to fix any problems identified, the local PC and consequently the AMS was remote controllable via Ethernet or Wifi connection from the remote PC at Loughborough University using LogMeIn software (LogMeIn 2011). This feature ensured that once the AMS was installed, the occupants of the dwelling were not disturbed throughout the monitoring phase.

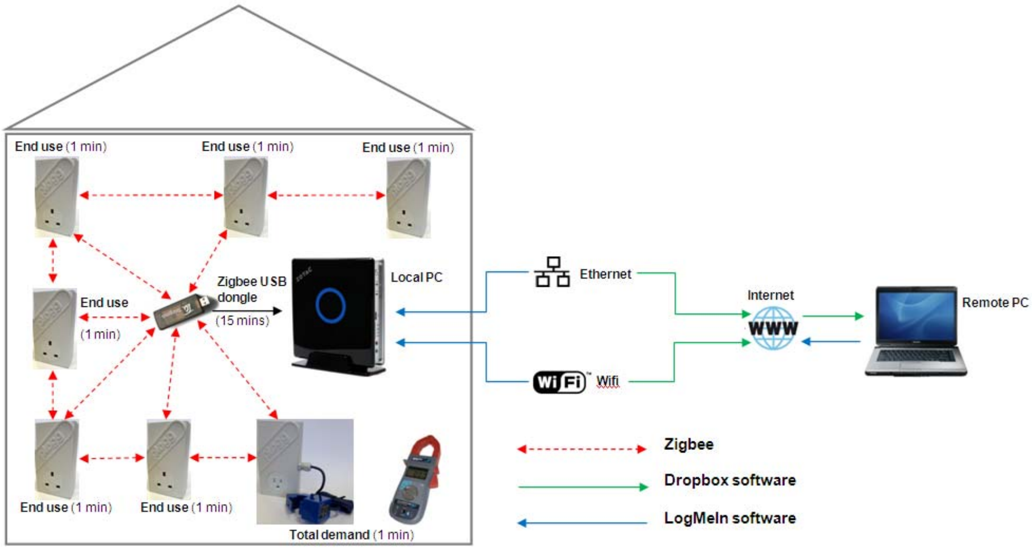


Figure 4-6 Monitoring schematic of the AMS and whole house measurement

The AMS was setup to log the appliance electricity consumption at 1 minutely intervals using the AMS's dedicated software (*Plogg Manager*). Each of the SMPs stored data regarding the date and time, average Watts and kWh consumed over one minute. Table 4-7 shows the specification of the *Plogg* SMP, which is a Class 1 metering device with an accuracy of +/- 1%.

Table 4-7 Summary of the Plogg SMP specifications (Energy Optimizers 2010)

Specification: Plogg Smart Meter Plug	
Connection	Single phase AC mains supply rated at nominal 230 V, 50 Hz via a socket
Measured parameters	Volts, Amps, reactive power, phase angle
Derived parameters	kW, kWh, kVARh
Accuracy	+/- 1%
Logging interval	1minute to 1 month
Storage capacity	1 minute with 13 parameters (1,253 logs or 20.88 hours)
Memory	64kB FRAM
Software	Plogg Manager

The primary reason for choosing to store only three out of the thirteen potential parameters was to maximise the small 64 kB internal memory of each SMP. With three parameters stored at one minutely intervals, the maximum number of logs that could be stored was 5,429 or 90 hours, whereas with thirteen this was reduced to 1,253 or 20.88 hours. Also, should a problem have occurred with the AMS, 90 hours (i.e. 3.75 days) provided a sufficiently larger time frame to notice, diagnose and correct a problem before data loss occurred. It should be noted that even though the SMPs were not storing the additional parameters (i.e. voltage, current, reactive power, or phase angle), these were still taken into account in the logged Watts and kWh consumed.

Like the *Plogg with external CT*, a significant benefit of using the *Plogg* SMPs was that the meter system chip contained within the loggers sampled the current and voltage at 2,500 times per second and averaged the electrical consumption over the 1 minute sampling interval. This provided a more accurate measurement of the appliance electricity consumption than simply taking a single measurement at the end of each minute. This method of sampling also ensured that no electricity consumption was missed and unrecorded.

4.8.3.5. AMS characteristics and accuracy

The AMS was subjected to a number of tests prior to the main study commencing to examine its key characteristics and accuracy. Accuracy is defined as the “closeness of agreement between a test result and the accepted reference value” (AMC 2003). An electricity consumption measurement with high accuracy will therefore have a small error. Error can be defined as the “result of a measurement minus the true value of the measurand” (AMC 2003). Error is combination of (i) random error - “a component of the error which, in the course of a number of test results for the same characteristic, varies in an unpredictable way” (AMC 2003), and (ii) systematic error – “a component of the error which, in the course of a number of test results for the same characteristic, remains constant or varies in a predictable way” (AMC 2003).

The overall accuracy of the AMS was dependent on the individual accuracies of the SMPs. On request, the manufacturer provided details regarding the accuracy testing procedure of the SMPs. The manufacturer tested the accuracy of a sample of 100 SMPs using an Omicron CMC256 which delivered a known load and voltage. The results were then verified against a series of constant values. The results showed an overall accuracy level of < 1%. The manufacturer specified that the accuracy of individual SMPs however varied due to their supporting circuitry. The SMPs were not tested against any metering standard (e.g. BS EN 62053-21:2003 (BSI 2003)). In addition to the manufacturer’s accuracy tests, a series of independent calibration tests were undertaken in the Sir Frank Gibb Laboratories at Loughborough University in November 2010.

The calibration tests checked the accuracy of thirty SMPs (a 10% sample), by comparing the power measurements recorded by the SMPs against an accepted reference value. A reference value was obtained by using a *SPC Pro* data logger manufactured by *Elcomponent Ltd*, which had an accuracy of +/- 0.5%. The calibration tests measured loads of 1 W, 25 W, 40 W, 60 W, 100 W and 200 W using the SMP and *SPC Pro* simultaneously, under controlled test conditions. The 25 W to 200 W loads were achieved by using incandescent lamps and the 1 W load from a mobile phone charger. The SMPs and *SPC Pro* was setup to log the power measurements every minute for a period of one hour. The results obtained from the calibration tests were not collected in line with any standardised testing procedure and therefore only provided an opportunity to check rather than ascertain the SMPs accuracy. Figure 4-7 provides an example of the load profiles collected by the SMPs and *SPC Pro* for some of the power loads tested.

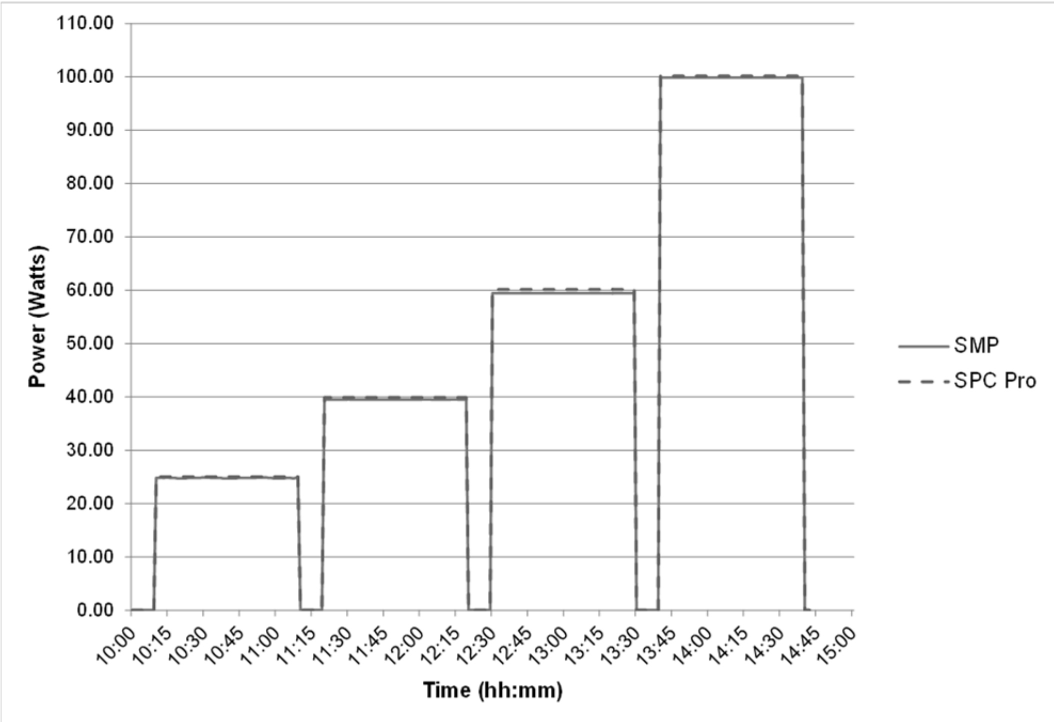


Figure 4-7 Load profile from calibration test

The results obtained from the calibration tests are shown below in Table 4-8. The average power measurements recorded for both the SMPs and *SPC Pro* are presented for each measured power load as well as the calculated accuracies. It can be seen that the majority of the power measurements obtained for the different power loads are within the +/- 1% accuracy stated by the manufacturer, with the main exception being the small 1 W power load which was within the +/- 2% range. The potential +/- 0.5% accuracy of the *SPC Pro* should also be considered in the interpretation of the test results attained. As the results achieved in the calibration tests suggested that the SMPs were able to measure the electricity consumption within the manufacturer's stated accuracy of +/- 1%, it was concluded that the AMS was appropriate for use in the proposed study.

Table 4-8 Average power measurements for SMPs and SPC Pro for power loads tested in calibration test

Power Load (W)	Average power (W)		
	30 SMPs (range)	**SPC Pro**	**Accuracy**
1W (mobile phone charger)	1.01 (0.99, 1.02)	1.03	-1.9%
25W (lamp)	24.80 (23.90, 25.00)	25.01	-0.8%
40W (lamp)	39.51 (38.95 40.12)	39.89	-1.0%
60W (lamp)	59.45 (58.75, 60.00)	60.12	-1.1%
100W (lamp)	99.87 (98.00, 100.21)	100.12	-0.2%
200W (2 x lamps)	200.10 (199.86, 200.15)	200.60	-0.2%

4.8.4 The AEUS electricity meter reading

In addition to the in depth whole house and appliance level electricity monitoring, three electricity meter reads were undertaken in the AEUS monitored households over an extended period of time, ranging from 11th July 2011 to 27th June 2012. The specific meter reading dates for the 27 AEUS households are stated in Table 4-9. Data collection was by manual reading of the household electricity meter during three periods defined as the 1st, 2nd and 3rd meter readings.

Manual meter reading was intended to span a summer and winter period to provide a more representative estimation of the annual electricity consumption of the dwellings. Manual meter reading was deemed an appropriate method because the extended monitoring period would reduce the effects of seasonal variation and infrequent influences on occupancy, whilst it did not restrict sample size as no monitoring equipment was required. Whole house current loggers were not used because only a limited number were available for the research and would have resulted in the collection of a large amount of unnecessary data.

The 1st meter reading was taken during the installation of the whole house and appliance monitoring system. The 1st meter readings were taken between 11th July and 8th November 2011. Meter readings were recorded using paper based forms and were incorporated in to an Excel spreadsheet.

The 2nd meter reading was taken during the collection of the whole house and appliance monitoring system. The 2nd meter readings were taken between 8th August and 14th December 2011.

The 3rd meter reading was by an arranged home visit followed by letter and telephone requests. Home visits took place between 19th April and 26th April 2012. This resulted in

22 meters being read. A letter was sent out on 30th May 2012, to the remaining five households asking for meter readings to be returned by post, telephone or email or an appointment made for a visit. The homeowners were responsible for self-reporting their electricity meter reading. A further four readings were obtained between 2nd May and 10th May 2012 by post and the final meter reading was obtained by direct telephone call to the household on 17th May 2012. The date of the meter reading for the postal replies was assumed to be the day before the reply was received, unless the reply stated otherwise.

The AEUS electricity meter reading data collection was undertaken by the thesis author (Jones).

Table 4-9 Specific meter reading dates for the 27 AEUS households

Serial	Meter reading 1	Meter reading 2	Meter reading 3
115061	15/07/2011	12/08/2011	-
116011	29/09/2011	28/10/2011	25/04/2012
116091	28/07/2011	01/09/2011	25/04/2012
116121	11/07/2011	08/08/2011	23/04/2012
116161	30/08/2011	27/09/2011	26/04/2012
117191	23/08/2011	22/09/2011	25/04/2012
119041	13/10/2011	21/11/2011	-
119191	05/09/2011	04/10/2011	24/04/2012
119211	06/10/2011	03/11/2011	25/04/2012
121151	27/07/2011	22/08/2011	26/04/2012
129141	26/10/2011	23/11/2011	26/04/2012
130091	31/08/2011	28/09/2011	26/04/2012
130101	28/10/2011	23/11/2011	24/04/2012
132091	05/09/2011	06/10/2011	23/04/2012
132111	25/07/2011	22/08/2011	23/04/2012
132261	25/07/2011	24/08/2011	23/04/2012
134021	08/11/2011	13/12/2011	26/04/2012
134081	28/09/2011	26/10/2011	27/06/2012
134161	23/08/2011	21/09/2011	24/04/2012
136211	08/08/2011	22/09/2011	26/04/2012
137161	12/10/2011	09/11/2011	19/04/2012
139071	29/09/2011	27/10/2011	17/05/2012
139091	08/11/2011	14/12/2011	-
143251	12/10/2011	09/11/2011	19/04/2012
144051	26/07/2011	24/08/2011	19/04/2012
144151	26/07/2011	24/08/2011	19/04/2012
146061	30/08/2011	27/09/2011	24/04/2012

4.8.5 The AEUS administered domestic appliance ownership survey

An administered domestic appliance ownership survey was undertaken with all of the households in the AEUS study to produce a comprehensive inventory of the domestic appliances owned. This was important because the number of SMPs in the AMS was limited to thirty and it was therefore expected that some appliances would be unmeasured. The administered survey collected information relating to the appliance type; location; size and age of main appliances; make and model; monitored or unmonitored; and occupant reported usage patterns for unmonitored appliances. Information regarding the size and age of the appliances were provided by the dwelling's occupants. The makes and models were recorded from inspection of the appliances.

The appliance ownership survey was completed during the installation of the whole house and appliance monitoring system by the thesis author (Jones). The search for appliances in the participant homes was led by the occupants with prompts from the researcher regarding common appliances which were not stored in view (e.g. hair dryer, blender, etc.). The 4M LIL appliance survey follow up, previously undertaken by Dr Liyan Guo, provided a good foundation for finding and planning which appliances would be measured in each home, 21 of the AEUS households had completed this previous 4M follow up study. The inventory was recorded using paper based forms and later incorporated into a database.

4.8.6 The AEUS unstructured interview

The purpose of conducting the unstructured interviews was to gather information to explain why large changes in the annual electricity consumptions of the occupant's homes occurred between 2007 and 2011. The interviews were conducted at the end of the detailed electricity monitoring. The interviews were facilitated by presenting the occupants with a chart which displayed their annual electricity consumptions over the five year period. The charts were produced from the data collected during 4M LIL meter reading follow up, the 4M energy supplier annual electricity use data and the meter readings collected during the AEUS.

The unstructured interview was undertaken by the thesis author (Jones) as part of a separate 4M interview completed by Dr Liyan Guo using the same households in the AEUS.

4.8.6.1 Interview location and participants

As the interview was focused around the discussion of a chart depicting the changes in the annual electricity consumption of the dwellings, a face-to-face interview method was essential, as other options such as a telephone interview would have been unsuitable. The interviews were therefore conducted at the occupants' homes with as many of the family members involved as possible. In all cases, the main homeowner/s was present at the interview but on occasions dependent children and teenagers were also involved. By involving more than one occupant in the unstructured interview, the generation of a discussion between the occupants was possible and the answers provided by one occupant was often enhanced by another. Also by undertaking the interviews in the participants' homes, the location itself often acted as an aide memoire for the occupants' reflections on the chart presented. In addition, participants were able to leave the interview to check other documentation which helped to define when the factors which they deemed important actually occurred (e.g. change of electricity meter type to pre-payment).

4.8.6.2 Interview procedure

Before the household interview commenced the interview's purpose was explained and permission was gained from the occupants to record the interview with a digital recorder. The interview began by presenting the occupants with a column chart displaying the annual electricity consumption of their home over the previous five years. An example chart is shown in Figure 4-8. The use of a column chart was considered a clear and understandable way of communicating the information to the occupants. The use of charts to facilitate interviews has also previously been used by (Wall & Crosbie 2009), whilst investigating lighting use in UK households. The researcher also provided a basic overview to ensure that the occupants understood the chart correctly and introduced them to the key characteristics for discussion.

In general the interview allowed the participants to discuss broadly their views and opinions in an open-ended manner, allowing the data to emerge naturally. In addition, prior to the interview the researcher had studied the annual electricity use data for the homes in detail and had prepared prompts to probe areas of interest unexplored by the occupants themselves. The average duration of the interviews was around thirty minutes. At the end of the interview the researcher provided a short summary of the discussions and the occupants were thanked for their participation.

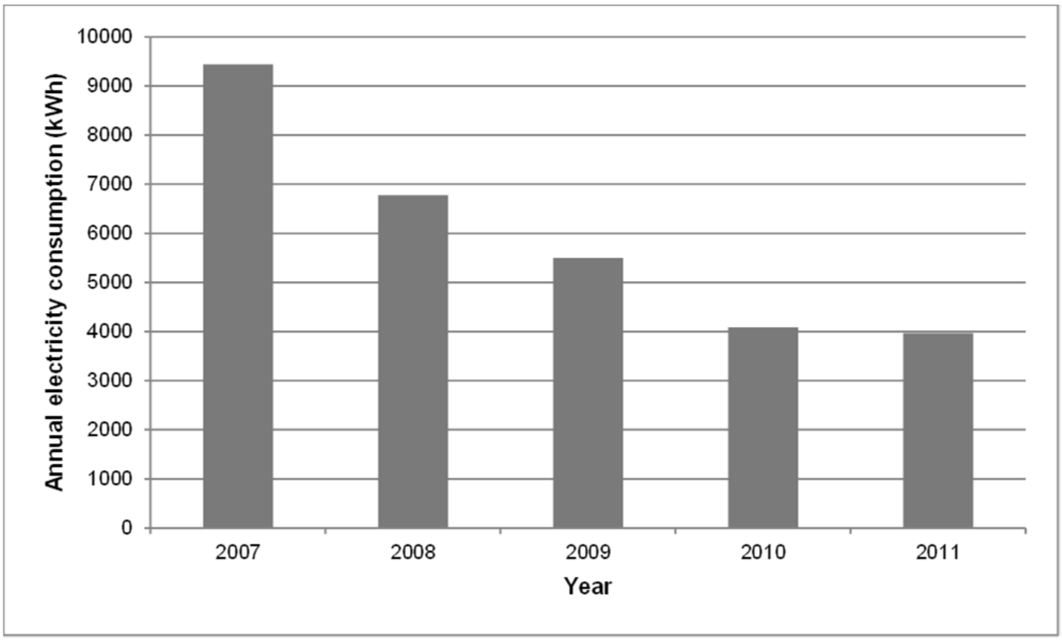


Figure 4-8 Example column chart of the variations in annual electricity consumption for household 134081 between 2007 and 2011

4.8.6.3 Interview pilot

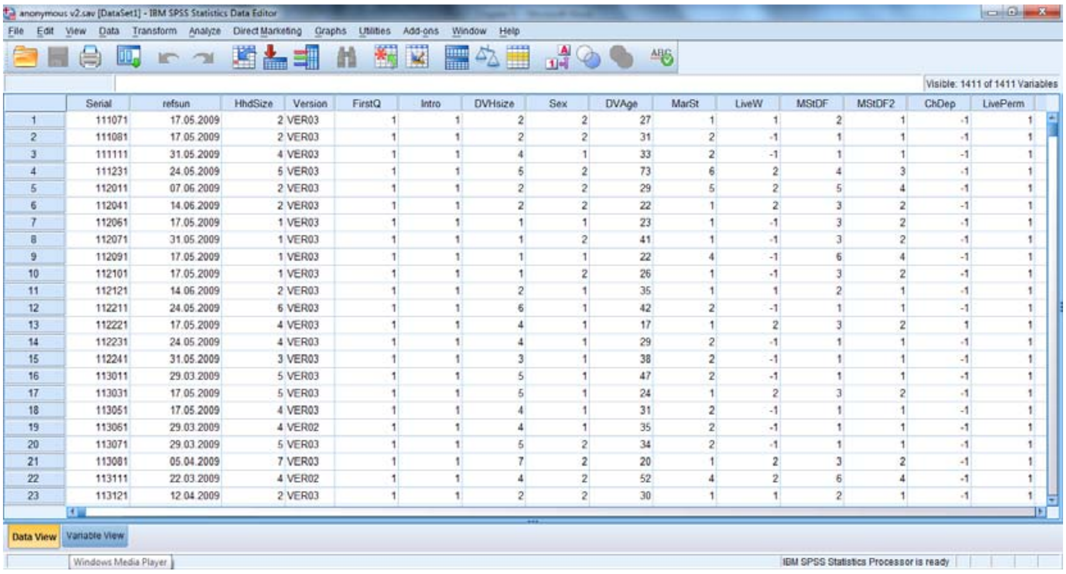
The interview procedure was tested on four of the researcher's colleagues using an example bar chart containing five years of annual electricity consumption data. The tests were helpful to develop the skills necessary to draw information from the participants and to identify graphical issues with the charts, but were restricted as the data did not relate to the test interviewees personally. The test interviewees did however demonstrate that the method could collect the data required as they were able to imagine possible explanations for the variations in the electrical demand of the dwelling shown in the chart. These explanations were in line with those expected by the researcher.

4.9 Data processing

The data processing of both the quantitative and qualitative data collected in both phases one and two of the thesis research process has employed a number of different techniques and software. The methods of data processing are outlined in the following sections for each of the data sources used in this thesis.

4.9.1 The 4M Living in Leicester household survey data

The data collected during the 4M LIL household survey from the 575 homes in Leicester were downloaded, cleaned and organised by the NatCen in an *IBM SPSS Statistics* database (Figure 4-9). The data processing stage to identify and correct or remove any obvious data error values was undertaken by Dr Katherine Irvine and Jill Fisher of the IESD at De Montfort University. There were a total of 1,411 anonymous and 157 confidential variables in the complete data set. All the data were contained within a single spreadsheet. The 4M LIL household survey database contained confidential information and was treated as a password protected file and only released to researchers who had signed a copy of the NatCen 4M Confidential Data Handover Agreement. Each of the 575 households was assigned a unique six digit serial code to protect their identities whilst undertaking the research.



	Serial	refsun	HhdSize	Version	FirstQ	Intro	DVHsize	Sex	DVAge	MarSt	LiveW	MStDF	MStDF2	ChDep	LivePerm
1	111071	17.05.2009	2	VER03	1	1	2	2	27	1	1	2	1	-1	1
2	111081	17.05.2009	2	VER03	1	1	2	2	31	2	-1	1	1	-1	1
3	111111	31.05.2009	4	VER03	1	1	4	1	33	2	-1	1	1	-1	1
4	111231	24.05.2009	5	VER03	1	1	5	2	73	6	2	4	3	-1	1
5	112011	07.06.2009	2	VER03	1	1	2	2	29	5	2	5	4	-1	1
6	112041	14.06.2009	2	VER03	1	1	2	2	22	1	2	3	2	-1	1
7	112061	17.05.2009	1	VER03	1	1	1	1	23	1	-1	3	2	-1	1
8	112071	31.05.2009	1	VER03	1	1	1	2	41	1	-1	3	2	-1	1
9	112091	17.05.2009	1	VER03	1	1	1	1	22	4	-1	6	4	-1	1
10	112101	17.05.2009	1	VER03	1	1	1	2	26	1	-1	3	2	-1	1
11	112121	14.06.2009	2	VER03	1	1	2	1	35	1	1	2	1	-1	1
12	112211	24.05.2009	6	VER03	1	1	6	1	42	2	-1	1	1	-1	1
13	112221	17.05.2009	4	VER03	1	1	4	1	17	1	2	3	2	1	1
14	112231	24.05.2009	4	VER03	1	1	4	1	29	2	-1	1	1	-1	1
15	112241	31.05.2009	3	VER03	1	1	3	1	38	2	-1	1	1	-1	1
16	113011	29.03.2009	5	VER03	1	1	5	1	47	2	-1	1	1	-1	1
17	113031	17.05.2009	5	VER03	1	1	5	1	24	1	2	3	2	-1	1
18	113051	17.05.2009	4	VER03	1	1	4	1	31	2	-1	1	1	-1	1
19	113061	29.03.2009	4	VER02	1	1	4	1	35	2	-1	1	1	-1	1
20	113071	29.03.2009	5	VER03	1	1	5	2	34	2	-1	1	1	-1	1
21	113081	05.04.2009	7	VER03	1	1	7	2	20	1	2	3	2	-1	1
22	113111	22.03.2009	4	VER02	1	1	4	2	52	4	2	6	4	-1	1
23	113121	12.04.2009	2	VER03	1	1	2	2	30	1	1	2	1	-1	1

Figure 4-9 Example data in the 4M LIL household survey database

4.9.2 The 4M Living in Leicester electricity meter reading follow up data

The data processing of the 4M LIL electricity meter reading data was carried out in three stages: (1) amalgamation of data sets; (2) simultaneous cleaning and checking; and (3) normalisation of the results to annual electricity consumptions for the dwellings. This data processing stage was undertaken by Dr David Allinson of the School of Civil and Building Engineering at Loughborough University.

4.9.2.1 Amalgamation of datasets

The electricity meter readings from the 4M LIL households were incorporated into a *Microsoft Excel* spreadsheet. Data for the first electricity meter readings were obtained from the 4M LIL household survey database, which contained the date of the visit (i.e. date of meter read) and the meter readings. Data for the 2nd and 3rd meter readings were compiled from the relevant letter, email and telephone returns as well as home visit forms. The amalgamated *Excel* spreadsheet was then used during the subsequent cleaning, checking and normalisation.

4.9.2.2 Cleaning and checking

The process of cleaning and checking was carried out manually on a house by house basis. Two stages of cleaning and checking occurred; initial cleaning of the data was followed by additional cleaning after calculating the annual electricity consumptions of the homes. The initial cleaning stage:

- Removed households from the *Excel* spreadsheet, where none or only one meter reading was obtained for a home, as it was not possible to calculate an annual electricity consumption using this data alone.
- Checked the order that the electricity readings were recorded for dual tariff meters and, where different, changed to match the 3rd meter reading (the 3rd meter reading was deemed the most reliable as it was read by the 4M researchers).
- The magnitude of meter readings was checked to identify where 1/10 and 1/100 units may have been entered as 10s or units, and vice versa.
- Where electricity meters had been “clocked” (e.g. meter rollover from 9999 to 0000) a new significant figure was added to the most recent reading in the usage calculation.

Following the initial cleaning stage, the annual electricity consumption for each home was calculated between each meter reading: 1-2; 2-3; and 1-3.The results were then checked for negative electricity consumptions (i.e. a meter reading was recorded as less than the previous one) and variations in consumptions between the three meter readings that were 10,000 or 100,000 kWh higher indicating that 1/10 and 1/100 units were still included in the dataset, these were subsequently removed from the *Excel* spreadsheet.

4.9.2.3 Normalisation to annual electricity consumption

As the electricity meter readings for each home was taken on varying dates for periods between 17th March 2009 and 18th August 2010, they were normalised to an annual electricity consumption figure for the 365 days between 1st January 2009 and 31st December 2009. These dates were chosen as they represent the 4M project base year.

The electricity consumption was normalised by assuming no seasonal variation in use (Equation 4-1). Where meter readings existed between multiple dates, the meter readings 1-3 were chosen in preference to the 2-3, which was chosen in preference to the 1-2. This was because the duration of 1-3 was greater than 2-3, and both were greater than 1-2. By visual inspection it was found that the normalisation from meter readings 1-3 was consistent with those calculated using 2-3 or 1-2 for the same home.

$$E_{pa}\ [\mathrm{kWhpa}] = \frac{M_3 - M_1}{T_3 - T_1} \times 365 \qquad\qquad Equation\ 4-1$$

Where: E_{pa} = Annual electricity consumption of dwelling [kWhpa]; M_1 = Meter reading 1 [kWh]; M_3 = Meter reading 3 [kWh]; T_1 = Date when M_1 was recorded; T_3 = Date when M_3 was recorded.

4.9.3 The 4M energy supplier annual electricity use data

Using the signed mandate and MPAN reference, annual electricity use data was obtained for 219 households for 2007 and 218 households for 2008. This data was obtained by Professor Mark Rylatt of the IESD at De Montfort University. The data was incorporated in an *Excel* spreadsheet, which was used for the cleaning and checking process. The electricity consumption figures for each home were the actual billed units of electricity usage in 2007 and 2008. The data cleaning and checking process was undertaken by the author (Jones). The first cleaning stage removed annual electricity consumption figures from the dataset where the existing participants of the study were not responsible for the whole annual consumption (i.e. the participants moved into the dwelling part way through either 2007 or 2008). This data processing was completed by referring to the 4M LIL household survey variable “when did your household take up residence at this address?”. Secondly, a manual check of the consistency in the annual electricity consumptions of the dwellings in 2007 and 2008 was carried out. Although, it was expected that some variations in electricity consumption may have occurred, not least because of the estimated meter readings that may have been used by the energy provider, any implausible, negative or extremely large variations were removed from the dataset.

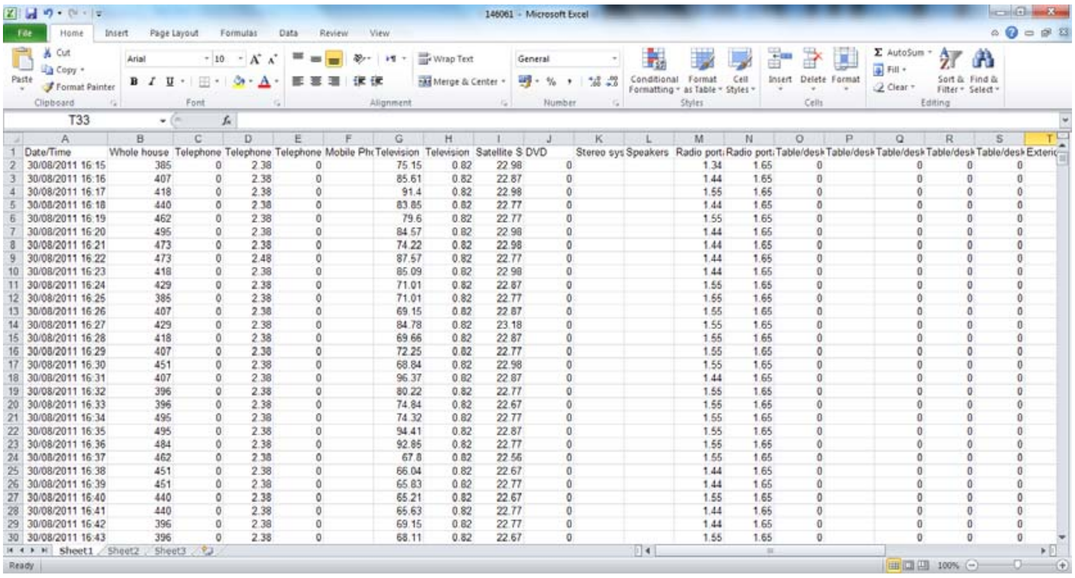
4.9.4 The 4M Living in Leicester appliance survey follow up data

The data collected from the paper based 4M LIL appliance survey was transferred into an *Excel* spreadsheet by Dr Liyan Guo of the School of Civil and Building Engineering at Loughborough University. During the data processing any obvious data error values were either corrected or removed from the dataset. The amalgamated spreadsheet contained three sections, relating to the ownership of appliances; usage patterns for main appliances; as well as size and age of main appliances.

4.9.5 The Appliance Electricity Use Survey

4.9.5.1 AEUS whole house and appliance level electricity monitoring data

The Appliance Monitoring System and whole house monitoring equipment automatically generated individual *Excel* spreadsheets for each monitored appliance and the overall electrical demand of the dwelling. The data contained in the separate spreadsheets were combined into a single *Excel* work sheet for each monitored home to ease the data cleaning and checking process. All data processing associated with the AEUS was undertaken by the author (Jones). Figure 4-10 shows an example of the worksheet produced for household 146061, which consisted of the following information: (Column A) Date/Time – the date and time the data were recorded; (Column B) Whole house – the total power demand averaged over a minute of the dwelling (W); (Column C forwards) Appliances – the power demand of the appliance averaged over a minute (W).



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
1	Date/Time	Whole house	Telephone	Telephone	Telephone	Mobile Ph	Television	Television	Satellite S	DVD	Stereo sys	Speakers	Radio port	Radio port	Table/desk	Table/desk	Table/desk	Table/desk	Table/desk	Exteric
2	30/08/2011 16:15	385	0	2.38	0		75.15	0.82	22.98	0			1.34	1.65	0		0	0	0	
3	30/08/2011 16:16	407	0	2.38	0		85.61	0.82	22.87	0			1.44	1.65	0		0	0	0	
4	30/08/2011 16:17	418	0	2.38	0		91.4	0.82	22.98	0			1.55	1.65	0		0	0	0	
5	30/08/2011 16:18	440	0	2.38	0		83.85	0.82	22.77	0			1.44	1.65	0		0	0	0	
6	30/08/2011 16:19	462	0	2.38	0		79.6	0.82	22.77	0			1.55	1.65	0		0	0	0	
7	30/08/2011 16:20	495	0	2.38	0		84.57	0.82	22.98	0			1.44	1.65	0		0	0	0	
8	30/08/2011 16:21	473	0	2.38	0		74.22	0.82	22.98	0			1.44	1.65	0		0	0	0	
9	30/08/2011 16:22	473	0	2.48	0		87.57	0.82	22.77	0			1.44	1.65	0		0	0	0	
10	30/08/2011 16:23	418	0	2.38	0		85.09	0.82	22.98	0			1.44	1.65	0		0	0	0	
11	30/08/2011 16:24	429	0	2.38	0		71.01	0.82	22.87	0			1.55	1.65	0		0	0	0	
12	30/08/2011 16:25	385	0	2.38	0		71.01	0.82	22.77	0			1.65	1.65	0		0	0	0	
13	30/08/2011 16:26	407	0	2.38	0		69.15	0.82	22.87	0			1.55	1.65	0		0	0	0	
14	30/08/2011 16:27	429	0	2.38	0		84.78	0.82	23.18	0			1.55	1.65	0		0	0	0	
15	30/08/2011 16:28	418	0	2.38	0		69.66	0.82	22.87	0			1.55	1.65	0		0	0	0	
16	30/08/2011 16:29	407	0	2.38	0		72.25	0.82	22.77	0			1.55	1.65	0		0	0	0	
17	30/08/2011 16:30	451	0	2.38	0		68.84	0.82	22.98	0			1.55	1.65	0		0	0	0	
18	30/08/2011 16:31	407	0	2.38	0		96.37	0.82	22.87	0			1.44	1.65	0		0	0	0	
19	30/08/2011 16:32	396	0	2.38	0		80.22	0.82	22.77	0			1.55	1.65	0		0	0	0	
20	30/08/2011 16:33	396	0	2.38	0		74.84	0.82	22.67	0			1.55	1.65	0		0	0	0	
21	30/08/2011 16:34	495	0	2.38	0		74.32	0.82	22.77	0			1.55	1.65	0		0	0	0	
22	30/08/2011 16:35	495	0	2.38	0		94.41	0.82	22.87	0			1.55	1.65	0		0	0	0	
23	30/08/2011 16:36	484	0	2.38	0		92.85	0.82	22.77	0			1.55	1.65	0		0	0	0	
24	30/08/2011 16:37	462	0	2.38	0		67.8	0.82	22.56	0			1.55	1.65	0		0	0	0	
25	30/08/2011 16:38	451	0	2.38	0		66.04	0.82	22.67	0			1.44	1.65	0		0	0	0	
26	30/08/2011 16:39	451	0	2.38	0		65.83	0.82	22.77	0			1.44	1.65	0		0	0	0	
27	30/08/2011 16:40	440	0	2.38	0		65.21	0.82	22.67	0			1.55	1.65	0		0	0	0	
28	30/08/2011 16:41	440	0	2.38	0		65.63	0.82	22.77	0			1.44	1.65	0		0	0	0	
29	30/08/2011 16:42	396	0	2.38	0		69.15	0.82	22.77	0			1.44	1.65	0		0	0	0	
30	30/08/2011 16:43	396	0	2.38	0		68.11	0.82	22.67	0			1.55	1.65	0		0	0	0	

Figure 4-10 Example AMS and whole house data in combined Excel work sheet for household 146061

The next stage of the data processing was to identify and remove any obvious data error values for the power consumption of the appliances and whole house data. A macro was written in Visual Basic, which automatically plotted X Y scatter graphs of power demand against time for each of the appliances as well as for the whole house. The graphs produced were then manually checked by a procedure of "eyeballing" for implausible, negative or extremely large power consumptions. Figure 4-11 shows the identification of a number of irregular power consumption values of around 1,300 Watts for a toaster, which were subsequently removed from the toaster's load profile. In this case, it became apparent when removing the irregular values from the worksheet that a similar power demand of around 1,300 Watts was also being recorded by a vacuum cleaner at around the same time, thereby indicating that the homeowner had unplugged the vacuum cleaner from its assigned SMP and reconnected it to the toaster SMP. When such events were evident the power consumption measurements were transferred to the appropriate appliance.

This was a very time consuming process, considering around 800 appliances and 27 whole house measurements required manual checking. This process was made longer when irregular values had to be moved to the correct appliances and when close attention was required to define whether a measurement was in fact an error or not. On instances when it was not entirely clear whether a value was an error, the power consumption measurement remained in the dataset.

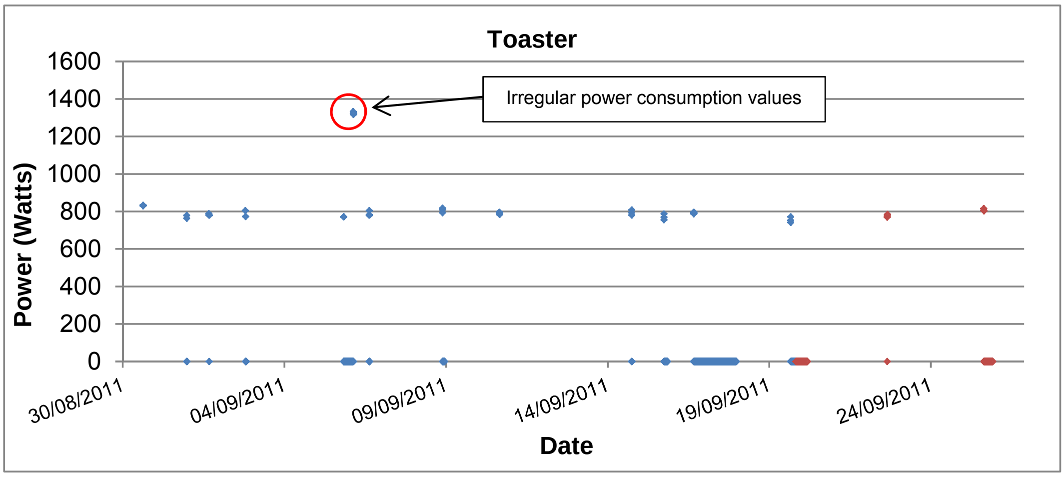


Figure 4-11 Irregular power consumption values identified and removed for a toaster

4.9.5.2 AEUS electricity meter reading data

The three electricity meter readings undertaken in the monitored households were input into an *Excel* spreadsheet for cleaning, checking and normalisation to annual electricity consumption values. In addition, any 2009 meter readings that were collected for the monitored households during the 4M LIL electricity meter reading follow up were also incorporated into the spreadsheet. This permitted the calculation of an annual usage values for the years 2010 and 2011. An identical method of data checking and cleaning used during the 4M LIL electricity meter reading follow up was also applied to the meter readings collected from the monitored homes (section 4.9.2.3.).

As three meter readings were collected in the monitored homes, the meter readings 1-3 were chosen for the calculation of the annual electricity consumptions, in preference to the 2-3, which was chosen in preference to the 1-2. This was because the duration of 1-3 was greater than 2-3, and both were greater than 1-2. The annual electricity consumptions were normalised to 365 days assuming no seasonal variation in use (Equation 4-1) for the years 2010 and 2011. The same normalisation process was used for the AEUS electricity meter reading data as used in the 4M LIL electricity meter reading follow up (section 4.9.2.3.)

4.9.5.3 AEUS administered domestic appliance ownership survey data

The data captured on the paper based forms used to record the appliance inventories for each monitored home were later converted into an *Excel* spreadsheet. A separate worksheet was setup for each home. The work sheets listed all of the appliances owned by a household, their locations, sizes, ages, makes and models and whether or not they were monitored. A separate column reported the occupant stated usage patterns for unmonitored appliances.

The spreadsheets were manually checked and cleaned. Any data error values that resulted from mistakes in data recording during equipment installation were checked during equipment collection and corrected in the spreadsheet.

4.9.5.4 Unstructured interview data

The recordings of the unstructured interviews with the occupants of the monitored dwellings regarding the large variations in the annual electricity consumption of their homes were converted by a transcription service into individual *Microsoft Word* documents for each home. The transcriptions of the interviews were checked by the author by again listening to the interview and comparing with the transcriptions provided. Any errors in the interview transcriptions identified were corrected in the document.

4.10 Data analysis

The data analysis of both the quantitative and qualitative data collected in both phases one and two of the thesis research process has employed a number of different techniques and software. The methods of data analysis are outlined in the following sections as they relate to the thesis research questions.

4.10.1 Research question Q1: Does a sample of UK households demonstrate that large variations in electrical energy demand exist between homes?

To address research question Q1 data from two samples of the 4M LIL households were used. Firstly, the distribution of annual electricity consumptions of 315 of the households in 2009, from here in referred to as the Leicester 315 cohort (L315), were investigated. The electricity use data for these homes were obtained from a combination of the 4M LIL electricity meter reading and 4M energy supplier annual electricity use follow ups. For households where electricity consumption data was available from both sources, the usage obtained from the 4M LIL electricity meter reading was chosen in preference. In total 256 households' electricity consumptions were from the 4M LIL electricity meter reading and 59 from the energy supplier.

Secondly, the distribution of annual electricity consumptions of the 27 households in 2011 that were involved in the Appliance Electricity Use Survey (AEUS), denoted as the Leicester 27 cohort (L27), were also studied. The annual electricity consumptions for these homes were calculated from the electricity meter readings undertaken during the AEUS.

The analysis of the two distributions of electricity consumption from both samples of the 4M LIL households was undertaken in Microsoft Excel, as a result of its proven capability to manage the type of data collected, the availability of the statistical functions required, and the researcher's knowledge of the software. The electricity use data collected for both the L315 and L27 cohorts were initially sorted from the smallest to largest household consumptions and then represented using clustered column charts. The clustered column chart permitted visual analysis of the annual electricity use distributions of the two samples.

The two distributions were analysed using descriptive statistics. Descriptive statistics provide simple summaries of a sample and may be either quantitative or visual (Field 2005).

In addition, the L315 and L27 cohorts were compared with both Great Britain's distribution of electricity consumption for the domestic sector (DECC 2011) as well as those observed in previous studies. The purpose was to attain whether the L315 and L27 cohorts were nationally representative samples. The two cohorts were plotted on a clustered column chart alongside the Great Britain distribution for visual analysis. The representativeness of the L315 cohort was also tested statistically using a Pearson's chi-squared test. The test assessed whether the electricity consumptions of the L315 cohort (observed values) were consistent with those in Great Britain (expected values). A non-significant p-value ($p > 0.05$) from the chi-squared test would indicate that there was no significant difference between the L315 and national distributions. It was not possible to undertake the same statistical test for the L27 cohort as the sample size was too small.

4.10.2 Research question Q2: Is the electricity consumption of a sample of UK households with high electrical energy demand increasing over time?

Previous studies (Summerfield et al. 2010; Firth et al. 2008; Summerfield et al. 2007) have identified that the electricity demand of the highest consuming domestic buildings are increasing over time. To answer research question Q2 and to validate these earlier findings, electricity consumption data relating to both the L315 and L27 cohorts were analysed. The changes in electrical demand of the L315 homes were analysed over a period of three years from 2007 to 2009. The electricity consumption data for 2007 and 2008 came from the 4M energy supplier annual electricity use follow up and for 2009 from the 4M LIL electricity meter reading follow up. The changes in electrical demand of the L27 homes were analysed over an additional two year period from 2007 to 2011. The same data sources were used for the years 2007 to 2009 but the further year's annual electricity consumptions were calculated using the meter readings collected during the AEUS.

The annual electricity consumption data from each source was compiled in a *Microsoft Excel* spreadsheet for both the L315 and L27 households and all data analysis was carried out using the software. For the purpose of this analysis, the L315 homes were stratified into three equally sized groups (thirds) based on the total annual electricity consumptions. The 105 lowest consuming households were classified as the ‘low electrical demand group’, the middle 105 as the ‘medium electrical demand group’, and the highest 105 as the ‘high electrical demand group’.

This method of stratification was used previously by Summerfield et al. (2010), Firth et al. (2008), Summerfield et al. (2007), and Gram-Hanssen et al. (2004), thereby the current study maintains comparability with the existing body of literature. Table 4-10 provides a comparison of the L315 electrical demand groups with those in previous UK studies. Some variation existed between the ranges and means of the groups. It is assumed that these originate from the smaller sample sizes, the variations in the year of research, the fact that the Summerfield et al. (2010), Firth et al. (2008), and Summerfield et al. (2007) studies do not include electrically heated homes, and the specific contexts of low-energy and social housing. Observing the stratification obtained using this method with the national picture (DECC 2011) confirms that splitting the L315 cohort into three groups of a third each is sufficient for the purpose of the analysis, as the ranges and means of all groups lie within a couple of hundred kWh of that seen nationally, whilst maintaining an adequate sample size in each group.

Table 4-10 Comparison of the L315 electrical demand groups with those in previously reported studies

Study	N	Electrical demand group	Electricity consumption range (kWh per annum)		Mean electricity consumption (kWh per annum)
			Min	Max	
Leicester city 4M LIL project L315 (2009)	315	Low	**259**	**2,543**	**1,735**
		Medium	**2,554**	**4,041**	**3,232**
		High	**4,048**	**25,587**	**6,588**
Milton Keynes "Low energy" owner occupied households Gas central heating (1989/90 – 2005/06) (Summerfield et al. 2007)	14	Low	-	-	2,299 (1990) 2,774 (2005)
		Medium	-	-	4,636 (1990) 4,344 (2005)
		High	-	-	5,913 (1990) 10,330 (2005)
Five different sites (4 sites were social housing) Gas central heating (2002 – 2006) (Firth et al. 2008)	72	Low	902 (yr 1) 920 (yr 2)	2,160 (yr 1) 3,447 (yr 2)	1,170 (yr 1) 1,964 (yr 2)
		Medium	2,174 (yr 1) 1,195 (yr 2)	3,247 (yr 1) 4,600 (yr 2)	2,689 (yr 1) 2,670 (yr 2)
		High	3,273 (yr 1) 2,994 (yr 2)	7,743 (yr 1) 8,775 (yr 2)	4,841 (yr 1) 5,088 (yr 2)
Milton Keynes "Low energy" owner occupied households Gas central heating (1989/90 – 2005/06) (Summerfield et al. 2010)	36	Low	-	-	2,336 (1990) 3,139 (2005)
		Medium	-	-	4,052 (1990) 3,687 (2005)
		High	-	-	5,037 (1990) 8,651(2005)
Energy supplier meter data for UK homes (2007) (DECC 2011)	20,851,507	Low	10	2,480	1,568
		Medium	2,481	4,310	3,339
		High	4,311	25,000	6,850

The L27 cohort was also divided into three electrical demand groups for the analysis but were instead categorised into three groups based on the consumption thresholds defined by the L315 stratification. The households were stratified based on their annual electricity consumptions. Therefore, L27 households with an annual consumption below 2,543 kWh were classified in the ‘low demand group’, those between 2,543kWh and 4,041 kWh in the ‘medium demand group’ and those greater than 4,042 kWh in the ‘high demand group’. This resulted in five households being classified in the ‘low demand group’, ten households in the ‘medium demand group’, and ‘12 households in the high demand group’. The option to stratify the L27 in this way was because the sample was a subset of the L315 cohort and it was therefore desirable to examine the L27 cohort using the same stratification criteria to allow comparisons of the results obtained.

Once the three electrical demand groups were established for both the L315 and L27 cohorts, the first stage of the analysis entailed calculating the mean annual electricity consumption for each demand group during each year. The percentage changes in mean annual electricity consumption were then calculated for each demand group between consecutive years. The significance of the changes in the mean annual electricity consumption of the L315 households was also tested statistically using two-tailed t-tests (Field 2005). A significant p-value ($p < 0.05$) from a t-test would indicate that there was a significant change in the mean electricity consumption over the year for an electrical demand group. It was not possible to undertake the same statistical test for the L27 cohort as the sample size was too small.

In addition, for the L27 cohort a further qualitative analysis investigating the occupants' perspectives on which factors contribute to large changes in the electrical energy demand of their homes over time was undertaken. The unstructured interviews conducted with the L27 cohort was used for this analysis.

A qualitative data analysis technique termed “template analysis” (King 2007) was used to condense the broad qualitative interview data into a series of discrete factors that the occupants of the dwellings believed were responsible for large changes in the annual electrical energy demand of their homes. This was undertaken by a method of data coding, which attributes sections of the interview to a particular concept or theme (King 2007). A predefined coding approach was established to classify the occupants' responses, which was based on the factors identified as affecting the electricity demand of domestic buildings from the literature review. However, the coding was not limited to these predefined categories in the event of a new concept or theme arising.

The data analysis was carried out following King (2007)'s template analysis framework, which provides a clearly defined process for coding and analysing qualitative data. Table 4-11 highlights the main stages involved in the template analysis process (King 2007).

Table 4-11 Template analysis process

Stage 1. Definition of the a priori themes and codes
This stage involves the definition of themes, which are features of participants' responses that characterise perceptions and experiences that the researcher believes are relevant to the research questions, and codes, which are the specific labels attached to the themes. For this thesis, the codes developed were based on the factors identified as affecting the electricity demand of domestic buildings from the literature review.
Stage 2. Transcription and familiarisation with the data
This stage entails writing up the interview data. For this thesis, a full transcription of the interviews was undertaken by a professional transcription service.
Stage 3. Initial coding of the data
This stage involves the identification of parts of the transcripts that are relevant to the research questions. A code is attached to the sections that relate to a theme. If they are not encompassed by a relevant theme, existing themes are modified or new codes are defined.
Stage 4. Initial template
This stage aims at producing a hierarchical template that structures the codes, by grouping the codes previously defined into a smaller number of higher order codes, which describe broader themes in the data.
Stage 5. Validation of the template
This stage is completed to check the quality of the coding and reduce the effects of the researcher's bias in the coding process.
Stage 6. Development of the template
This stage involves developing the final template by applying the initial template to all of the data and modifying it if necessary to ensure a better fit with the data. The changes included defining new code, changing the hierarchy of codes and deleting irrelevant codes.
Stage 7. Interpret and write-up findings
The final template is used to help interpret the data and write up the research findings.

The data coding was undertaken in copies of the Microsoft Word transcripts of the interviews. The number of instances that a factor was cited by the participants as a possible reason for a change in the electricity demand of their home was recorded in a separate Excel spreadsheet. These stated factors were then ranked based on the frequency with which they were indicated by all L27 cohort homes combined.

4.10.3 Research question Q3: Which socio-economic, technical and appliance factors contribute to high electrical energy demand in a sample of UK households?

The existing literature has demonstrated that many socio-economic, technical and appliance factors can influence the electricity consumption of a domestic building. However, very few studies have explicitly investigated the factors that lead to high electrical energy demand in domestic buildings. To answer research question Q3, data relating to the socio-economic, technical and appliance related characteristics and electricity consumption of the L315 cohort were analysed in parallel using a method called odds ratio.

The socio-economic, technical and appliance data for the L315 dwellings were obtained from the 4M LIL household survey and 4M LIL appliance survey follow up. The electricity consumption data used was from the 4M LIL electricity meter reading and 4M energy supplier annual electricity use follow ups. For households where electricity consumption data was available from both sources, the usage obtained from the 4M LIL electricity meter reading was chosen in preference. In total 256 households' electricity consumptions were from the 4M LIL meter reading and 59 from the energy supplier.

Odds ratio analysis was the method chosen to investigate the influence of a range of socio-economic, technical and appliance factors on the electrical energy demand of the L315 households. An odds ratio (OR) is a measure of association between an exposure and an outcome. The OR represents the odds that an outcome will occur given a particular exposure, compared to the odds of the outcome occurring in the absence of that exposure (Szumilas 2010). Simply, ORs are used to compare the relative odds of the occurrence of the outcome of interest (a dwelling having high electricity consumption), given exposure to a factor of interest (e.g. number of occupants, presence of electric space heating, number of televisions owned etc.). The OR can also be used to compare the change in likelihood of a household being a high electricity consumer based on a change in the socio-economic, technical and appliance factors, for example, the change in the likelihood if the household size increases from three to four occupants.

The known socio-economic, technical and appliance factors and annual electricity consumption data for each of the L315 homes were compiled in a *Microsoft Excel* spreadsheet. The calculation of the ORs for each socio-economic, technical and appliance related factor was undertaken using *Microsoft Excel*.

The socio-economic characteristics that were investigated in the analysis were the number of occupants, presence of children and teenagers, age of the HRP, employment status of the HRP, education level of the HRP, the National Statistics Socio-economic classification of the HRP, tenure and annual household income.

The technical characteristics examined were dwelling type, period dwelling was built, number of bedrooms and floors, total floor area, presence of electric space heating, presence of fixed electric heating, presence of portable electric heating and presence of electric water heating.

The appliance related factors considered in the study were the total number of appliances owned, number of IT, telephony, entertainment, HVAC, minor cooking, preservation and cooling, washing, laundry, building and outdoors maintenance and hygiene, beauty and leisure appliances owned, number of desktop and laptop computers owned, working hours per day for weekdays and weekend for the main desktop and laptop computer, number of televisions owned, main television type, working hours per day for weekdays and weekend for the main television, presence of electric cooking, working hours per day for weekdays and weekend for electric oven and hob, ownership of refrigerators, fridge-freezers, upright freezers and chest freezers, ownership of a dishwasher, loads of dishwashing per week, temperature of dishwashing, ownership of washing machines, washer-dryers and tumble dryers, loads of clothes washing per week, temperature of clothes washing and loads of clothes drying in the summer and winter, presence of electric showers and use of electric showers.

In an *Excel* spreadsheet, the known socio-economic, technical and appliance characteristics of the L315 cohort were listed. The number of homes that were high electrical energy consumers and the number that were low or medium consumers were then tabulated against each characteristic (for example see Table 4-12). The low and medium consumption groups of the L315 cohort were merged for the analysis because the purpose was to understand the influence of a range of socio-economic, technical and appliance factors on the probability of being a high electrical energy consumer only.

Table 4-12 Odds ratio example for presence of children

Factor	Number of homes with electricity demand		Total homes	Odds ratio (95% CI)
	< 4042 kWh pa (Low-Medium group)	> 4041 kWh pa (High group)		
Children				
No Children	161	62	223	REFERENCE
Children	49	43	92	2.28 (1.38, 3.77)

For each socio-economic, technical and appliance factor the OR was calculated, which reflects the likelihood that a household will be a high electrical energy user relative to a reference household in the same category. The reference for each characteristic was chosen for one of two reasons; either the household did not have the factor (e.g. no children, no electric space heating) or, the factor represented the majority of the sample.

For a given factor, the OR was the number of homes with high electricity demand (> 4,041 kWh pa) divided by the number with low or medium demand (< 4,042 kWh pa), divided by the same ratio for the reference group (Agresti 2007). Equation 4-2 below shows an example of the odds ratio calculation for the presence of children.

Equation 4 - 2

$$OR = \frac{C_H / C_{LM}}{NC_H / NC_{LM}} = \frac{C_H \times NC_{LM}}{NC_H \times C_{LM}} = \frac{43 \times 161}{62 \times 49} = \frac{6923}{3038} = 2.28\ (95\%\ CI = 1.38, 3.77)$$

Where: OR = Odds ratio; C_H = Number of homes with children and high electric demand; C_{LM} = Number of homes with children and low or medium electric demand; NC_H = Number of homes with no children and high electric demand; NC_{LM} = Number of homes with no children and low or medium electric demand.

An OR value of 1 indicated that households with a given socio-economic, technical and appliance characteristic were equally likely to be high electrical energy users as those households in the reference group. An OR greater than 1 indicated a higher probability that the households would be high users, whereas a ratio below 1 indicated the probability was lower. In addition, the higher the value of the OR, the more likely it was that the households will be high consumers.

The 95% confidence interval (CI) associated with each OR describes the uncertainty in the estimate (Agresti 2007). Equation 4-3 shows the formula for calculating the 95% CI for the presence of children. A narrow CI indicated that the effect was known precisely, whereas a wider interval indicated the uncertainty was greater, but there may still be enough precision to draw inferences about the effect. It is important to note that the CI does not report statistical significance. In practice, the CI is often used as a proxy for the presence of statistical significance if it does not overlap the value 1 (Szumilas 2010). A CI spanning the value 1 (e.g. CI = 0.5, 1.5) would indicate that the influence of a socio-economic, technical and appliance factor on electricity consumption was unclear, however it would be incorrect to interpret a CI spanning the value 1 as indicating evidence for lack of association between the factor and high electricity consumption altogether.

Equation 4 - 3

$$CI_{+95\%} = e^{\ln OR + 1.96\sqrt{\frac{1}{a}+\frac{1}{b}+\frac{1}{c}+\frac{1}{d}}} = e^{\ln 2.28 + 1.96\sqrt{\frac{1}{43}+\frac{1}{62}+\frac{1}{49}+\frac{1}{161}}} = 3.77$$

$$CI_{-95\%} = e^{\ln OR - 1.96\sqrt{\frac{1}{a}+\frac{1}{b}+\frac{1}{c}+\frac{1}{d}}} = e^{\ln 2.28 - 1.96\sqrt{\frac{1}{43}+\frac{1}{62}+\frac{1}{49}+\frac{1}{161}}} = 1.38$$

The width of the CI is influenced by sample size and the variability in the data. Large sample sizes tend to give more precise OR estimates than smaller ones (Agresti 2007; Field 2005). The CI was taken into consideration when interpreting the effects of the households' socio-economic, technical and appliance characteristics.

4.10.4 Research question Q4: To what extent do the ownership, power demand and use of different domestic appliances contribute to high electrical energy demand in a sample of UK households?

Although the odds ratio analysis provides a means to understand the socio-economic, technical and appliance context influencing high electricity consumption in domestic buildings, ultimately, with the exception of those homes with electric space or water heating, the electricity supplied to UK homes is used to power lighting and appliances. Consequently, variations in appliance electricity consumption should determine the differences in overall electrical demand between dwellings. Fundamentally, variations in appliance electricity consumption relate to three factors:

1. The number of appliances owned by households;
2. The power demands of the appliances in the different power modes;
3. The patterns of use in the households (i.e. occupant's behaviour influences the appliances duration of use in the different power modes).

To answer research question Q4, data relating to these three factors, as well as the appliance electricity consumption measured during the 4M LIL detailed electricity monitoring study were analysed. The same method of stratifying the L27 cohort into three electrical demand groups (low, medium and high) based on the total annual electricity consumptions of the dwellings was employed for the analysis. The methods of data analysis are outlined in the following subsections. Firstly, the analysis techniques used to investigate the variations in annual appliance electricity consumption between the electrical demand groups are described. This is followed by the methods of analysis used to examine the variations in appliance ownership, appliance power demand, and appliance use between the electrical demand groups. Before these analyses are outlined, two core classification techniques used in the analysis are described: an appliance taxonomy and appliance power modes.

4.10.4.1 Appliance taxonomy

In the analysis of research question Q4, a modified appliance taxonomy initially developed by the Carbon Reduction in Buildings (CaRB) project (Marjanovic et al. 2008) was used to provide a systematic categorisation of the appliances measured. The hierarchical taxonomy provided an organised four tiered structure that subdivided the appliances into a number of clear and systematically grouped categories for the subsequent analyses. Table 4-13 illustrates the modified appliance taxonomy employed.

The hierarchical taxonomy classified the appliances into four grouped levels. *Appliance category:* the appliances were grouped into nine main appliance categories of office equipment and infotainment, non-fixed lighting, HVAC, transportation, catering, washing, laundry, building and outdoors maintenance and hygiene, beauty and leisure.

Appliance subcategory level 1: the appliance categories of office equipment and infotainment and catering also contained a series of subcategories of IT, telephony, office accessories, and entertainment, as well as, major cooking, minor cooking and preservation and cooling.

Appliance subcategory level 2: the appliance subcategory level 1 was further subdivided into a level 2 for the office equipment and infotainment appliance category, which included computer, imaging, networking and storage for IT and television, video amplifier (booster), set top boxes, video and recording, audio, and video console for entertainment.

Appliance types: all the measured appliances were grouped into 104 individual appliance types. For example, desktop computer, LCD television, refrigerator, washing machine etc.

Table 4-13 Modified appliance taxonomy used in the data analysis

OFFICE EQUIPMENT AND INFOTAINMENT

IT

- Computer
  - Desktop computer
  - Laptop computer
- Imaging
  - Printer
- Networking
  - Wireless router
  - DSL
  - Ethernet HUB
- Storage
  - Portable hard-drive

Telephony

- Telephone
- Telephone with answering machine

Office accessories

- Shredder
- Laminator

Entertainment

- Television
  - CRT television
  - LCD television
- Video amplifier (booster)
  - Video amplifier (booster)
- Set Top Boxes
  - Digital Set Top Box
  - Satellite Set Top Box
  - Cable Set Top Box
  - Internet Set Top Box
- Video and recording
  - DVD player
  - VCR player
  - Blu-ray player
  - DVD with VCR
  - Portable DVD player
- Audio
  - Stereo system
  - Digital radio
  - Analogue radio
  - Clock radio
  - Personal CD player
  - Turntable
  - Speakers
  - MP3 docking station
  - Keyboard/organ
  - Guitar/keyboard amplifier
  - Home music studio
  - Home theatre system
- Video console
  - Video console
  - ebook reader

NON-FIXED LIGHTING

- Incandescent
- CFL
- LED
- Halogen

HVAC

- Desk fan
- Electric fire
- Electric blanket
- Portable halogen radiator
- Portable oil filled radiator

TRANSPORTATION

- Reclining furniture
- Mobility scooter
- Bath lift
- Golf trolley
- Chair lift

CATERING

Major cooking

- Electric oven
- Electric hob

Minor cooking

- Small ovens
- Microwave
- Grill plate
- Deep fryer
- Toaster
- Slow cooker
- Steamer
- Kettle
- Blender
- Food mixer
- Juicer
- Food processor
- Coffee grinder
- Coffee maker
- Ice maker
- Popcorn maker
- Can opener
- Knife

Preservation and cooling

- Refrigerator
- Fridge-freezer
- Upright freezer
- Chest freezer
- Beer and wine cooler

WASHING

- Dishwasher

LAUNDRY

- Iron
- Washing machine
- Washer-dryer
- Tumble-dryer

BUILDING AND OUTDOORS MAINTENANCE

- Vacuum cleaner
- Security systems (Alarm)
- Plug in air freshener
- Door bell
- Utility meters
- Automatic door opener
- Saw
- Sander
- Sewing machine
- Electric lawn mowers
- Indoor aquarium
- Outdoor aquarium
- Battery chargers
- Pest alarms

HYGIENE, BEAUTY AND LEISURE

- Electric shower
- Hair dryer
- Hair straighteners
- Hot air styler
- Hair clippers
- Shaver
- Massager
- Toothbrush
- Medical

4.10.4.2 Power modes of appliances

In the analysis of research question Q4, the electricity consumption of the appliances in their various power modes was investigated in relation to electrical demand groups. As a result of the number of different features domestic appliances can now perform, many devices will have a number of different power requirements (Fung et al. 2003). For this thesis the definitions of the power modes was adopted from the International Standby Power Data Project (2008). Table 4-14 provides the definitions of these power modes.

Table 4-14 Definitions of appliance power modes (International Standby Power Data Project 2008)

Power mode	Definition
Active	The power used when the appliance is performing its primary function (e.g. when a television is on providing images and/or sound).
Active Standby	The power used when the appliance is on, but not performing its main function (e.g. when a DVD player is on but not recording or playing).
Passive Standby	The power used when the appliance is not performing its main function, but is in a state waiting to be switched on or is performing a secondary function (e.g. when a television has been switched off by the remote control).
Off Standby	Off standby mode is when an appliance, that has an off switch, is connected to a power source, but is not waiting or performing any function. It can only be activated when the power switch on the appliance is activated (e.g. when a television is switched off, but still plugged into the mains power supply).

These definitions were chosen because they incorporated the terms used in the most recent Eco-design of Energy-using Products (EUP) Directive (EC 2008), as well as in previous research studies and policy documents (Coleman et al. 2012; IEA 2007; EES 2006). The definitions of the standby power modes used also recognise that different low power modes exist in between the active and unplugged states of appliances beyond the simplistic definitions provided by the European and British Standards document BS EN 62301:2005 (BSI 2005), the US Department of Energy (DOE) and the International Electrotechnical Commission (IEC). It should be noted however that the definitions used did exclude some standby power modes suggested by other studies, like “active standby high” and “active standby low” (Jones and Harrison 2007) and “sleep” (Payne & Meier 2004). Despite these exclusions, it was thought that a sufficiently detailed analysis of standby power could be gained from using this approach. Furthermore, the definitions used also echo those of the US Environmental Protection Agency’s Energy Star energy labelling program for domestic appliances (Energy Star 2009), thereby providing a level of harmonisation with power mode definitions internationally.

The definitions of the adopted power modes outlined above were however primarily developed in relation to infotainment appliances (e.g. televisions, computers, DVD players, etc.), which posed an issue for the current research as this thesis' scope exceeded this limited category of appliances and sort to investigate all domestic appliance types. It was found that whilst the definitions of the standby modes were adequate, for other appliance types different active power modes also existed. The additional active power modes related to devices in the preservation and cooling appliance subcategory (level 1), as well as the washing and laundry appliance categories. Table 4-15 provides the definitions of these additional active power modes.

Table 4-15 Definitions of additional active power modes

Active Power mode	Definition	Appliances
Preservation and cooling		
Cooling cycle	The power used when the engine of the preservation and cooling appliance is cooling the internal temperature.	Refrigerator, Fridge-freezer, Upright freezer, Chest freezer, Beer and wine cooler
Non-cooling cycle	The power used when the engine of the preservation and cooling appliance is not cooling the internal temperature.	
Washing		
Washing cycle	The power used when the washing appliance is heating the water to the appropriate temperature and shooting water through jets to clean the dishes.	Dishwasher
Drying cycle	The power used when the washing appliance is heating the air to dry the dishes.	
Laundry		
Water heating cycle	The power used when the laundry appliance is heating the water for cold fill devices.	Washing machine, Washer-dryer, Tumble-dryer
Washing cycle	The power used when the laundry appliance is washing the clothes.	
Heating cycle	The power used when the laundry appliance is heating the air to dry the clothes.	
Tumble cycle	The power used when the laundry appliance is rotating to move the clothes inside.	

Once the definitions of the different power modes were established, the next stage was to attribute the power demands recorded for each monitored appliance to the relevant power modes. To identify the power modes, the macro developed in Visual Basic during the data processing stage was used, which automatically plotted X Y scatter graphs of power demand against time. The graphs created for all the appliances were visually checked and thresholds for the different power modes were defined. Figure 4-12 shows the power mode thresholds for an example television.

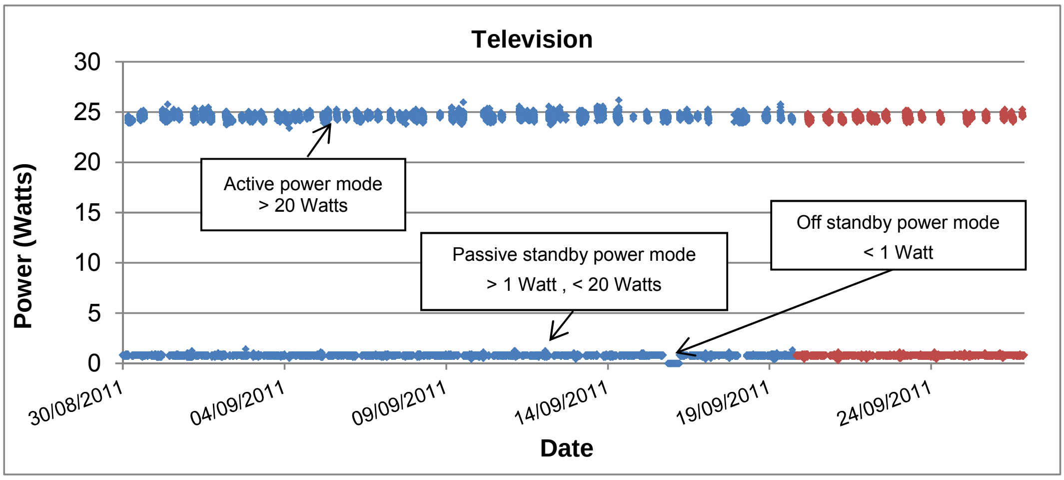
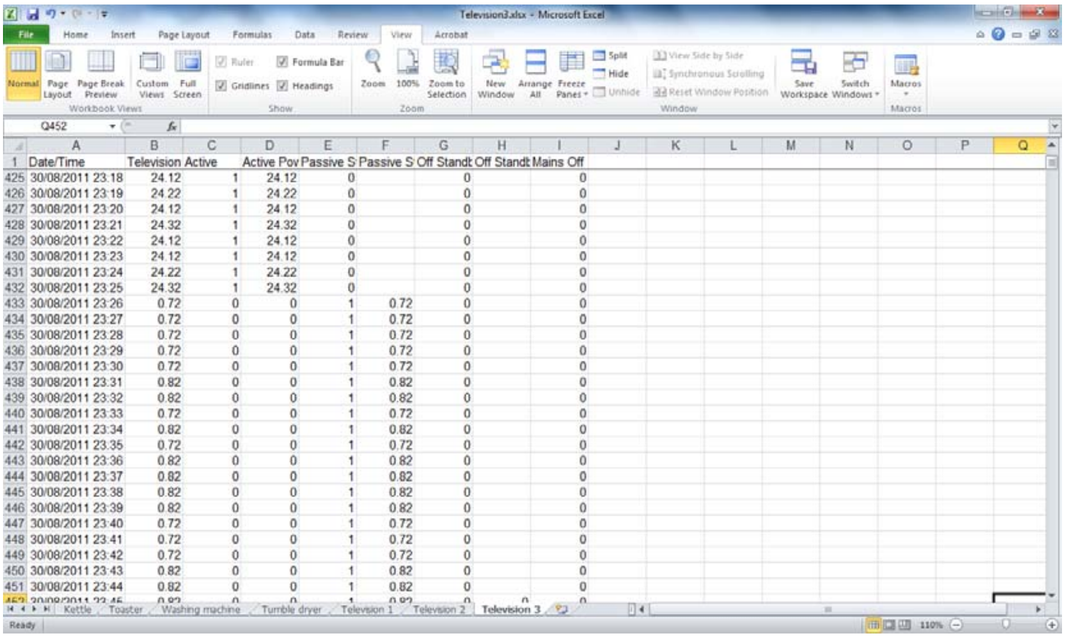


Figure 4-12 Power mode thresholds for an example television

Despite the inclusive definitions of the power modes used, the practical process of attributing measured power loads to specific power modes was complicated and time consuming. Due to the wide variations in the power load requirements of the same appliances types, which related to the size, age and features of the devices, tailored thresholds of the power modes had to be developed for every monitored appliance. The thresholds were established based on the researcher's instinct and familiarity with the data whilst observing the X Y scatter graphs; however it should be accepted that the differentiation between power modes was sometimes difficult as there were only small variations in the power loads between them. The resolution of the smart meter plugs (SMPs) used in the monitoring compared with appliance laboratory testing equipment may also have restricted the accurate identification of the power modes.

Finally, for each of the L27 households an *Excel* workbook was created to stratify the power demand data of the monitored appliances into power modes based on the thresholds identified. A separate work sheet was setup for each appliance monitored. Figure 4-13 shows an example of a work sheet produced for a television, which consisted of the following information: (Column A) Date/Time – the date and time the data were recorded; (Column B) the power demand of the appliance averaged over a minute; (Column C) an IF statement to express the thresholds of the active power mode (i.e. =IF(B2>4,1,0); (Column D) any power demands attributed to the active power mode; (Column E) an IF statement to express the thresholds of the passive standby power mode (i.e. =IF(AND(B2<4, B2>0.01),1,0); (Column F) the power demands attributed to the passive standby power mode; (Column G) an IF statement to express the thresholds of the off standby power mode (i.e. =IF(AND(B2>-1, B2<0.01),1,0); (Column H) the power demands attributed to the off standby power mode; (Column I) an IF statement to express whether the television was switched off from the mains power supply (i.e. =IF(B2=-1,1,0).



	A	B	C	D	E	F	G	H	I
1	Date/Time	Television	Active	Active Pov	Passive S	Passive S	Off Standt	Off Standt	Mains Off
425	30/08/2011 23:18	24.12	1	24.12	0		0		0
426	30/08/2011 23:19	24.22	1	24.22	0		0		0
427	30/08/2011 23:20	24.12	1	24.12	0		0		0
428	30/08/2011 23:21	24.32	1	24.32	0		0		0
429	30/08/2011 23:22	24.12	1	24.12	0		0		0
430	30/08/2011 23:23	24.12	1	24.12	0		0		0
431	30/08/2011 23:24	24.22	1	24.22	0		0		0
432	30/08/2011 23:25	24.32	1	24.32	0		0		0
433	30/08/2011 23:26	0.72	0	0	1	0.72	0		0
434	30/08/2011 23:27	0.72	0	0	1	0.72	0		0
435	30/08/2011 23:28	0.72	0	0	1	0.72	0		0
436	30/08/2011 23:29	0.72	0	0	1	0.72	0		0
437	30/08/2011 23:30	0.72	0	0	1	0.72	0		0
438	30/08/2011 23:31	0.82	0	0	1	0.82	0		0
439	30/08/2011 23:32	0.82	0	0	1	0.82	0		0
440	30/08/2011 23:33	0.72	0	0	1	0.72	0		0
441	30/08/2011 23:34	0.82	0	0	1	0.82	0		0
442	30/08/2011 23:35	0.72	0	0	1	0.72	0		0
443	30/08/2011 23:36	0.82	0	0	1	0.82	0		0
444	30/08/2011 23:37	0.82	0	0	1	0.82	0		0
445	30/08/2011 23:38	0.82	0	0	1	0.82	0		0
446	30/08/2011 23:39	0.82	0	0	1	0.82	0		0
447	30/08/2011 23:40	0.72	0	0	1	0.72	0		0
448	30/08/2011 23:41	0.72	0	0	1	0.72	0		0
449	30/08/2011 23:42	0.72	0	0	1	0.72	0		0
450	30/08/2011 23:43	0.82	0	0	1	0.82	0		0
451	30/08/2011 23:44	0.82	0	0	1	0.82	0		0

Figure 4-13 Attributing measured power loads to specific power modes for a television

4.10.4.3 Variations in annual appliance electricity consumption between electrical demand groups

The variations in annual electricity consumption between electrical demand groups were investigated. The results demonstrate the contribution of different appliance types in driving high electrical energy demand (i.e. appliances with a higher mean annual electricity consumption when owned by high consumers, rather than low or medium consumers, contribute greater to the overall higher electrical energy demand). The average annual electricity consumptions for appliance types were derived by dividing the sum of annual electricity consumptions for an appliance type by the number of households in the electrical demand group (Equation 4-4).

$$\overline{E_{a,m,e}}\,[kWhpa] = \frac{\sum_{i=1}^{N_e} E_{a,m}}{N_e} \qquad Equation\ 4-4$$

Where: $\overline{E_{a,m,e}}$ = Total average annual appliance electricity consumption for power mode for electrical demand group [kWhpa]; $E_{a,m}$ = Annual appliance electricity consumption for power mode [kWhpa]; N_e= Number of homes in electrical demand group; being *a* = appliance type (e.g. TV, washing machine, tumble dryer), *m* = power mode (e.g. active, active standby, passive standby), *e* = electrical demand group (low, medium, high).

Before a group annual electricity consumption could be calculated for an appliance type, firstly, annual electricity consumption values were required for all of the individual domestic appliances monitored in the L27 cohort households. To achieve this, a number of *Excel* formulas were inserted in the final row of the *Excel* workbooks created to stratify the power data of the appliances into power modes (Figure 4-13). The annual electricity consumption in each power mode was calculated using the formulas in Table 4-16. The formulas calculated the electricity consumed in kWh over the monitoring period, divided this figure by the number of days that monitoring was undertaken in the household (kWh per day), and multiplied by 365 to produce an annual electricity consumption (kWh per annum). Figure 4-14 shows an example screen shot of the data columns used to calculate the annual electricity consumption of a television in each power mode.

Table 4-16 Example Excel formulas used to calculate the annual electricity consumption of a television in active, passive standby and off standby modes

Column	Description	*Excel* formula
B	Total annual electricity consumption	=SUM(B2:B41845)/60/1000/ NUMBER OF MONITORED DAYS (30 DAYS)*365
D	Annual electricity consumption in active power mode	=SUM(D2:D41845)/60/1000/ NUMBER OF MONITORED DAYS (30 DAYS)*365
F	Annual electricity consumption in passive standby power mode	=SUM(F2:F41845)/60/1000/ NUMBER OF MONITORED DAYS (30 DAYS)*365
H	Annual electricity consumption in off standby power mode	=SUM(H2:H41845)/60/1000/ NUMBER OF MONITORED DAYS (30 DAYS)*365

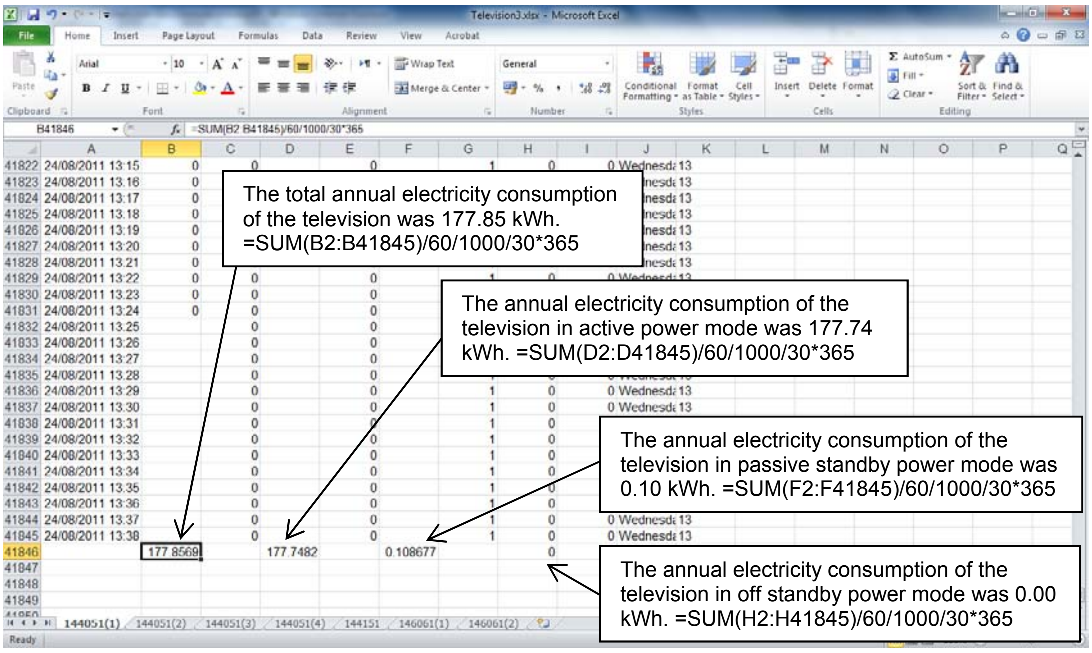


Figure 4-14 Example screen shot of the data columns used to calculate the annual electricity consumption of a television in each power mode

Once annual electricity consumption figures were produced for all of the monitored domestic appliances, average annual electricity consumption figures for each power mode was calculated for the electrical demand groups using Equation 4-4. The results obtained are appliance consumption averages and are derived by dividing the sum of each appliances type's annual electricity consumption in a specific power mode by the number of households in an electrical demand group.

The average annual appliance electricity consumptions for electrical demand groups was calculated in Microsoft *Excel* by grouping the calculated annual appliance electricity consumptions by electrical demand group and dividing by the number of households. Figure 4-15 shows a screen shot of the process of calculating the average annual electricity consumptions of televisions in each power mode for the three electrical demand groups.

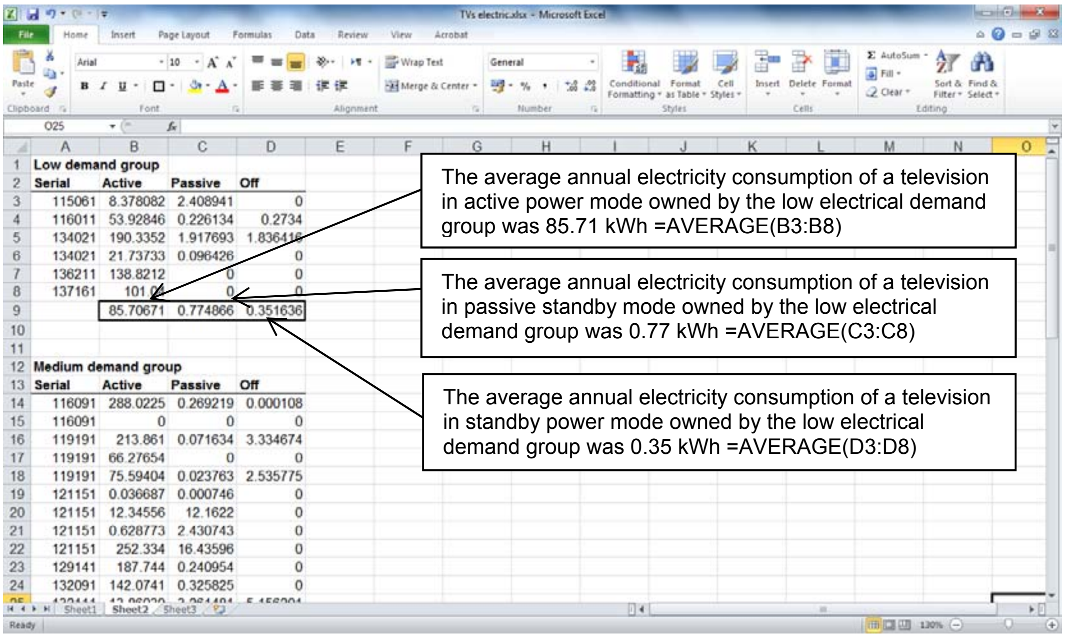


Figure 4-15 Example screen shot of the process of calculating the average annual electricity consumptions of televisions in each power mode for the electrical demand groups

A comparison of the variations in annual appliance electricity consumption between the electrical demand groups was undertaken and described, specifically highlighting those appliances types which had a greater electricity use when owned by high consumers and therefore contribute to high electrical energy demand. The results were presented in a series of tables, demonstrating an appliance type's annual electricity consumption by power mode and electrical demand group.

4.10.4.4 Variations in appliance ownership between electrical demand groups

An analysis of the differences in appliance ownership[2] between the three electrical demand groups was undertaken. To compare the differences in ownership of appliances between the electrical demand groups, an ownership rate for each appliance type was calculated using Equation 4-5. The ownership rates represented as a percentage the average household ownership of the appliance types for an electrical demand group. It should be clarified that the ownership rate does not reflect the percentage of homes in each electrical demand group that owned the specified domestic appliance. For example, nine digital set top boxes were monitored in high electrical demand households during the study, which gives an ownership rate of 75%. However, this appliance type was only found in six of the households (i.e. 50%). This is the result of a combination of multiple ownership of given appliances in some dwellings and no ownership in others.

$$\overline{O_{a,e}}\ [\%] = \frac{\sum_{i=1}^{N_e} O_{a,e}}{N_e} \times 100 \qquad Equation\ 4-5$$

Where: $\overline{O_{a,e}}$ = Average percentage of appliance ownership rate for appliance type for electrical demand group [%]; $O_{a,e}$ = Number of appliances of an appliance type owned by each home in electrical demand group; N_e = Number of homes in electrical demand group; being *a* = appliance type (e.g. TV, washing machine, tumble dryer), *e* = electric demand group (low, medium, high).

The appliance ownership rates for electrical demand groups were calculated from the administered domestic appliance ownership survey data collected during the AEUS. As a result, the ownership rates incorporated all known appliances that the L27 households possessed not just those that were monitored using a smart meter plug.

The *Excel* spreadsheet which was designed to store the appliance ownership survey data was used as a platform to produce the ownership rates for each electrical demand group. The data contained in the initial twenty-seven separate work sheets setup for each home were amalgamated into three worksheets, one for each electrical demand group. The ownership rates for the appliances types were then calculated from the combined data using the formula presented in Equation 4-5.

A comparison of the ownership rates of appliance types between the electrical demand groups was undertaken and described and the results presented using clustered bar graphs. Nine clustered bar graphs were produced to merge the ownership rates of individual appliance types into their appliance categories. In addition, a further

[2] Ownership is intended to mean 'presence' of an appliance in a home, rather than 'ownership' in the legal sense.

overarching appliance ownership rate was calculated for each appliance category to investigate the variations in ownership of groups of appliances both between electrical demand groups and within an electrical demand group.

4.10.4.5 Variations in appliance power demand between electrical demand groups

An analysis of the variations in power demand of appliance types between the electrical demand groups was undertaken as power demand affects appliance electricity demand. In order to establish average appliance type power demands for each electrical demand group, initially, average power loads were calculated for all individual appliance types owned by the L27 households. Using the *Excel* workbooks created to stratify the power data of the monitored appliances into power modes (Figure 4-13), an average power demand for each power mode was calculated using a series of *Excel* formulas. Table 4-17 provides an example of the *Excel* formulas used to calculate the average power demands of a television in active, passive standby and off standby modes. Figure 4-16 shows a screen shot of the data columns used to calculate the average power demands of the television.

Table 4-17 Example Excel formulas used to calculate the average power demands of a television in active, passive standby and off standby modes

Column	Description	***Excel* formula**
D	Average power demand in active power mode	=AVERAGE(D2:D41845)
F	Average power demand in passive standby power mode	=AVERAGE(F2:F41845)
H	Average power demand in off standby power mode	=AVERAGE(H2:H41845)

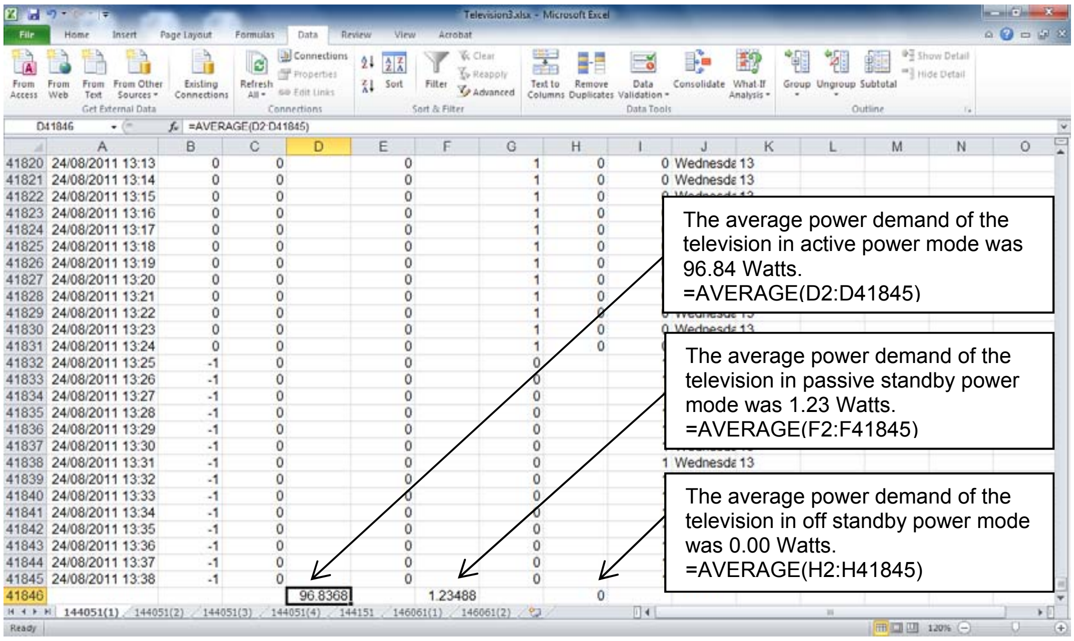


Figure 4-16 Example screen shot of the data columns used to calculate the average power demands of a television

After average power demands were attained for all of the appliances owned by the L27 households, average power demands of appliance types in each power mode was calculated for the electrical demand groups using Equation 4-6. The results obtained are appliance averages and are derived by dividing the sum of each appliance type's average power demand in a specific power mode by the number of appliances monitored for each electrical demand group.

$$\overline{P_{a,m}}\,[W] = \frac{\sum_{i=1}^{A_{a,m}} \bar{p}_m}{A_{a,m}} \qquad \textit{Equation } 4-6$$

Where: $\overline{P_{a,m}}$ = Total average appliance power demand for power mode for appliance type [W]; $\bar{p}_m$ = Average individual appliance power demand for power mode [W]; $A_{a,m}$ = Number of appliances monitored of each appliance type and power mode; being *a* = appliance type (e.g. TV, washing machine, tumble dryer), m = power mode (e.g. active, active standby, passive standby).

The average power demands of the appliances types for electrical demand groups was calculated in Microsoft *Excel* by grouping the average power demands calculated for the individual appliances by electrical demand group and dividing by the number of appliances monitored. Figure 4-17 shows a screen shot of the process of calculating the average power demand of televisions in each power mode for the three electrical demand groups.

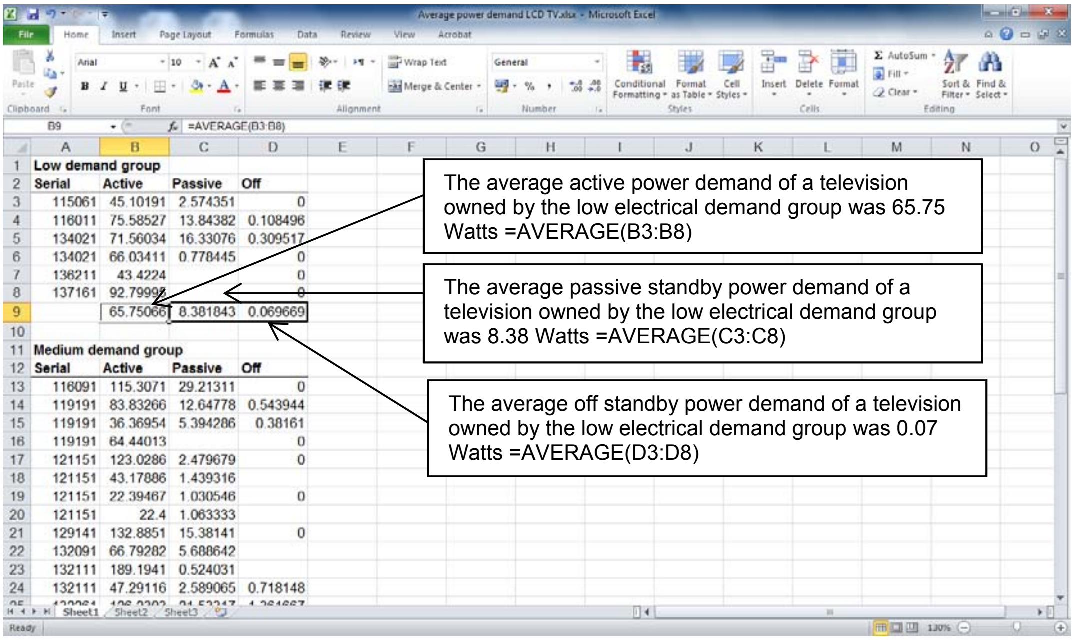


Figure 4-17 Example screen shot of the process of calculating the average power demand of televisions in each power mode for the electrical demand groups

As some of the appliance types were not operated in all their power modes during the detailed monitoring study (i.e. some appliances were constantly in their active power mode), it was not always possible to calculate the average power demands of all of the power modes. As a consequence, in some instances a higher average power demand was obtained for a standby power mode than an active power mode for a specific appliance type.

Finally, a comparison of the power demands of appliance types between the electrical demand groups was undertaken and described and the results presented in a series of tables which demonstrated the variations in appliance power characteristics by power mode and electrical demand group. The summary tables present the average power demand data of the appliance types by appliance category.

4.10.4.6 Variations in appliance use between electrical demand groups

The third dimension of appliance electricity consumption that was investigated was the differences in patterns of appliance use between the electrical demand groups. Average daily duration of use figures were produced for each appliance type, which provided an indication of the extent that the appliances were used in the different power modes by the electrical demand groups. To compare the differences in use between the groups, an average daily appliance usage figure was calculated by dividing the sum of total daily use for an appliance type, by the number of homes in the electrical demand group (Equation 4-7).

$$\overline{U_{a,e}}\ [hours\ per\ day] = \frac{\sum_{i=1}^{N_e} \overline{u_{a,e}}}{N_e} \qquad Equation\ 4-7$$

Where: $\overline{U_{a,e}}$ = Average daily use of appliance type for electrical demand group [hours per day]; $\overline{u_{a,e}}$ = Average individual daily use of appliance type for electrical demand group [hours per day]; N_e = Number of homes in electrical demand group; being *a* = appliance type (e.g. TV, washing machine, tumble dryer), *e* = electric demand group (low, medium, high).

To establish average appliance daily use values for each electrical demand group, firstly, average daily use values had to be calculated for all of the appliances owned by the L27 households. To achieve this, the *Excel* workbooks created to stratify the power data of the monitored appliances into power modes were used as a platform for the calculations (Figure 4-13).

An average daily use for each power mode was calculated in hours using a number of *Excel* formulas. Table 4-18 provides an example of the *Excel* formulas used to calculate the average daily use of a television in active, passive standby and off standby modes. In addition, the average daily duration of time that the television was unplugged from the mains electricity is also presented but was not analysed further in this thesis. Figure 4-18 shows a screen shot of the data columns used to calculate the average daily use for the example television. The *Excel* formulas summed the number of minutes an appliance operated in a power mode over the duration of the detailed electricity monitoring study, divided this figure by sixty to produce the equivalent number of hours, and then divided this figure by the number of days the monitoring was undertaken for in the household to normalise.

Table 4-18 Example Excel formulas used to calculate the average daily use of a television in active, passive standby, off standby modes and unplugged

Column	Description	***Excel* formula**
C	Average daily use in active power mode	=SUM(C2:C40156)/60/NUMBER OF MONITORED DAYS (29 DAYS)
E	Average daily use in passive standby power mode	=SUM(E2:E40156)/60/NUMBER OF MONITORED DAYS (29 DAYS)
G	Average daily use in off standby power mode	=SUM(G2:G40156)/60/NUMBER OF MONITORED DAYS (29 DAYS)
I	Average daily unplugged	=SUM(I2:I40156)/60/NUMBER OF MONITORED DAYS (29 DAYS)

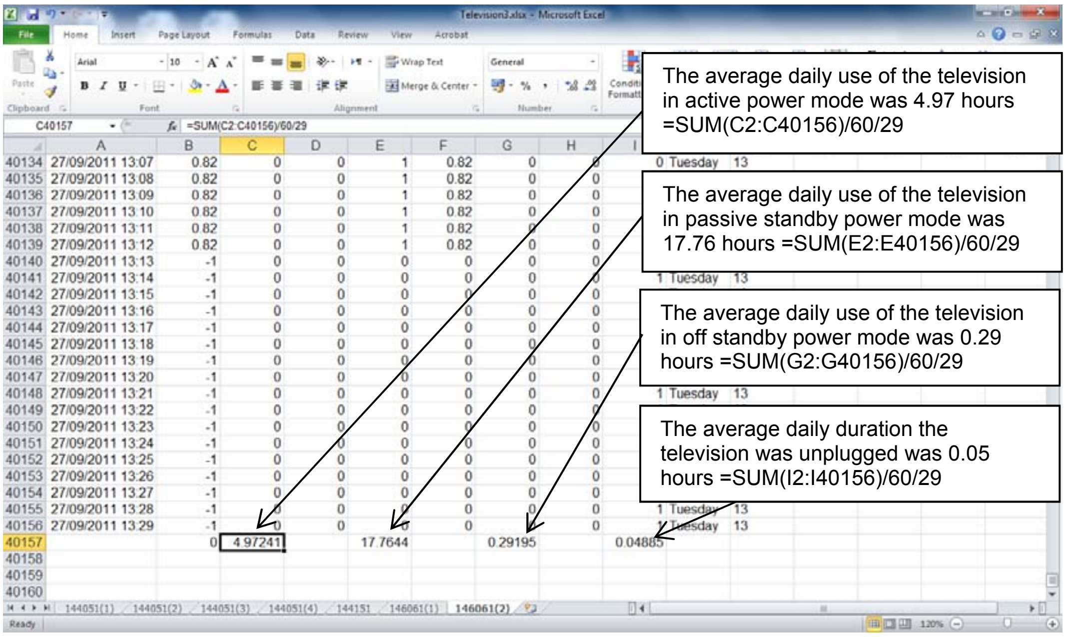


Figure 4-18 Example screen shot of the data columns used to calculate the average daily use of a television

After average daily appliance use figures were produced for all of the appliances owned by the L27 households, an average daily use for each appliance type was calculated for the three electrical demand groups using Equation 4-7. The calculations were undertaken in Microsoft *Excel* by grouping the average daily appliance uses for the individual appliances by electrical demand group and then dividing by the number of households in the group (see power demand example in Figure 4-17). It should be noted that Equation 4-7 was modified when a household in an electrical demand group was known to own an appliance but it was unmeasured due to physical limitations or lack of SMPs. In these circumstances the household was excluded from the daily use calculation and instead the sum of daily uses for an appliance type was divided by the remaining number of households in the group.

A comparison of the variations in daily use of appliance types between the electrical demand groups was undertaken and described, along with the results obtained presented in a number of summary tables by appliance category, which demonstrate the variations in appliance use by power mode and electrical demand group.

4.11 Chapter 4: Summary

The research design and methodology used in this research to meet the aim and objectives of this thesis defined in Chapter 1 and answer the research questions identified in this Chapter have been presented and described. This research has employed a mixed methods approach which has collected both quantitative and qualitative data. The different research methods used to collect the data for this thesis were employed across a series of individual studies, as part of a larger research project called 4M: 'Measurement, Modelling, Mapping and Management 4M: an Evidence Based Methodology for Understanding and Shrinking the Urban Carbon Footprint'.

The data used in this thesis have been collected in two phases: phase 1 comprised an administered housing survey called the 4M Living in Leicester (LIL) household survey, which was undertaken with a representative sample of Leicester households which collected socio-economic, technical and some appliance data. Phase 2 contained four follow up studies undertaken with subsets of the 4M LIL cohort. The follow up activities included: recording periodic electricity meter readings; obtaining annual whole house electricity use data from the households' energy suppliers; administering an appliance survey; and an appliance electricity use survey.

This chapter has also outlined the stages of data processing and the methods of data analysis used. Potential threats to the validity of the results have been identified and the actions taken to reduce error have been described. The results presented in this thesis are believed to provide a robust understanding of the socio-economic, technical and appliance factors affecting high electrical energy demand in a sample of UK homes. The subsequent three chapters present the results of this research. Chapter 5 provides the results used to answer research questions Q1 and Q2. Chapter 6 answers research question Q3 and presents the results of the analysis of the socio-economic, technical and appliance factors that influence households' electricity demand. Chapter 7 presents the findings of the appliance electricity use survey (AEUS) which responds to research question Q4: to what extent do the ownership, power demand and usage of different domestic appliances contribute to high electrical energy demand in a sample of UK households?.

Chapter 5

Results: Variations in annual electricity use and changes in demand over time

5.1 Introduction

This chapter presents results from a number of data sources including the 4M Living In Leicester (LIL) household survey, the 4M LIL electricity meter reading undertaken with the L315 cohort, 4M energy supplier annual electricity use data, and the Appliance Electricity Use Survey (AEUS), which also included electricity meter reads, a domestic appliance ownership survey and interview data from the L27 households.

Initially, the meter readings and energy supplier annual electricity use data are used to illustrate the variations in annual electricity consumption within the L315 and L27 study samples. These data are subsequently employed to investigate changes in the electricity use of the L315 and L27 cohorts over time. Then, an analysis of the L27 householder interviews is presented, which highlights the factors that the occupants believe were responsible for changes in the electrical demand of their homes.

In the following sections, results are presented in respect to the total annual electricity consumptions of the L315 and L27 cohorts. Some of the implications from these results are introduced during the chapter, but will be discussed in more detail in Chapter 8.

The chapter begins by presenting the electricity consumption distributions of the L315 and L27 cohorts and compares their representativeness with both the national distribution of domestic electricity consumption as well as those recorded in previous studies (section 5.2). Secondly, the trends in change of electricity consumption of the L315 and L27 cohorts over time split into electrical demand groups are presented. In addition, an in-depth analysis of the changes in electricity use of individual L27 dwellings is completed and occupant explanations analysed (section 5.3). Uncertainties in the results are presented (section 5.4). Finally, a summary of the chapter is presented to briefly highlight the key findings (section 5.5).

5.2 Electricity use of the L315 and L27 cohorts

As previous domestic energy use studies (Summerfield et al. 2010; Firth et al. 2008; Summerfield et al. 2007) have demonstrated that large variations in electricity demand exist between dwellings, the electricity use data from both the L315 and L27 cohorts were examined to see whether similar patterns would emerge in the current study. This section initially presents the results from the main L315 households followed by the L27 sub-set of households which were involved in the Appliance Electricity Use Survey (AEUS). The final sub-section tests the representativeness and main characteristics of the electricity distributions of the L315 and L27 cohorts against the national distribution of electricity consumption (DECC 2011), as well as with earlier studies.

5.2.1 Annual electricity consumption distribution for the L315 cohort

The annual electricity consumption of the L315 cohort in 2009 is shown in Figure 5-1. The electricity usage data presented are a combination of calculated annual consumptions from the meter readings collected during the 4M study (256 homes) and energy supplier annual electricity use data (59 homes). Each vertical bar indicates the annual total electricity used in an individual dwelling. The results are arranged from the smallest to the largest household consumptions. The blue vertical bars indicate the annual electricity consumptions obtained from the 4M LIL electricity meter reading and the red vertical bars from the 4M energy supplier annual electricity use data.

It is clear that, as in previous studies, there was a large range in electricity consumptions observed amongst the L315 households. The lowest annual electricity usage was 259 kWh and the highest was 25,587 kWh, almost 100 times greater. The mean electricity consumption was 3,852 kWh per annum, but due to the highly skewed distribution of electricity usage across the households, the median was less at 3,184 kWh per annum.

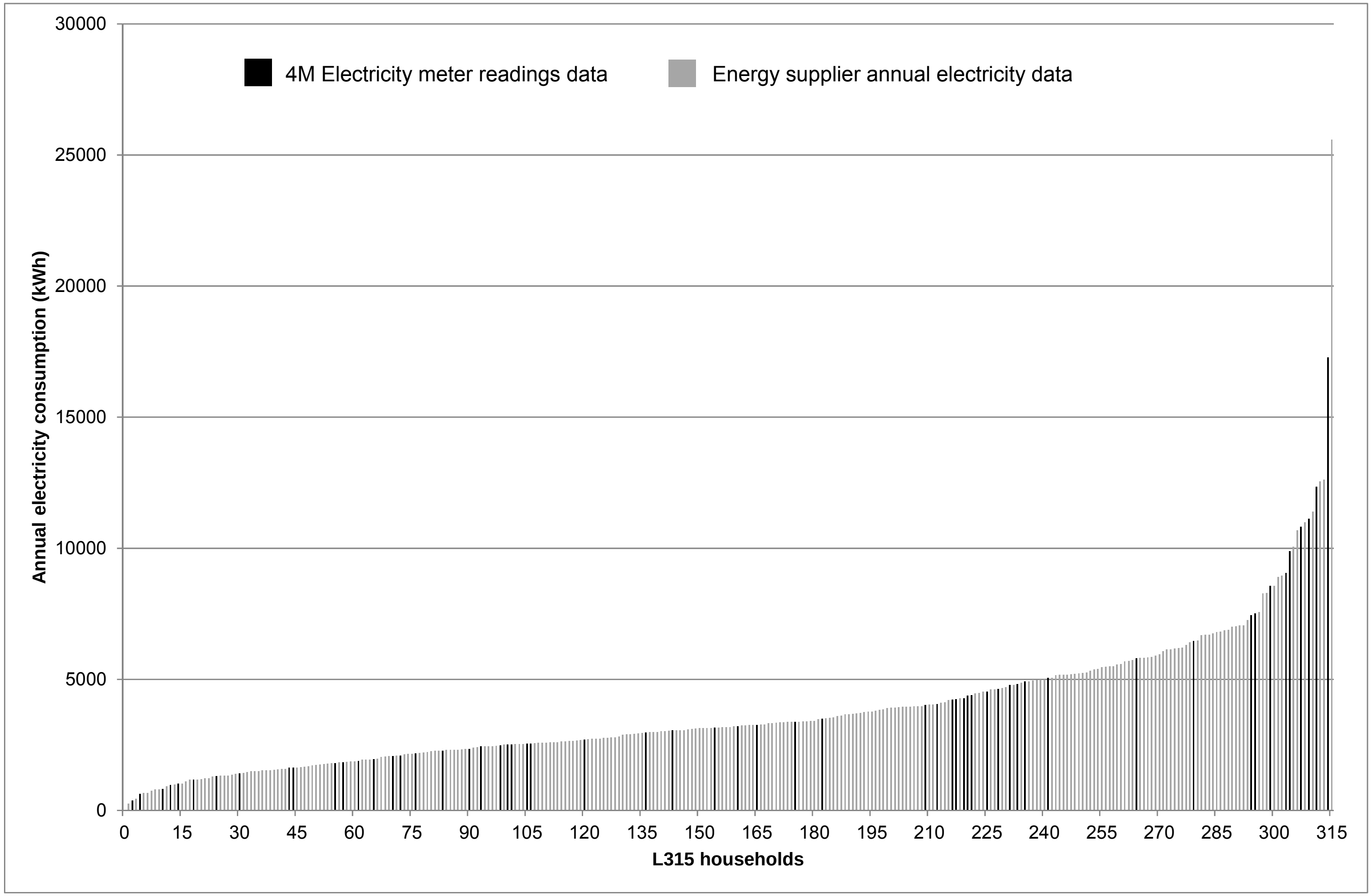


Figure 5-1 The annual electricity consumptions of the L315 households ranked from smallest to largest in 2009

5.2.2 Annual electricity consumption distribution for the L27 cohort

The total annual electricity consumption for each of the L27 monitored dwellings in 2011-2012 are shown in Figure 5-2. The electricity use totals presented were calculated from the meter readings taken during the Appliance Electricity Use Survey (AEUS). Again, each vertical bar represents the annual total electricity used in an individual dwelling. The results are arranged in the order of the annual total consumption.

It is evident from the results collected that there was a large variation in electricity consumption across the L27 cohort. The lowest annual total electricity consumption was 1,355 kWh. The highest annual total electricity consumption was 9,627 kWh. For all dwellings the mean total electricity consumption was 4,114 kWh. The median consumption was 3,731 kWh per annum.

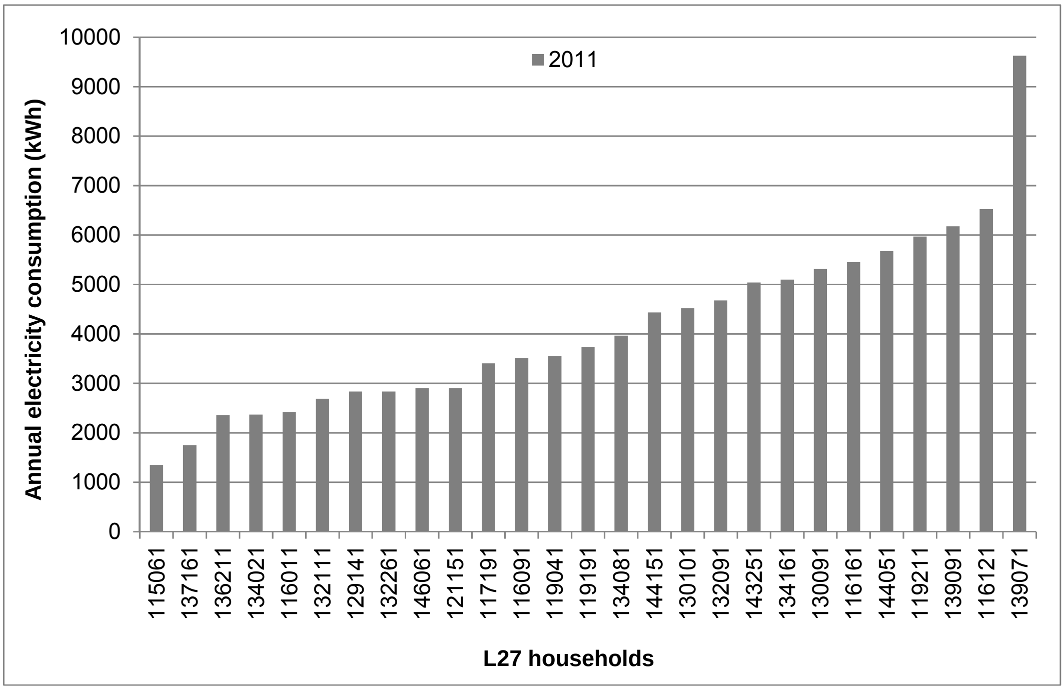


Figure 5-2 The annual electricity consumptions of the L27 households ranked from smallest to largest in 2011-2012

5.2.3 Representativeness of the L315 and L27 electricity distributions

The annual electricity consumptions of both the L315 and L27 cohorts as well as Great Britain (DECC 2011) are represented in Figure 5-3. Each bar shows the percentage of households in each 1,000 kWh per annum band. The mean annual electricity consumption of the L315 households was 3,852 kWh and 4,114 kWh for the L27 households, compared to 4,392 kWh for Great Britain. The median was also less at 3,184 kWh per annum for the L315 homes but higher at 3,731 kWh for the L27 homes compared to 3,550 kWh for Great Britain.

Visually, the L315 and Great Britain electricity demand distributions appeared to be similar as the majority of the dwellings were grouped around the mean with a long tail towards the highest consumptions. This observation was tested statistically using a Chi-squared test. This statistical method is based on the assumption that the observed and expected values are the same. The percentage of households in each 1,000 kWh data band for Great Britain were used as the expected values, and were subsequently tested against the observed values for the L315 households. The test result was χ^2 (13, N = 315) = 17.24, p = 0.14[3]. As the p-value for the Chi-squared test was not significant ($p > 0.05$), it could be confirmed that there was no significant difference between the L315 and national distributions.

Conversely, whilst the households in the L27 were also gathered around the mean, the L27 cohort had a lower percentage of dwellings with annual consumptions less than 2,001 kWh per annum and greater than 7,001 kWh per annum, compared to the national distribution. In addition, the percentage of L27 dwellings in the data bands 2,001 – 3,000 kWh and 9,001 – 10,000 kWh per annum was over represented. Due to the low number of samples in the L27 distribution (Field 2005), it was not statistically valid to complete a Chi-squared test to assess its representativeness against the Great Britain distribution. The visual examination of the two distributions would however suggest that the L27 cohort was not representative of the national situation.

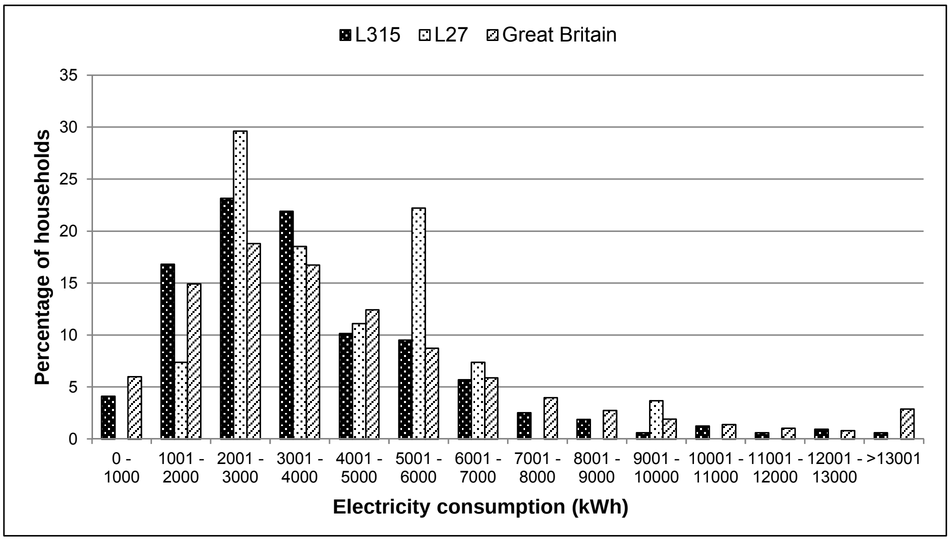


Figure 5-3 Comparison of the L315, L27 and Great Britain distributions of domestic electricity consumption

[3] χ^2 (degrees of freedom, sample size) = Pearson chi-squared value (rounded to two decimal places), significance value.

A comparison of the main characteristics of both the L315 and L27 cohorts with those reported in previous studies is presented in Table 5-1. It can be seen that, with the exception of those studies with government involvement (DECC 2011; DECC 2010b; BRE 2008) which have used metering data collected by energy companies, the L315 sample was much larger as was the range of electricity consumptions recorded. The L27 cohort had a similar sample size and electricity range to those considered in previous non-governmental research projects. The maximum monitoring period of the L315 and L27 studies was comparable with the period of monitoring in the previous studies. Importantly, the mean and median annual electricity consumptions of the L315 and L27 studies were similar to that observed in the very large (nearly 21 million households) national survey (DECC 2011). The mean annual electricity use of the L315 cohort was also similar to that found in the large (approximately 126,000 homes) regional study (DECC 2010b).

Table 5-1 Comparison of the main characteristics of the L315 and L27 cohorts with previously reported studies

Study	N	Monitoring dates	Maximum monitored consumption period	Electricity consumption (kWh per annum)				Sample includes dwellings with		Dwelling Characteristics
				Min	Max	Mean	Median	Electric space heating	Electric water heating	
L315	**315**	**March 2009 to July 2010**	**1 year, 4 months**	**259**	**25,587**	**3,852**	**3,184**	**Yes**	**Yes**	
L27	**27**	**July 2011 to April 2012**	**287 days**	**1,355**	**9,627**	**4,114**	**3,731**	**Yes**	**Yes**	
(Summerfield et al. 2007)	14	January 1989 to September 1990	9 months	2,299 (1990)	5,913 (1990)	4,161 (1990)	-	No	-	'Low-energy' dwellings – conventional UK design, but built to have higher standards than required under the prevailing building regulations
		February 2005 to July 2006	1 year, 5 months	2,774 (2005)	10,330 (2005)	5,475 (2005)	-	No	-	
(BRE 2008)	7,370	May 2001 to May 2003	2 years	1,000	25,000	5,282	-	Yes	Yes	
(Firth et al. 2008)	72	June 2002 to October 2006	2 years	902 (yr 1)	7,743 (yr 1)	3,100	-	No	-	Majority social housing
				920 (yr 2)	8,775 (yr 2)	3,241	-	No	-	
(DECC 2010b)	126,489	2009	1 year	-	-	3,589	-	Yes	Yes	
(Summerfield et al. 2010)	36	January 1989 to September 1990	9 months	2,336 (1990)	5,037 (1990)	3,832 (1990)	-	No	-	'Low-energy' dwellings
		February 2005 to July 2006	1 year, 5 months	3,139 (2005)	8,651 (2005)	5,256 (2005)	-	No	-	
(DECC 2011)	20,852,507	2007	1 year	10	25,000	3,922	3,310	Yes	Yes	

Note: Firth et al.'s (2008) Year 1 and Year 2 varies with each monitored site location, where the earliest was from June 2002 to May 2004 and the latest from November 2004 to October 2006.

5.3 Changes in electricity use over time

Previous studies (DECC 2011; DECC 2010b; BRE 2008) have identified that the electricity demand of the highest consuming domestic properties are increasing over time. To validate these findings, the dwellings in the L315 and L27 cohorts were stratified into three electrical demand groups (low, medium and high) based on the total annual electricity consumptions measured in this research (see Chapter 4, Section 4.10.2). The year-on-year percentage changes in electrical demand of these three groups were then observed from 2007 to 2009 for the L315 and from 2007 to 2011 for the L27 cohorts.

The data used in the analysis are a combination of two different sources. The annual electricity consumptions of the dwellings in 2007 and 2008 were obtained from the 4M energy supplier annual electricity use follow up and the years 2009 to 2011 values were calculated from meter readings taken as part of the 4M LIL electricity meter reading follow up and AEUS.

In addition, an analysis of the changes in annual electricity consumption of each dwelling in the L27 cohort between 2007 and 2011 is presented. An explanation for the patterns of change observed in each home are suggested from the unstructured qualitative interview undertaken with the homeowners during the AEUS.

For the purpose of this analysis, the L315 homes were stratified into three equally sized groups (thirds) based on the total annual electricity consumptions in 2007 (see Chapter 4, Section 4.10.2). The 105 lowest consuming households were classified as the ‘low electrical demand group’, the middle 105 as the ‘medium electrical demand group’, and the highest 105 as the ‘high electrical demand group’.

The L27 cohort was also divided into three electrical demand groups for the analysis but were instead categorised into three groups based on the consumption thresholds defined by the L315 stratification. The households were stratified based on their annual electricity consumptions in 2007. Therefore, L27 households with an annual consumption below 2,543 kWh were classified in the ‘low demand group’, those between 2,543kWh and 4,041 kWh in the ‘medium demand group’ and those greater than 4,042 kWh in the ‘high demand group’.

Once the three electrical demand groups were established for both the L315 and L27 cohorts based on the 2007 data, the households in each electrical demand group were fixed throughout the three year and five year periods investigated.

5.3.1 Changes in the electrical demand of the L315 cohort from 2007 to 2009

The average electricity consumption for each electrical demand group for the L315 dwellings from 2007 to 2009 is shown in Figure 5-4. Each line represents the change in mean annual electricity demand for a demand group over the three year period.

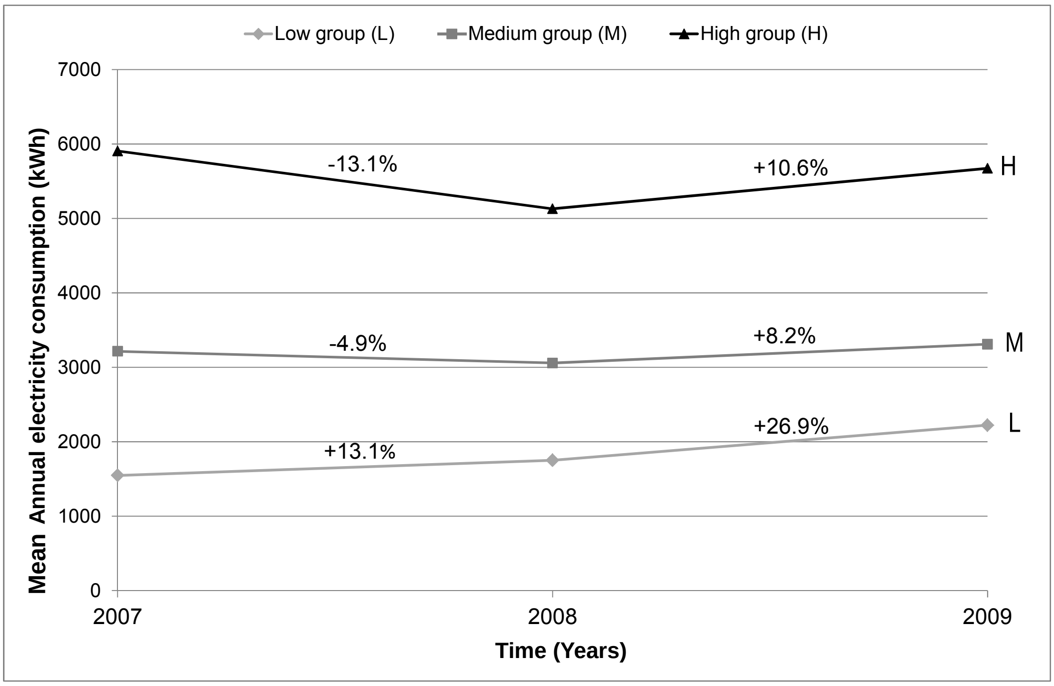


Figure 5-4 Year-on-year change in mean electrical consumption for each electrical demand group for the L315 cohort from 2007 to 2009

For the low electrical demand group it can be seen that there was a 13.1% increase in the average total consumption from 1,548 kWh to 1,751 kWh between 2007 to 2008 and this increased a further 26.9% to 2,222 kWh in 2009; totalling a 43.6% increase in mean electrical demand over two years. The medium demand group slightly reduced consumption (-4.9%) from 3,214 kWh in 2007 to 3,058 kWh in 2008, but increased by 8.2% in 2009 to 3,310 kWh. Cumulatively, on average the medium group showed a 3.0% increase in electricity use over the period. The mean electricity demand of the high demand group was reduced by 13.1% from 5,905 kWh in 2007 to 5,129 kWh in 2008. Subsequently in 2009, the electricity demand increased to 5,673 kWh (+10.6%). Despite this increase, overall, the high demand group reduced its electricity use by 3.9%.

A series of two-tailed t-tests showed that the increase in electrical demand between 2008 and 2009 for the low demand group was significant at the $p < 0.05$ level ($t(78.30) = -2.202$, $p = 0.031$)[4], although the change between 2007 and 2008 was found to be non-

[4] *t* (degrees of freedom) = *t* statistic (rounded to two decimal places), significance value.

significant ($t(106) = -1.633$, $p = 0.106$)[4]. For the medium demand group, both the decrease in average electricity use between 2007 and 2008 ($t(60.43) = 0.954$, $p = 0.343$)[4] and increase from 2008 to 2009 ($t(84) = -1.182$, $p = 0.240$)[4] were not significant. Concerning the trends of the high demand group, the reduction in mean electricity use between 2007 and 2008 was found to be statistically significant ($t(100) = 2.224$, $p = 0.028$)[4], however the rise in use from 2008 to 2009 was not significant ($t(99) = -1.480$, $p = 0.142$)[4].

From the observed trends in change of electrical consumption of the L315 homes, it can be assessed that the low demand group is increasing the electricity use over time, the medium demand group has no significant change in demand, and the high demand group appears to be slightly reducing its consumption. As a consequence, the electrical demand groups are contracting their variances in electricity use, but rather than the ideal situation where high consumers reduce their consumption to a lower level, instead the low demand dwellings are becoming higher electricity consumers over time. The electricity consumption data from the L315 cohort therefore does not support previous findings that high electricity consuming households are increasing their usage with time.

5.3.2 Changes in the electrical demand of the L27 cohort from 2007 to 2011

The five-year changes in average electricity consumption for each electrical demand group for the L27 cohort is shown in Figure 5-5.

Figure 5-6 and Table 5-2 provide the year-on-year changes in annual electricity consumption for each individual household in the L27 cohort. These illustrate the impact of individual household changes, on the overall group mean changes observed. Table 5-2 also highlights where missing annual electricity consumptions are present in the dataset.

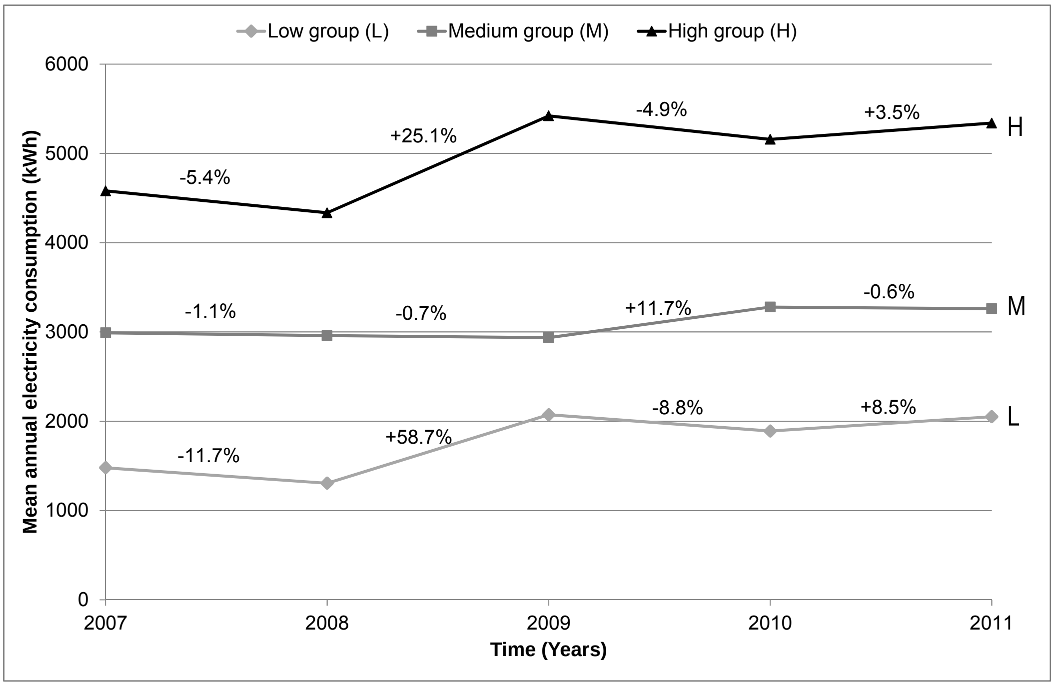


Figure 5-5 Year-on-year change in mean electrical consumption for each electrical demand group for the L27 cohort from 2007 to 2011

For the low electrical demand group it can be seen that there was initially a decrease in electricity use of 11.7% from 1,479 kWh to 1,306 kWh between the years 2007 and 2008, but the following year (2009) the group experienced a large increase of 58.7% to 2,072 kWh. In 2010, the demand fell by 8.8% to 1,890 kWh, but in the succeeding year (2011) an almost identical increase (8.5%) occurred, bringing the average consumption back to 2,051 kWh. The average consumptions in the first two years were found to be relatively similar, and following the great increase in 2009, the subsequent year's consumptions were also relatively stable. Overall, during the five-year period, the average electrical energy demand of the low consumption group increased by 38.7%.

The mean electricity use of the medium demand group was quite stable for the period investigated. Overall, a 9% increase in consumption occurred between 2007 and 2011, with the majority of the change occurring in 2010. The average electricity demand in the first three years was consistent at 2,990 kWh in 2007, 2,958 kWh in 2008, and 2,937 kWh in 2009 respectively. From 2009 to 2010 an 11.7% increase in consumption occurred, raising the mean demand to 3,280 kWh. In 2011, the electricity consumption of the medium demand group stabilised at this new level with a usage of 3,260 kWh.

The mean electricity demand of the high demand group was found to be relatively stable between both 2007 and 2008, and 2009 and 2011. A large increase in consumption occurred in the middle of these two periods. Firstly, from 2007 to 2008 the electricity use of the high group fell slightly (-5.4%) from 4,580 kWh to 4,334 kWh. In the following year

(2009), the electricity demand greatly increased to 5,420 kWh (+25.1%). In 2010, a 4.9% decrease in use was observed but the year after almost entirely recovered by increasing 3.5% in 2011 to 5,339 kWh. Overall, during the five-year period considered, the high electrical energy group increased usage by 16.6%.

Although, not tested statistically due to insufficient sample sizes (Field 2005), the trends in electricity consumption observed amongst the L27 cohort imply that all electrical demand groups are increasing their use of electricity over time. The low consuming dwellings are increasing their demand at the greatest rate, followed by the high demand and then the medium demand groups. Although, these findings do support the previous studies assertions that high consumers are increasing their electricity use with time. Considering the L27 is a sub-set of the L315 cohort, which provided contradictory results, this may highlight an issue of drawing conclusions based on small sample sizes or observing changes in electricity demand over a short period of time. This would also therefore be a problem with the studies by Summerfield et al. (2010), Firth et al. (2008), and Summerfield et al. (2007).

5.3.3 Changes in the electrical demand of individual dwellings in the L27 cohort from 2007 to 2011 and the occupants stated explanations

Figure 5-6 shows that in the monitoring year 2011, 5 households of the L27 cohort were low electrical energy consumers (<2,544 kWhpa), 10 were medium consumers (2,543 - 4,042 kWhpa) and 12 were high consumers (>4,041 kWhpa). During the up to 5 year period investigated, it was observed that 7 of the L27 households changed their electrical demand group once. Households 132111 and 143251 changed their group 3 times and Households 146061 and 144151 twice. It should be noted however that Households 132111 and 144151 fluctuated just a couple of 100 kWh above and below the boundaries of different electrical demand groups and therefore, despite the change in classified group, in reality their annual electricity consumption remained quite stable. The remaining 16 households in the cohort did not change electrical demand group at all during the period of time investigated. The 5 low consuming households were consistently classified as low throughout all the years.

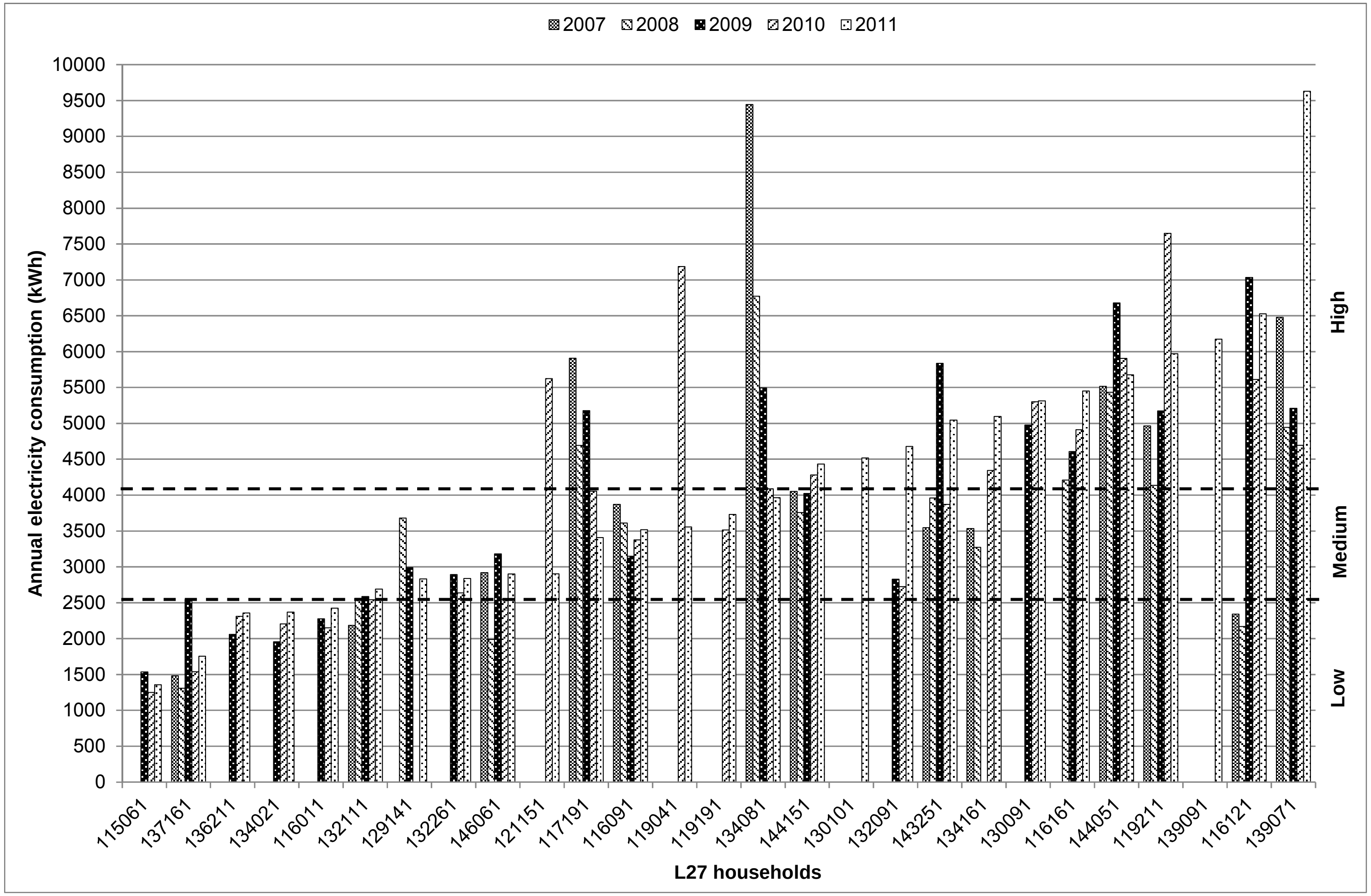


Figure 5-6 Year-on-year change in annual electricity use for each L27 household from 2007 to 2011

Table 5-2 Year-on-year changes in annual electrical consumption for each home in the L27 cohort from 2007 to 2011, including missing data

Electrical demand group	**Annual electricity consumption (kWh)**				
Low group	**2007**	**2008**	**2009**	**2010**	**2011**
115061	-	-	1534	1249	1355
116011	-	-	2274	2148	2423
134021	-	-	1955	2205	2368
136211	-	-	2056	2311	2355
137161	1479	1306	2542	1538	1753
Low group mean annual electricity consumption (kWh)	**1479**	**1306**	**2072**	**1890**	**2051**
Medium group					
116091	3868	3612	3149	3375	3515
119191	-	-	-	3513	3731
121151	-	-	-	5623	2904
129141	-	3677	2989	-	2832
132091	-	-	2826	2725	4677
132111	2183	2558	2585	2540	2688
132261	-	-	2894	2635	2837
146061	2918	1987	3180	2546	2900
Medium group mean annual electricity consumption (kWh)	**2990**	**2958**	**2937**	**3280**	**3260**
High group					
116121	2339	2167	7032	5610	6524
116161	31	4209	4605	4912	5452
117191	5908	4692	5175	4055	3406
119041	-	-	-	7187	3556
119211	4962	4135	5175	7647	5969
130091	-	-	4976	5299	5312
130101	-	-	-	-	4516
134081	9442	6772	5494	4086	3962
134161	3532	3272		4342	5097
139071	6478	4943	5210	4693	9627
139091	-	-	-	-	6174
143251	3545	3959	5838	3868	5043
144051	5516	5433	6679	5905	5673
144151	4052	3757	4020	4281	4433
High group mean annual electricity consumption (kWh)	**4580**	**4334**	**5420**	**5157**	**5339**

Note: (-) indicates missing annual electricity consumption values.

Through a combination of formal unstructured qualitative interview as well as general discussion with the occupants of households during monitoring visits, it was possible to offer suggestions as to the causes of some of the large changes in annual electricity demand observed amongst the L27 cohort homes as shown in Figure 5-6. As a result of discussing the changes in annual electricity use observed in the homes with the occupants, it was possible to establish a picture of the factors that the occupants believed were responsible for affecting the amount of electricity they used. Households with similar levels of electricity consumption throughout the up to five year period were not investigated in detail and in some cases large changes in demand could not be explained by the building occupants.

Household 137161 experienced a much higher annual consumption of electricity (2,542 kWh) in 2009, compared with data from both the previous and following two years. It was established that this fluctuation may be explained by an additional occupant who moved into the dwelling during that year who had serious medical problems. The additional occupant died later that year which possibly explains why the electrical demand then returned to the consistent consumption level previously observed.

In 2008, Household 146061 was found to have consumed less electricity than usual (1,987 kWh), based on a comparison with the usages in 2007 and the years from 2009 to 2011. Despite discussing this anomaly with the occupants, it was not possible to ascertain a firm reason for the result observed. The occupants assumed that it may have been due to spending less time at home due to family problems.

Household 121151 had a large decrease in annual electricity use from 5,623 kWh in 2010 to 2,904 kWh in 2011. The reduction was explained by the homeowner as the consequent effect of one of the occupants dying. Not only was the number of occupants reduced, but also this particular occupant had required a higher electrical demand to power medical equipment in the home due to poor health. The medical equipment had subsequently been removed from the property.

With the exception of 2009, Household 117191 was found to be on a trend of reducing their annual electricity consumption. This result was in line with the attitudes of the building occupants, who were amongst the most energy aware in the L27 cohort. The occupants had installed both gas and electric smart meters, which were linked to an energy feedback monitor operating a traffic light system. The occupants classified themselves as early adopters of energy saving technologies and were determined to reduce their energy consumption wherever possible. The occupants at the time of undertaking the monitoring were also in the process of having solar PV installed at their property.

Household 134081 had made large year-on-year reductions in electricity use between 2007 and 2011. In fact, the electricity demand of the dwelling had decreased by more than half over this period of time from 9,442 kWh to 3,962 kWh. This notable reduction was however primarily related to the fact that the property was increasingly less occupied as the owners were residing at a mobile holiday home for up to 4 days per week. Therefore, although significant reductions were observed for Household 134081, this ‘reduction’ in electricity use was in reality being shifted and consumed at a different location instead.

Household 132091 experienced a large increase in electricity use in 2011. This may be because the occupant of the dwelling had chosen not to use the gas boiler for the space and water heating as in previous years, but instead had switched to a portable electric heater, which he moved to the current occupied space. In addition, the occupant used an electric kettle to heat water for washing. These choices had clearly impacted on the household's annual electricity consumption. Although, it was not investigated in this current study, it could be hypothesised that these behavioural changes should have had the inverse impact on the dwelling's gas consumption.

Household 143251 was characterised as having variable annual electricity consumptions between 2008 and 2011. The dwelling's electrical demand increased greatly in 2009, decreased back to a similar demand seen in 2008 in 2010, but increased again in 2011. This pattern of demand might be explained because after the highest demand year (2009), the occupants took the decision to install pre-paid gas and electricity meters to better control their energy usage and cost. The occupants believed that changing the meters increased their energy consciousness as a result of having to physically top-up the meters. They attempted to relate the frequency of top-up to the energy using activities undertaken in the home during the period from the previous top-up. It would appear that the decision to change the meters initially made a difference as the dwelling's demand reduced (2010); however this reduction did not endure as the electricity usage again increased in the second year following the meters installation (2011).

In both 2010 and 2011, the electricity use in Household 134161 was observed to be increasing. The occupants believed that this was primarily due to a change in the employment status of one of the occupants. In 2007 and 2008, the dwelling was unoccupied during the weekdays because all of the occupants were either at school or at work. In 2009, the eldest son finished school and was consequently unemployed for the following two years and spent the majority of the day at home using the additional electricity. The homeowner also thought that as her sons had become older teenagers during that period, an impact on the electricity consumption had occurred because their electricity consumption behaviours had become more intensive, due to their use of infotainment equipment in the home.

Household 116161 consistently increased electrical demand year-on-year between 2008 and 2011. The occupants thought that this was primarily related to the increasing number of occupants residing in the dwelling due to having children. In addition, the occupants stated that due to the additional parenting requirements of the young children, the parents were increasingly working from home thereby shifting a proportion of the electricity use normally consumed at their place of work to the dwelling instead.

Household 119211 was observed to have a much higher annual electricity demand in 2010. The building occupants assumed that this was because the winter period was very cold and secondary electric heating was used to supplement the gas space heating. The occupants believed that the following winter period (2011) was less cold and may in part explain the reduction in electricity use observed in 2011, in addition to, a reduction in the number of permanent occupants of the dwelling, as the daughter started University and during term time resided elsewhere. The overall high demand of the dwelling throughout all the years investigated was attributed to the fact that the mother was at home all day owing to medical reasons.

Household 139071 which was the highest consumer of electricity in the L27 cohort in 2011 greatly increased electrical demand by 4,934 kWh from 2010. The previous three years electricity consumptions had been relatively stable. The occupants believed that the significant increase was principally the consequence of using secondary electric heating for the majority of the year as one of the occupants had a medical condition. In addition, during the Appliance Electricity Use Survey, it was discovered that the household was being incorrectly billed for the electricity used. The energy provider believed that the night consumption was actually the day consumption; therefore the household was being significantly undercharged for the electricity used due to the difference in energy price for day and night units (Economy 7). This error may have meant that the financial implication of having a higher electricity demand was not experienced by the occupants in their energy bill and were therefore not encouraged to reduce their demand.

Overall from the L27 cohort, occupant stated reasons for significant changes in the annual electricity use of 11 of the dwellings were obtained, 6 households (129141, 116091, 119041, 144151, 144051, and 116121) with large changes in electricity demand were unexplained by the building occupants, the remaining 10 households were not examined as their electrical energy demand was relatively stable throughout the period investigated.

Table 5-3 provides a ranking of the factors that the occupants believed were primarily responsible for significant increases or decreases in the electricity used in their homes. Column 1 states the factors mentioned by the building occupants and column 2 provides the total number of times a factor was stated as being responsible by occupants of different homes.

Table 5-3 Factors that the occupants of the L27 households believed were responsible for significant increases or decreases in the annual electricity consumption of their homes

Factors	Number of times occupants stated that the factor was responsible
Duration the dwelling was occupied	5
Change in the number of residing occupants	4
Health / medical	4
Using secondary electric heating	3
Occupant behaviour	3
Change of electricity meter type	2
Occupants were conscious of the amount of electricity used	2
Occupants were attempting to save electricity	1
Age of occupants	1
External weather conditions	1
Cost of electricity	1

As a result of ranking the factors that the building occupants believed were responsible for large changes in the annual electricity consumption of their homes, it can be seen that some potential factors were more commonly stated as an influence than others. The majority of the factors are well established in the literature as potentially having an influence on the electricity consumption of domestic properties. In the current study, health and medical problems were surprisingly ranked highly by the occupants as this factor has not been established in the literature. However, this finding probably reflects the overrepresentation of elderly participants in the study (see Chapter 4, Section 4.8.2.).

In general, from the range of factors identified by the L27 cohort, it can be established that changes in the electricity use of domestic buildings may result from a wide combination of factors.

5.4 Uncertainty in results presented in Chapter 5

The main uncertainty in the results presented in Chapter 5 relates to the different sources of energy data (4M LIL electricity meter reading data and 4M energy supplier annual electricity use data) and normalisation treatments used in the analyses of variations in annual electricity use and changes in demand over time for both the L315 and L27 cohorts.

The 4M LIL electricity meter reading data were normalised to annual electricity consumption figures for the years 2009 (L315 and L27 cohorts), 2010 (L27 cohort only) and 2011 (L27 cohort only) assuming no seasonal variation in use. Whereas, the 4M energy supplier annual electricity use data for the years 2007 and 2008 (L315 and L27 cohorts) were adjusted for seasonal variation. As winter electricity consumption can be between 25-90% higher than summer (Yohanis et al. 2008), not adjusting for seasonal variation could have a significant effect on the precision of the annual electricity consumption values for the L315 and L27 homes. Seasonal variation in domestic electricity use relates primarily to a higher electricity demand for lighting, cooking and electric space heating (only 16 homes in the L315 cohort had electric space heating) during the winter, little seasonality is evident however for electrical appliances (EST 2012).

The periods over which the energy meter readings were taken, will determine the magnitude of the effect on the annual electricity consumption values presented. The annual electricity consumption figures for 2009 were calculated based on meter readings taken over the period from 17th March 2009 to 18th August 2010. This period includes spring, summer, autumn and winter months. As two summer and two spring periods are incorporated in the calculation, whereas only one for both winter and autumn, the annual electricity consumption totals for 2009 are likely to be underestimated. The annual electricity consumption values for 2010 and 2011, calculated for the L27 homes only, were based on the meter reading periods 18th August 2010 to 11th July 2011 and 11th July 2011 and 27th June 2012, thereby accounting for almost entirely one year and all seasons. The 2010 and 2011 electricity consumption values should be reliable.

The reliability of the seasonally adjusted annual electricity consumptions for 2007 and 2008 are also likely to be affected by the fact that the calculations will have been based on some estimated meter readings. Although the majority of homes will have a meter reading at least once per year, some even quarterly, estimated meter readings are possible because UK energy suppliers are only required to read domestic electricity meters once every two years. The estimated meter readings may have resulted in either an over or under prediction of the actual electricity consumptions of the dwellings for 2007 and 2008. Furthermore, the standardised adjustment factor applied by energy companies to account for seasonal variation in use, whilst based on a large sample of energy data, is unlikely to be applicable for all dwellings, which may further result in inaccurate estimations of actual electricity consumption.

The uncertainties contained in the sources of data used in Chapter 5, may have an effect on the results obtained for both the variations in annual electricity use for the L315 and L27 cohorts, as well as the changes in electricity demand over time.

5.5 Chapter 5: Summary

This chapter has focused on analysing the annual electricity consumptions of the L315 and L27 cohorts. The results introduced in this chapter will be discussed in detail in Chapter 8. An overview of the key results in this chapter are:

- Data from both the L315 and L27 cohorts support previous findings that large variations in electrical energy demand exist between domestic buildings.
- The L315 cohort's electricity consumption data is representative of Great Britain and both the L315 and L27 electricity consumption data (min, max, mean and median) are comparable with those used in previous studies. Thereby, comparisons can be made between the current and previous studies and the results may demonstrate national scale trends.
- Data from the L315 cohort does not support the current consensus that high electricity consumers are increasing their electrical energy demand over time. Results from the L27 cohort supports previous findings, however as the L27 is a sub-set of the L315; this may highlight an issue with the small sample size investigated and observing changes in electrical energy demand of domestic buildings over short periods of time, which were also evident in the previous studies.
- At an individual house level, the L27 electricity use data demonstrate that annual fluctuations in demand can occur. Out of the 27 households investigated, 11 changed their electrical demand group at least once during the up to 5 year period. Of particular note, all households classified as low electricity consumers remained in this group throughout all the years examined.
- Occupants' stated factors for significant changes in the electrical energy demand of their homes covered a broad range of factors.

Chapter 6

Results: The socio-economic, technical and appliance drivers of high electrical energy use

6.1 Introduction

This chapter presents results from an odds ratio (OR) analysis of the socio-economic, technical and appliance drivers of high electricity consumption in domestic buildings. The analysis brings together data collected in the 4M LIL household survey, 4M LIL domestic appliance survey and the 4M electricity meter reading follow up for the L315 households.

The chapter begins by presenting a table of results for the socio-economic, technical and appliance characteristics investigated in the odds ratio analysis (section 6.2). Secondly, an examination of the ORs obtained for the socio-economic characteristics is undertaken (section 6.3). The ORs for the technical characteristics are then analysed (section 6.4), followed by the ORs for the appliance characteristics (section 6.5). Uncertainties in the results are presented (section 6.6). Finally, a summary of the key findings are outlined (section 6.7). The results introduced during this chapter will be discussed in detail in Chapter 8.

6.2 Factors contributing to high electricity consumption amongst the L315 cohort

The existing literature (see Chapter 2) has demonstrated that many socio-economic, technical and appliance factors can influence the electricity consumption of a domestic building. However, very few studies have explicitly investigated the factors that lead to high electrical energy demand. The following sections present the results of an odds ratio analysis (see section 4.10.3), which combined data from the 4M LIL household survey and 4M LIL appliance survey with the electricity consumptions of the L315 cohort in 2009 to explore this gap. Table 6-1 presents the results of the odds ratio (OR) analysis.

Table 6-1 Odds ratio results for the socio-economic, technical and appliance characteristics affecting high electricity consumption

Characteristics and factors	Number of homes with electricity demand < 4041 kWhpa (Low-medium group)	> 4041 kWhpa (High group)	Total homes	Odds ratio (95% CI)
Socio-economic characteristics				
Number of occupants				
1	73	8	81	*0.30* (0.13, 0.70)***
2	74	27	101	REFERENCE
3	22	26	48	**3.24** (1.58, 6.65)***
4	26	26	52	**2.74** (1.36, 5.52)***
5+	15	18	33	**3.29** (1.46, 7.43)***
Children				
No children	161	62	223	REFERENCE
Children	49	43	92	**2.28** (1.38, 3.77)***
Teenagers				
None	187	72	259	REFERENCE
1	14	20	34	**3.71** (1.78, 7.74)***
2	9	13	22	**3.75** (1.54, 9.16)***
Age of HRP				
< 35	44	23	67	0.66 (0.34, 1.25)
36 - 50	54	43	97	REFERENCE
51 - 65	50	26	76	0.65 (0.35, 1.21)
> 65	62	13	75	*0.26* (0.13, 0.54)***
Employment status of HRP				
Employed (Full-time or Part-time)	99	67	166	REFERENCE
Unemployed	40	20	60	0.74 (0.40, 1.37)
Retired	71	18	89	*0.37* (0.21, 0.68)***

Education level of HRP				
Degree level or above	43	23	66	1.01 (0.54, 1.88)
Less than degree level	87	46	133	REFERENCE
National Statistics Socio-economic classification of HRP				
Managerial or professional occupation	48	29	77	1.42 (0.77, 2.60)
Lower supervisory or technical occupation	15	7	22	1.09 (0.41, 2.91)
Small employers or own account workers	19	10	29	1.23 (0.52, 2.92)
Intermediate occupation	20	12	32	1.41 (0.62, 3.18)
Semi-routine or routine occupation	82	35	117	REFERENCE
Tenure				
Own house outright	85	41	126	REFERENCE
Buying house with mortgage	56	38	94	1.41 (0.81, 2.45)
Rented or rent free	69	26	95	0.78 (0.44, 1.40)
Annual household income				
< £20,000	129	49	178	REFERENCE
£20,000 - £50,000	59	43	102	**1.92** (1.15, 3.20)**
> £50,000	4	9	13	**5.92** (1.74, 20.12)***
Technical characteristics				
Dwelling type				
Detached	19	17	36	1.31 (0.62, 2.79)
Semi-detached	69	47	116	REFERENCE
Mid-terrace	73	17	90	*0.34* (0.18, 0.65)***
End-terrace	27	14	41	0.76 (0.36, 1.60)
Flat	22	10	32	0.67 (0.29, 1.54)
Period dwelling was built				
< 1900	10	9	19	1.76 (0.67, 4.63)
1900 - 1944	92	47	139	REFERENCE
1945 - 1990	92	40	132	0.85 (0.51, 1.42)
> 1900	16	9	25	1.10 (0.45, 2.68)

Number of bedrooms				
1	19	4	23	0.35 (0.11, 1.10)*
2	52	17	69	0.55 (0.29, 1.05)*
3	82	49	131	REFERENCE
> 4	18	17	35	1.58 (0.75, 3.35)
Number of floors				
1 or 1.5	38	18	56	0.91 (0.49, 1.72)
2 or more	133	69	202	REFERENCE
Total floor area				
0 - 50 m^2	24	9	33	0.85 (0.37, 1.91)
50 - 100 m^2	158	70	228	REFERENCE
> 100 m^2	28	26	54	**2.10** (1.15, 3.83)**
Electric space heating				
None	204	95	299	REFERENCE
Electric central heating and/or night electric storage heaters	6	10	16	**3.58** (1.26, 10.14)**
Fixed electric heating				
None	184	97	281	REFERENCE
Fixed electric heater	26	8	34	0.58 (0.25, 1.34)
Portable electric heating				
None	168	73	241	REFERENCE
Portable electric heater	42	32	74	**1.75** (1.03, 3.00)**
Electric water heating				
None	190	82	272	REFERENCE
Electric immersion heater and/or instant electric water heater	20	23	43	**2.66** (1.39, 5.12)***
Low-energy lighting				
None	24	12	36	REFERENCE
Up to half the lights	58	33	91	1.14 (0.50, 2.57)
More than half of the lights	54	36	90	1.33 (0.59, 3.00)
All lights	73	23	96	0.63 (0.27, 1.45)

Appliance characteristics				
Total number of electrical appliances owned				
30 or less	97	11	108	REFERENCE
31 - 35	17	6	23	**3.11** (1.02, 9.54)**
36 - 40	8	15	23	**16.53** (5.72, 47.76)***
41 - 45	6	9	15	**13.23** (3.96, 44.21)***
46 or more	5	9	14	**15.87** (4.51, 55.88)***
IT electrical appliances owned				
0 - 1	43	7	50	REFERENCE
2	19	5	24	1.62 (0.45, 5.75)
3	38	12	50	1.94 (0.69, 5.43)
4	18	10	28	**3.41** (1.13, 10.37)**
5	7	7	14	**6.14** (1.65, 22.94)***
6 or more	8	9	17	**6.91** (1.99, 23.95)***
Number of desktop computers owned				
0	68	21	89	REFERENCE
1	61	21	82	1.11 (0.55, 2.24)
2 and 3	4	8	12	**6.48** (1.77, 23.67)***
Main desktop computer working hours per day for weekday				
0 to 2 hours	35	11	46	REFERENCE
2 to 4 hours	11	8	19	2.31 (0.74, 7.20)
> 4 hours	12	7	19	1.86 (0.59, 5.88)
Main desktop computer working hours per day for weekend				
0 to 2 hours	27	8	35	REFERENCE
2 to 4 hours	15	6	21	1.35 (0.39, 4.63)
> 4 hours	13	12	25	**3.12** (1.02, 9.48)
Number of laptop computers				
0	76	12	88	REFERENCE
1	46	22	68	**3.03** (1.37, 6.69)***
2 and 3	11	16	27	**9.21** (3.46, 24.54)***

Main laptop computer working hours per day for weekday				
0 to 2 hours	33	13	46	REFERENCE
2 to 4 hours	7	10	17	**3.63** (1.14, 11.56)**
> 4 hours	10	10	20	2.54 (0.86, 7.52)*
Main laptop computer working hours per day for weekend				
0 to 2 hours	26	12	38	REFERENCE
2 to 4 hours	13	8	21	1.33 (0.44, 4.07)
> 4 hours	12	13	25	2.35 (0.83, 6.65)
Telephony electrical appliances owned				
0 - 1	35	5	40	REFERENCE
2	51	6	57	0.82 (0.23, 2.91)
3	31	16	47	**3.61** (1.19, 11.01)**
4	12	11	23	**6.42** (1.85, 22.26)***
5 or more	4	12	16	**21.00** (4.83, 91.26)***
Entertainment electrical appliances owned				
0 - 5	66	13	79	REFERENCE
6 - 10	60	29	89	**2.45** (1.17, 5.15)**
11 or more	7	8	15	**5.80** (1.79, 18.81)***
Number of televisions owned				
1	63	11	74	REFERENCE
2	44	13	57	1.69 (0.69, 4.12)
3	16	17	33	**6.09** (2.39, 15.52)***
4 and 5	6	6	12	**5.73** (1.56, 21.02)***
Main television type				
CRT	61	12	73	0.47 (0.21, 1.05)*
LCD	53	22	75	REFERENCE
PLASMA	12	13	25	**2.61** (1.03, 6.61)**

Main television size				
Up to 32”	55	11	66	REFERENCE
32” to 39”	43	19	62	2.21 (0.95, 5.13)*
40” or more	14	13	27	**4.64** (1.72, 12.55)***
Main television working hours per day for weekday				
0 to 2 hours	11	3	14	0.58 (0.14, 2.37)
2 to 4 hours	36	12	48	0.71 (0.29, 1.71)
4 to 6 hours	34	16	50	REFERENCE
6 to 8 hours	17	3	20	0.38 (0.10, 1.47)
8 to 10 hours	12	3	15	0.53 (0.13, 2.15)
> 10 hours	12	10	22	1.77 (0.63, 4.95)
Main television working hours per day for weekend				
0 to 4 hours	30	8	38	0.55 (0.20, 1.54)
4 to 6 hours	27	13	40	REFERENCE
6 to 8 hours	23	10	33	0.90 (0.33, 2.44)
8 to 10 hours	20	7	27	0.73 (0.25, 2.15)
> 10 hours	22	9	31	0.75 (0.31, 2.35)
HVAC electrical appliances owned				
0	32	5	37	REFERENCE
1	39	5	44	0.82 (0.22, 3.09)
2	28	13	41	2.97 (0.94, 9.38)
3	18	11	29	**3.91** (1.17, 13.05)**
4	10	7	17	**4.48** (1.16, 17.27)**
5 or more	6	9	15	**9.60** (2.37, 38.87)***
Major cooking				
None	108	36	144	REFERENCE
Electric oven and/or electric hob and/or electric range cooker	102	69	171	**2.03** (1.25, 3.30)***

Electric oven working hours per day for weekday				
0 to 0.5 hour	33	7	40	0.54 (0.19, 1.52)
0.5 to 1 hour	33	13	46	REFERENCE
1 to 2 hours	23	13	36	1.43 (0.56, 3.66)
2 to 3 hours	10	3	13	0.76 (0.18, 3.22)
> 3 hours	11	8	19	1.85 (0.61, 5.63)
Electric oven working hours per day for weekend				
0 to 0.5 hour	22	3	25	0.30 (0.08, 1.13)*
0.5 to 1 hour	29	10	39	0.75 (0.30, 1.88)
1 to 2 hours	37	17	54	REFERENCE
2 to 3 hours	12	9	21	1.63 (0.58, 4.61)
> 3 hours	6	6	12	2.18 (0.61, 7.74)
Electric hob working hours per day for weekday				
0 to 0.5 hour	29	9	38	0.91 (0.34, 2.41)
0.5 to 1 hour	38	13	51	REFERENCE
1 to 2 hours	10	13	23	**3.80** (1.35, 10.72)**
> 2 hours	27	8	35	0.87 (0.31, 2.38)
Electric hob working hours per day for weekend				
0 to 0.5 hour	25	8	33	1.05 (0.37, 2.97)
0.5 to 1 hour	36	11	47	REFERENCE
1 to 2 hours	20	17	37	**2.78** (1.09, 7.09)**
> 2 hours	23	8	31	1.14 (0.40, 3.25)
Minor cooking electrical appliances owned				
1 - 3	51	11	62	0.52 (0.24, 1.15)
4 - 6	68	28	96	REFERENCE
7 or more	14	11	25	1.91 (0.77, 4.71)
Preservation and cooling electrical appliances owned				
0 - 1	75	14	89	REFERENCE
2	48	20	68	**2.23** (1.03, 4.84)**
3 or more	10	16	26	**8.57** (3.23, 22.72)***

Refrigerator				
None	77	22	99	REFERENCE
1 or more	56	28	84	1.75 (0.91, 3.37)*
Fridge-freezer				
None	48	17	65	REFERENCE
1 or more	85	33	118	1.10 (0.55, 2.17)
Upright freezer				
None	108	28	136	REFERENCE
1 or more	25	22	47	**3.39** (1.67, 6.89)***
Chest freezer				
None	108	40	148	REFERENCE
1 or more	25	10	35	1.08 (0.48, 2.45)
Washing electrical appliances owned				
0	111	28	139	REFERENCE
1	22	22	44	**3.96** (1.93, 8.16)***
Dishwasher				
None	111	28	139	REFERENCE
1	22	22	44	**3.96** (1.93, 8.16)***
Loads of dishwashing per week				
0	4	3	7	0.34 (0.05, 2.13)
1 or 2	9	3	12	*0.15* (0.03, 0.81)**
3 or 4	3	5	8	0.75 (0.13, 4.49)
5 or more	5	11	16	REFERENCE
Temperature of dishwashing				
40 ^{O}C or less	4	4	8	0.44 (0.07, 2.74)
41 – 59 ^{O}C	4	9	13	REFERENCE
60 ^{O}C or more	5	5	10	0.44 (0.08, 2.46)
Laundry electrical appliances owned				
1 - 2	96	20	116	REFERENCE
3 or more	37	30	67	**3.89** (1.97, 7.69)***

Washing machine				
None	16	5	21	REFERENCE
1	117	45	162	1.23 (0.43, 3.56)
Washer-dryer				
None	120	45	165	REFERENCE
1	13	5	18	1.03 (0.35, 3.04)
Tumble dryer				
None	99	19	118	REFERENCE
1	34	31	65	**4.75** (2.38, 9.48)***
Loads of clothes washing per week				
1 or 2	67	9	76	REFERENCE
3	27	14	41	**3.86** (1.49, 9.97)***
4	12	4	16	2.48 (0.66, 9.37)
5 or more	23	23	46	**7.44** (3.01, 18.39)***
Temperature of clothes washing				
30 ^{O}C or less	36	11	47	0.68 (0.31, 1.52)
31 – 40 ^{O}C	67	30	97	REFERENCE
41 ^{O}C or more	19	5	24	0.59 (0.20, 1.72)
Loads of clothes drying per week in Summer				
0	28	12	40	REFERENCE
1 or 2	6	12	18	**4.67** (1.42, 15.35)**
3 or more	3	7	10	**5.44** (1.20, 24.70)**
Loads of clothes drying per week in Winter				
0	6	3	9	REFERENCE
1 or 2	20	5	25	0.50 (0.09, 2.73)
3	6	6	12	2.00 (0.33, 11.97)
4 or more	6	18	24	**6.00** (1.13, 31.74)**

Building and outdoors maintenance electrical appliances owned				
0 - 1	45	9	54	REFERENCE
2	44	8	52	0.91 (0.32, 2.57)
3	13	14	27	**5.38** (1.90, 15.24)***
4	14	4	18	1.43 (0.38, 5.36)
5 or more	17	15	32	**4.41** (1.63, 11.96)***
Hygiene, beauty and leisure electrical appliances owned				
0	54	14	68	REFERENCE
1	49	16	65	1.26 (0.56, 2.85)
2	20	13	33	**2.51** (1.01, 6.25)**
3 or more	10	7	17	2.70 (0.87, 8.36)*
Electric showers				
None	112	42	154	REFERENCE
Electric Showers	98	63	161	**1.71** (1.07, 2.76)**
Number of electric showers per week				
0	10	4	14	REFERENCE
1 - 10	57	23	80	1.01 (0.29, 3.54)
11 - 20	27	20	47	1.85 (0.51, 6.77)
> 21	4	16	20	**10.00** (2.03, 49.30)***

Note: REFERENCE represents the reference category. Odds ratios in **bold** indicate that the factor increases the likelihood that a household will be a high electricity consumer (lower bound of CI greater than unity), whereas those in *italics* indicate that a household is less likely to be a high consumer (upper bound of CI less than unity).

* Significant at the 10% level.

** Significant at the 5% level.

*** Significant at the 1% level.

6.3 Odds ratios for socio-economic characteristics

In general, it would appear that a greater number of occupants residing in a dwelling increases the probability of being a high electrical energy user. Single occupant homes were significantly much less likely ($p < 0.01$) to be high electrical energy consumers than dwellings in the reference category with two occupants (OR = 0.30). Households with three or more occupants were all significantly more likely to be high consumers at the 1% level than those with two occupants. There was little change in the observed likelihood for those dwellings with 3 to 5+ occupants, however the extent to which increasing numbers of occupants affects the probability of being in the high use group is less clear, as the CI for all households with greater than two occupants was wide.

Compared to homes without any children, the results show that those with at least one child were more than twice as likely to be in the high demand group (OR = 2.28). The OR result was also significant at the 1% level. As this was a binary factor (children/no children), the OR value does not specify for differences in the number or age of the children. From the results relating to total number of occupants, it can be imagined that dwellings with more children would use a greater amount of electricity. In the 4M LIL household survey, children were defined as any occupants under the age of 15.

A factor associated with the total number of occupants and the number of children is the number of teenagers residing in the dwelling. The OR results indicated that households with teenagers living in them are significantly more likely to be high electrical energy consumers than those without any ($p < 0.01$). Dwellings with either one (OR = 3.71) or two teenagers (OR = 3.75) were found to be more than three times more likely to be high consumers. Despite the fact that the maximum number of teenagers residing in any of the sample households was two, the similar OR values for both one and two teenagers may indicate that mere presence, rather than number of teenagers, is the more important factor.

The OR results for the age of the Household Representative Person (HRP), which is the age of the highest income earner in the household, indicated that dwellings with a HRP over 65 years old were significantly less likely at the 1% level to be high electricity consumers than those with a HRP between 36 and 50 years old (OR = 0.26). Households with a HRP aged less than 35 or from 51 to 65 years old were just as likely to be high electrical energy consumers as those in the reference category, demonstrated by the CI spanning the value 1.

The employment status of the HRP was only found to affect the likelihood of a dwelling being a high consumer if the HRP was retired. Homes with a retired HRP were significantly less likely ($p < 0.01$) to have high electrical energy demand than those with an employed HRP (OR = 0.37). Households with an unemployed HRP were equally likely to be high or low consumers compared to those with an employed HRP (signified by the CI value crossing 1).

The education level of the HRP was established to have no effect on the probability of a household being a high electricity consumer. Households in the reference category with a HRP with an education below degree level were similarly likely to be high consumers as those with a HRP with a degree education or higher. This finding is highlighted by both the OR result being almost exactly unity (OR = 1.01) and the CI spanning the value 1.

The OR results for annual household income indicate that households with a higher income are more likely to be high electrical energy users. There was a small but significant increase ($p < 0.05$) in the probability that those earning between £20,000 and £50,000 would use more electricity than those in the reference group that earn less than £20,000 (OR = 1.92). Households with an income greater than £50,000 per annum however were almost six times more likely to be high consumers ($p < 0.01$) but due to the small sample size in this category, the precision of the estimation is low.

The National Statistics Socio-economic Classification of the HRP had little or no influence on the likelihood of being a high electrical demand household (the CI for all social classes span the value 1). This finding is perhaps unexpected, as it could be hypothesised that the HRPs' occupation would be indicative of the annual household income, which was previously seen to affect the likelihood of being a high electrical energy consumer. This relationship may not have emerged however, because households may have multiple incomes such that two occupants working in routine occupations could earn as much as one occupant working in a managerial occupation.

The OR results relating to tenure showed that the way in which residents occupied the dwelling did not affect the possibility of being a high electricity user. Households who were buying their home with a mortgage or renting were just as likely to be high or low consumers as those households who owned their property entirely. This was demonstrated by the CI values for both groups crossing unity.

6.4 Odds ratios for technical characteristics

The OR results showed that, with the exception of mid-terrace dwellings, which are significantly less likely ($p < 0.01$) to be high consumers than the reference, semi-detached properties (OR = 0.34), all other house types could equally be high or low consumers compared to the reference. This is implied by the CI crossing the value 1.

The period in which a dwelling was built was found to have little or no influence on the likelihood of being a high electricity consumer. Homes constructed before 1900, between

1945 and 1990, and after 1990 were just as likely to be high consumers as those homes built between 1900 and 1944, indicated by the CIs for all groups spanning unity.

The number of bedrooms a dwelling possesses was established to have little or no effect on the probability of being a high electrical energy consumer. Households with one, two or more than four bedrooms could be equally low or high consumers compared to the reference category with three bedrooms, as the CI spans the value 1.

The number of floors was also found to not increase the probability of a household being a high electricity consumer. Dwellings with either one or one and a half floors were just as likely to be high consumers as those dwellings with two or more floors (CI spans unity).

The OR results suggest that as the floor area of a dwelling increases, so does the probability of being a high electricity consumer. A modest difference was recognised for homes with a floor area up to 100 m^2, but dwellings with a floor area greater than 100 m^2 were estimated to be twice as likely to be high electrical energy users (OR = 2.1). Homes with a floor area greater than 100 m^2 were significantly more likely to be high electricity consumers at the 5% level than dwellings in the reference group with a floor area between 50 and 100 m^2. This result is contrary to the suggestion provided by the results for the number of bedrooms and floors, which could be indicative of floor area.

Dwellings in which electric space heating was the primary form of heating were significantly more likely ($p < 0.05$) to be high electricity consumers than dwellings heated using other fuel types (OR = 3.58). Although the precision of the OR calculation is low due to the small sample, it is easy to understand that as space heating accounts for about 60% of the total energy use in a domestic property (DECC 2012), if this service is provided by electricity rather than say gas, the likelihood of being a high electricity consumer should be greatly increased.

Regarding secondary electric heating for dwellings (fixed electric heating and portable electric heating), the OR results indicate that households with a fixed electric heater could be either high or low consumers signified by the CI spanning the value 1. However, those households reporting owning a portable electric heater were significantly more likely at the 5% level to be high electrical energy users than those with none (OR = 1.75).

Domestic buildings which heated water using electricity were significantly more likely ($p < 0.01$) to be high consumers than those without (OR = 2.66). As water heating represents on average 6% of electricity use in UK dwellings (DECC 2012), those with electric water heating have an elevated potential for electricity consumption. It should be noted that some of the households that reported using an electric immersion heater or instant electric water heater, also stated they had a gas fuelled boiler. The portion of water heating undertaken by each method is not known.

A significant energy-efficiency strategy imposed under the European Union's 2005 Eco-Design Directive (EU 2005), is the phasing out of inefficient incandescent and halogen lighting between 2009 and 2012; thereby 'encouraging' households to use low-energy lamps instead. However, the OR results indicate that it is not until all lights are fitted with low-energy lamps, that the probability of being in the high electrical demand group is reduced, but the effect is weak (the CI spans unity). As lighting accounts for less than a fifth of total electricity use in an average UK household (EST 2011), it is not unreasonable to expect a weak impact on electricity demand.

6.5 Odds ratios for appliance characteristics

The total number of electrical appliances a household owns appears to play a very important role in whether a household will be a high electrical energy user or not. It was found that as the number of electrical appliances owned increased above thirty (the mean number of appliances owned by the respondents to the 4M LIL domestic appliance survey), the probability of being a high electrical energy consumer also increased. Households owning between 31 and 35 appliances were three times more likely to be high consumers than those owning 30 or less and the result was significant at the 5% level (OR = 3.11). Despite the wide CIs, which shows that there is a large uncertainty in the estimation, households owning more than 36 appliances were between 13 and 16 times more probable to have a high electrical energy demand than those in the reference category (ORs = 13.23 – 16.53). The results for all three categories were significant at the 1% level. Ownership of more than 36 appliances was a strong influencing characteristic that a household will be a high electricity consumer, as even the lower bound of the CIs are well above unity.

The number of IT appliances owned by a household was found to affect the likelihood of being a high electricity consumer. Although, owning two or three IT appliances had little effect compared to owning zero or one appliance, households possessing four or more appliances were around 3 to 6 times more likely to be high electricity consumers (ORs = 3.41 – 6.91). The increased probability compared to the reference group was significant at the 5% level for four appliances and at the 1% level for five, and six or more appliances.

In the IT appliance subcategory, the effect of ownership and use of desktop and laptop computers on high electricity consumption was examined. Households that owned two or three desktop computers were significantly more likely ($p < 0.01$) to be high electricity consumers than those dwellings without any (OR = 6.48). The ownership of one desktop computer had little or no effect, highlighted by both the OR result being almost exactly unity (OR = 1.11) and the CI spanning the value 1. The working hours of the main desktop computer per day for a weekday had little impact on the possibility of being a high consumer; households using the computer for more than two hours per day were as likely to be high consumers as those using the computer less than 2 hours (CIs spanning unity). At the weekend, households using their desktop computers for more than four hours per day were about three times more likely to be high consumers (OR = 3.12) than dwellings in the reference category.

In relation to laptop computers, it was observed that as the ownership increased, so does the likelihood that a home will have high electrical energy demand. Homes owning between one and three laptops were around 3 to 9 times more likely to be high consumers than homes without a laptop (ORs = 3.09 – 9.21). The effect for both the ownership of one or two to three laptops was significant at the 1% level. The working hours of the main laptop computer for a weekday had a significant impact; homes operating the main laptop for two to four hours per day were around 3 times more likely to be high consumers (OR = 3.63, $p < 0.05$) and those using it for greater than four hours were more than twice as likely (OR = 2.54, $p < 0.10$). The use of the main laptop at the weekend was however found to have little or no effect on increasing the chance of high domestic electricity use, indicated by the CIs crossing the value 1.

The OR results show that households owning more than three telephony appliances are significantly more likely to be high electricity consumers. Dwellings with three appliances were 3 times more likely (OR = 3.61, $p < 0.01$) to have high electricity use than those owning zero or one device. The likelihood of high electrical energy demand was increased by around 6 times for households possessing four appliances (OR = 6.42, $p < 0.01$) and 21 times for more than five appliances (OR = 21.00, $p < 0.01$). It should be noted that the CIs are wide, highlighting low precision in the estimation of the effects.

The OR results relating to the ownership of entertainment appliances showed that the more entertainment appliances that are owned by a household, the higher the probability that the dwelling will have a high electricity demand. Households owning between six and ten appliances (OR = 2.45, $p < 0.05$) and eleven or more appliances (OR = 5.80, $p < 0.01$) are significantly more likely to be high electricity users than households with five or less appliances.

In the entertainment appliance subcategory, the effects of ownership, type, size and use of televisions on high electrical energy consumption was also investigated. The OR results showed that there is no clear impact on the probability of being a high consumer by owning two as opposed to one TV, indicated by the CI crossing unity. However, households owning three or more TVs are significantly ($p < 0.01$) more likely to be high consumers than homes in the reference category with a single TV.

The main television type, which is defined as the TV that the family watch together, was found to have a significant effect on high domestic electricity consumption. Households with an old-style CRT as their main TV appear to be significantly less likely ($p < 0.10$) to be high consumers than those with a reference LCD TV (OR = 0.47). The CI for CRT TV does however marginally span the value 1 indicating that the result should be treated with some caution. On the other hand, dwellings with a plasma TV are significantly more likely ($p < 0.05$) to have high electrical energy demand than dwellings in the reference category with a LCD TV (OR = 2.61).

The size of the main television was also demonstrated to have an impact on the probability of high electricity consumption. Households with a main TV between 32” and 39” were significantly more likely ($p < 0.10$) to be high consumers than those with a TV up to 32” (OR = 2.21). The lower CI does however cross the value 1 highlighting that the effect is not certain. Dwellings with a main TV 40” or more were greater than 5 times more likely to be high consumers (OR = 5.73) than dwellings in the reference category with a main TV up to 32”. This result was statistically significant at the 1% level.

The influence of the occupants’ use of the main television both during the week and at the weekend on the likelihood of high electricity consumption was studied. The OR results surprisingly showed that the number of working hours per day for a weekday and weekend had no effect on the probability of being a high electricity consumer. The OR results for all usage bands were around the value 1 and the CIs spanned unity.

The ownership of three or more HVAC appliances had a significant influence on the probability of being a high electricity user. Households owning three or four HVAC appliances were around 4 times more likely to be high consumers than those homes without any HVAC appliances (ORs = 3.91 – 4.48, $p < 0.05$). Homes owning five or more devices were around 9 times more likely to be a high electrical energy consumer (OR = 9.60, $p < 0.01$). Although the CIs are wide, indicating a large uncertainty in the estimation, the lower CI is below unity demonstrating the positive influence.

The OR results also show that if occupants do some of their cooking with electricity, the probability of being a high demand household is doubled in comparison to households using alternative fuel types (OR =2.03). This result was statistically significant at the 1% level. In this case, electric cooking refers to ovens, hobs and range cookers not microwaves, toasters, kettles, etc.

The OR results investigating the use of electric ovens and hobs indicated that the number of working hours during the week and at the weekend had little or no effect on the probability of a dwelling being a high electricity user. The occupants’ use of the electric oven during a weekday and weekend had no clear impact on the likelihood of a home having high consumption indicated by the CIs of the ORs crossing unity in all cases. A similar result was observed for the use of the electric hob, with the exception of one to two hours operation during both weekdays and weekends, which increased the probability of high consumption compared to the reference category (ORs = 3.80 and 2.78). Both results were also statistically significant at the 5% level.

The ownership of minor cooking devices was estimated to have no effect on the probability of a household being a high consumer. Households in the reference category owning four to six minor cooking appliances were similarly likely to be high consumers as those with one to three (OR = 0.52) or seven or more appliances (OR = 1.91). This finding is highlighted by the CI spanning the value 1.

The OR results demonstrated that households possessing more preservation and cooling appliances had an increased chance of being a high electricity consumer. Homes owning two appliances were significantly more likely ($p < 0.05$) to be high consumers than those owning zero or one appliance (OR = 2.23). Households owning three or more appliances were around 8 times more probable to be high consumers than those in the reference category (OR = 8.57). The wide CI indicates the precision of the estimation is low, but the variation in probability is statistically significant at the 1% level.

Regarding the effects of owning specific preservation and cooling appliances, the OR results showed that the mere ownership of a refrigerator (OR = 1.75), fridge-freezer (OR = 1.10) and chest freezer (OR = 1.08) had little or no influence on the likelihood of being a high electricity consumer. However, households that owned one or more upright freezers were significantly more likely ($p < 0.01$) to be high consumers than those without the appliance (OR = 3.39).

The ownership of a washing appliance has a significant effect ($p < 0.01$) on the probability of a dwelling being a high electricity consumer. Households owning one washing appliance were almost 4 times more likely to be a high consumer than households without any (OR = 3.96). In this study, washing appliances referred to dishwashers only, therefore the same OR results were obtained for the ownership of a dishwasher (OR = 3.96, $p < 0.01$). In relation to the usage and temperature selected for dishwashing, the OR results showed that households using the dishwasher once or twice per week, as opposed to five times or more, were significantly less likely ($p < 0.05$) to be high consumers (OR = 0.15). The choice of temperature setting for dishwashing had no clear effect. Occupants choosing to operate their dishwasher at less than $40^{o}C$ (OR = 0.44) or more than $60^{o}C$ (OR = 0.44) were as likely to be high consumers as those in the reference category, as shown by the CIs crossing the value 1.

The OR results demonstrated that homes with three or more laundry appliances were significantly more likely ($p < 0.01$) to be high electricity users than those with one or two laundry appliances (OR = 3.89). With regard to the ownership of specific laundry appliances, households possessing a single washing machine (OR = 1.23) or washer-dryer (OR = 1.03) were just as likely to be high consumers as homes with none, indicated by the ORs being close to unity and the CIs spanning the value 1. Owning a tumble dryer however, was identified as having a significant effect ($p < 0.01$) on the likelihood of a dwelling being a high electricity consumer (OR = 4.75).

The OR results for use and temperature selected for washing and drying clothes revealed that, in general, as the number of loads of clothes washing and drying increases, so does the probability of being a high electricity consumer. For clothes washing, households doing three (OR = 3.86) or more than five loads per week (OR = 7.44) were significantly more likely at the 1% level to be high electricity users than those doing one or two loads. For clothes drying, households undertaking one or more loads per week in summer (ORs = 4.67 and 5.44) were significantly more likely ($p < 0.05$) to be high consumers in comparison to those not doing any. In the winter, the OR results showed that only households doing four or more loads of drying per week (OR = 6.00) had an increased probability of high consumption. The temperature chosen for washing clothes was found to have little or no effect on the chance of being a high consumer, highlighted by all CIs spanning unity.

Compared to homes owning zero or one building and outdoors maintenance appliances, dwellings owning three (OR = 5.38) or more than five appliances (OR = 4.41), were around 5 times more likely to have high electrical energy demand. In both cases the result was statistically significant at the 1% level.

The effect of owning more hygiene, beauty and leisure appliances was unclear from the OR results. Whilst, homes owning one appliance could equally be a high or low consumer compared to the reference category with zero appliances (OR = 1.26), homes owning two appliances had double the probability of high electricity demand (OR = 2.51). This result was significant at the 5% level.

Electric showers are likely to have the highest power consumption (typically 7 - 11 kW) of any household electrical end-use. Although used for a short time the analysis reflects that if a dwelling has at least one electric shower, the probability of being a high electrical demand household is high compared to those without any electric showers (OR = 1.71). The variation in probability was statistically significant at the 5% level. The number of electric showers taken by a dwelling’s occupants was also found to greatly affect the possibility of being a high consumer. Households using an electric shower twenty-one or more times per week were significantly more likely ($p < 0.01$) to be a high electricity consumers than those not taking any (OR = 10.00), however the precision in the estimation was low. No variation in the probability of being a high consumer was observed for homes using an electric shower between one and twenty times per week.

6.6 Uncertainty in results presented in Chapter 6

The main uncertainty in the results presented in Chapter 6 relates to the reliability of the self-reported data collected from the 4M LIL household survey and 4M LIL domestic appliance survey, as well as the sampling error in the L315 data for the low, medium and high demand groups.

The first source of uncertainty in the odds ratio (OR) results is due to the fact that the socio-economic, technical and appliance data were collected through self-report surveys. The ability of the general public to accurately report technical information about the construction and systems installed in their homes is questionable. Also, in relation to the sensitive socio-economic and appliance factors (annual household income, employment status, ownership and use of domestic appliances), it is perhaps understandable, that participants may not have wished to precisely disclose the information.

The second source of uncertainty is the sampling error inherent in the L315 sample size studied. In other words, how well does the L315 sample used in the OR analysis represent the larger 280,000 household population of Leicester, UK. The sampling error in both the 210 household low-medium demand group and 105 household high demand group was calculated using the software G*Power (Faul et al. 2007). The results showed that the sampling error for the low-medium demand group was 6.8% and 9.6% for the high demand group at the 95% confidence interval. The recommended acceptable margin of error typically used by survey researchers falls between 4% and 8% at the 95% confidence level (Field 2005). Therefore, the sampling error for the high demand group slightly exceeds this value, whilst the low-medium demand group size is in the acceptable range.

6.7 Chapter 6: Summary

This chapter has analysed the underlying socio-economic, technical and appliance factors leading to high electrical energy consumption in domestic buildings. The results introduced in this chapter will be discussed in detail in Chapter 8. An overview of the key results in this chapter are:

- An odds ratio (OR) analysis of the L315 electricity use data combined with socio-economic, technical and appliance data gathered from the 4M LIL household survey and 4M LIL domestic appliance survey suggest that high electrical energy consumption in domestic buildings is related to a broad range of socio-economic, technical and appliance related factors.
- The OR results obtained for the socio-economic characteristics demonstrated that households with: more occupants, children, teenagers, and higher annual

household incomes are more likely to be high electrical energy consumers. Families with a HRP over 65 years old or a retired HRP are less likely to have high electrical energy demand than those with differing characteristics.

- The OR results obtained for the technical characteristics of the dwellings established that domestic buildings with: a floor area greater than 100 m^2, electric space heating as the primary form of heating, secondary portable electric heating, and electric water heating have a greater probability of high electricity consumption. Mid-terrace dwellings were less likely to have a high electrical energy use than those with differing characteristics.
- The OR results obtained for the ownership of electrical appliances showed that households owning: more than 30 appliances have an increased probability of high electrical energy demand. More specifically, a household owning: 4 or more IT appliances, 3 or more telephony appliances, more than 5 entertainment appliances, 3 or more HVAC appliances, any major electrical cooking appliance, 2 or more preservation and cooling appliances, 1 washing appliance, 3 or more laundry appliances, 3 or more than 5 building and outdoors maintenance appliances, or 2 hygiene, beauty and leisure appliances, have an increased probability of being a high electricity consumer than those with differing characteristics.
- The OR results for the ownership of specific appliance types revealed that households owning: 2 or 3 desktop computers, 1 or more laptop computers, 3 or more TVs, a plasma screen as their main TV, a main TV 40” or larger, an upright freezer, dishwasher, tumble dryer, or electric shower, have a greater likelihood of having a high electrical energy use than those with differing characteristics.
- The OR results for the usage of appliances showed that households using: their main desktop computer for more than 4 hours each day at the weekend, their main laptop computer for more than 2 hours each day during weekdays, an electric hob between 1 and 2 hours each day both on a weekday and at the weekend, undertaking more loads of clothes washing each week, undertaking more clothes drying each week in the summer, 4 or more loads of clothes drying each week in the winter, and more than 21 electric showers each week, are more likely to be high electricity consumers than those with differing characteristics.

Chapter 7

Results: Variations in appliance electricity consumption, ownership, power demand and use

7.1 Introduction

Although the results presented in Chapters 5 and 6 provide a means to understand the variations and drivers of total annual electricity consumption that occurred in the L315 and L27 study samples, the total values hide some of the important underlying variations in appliance characteristics which impact overall electricity consumption. With the exception of those homes with electric space or water heating, primarily, the electricity supplied to UK homes is used to power lighting and appliances, and consequently variations in appliance electricity consumption should determine the differences in overall electrical demand between dwellings. Fundamentally, the variations in appliance electricity consumption relate to three factors:

1. The number of appliances owned by households;
2. The power demands of the appliances in the different power modes;
3. The patterns of use in the households (i.e. occupant’s behaviour influences the appliances duration of use in the different power modes).

In general, the number and types of appliances owned by a household will define the physical infrastructure in which electricity consumption can occur. In simple terms, the greater the number of appliances owned, the more opportunities exist for electricity use. This was evident from the odds ratio results previously presented in Chapter 6, Section 6.5, which showed that dwellings with a greater number of electrical appliances were more likely to be high electricity consumers. The different power demands of the appliances in each of the power modes will also determine the amount of electricity that is used. In addition, the occupants' patterns of use of appliances will control the amount of time in which they are actively used or in standby power modes.

In this chapter, using the same framework of low, medium and high electrical energy demand groups, the variations in mean annual electricity consumption on a range of domestic appliances are explored. The focus is on identifying those appliances which have higher annual electricity use when owned by households in the high electrical energy demand group, as these should contribute to the variation in electricity demand between groups. The variations in ownership, power demands, and patterns of use of appliances for each electrical demand group are then investigated in order to help explain the differences in appliance electricity consumptions identified.

The appliance types and categories described have been adopted from the Carbon Reduction in Buildings (CaRB) project's appliance taxonomy (Marjanovic et al. 2008) (see Chapter 4, Section 4.10.4.1).

This chapter begins with an assessment of the variations in average annual electricity consumption of domestic appliances between electrical demand groups (section 7.2). The differences in ownership of appliances between electrical demand groups are then examined (section 7.3). Variations in the power demands of the appliances between the electrical demand groups are then presented (section 7.4). This is followed by an investigation of the variations in patterns of appliance use between the electrical demand groups (sections 7.5). Uncertainties in the results are presented (section 7.6). Finally, a chapter summary is provided (section 7.7).

7.2 Variations in annual appliance electricity consumptions between electrical demand groups

This section describes the average annual electricity consumptions on domestic appliances for each electrical demand group. The results illustrate the relative importance of different appliance types contributing to high electrical energy demand in residential buildings. The average annual electricity consumption for an appliance was derived by dividing the sum of annual electricity consumptions recorded for an appliance type by the number of homes in the electrical demand group (See Chapter 4, Section 4.10.4.3). Values in **bold** indicate the highest annual electricity consumption observed for an appliance power mode.

7.2.1 Variations in annual electricity consumption on office equipment and infotainment appliances

This section presents results concerning the annual electricity consumptions of office equipment and infotainment appliances. The variations between electrical demand groups in mean annual electricity use for appliance types are presented in Table 7-1.

In the IT appliance subcategory, the data collected in the AEUS showed that households with high electrical energy demand have greater average annual electricity consumptions on desktop computers in both active (114.00 kWh) and active/passive standby modes (30.93 kWh) than households in the low and medium demand groups. In addition, high electricity consumers used more electricity on laptop computers in all operative power modes: active (22.88 kWhpa), active/passive standby (3.13 kWhpa) and off standby (1.57 kWhpa).

In relation to printers, whilst medium demand dwellings were found to have larger annual electricity uses on printers in active mode, high demand dwellings had greater electricity consumptions in standby power modes: active standby (0.48 kWhpa) and passive standby (0.68 kWhpa).

Wireless routers were the only networking appliances that high electrical energy demand dwellings had higher annual electricity consumptions on. Wireless routers possessed by high consumers had almost double the annual electricity use (82.93 kWh) of identical devices owned by medium consumers (42.50 kWh) and eight times higher than low consumers' devices (13.51 kWh).

In the telephony appliance subcategory, high electrical energy consumers were identified to have the lowest annual electricity consumptions on telephones and telephones with answering machines. In fact, low electrical energy demand dwellings had the highest consumptions on appliances in this subcategory.

In the office accessories appliance subcategory, households in the high electrical demand group had greater average annual electricity consumptions on shredders (3.29 kWh) than households in the low and medium demand groups. No electricity consumption was recorded for laminators in all electrical demand groups.

In the entertainment appliance subcategory, high electricity consumers were observed to have higher annual electricity consumptions on LCD televisions in active (196.70 kWh), passive standby (20.56 kWh) and off standby modes (1.32 kWh) than low and medium consumers. Conversely, low and medium consumers had greater electricity consumptions on CRT televisions.

Households in the high demand group had higher active power mode electricity consumptions on three out of the four set top box (STB) types found in the L27 cohort homes. These STB types were digital, cable and internet. The former and latter STBs were also identified to have greater annual electricity uses in the active standby modes when owned by high demand dwellings compared to low and medium demand.

Regarding the annual electricity consumptions of video and recording appliances, the study established that high consumers have larger mean electricity demands on DVD players in active (2.44 kWhpa) and active standby modes (0.54 kWhpa), and VCR and DVD with VCR players in passive standby mode (6.96 kWhpa and 1.07 kWhpa).

For audio devices, the monitoring results identified that households in the high electrical demand group had increased electricity consumptions on three appliances: analogue radios in passive standby mode (3.07 kWhpa), personal CD players in active (0.72 kWhpa) and passive standby mode (3.35 kWhpa) and MP3 docking stations in active (2.57 kWhpa) and passive standby modes (1.31 kWhpa).

Finally, high electrical energy consumers in this study were found to have greater annual electricity consumptions on video consoles in both passive standby (6.22 kWh) and off standby modes (1.53 kWh) and ebook readers in active mode (0.06 kWh).

Table 7-1 Mean annual electricity consumptions on office equipment and infotainment appliances by power mode and electrical demand group

Appliance type	**Power mode**	**Mean annual electricity consumption (kWh) in the electrical demand group**			
		Low (n=5)	**Medium (n=10)**	**High (n=12)**	**All (n=27)**
IT					
Desktop	Active	10.40 (n=1)	62.15 (n=7)	**114.00** (n=11)	74.73 (n=19)
	Active/Passive Standby	5.61 (n=1)	19.09 (n=7)	**30.93** (n=11)	22.53 (n=19
	Off Standby	0.00 (n=1)	**0.60** (n=7)	0.05 (n=11)	0.33 (n=19)
Laptop	Active	8.27 (n=3)	22.72 (n=7)	**22.88** (n=10)	20.13 (n=20)
	Active/Passive Standby	2.13 (n=3)	0.18 (n=7)	**3.13** (n=10)	1.53 (n=20)
	Off Standby	0.09 (n=3)	0.78 (n=7)	**1.57** (n=10)	1.02 (n=20)
Printer	Active	0.00 (n=1)	**0.22** (n=5)	0.00 (n=6)	0.21 (n=11)
	Active Standby	0.11 (n=1)	0.20 (n=5)	**0.48** (n=6)	0.30 (n=11)
	Passive Standby	0.15 (n=1)	0.36 (n=5)	**0.68** (n=6)	0.65 (n=11)
	Off Standby	0.00 (n=1)	0.00 (n=5)	0.00 (n=6)	0.00 (n=11)
Wireless router	Active	13.51 (n=2)	42.50 (n=6)	**82.93** (n=10)	55.18 (n=18)
DSL	Active	0.00 (n=0)	0.00 (n=1)	0.00 (n=1)	2.00 (n=2)
Ethernet HUB	Active	0.00 (n=0)	**2.34** (n=1)	0.00 (n=0)	0.87 (n=1)
Portable hard-drive	Active	0.00 (n=0)	0.00 (n=0)	0.00 (n=1)	0.00 (n=1)

Appliance type	Power mode	Mean annual electricity consumption (kWh) in the electrical demand group			
		Low (n=5)	**Medium (n=10)**	**High (n=12)**	**All (n=27)**
Telephony					
Telephone	Active	**22.79** (n=8)	15.32 (n=14)	10.18 (n=11)	15.95 (n=33)
Telephone with answering machine	Active	**25.72** (n=2)	0.00 (n=0)	0.00 (n=0)	4.77 (n=2)
Office accessories					
Shredder	Active	0.55 (n=2)	0.21 (n=4)	**3.29** (n=3)	1.38 (n=9)
Laminator	Active	0.00 (n=0)	0.00 (n=1)	0.00 (n=0)	0.00 (n=1)
Entertainment					
CRT television	Active	**71.58** (n=5)	23.87 (n=6)	18.47 (n=4)	30.55 (n=15)
	Passive Standby	1.23 (n=5)	**2.05** (n=6)	1.22 (n=4)	1.94 (n=15)
	Off Standby	0.00 (n=5)	**0.45** (n=6)	0.34 (n=4)	0.35 (n=15)
LCD television	Active	38.16 (n=1)	163.28 (n=16)	**196.70** (n=18)	166.73 (n=35)
	Passive Standby	0.36 (n=1)	19.99 (n=16)	**20.56** (n=18)	18.99 (n=35)
	Off Standby	0.37 (n=1)	0.44 (n=16)	**1.32** (n=18)	0.84 (n=35)
Video amplifier (booster)	Active	0.00 (n=0)	**1.76** (n=1)	1.28 (n=2)	1.20 (n=3)
Digital Set Top Box	Active	16.09 (n=3)	4.36 (n=3)	**29.92** (n=9)	17.77 (n=15)
	Active Standby	1.43 (n=3)	0.66 (n=3)	**2.87** (n=9)	2.23 (n=15)
	Passive Standby	**0.34** (n=3)	0.00 (n=3)	0.00 (n=9)	0.06 (n=15)
	Off Standby	0.00 (n=3)	0.00 (n=3)	0.00 (n=9)	0.00 (n=15)
Satellite Set Top Box	Active	11.09 (n=3)	**35.83** (n=4)	26.91 (n=4)	26.89 (n=11)
	Active Standby	**23.83** (n=3)	10.73 (n=4)	0.00 (n=4)	9.72 (n=11)
	Passive Standby	0.00 (n=3)	0.00 (n=4)	0.00 (n=4)	0.00 (n=11)
	Off Standby	0.00 (n=3)	0.00 (n=4)	0.00 (n=4)	0.00 (n=11)
Cable Set Top Box	Active	0.00 (n=0)	4.06 (n=1)	**35.29** (n=4)	15.49 (n=5)
	Active Standby	0.00 (n=0)	**3.63** (n=1)	0.99 (n=4)	0.49 (n=5)
	Passive Standby	0.00 (n=0)	0.00 (n=1)	0.00 (n=4)	0.00 (n=5)
	Off Standby	0.00 (n=0)	0.00 (n=1)	0.00 (n=4)	0.00 (n=5)
Internet Set Top Box	Active	0.00 (n=0)	0.00 (n=0)	**0.76** (n=1)	0.35 (n=1)
	Active Standby	0.00 (n=0)	0.00 (n=0)	**0.54** (n=1)	0.26 (n=1)
	Passive Standby	0.00 (n=0)	0.00 (n=0)	0.00 (n=1)	0.00 (n=1)
	Off Standby	0.00 (n=0)	0.00 (n=0)	0.00 (n=1)	0.00 (n=1)
DVD player	Active	0.00 (n=3)	0.48 (n=6)	**2.44** (n=6)	1.17 (n=15)
	Active Standby	0.00 (n=3)	0.11 (n=6)	**0.54** (n=6)	0.28 (n=15)
	Passive Standby	0.00 (n=3)	**1.99** (n=6)	1.15 (n=6)	1.18 (n=15)
	Off Standby	0.00 (n=3)	0.00 (n=6)	0.00 (n=6)	0.00 (n=15)

Appliance type	Power mode	Mean annual electricity consumption (kWh) in the electrical demand group			
		Low (n=5)	**Medium (n=10)**	**High (n=12)**	**All (n=27)**
VCR player	Active	**14.92** (n=2)	2.17 (n=2)	0.25 (n=5)	3.81 (n=9)
	Active Standby	0.00 (n=2)	**5.33** (n=2)	1.32 (n=5)	2.48 (n=9)
	Passive Standby	5.77 (n=2)	2.27 (n=2)	**6.96** (n=5)	5.04 (n=9)
	Off Standby	0.00 (n=2)	0.00 (n=2)	0.00 (n=5)	0.00 (n=9)
Blu-ray player	Active	0.00 (n=0)	**0.53** (n=2)	0.00 (n=1)	0.22 (n=3)
	Active Standby	0.00 (n=0)	0.00 (n=2)	0.00 (n=1)	0.00 (n=3)
	Passive Standby	0.00 (n=0)	**0.40** (n=2)	0.00 (n=1)	0.14 (n=3)
	Off Standby	0.00 (n=0)	0.00 (n=2)	0.00 (n=1)	0.00 (n=3)
DVD with VCR	Active	0.00 (n=0)	0.00 (n=0)	0.00 (n=1)	0.00 (n=1)
	Active Standby	0.00 (n=0)	0.00 (n=0)	0.00 (n=1)	0.00 (n=1)
	Passive Standby	0.00 (n=0)	0.00 (n=0)	**1.07** (n=1)	0.47 (n=1)
	Off Standby	0.00 (n=0)	0.00 (n=0)	0.00 (n=1)	0.00 (n=1)
Portable DVD player	Active	0.00 (n=0)	**0.36** (n=1)	0.00 (n=0)	0.14 (n=1)
	Active Standby	0.00 (n=0)	0.00 (n=1)	0.00 (n=0)	0.00 (n=1)
	Passive Standby	0.00 (n=0)	0.00 (n=1)	0.00 (n=0)	0.00 (n=1)
	Off Standby	0.00 (n=0)	0.00 (n=1)	0.00 (n=0)	0.00 (n=1)
Stereo system	Active	**3.80** (n=3)	0.44 (n=6)	0.49 (n=8)	1.29 (n=17)
	Active Standby	1.37 (n=3)	**4.93** (n=6)	0.11 (n=8)	2.37 (n=17)
	Passive Standby	**3.78** (n=3)	1.72 (n=6)	1.77 (n=8)	2.96 (n=17)
	Off Standby	0.00 (n=3)	0.00 (n=6)	0.00 (n=8)	0.00 (n=17)
Digital radio	Active	0.05 (n=3)	**1.22** (n=5)	0.16 (n=2)	0.53 (n=10)
	Active Standby	0.00 (n=3)	**5.92** (n=5)	0.05 (n=2)	2.37 (n=10)
	Passive Standby	**2.48** (n=3)	0.00 (n=5)	0.12 (n=2)	0.56 (n=10)
	Off Standby	0.00 (n=3)	0.00 (n=5)	0.00 (n=2)	0.00 (n=10)
Analogue radio	Active	**0.40** (n=4)	**0.40** (n=3)	0.10 (n=3)	0.29 (n=10)
	Active Standby	0.02 (n=4)	**3.85** (n=3)	0.01 (n=3)	1.12 (n=10)
	Passive Standby	0.55 (n=4)	2.19 (n=3)	**3.07** (n=3)	2.36 (n=10)
	Off Standby	0.00 (n=4)	0.00 (n=3)	0.00 (n=3)	0.00 (n=10)
Clock radio	Active	5.36 (n=2)	**11.51** (n=6)	5.66 (n=4)	7.90 (n=12)
Personal CD player	Active	0.00 (n=0)	0.00 (n=0)	0.00 (n=2)	0.02 (n=2)
	Active Standby	0.00 (n=0)	0.00 (n=0)	**0.72** (n=2)	0.37 (n=2)
	Passive Standby	0.00 (n=0)	0.00 (n=0)	**3.35** (n=2)	2.16 (n=2)

Appliance type	Power mode	Mean annual electricity consumption (kWh) in the electrical demand group			
		Low (n=5)	Medium (n=10)	High (n=12)	All (n=27)
	Off Standby	0.00 (n=0)	0.00 (n=0)	0.00 (n=2)	0.00 (n=2)
Turntable	Active	0.00 (n=0)	0.00 (n=0)	0.00 (n=1)	0.00 (n=1)
	Off Standby	0.00 (n=0)	0.00 (n=0)	0.00 (n=1)	0.00 (n=1)
Speakers	Active	0.00 (n=0)	**0.11** (n=3)	0.00 (n=0)	0.04 (n=3)
	Active Standby	0.00 (n=0)	**8.84** (n=3)	0.00 (n=0)	3.27 (n=3)
	Passive Standby	0.00 (n=0)	0.00 (n=3)	0.00 (n=0)	0.00 (n=3)
	Off Standby	0.00 (n=0)	0.00 (n=3)	0.00 (n=0)	0.00 (n=3)
MP3 docking station	Active	**0.05** (n=1)	0.04 (n=1)	0.03 (n=1)	0.04 (n=3)
	Active Standby	0.04 (n=1)	0.02 (n=1)	**2.57** (n=1)	1.44 (n=3)
	Passive Standby	0.00 (n=1)	0.00 (n=1)	**1.31** (n=1)	0.58 (n=3)
	Off Standby	0.00 (n=1)	0.00 (n=1)	0.00 (n=1)	0.00 (n=3)
Keyboard/organ	Active	0.00 (n=0)	0.00 (n=1)	0.00 (n=2)	0.00 (n=3)
Guitar/keyboard amplifier	Active	0.00 (n=0)	0.00 (n=0)	0.00 (n=2)	0.00 (n=2)
Home music studio	Active	1.07 (n=1)	**1.15** (n=1)	0.00 (n=0)	0.57 (n=2)
	Active Standby	**2.47** (n=1)	1.40 (n=1)	0.00 (n=0)	1.00 (n=2)
	Passive Standby	**4.41** (n=1)	0.05 (n=1)	0.00 (n=0)	0.92 (n=2)
	Off Standby	0.00 (n=1)	0.00 (n=1)	0.00 (n=0)	0.00 (n=2)
Home theatre system	Active	0.00 (n=0)	**5.94** (n=1)	0.00 (n=0)	2.23 (n=1)
	Active Standby	0.00 (n=0)	0.00 (n=1)	0.00 (n=0)	0.00 (n=1)
	Passive Standby	0.00 (n=0)	**0.28** (n=1)	0.00 (n=0)	0.10 (n=1)
	Off Standby	0.00 (n=0)	0.00 (n=1)	0.00 (n=0)	0.00 (n=1)
Video console	Active	0.00 (n=0)	**49.33** (n=8)	28.68 (n=14)	32.83 (n=22)
	Passive Standby	0.00 (n=0)	2.48 (n=8)	**6.22** (n=14)	3.88 (n=22)
	Off Standby	0.00 (n=0)	0.26 (n=8)	**1.53** (n=14)	0.00 (n=22)
ebook reader	Active	0.00 (n=0)	0.04 (n=1)	**0.06** (n=1)	0.06 (n=2)
	Off Standby	0.00 (n=0)	**0.09** (n=1)	0.08 (n=1)	0.00 (n=2)

7.2.2 Variations in annual electricity consumption on non-fixed lighting

The average annual electricity consumptions on non-fixed lighting between electrical demand groups are presented in Table 7-2. It was observed that dwellings in the medium electrical demand group primarily had the highest annual consumptions on non-fixed lighting; with an annual electricity use of 8.54 kWh on CFL, 0.34 kWh on LED and 80.83 kWh on halogen lamps. Households in the high electrical demand group however had a greater electricity use on incandescent lamps (15.62 kWhpa) than medium (5.58 kWhpa) and low demand (4.29 kWhpa) households. The electricity use of incandescent lamps can be thought to be a factor of high electrical energy demand.

Table 7-2 Mean annual electricity consumptions on non-fixed lighting appliances by power mode and electrical demand group

Lighting type	Power mode	Mean annual electricity consumption (kWh) in the electrical demand group			
		Low (n=5)	**Medium (n=10)**	**High (n=12)**	**All (n=27)**
Incandescent	Active	4.29 (n=2)	5.58 (n=14)	**15.62** (n=14)	10.77 (n=30)
CFL	Active	3.61 (n=10)	**8.54** (n=10)	3.26 (n=5)	5.56 (n=25)
LED	Active	0.17 (n=1)	**0.34** (n=1)	0.00 (n=1)	0.19 (n=3)
Halogen	Active	0.00 (n=0)	**80.83** (n=1)	0.00 (n=0)	44.90 (n=1)

7.2.3 Variations in annual electricity consumption on HVAC appliances

Table 7-3 displays the differences in annual electricity consumption used for HVAC appliances among the electrical demand groups. On average, households in the high electrical demand group used more electricity in active power mode on all appliances in this category than low and medium demand households. The sole exception was desk fans which had higher mean annual electricity consumptions when owned by medium electricity consuming dwellings (2.05 kWhpa). These results therefore indicate that HVAC appliances appear to have an important contribution to high electricity consumption among the L27 cohort sample.

Table 7-3 Mean annual electricity consumptions on HVAC appliances category by power mode and electrical demand group

Appliance type	Power mode	Mean annual electricity consumption (kWh) in the electrical demand group			
		Low (n=5)	**Medium (n=10)**	**High (n=12)**	**All (n=27)**
Desk fan	Active	**2.05** (n=2)	0.84 (n=3)	0.00 (n=1)	0.82 (n=5)
	Off Standby	0.00 (n=2)	0.00 (n=3)	0.00 (n=1)	0.00 (n=5)
Electric fire	Active	0.00 (n=0)	0.00 (n=0)	**37.51** (n=2)	16.41 (n=2)
	Off Standby	0.00 (n=0)	0.00 (n=0)	0.00 (n=2)	0.00 (n=2)
Electric blanket	Active	0.00 (n=0)	0.00 (n=0)	**0.75** (n=1)	0.33 (n=1)
	Off Standby	0.00 (n=0)	0.00 (n=0)	0.00 (n=1)	0.00 (n=1)
Portable halogen radiator	Active	0.00 (n=0)	0.00 (n=0)	**24.05** (n=1)	9.62 (n=1)
	Off Standby	0.00 (n=0)	0.00 (n=0)	0.00 (n=1)	0.00 (n=1)
Portable oil filled radiator	Active	0.00 (n=0)	0.00 (n=0)	**42.49** (n=1)	18.88 (n=1)
	Off Standby	0.00 (n=0)	0.00 (n=0)	0.00 (n=1)	0.00 (n=1)

7.2.4 Variations in annual electricity consumption on transportation appliances

Table 7-4 illustrates the annual electricity consumptions on transportation appliances for the L27 cohort. In general, the annual appliance electricity consumptions identified were small for all electrical demand groups. The low electrical demand group had no electricity use on any of the transportation appliances found in the L27 households. Medium consumers had a greater annual electricity use on reclining furniture (5.24 kWhpa) in the active power mode than low and medium consumers. Households in the high electrical demand group were found to have increased electricity consumptions on mobility scooters (1.11 kWhpa), golf trolleys (13.12 kWhpa) and chair lifts (4.52 kWhpa) compared to households in the other two electrical demand groups. For the L27 sample these appliances can be associated with high electricity consumption.

Table 7-4 Mean annual electricity consumptions on transportation appliances by power mode and electrical demand group

Appliance type	Power mode	Mean annual electricity consumption (kWh) in the electrical demand group			
		Low (n=5)	Medium (n=10)	High (n=12)	All (n=27)
Reclining furniture	Active	0.00 (n=0)	**5.24** (n=4)	0.00 (n=0)	2.21(n=4)
	Off Standby	0.00 (n=0)	0.00 (n=4)	0.00 (n=0)	0.00 (n=4)
Mobility scooter	Active	0.00 (n=1)	0.00 (n=0)	**1.11** (n=2)	0.52 (n=3)
	Off Standby	0.00 (n=1)	0.00 (n=0)	0.00 (n=2)	0.00 (n=3)
Bath lift	Active	0.00 (n=1)	0.00 (n=0)	0.00 (n=0)	0.00 (n=1)
	Off Standby	0.00 (n=1)	0.00 (n=0)	0.00 (n=0)	0.00 (n=1)
Golf trolley	Active	0.00 (n=0)	0.00 (n=0)	**13.12** (n=1)	5.87 (n=1)
	Off Standby	0.00 (n=0)	0.00 (n=0)	0.00 (n=1)	0.00 (n=1)
Chair lift	Active	0.00 (n=0)	0.00 (n=0)	**4.52** (n=1)	2.01 (n=1)
	Off Standby	0.00 (n=0)	0.00 (n=0)	0.00 (n=1)	0.00 (n=1)

7.2.5 Variations in annual electricity consumption on catering appliances

The variations between electrical demand groups in mean annual electricity demand for catering appliances are presented in Table 7-5.

In the major cooking appliance subcategory no annual electricity consumption data was collected, as these appliances were wired directly into the mains electricity supply.

It was observed that the majority of appliances in the minor cooking appliance category had no annual consumption measurements recorded for any of the electrical demand groups as they were unused by the occupants of the L27 cohort homes during the AEUS.

Households in the high electrical demand group did however have marginally higher annual electricity consumptions on a number of minor cooking appliances. Microwaves owned by high consuming dwellings had an annual electricity consumption of 39.10 kWh in the active power mode, compared with 31.86 kWh for low consuming and 31.83 kWh for medium consuming dwellings. High consumers' kettles on average used 183.33 kWhpa in active mode, whereas those owned low and medium consumers' used 183.06 kWhpa and 176.57 kWhpa respectively. High demand dwellings also used more electricity on toasters (0.01 kWhpa), blenders (0.44 kWhpa) and coffee makers (0.13

kWhpa) in the passive standby mode than the other two electrical demand groups but the consumptions were very low.

Concerning preservation and cooling appliances, high electrical energy demand homes consumed more electricity on upright freezers in the non-cooling cycle (2.54 kWhpa) and beer and wine coolers in the cooling cycle (19.41 kWhpa) only. All other appliances in this category had greater mean annual electricity consumptions when owned by dwellings in either the low or medium electrical demand groups.

Table 7-5 Mean annual electricity consumptions on catering appliances by power mode and electrical demand group

Appliance type	**Power mode**	**Mean annual electricity consumption (kWh) in the electrical demand group**			
		Low (n=5)	**Medium (n=10)**	**High (n=12)**	**All (n=27)**
Major cooking					
Electric oven	Active	-	-	-	-
Electric hob	Active	-	-	-	-
Minor cooking					
Small ovens	Active	0.00 (n=0)	0.00 (n=0)	0.00 (n=1)	0.00 (n=1)
	Off Standby	0.00 (n=0)	0.00 (n=0)	0.00 (n=1)	0.00 (n=1)
Microwave	Active	31.86 (n=3)	31.83 (n=7)	**39.10** (n=13)	35.03 (n=23)
	Passive Standby	**20.61** (n=3)	7.14 (n=7)	10.78 (n=13)	12.01 (n=23)
	Off Standby	0.00 (n=3)	0.00 (n=7)	0.00 (n=13)	0.00 (n=23)
Grill plate	Active	0.00 (n=0)	0.00 (n=1)	0.00 (n=0)	0.00 (n=1)
	Off Standby	0.00 (n=0)	0.00 (n=1)	0.00 (n=0)	0.00 (n=1)
Deep fryer	Active	0.00 (n=0)	0.00 (n=3)	0.00 (n=1)	0.00 (n=4)
	Off Standby	0.00 (n=0)	0.00 (n=3)	0.00 (n=1)	0.00 (n=4)
Toaster	Active	11.85 (n=4)	**14.13** (n=8)	11.83 (n=11)	11.46 (n=23)
	Passive Standby	0.00 (n=4)	0.00 (n=8)	**0.01** (n=11)	0.36 (n=23)
	Off Standby	0.00 (n=4)	0.00 (n=8)	0.00 (n=11)	0.00 (n=23)
Slow cooker	Active	0.00 (n=0)	0.00 (n=1)	0.00 (n=2)	0.00 (n=3)
	Off Standby	0.00 (n=0)	0.00 (n=1)	0.00 (n=2)	0.00 (n=3)
Steamer	Active	0.00 (n=0)	0.00 (n=1)	0.00 (n=1)	0.00 (n=2)
	Off Standby	0.00 (n=0)	0.00 (n=1)	0.00 (n=1)	0.00 (n=2)
Kettle	Active	183.06 (n=5)	176.57 (n=9)	**183.33** (n=12)	176.12 (n=26)
	Off Standby	0.00 (n=5)	0.00 (n=9)	0.00 (n=12)	0.00 (n=26)
Blender	Active	0.00 (n=1)	0.00 (n=1)	0.00 (n=4)	0.00 (n=6)
	Passive Standby	0.00 (n=1)	0.00 (n=1)	**0.44** (n=4)	0.19 (n=6)
	Off Standby	0.00 (n=1)	0.00 (n=1)	0.00 (n=4)	0.00 (n=6)
Food mixer	Active	0.00 (n=0)	0.00 (n=0)	0.00 (n=1)	0.00 (n=1)
	Off Standby	0.00 (n=0)	0.00 (n=0)	0.00 (n=1)	0.00 (n=1)
Juicer	Active	0.00 (n=1)	0.00 (n=0)	0.00 (n=0)	0.00 (n=1)
	Off Standby	0.00 (n=1)	0.00 (n=0)	0.00 (n=0)	0.00 (n=1)

Appliance type	Power mode	Mean annual electricity consumption (kWh) in the electrical demand group			
		Low (n=5)	**Medium (n=10)**	**High (n=12)**	**All (n=27)**
Food processor	Active	0.00 (n=0)	0.00 (n=0)	0.00 (n=1)	0.00 (n=1)
	Off Standby	0.00 (n=0)	0.00 (n=0)	0.00 (n=1)	0.00 (n=1)
Coffee grinder	Active	0.00 (n=0)	0.00 (n=1)	0.00 (n=0)	0.00 (n=1)
	Off Standby	0.00 (n=0)	0.00 (n=1)	0.00 (n=0)	0.00 (n=1)
Coffee maker	Active	0.00 (n=0)	0.00 (n=1)	0.00 (n=1)	0.00 (n=2)
	Passive Standby	0.00 (n=0)	0.00 (n=1)	**0.13** (n=1)	0.13 (n=2)
	Off Standby	0.00 (n=0)	0.00 (n=1)	0.00 (n=1)	0.00 (n=2)
Ice maker	Active	0.00 (n=0)	0.00 (n=0)	0.00 (n=1)	0.00 (n=1)
Popcorn maker	Active	0.00 (n=1)	0.00 (n=0)	0.00 (n=0)	0.00 (n=1)
	Off Standby	0.00 (n=1)	0.00 (n=0)	0.00 (n=0)	0.00 (n=1)
Can opener	Active	0.00 (n=0)	0.00 (n=2)	0.00 (n=2)	0.00 (n=4)
	Off Standby	0.00 (n=0)	0.00 (n=2)	0.00 (n=2)	0.00 (n=4)
Knife	Active	0.00 (n=0)	0.00 (n=0)	0.00 (n=1)	0.00 (n=1)
Preservation and cooling					
Refrigerator	Cooling cycle	74.82 (n=3)	**108.72** (n=6)	71.81 (n=4)	87.61 (n=13)
	Non-cooling cycle	0.00 (n=3)	0.00 (n=6)	0.00 (n=4)	0.00 (n=13)
Fridge-freezer	Cooling cycle	**202.34** (n=3)	150.18 (n=5)	194.80 (n=5)	180.42 (n=13)
	Non-cooling cycle	**30.39** (n=3)	5.12 (n=5)	3.18 (n=5)	8.54 (n=13)
Upright freezer	Cooling cycle	66.73 (n=2)	**171.88** (n=4)	170.05 (n=5)	147.69 (n=11)
	Non-cooling cycle	1.28 (n=2)	0.70 (n=4)	**2.54** (n=5)	1.92 (n=11)
Chest freezer	Cooling cycle	0.00 (n=0)	**347.70** (n=7)	136.82 (n=3)	192.19 (n=10)
	Non-cooling cycle	0.00 (n=0)	0.00 (n=7)	0.00 (n=3)	0.00 (n=10)
Beer and wine cooler	Cooling cycle	0.00 (n=0)	12.82 (n=1)	**19.41** (n=1)	14.34 (n=2)
	Non-cooling cycle	0.00 (n=0)	0.00 (n=1)	0.00 (n=1)	0.00 (n=2)

7.2.6 Variations in annual electricity consumption on washing appliances

Table 7-6 shows the variations in average annual electricity consumptions of washing appliances between the electrical demand groups. The washing appliance category in this study relates to the appliance type dishwashers only. It can be seen that high electrical energy demand households had greater annual electricity consumptions in all power modes than low and medium demand households. Therefore, dishwashers operating in all power modes can be identified as an appliance type contributing to high electricity consumption in the L27 cohort sample.

Table 7-6 Mean annual electricity consumption on washing appliances by power mode and electrical demand group

Appliance type	Power mode	Mean annual electricity consumption (kWh) in the electrical demand group			
		Low (n=5)	**Medium (n=10)**	**High (n=12)**	**All (n=27)**
Dishwasher	Washing cycle	4.83 (n=1)	0.00 (n=0)	**7.11** (n=4)	4.34 (n=5)
	Drying cycle	34.38 (n=1)	0.00 (n=0)	**52.84** (n=4)	31.24 (n=5)
	Passive Standby	0.00 (n=1)	0.00 (n=0)	**2.73** (n=4)	1.12 (n=5)

7.2.7 Variations in annual electricity consumption on laundry appliances

The variations between electrical demand groups in mean annual electricity consumption on laundry appliances are presented in Table 7-7. The results demonstrate that laundry appliances are particularly important in driving high electricity consumption. Dwellings in the high electrical demand group were observed to have higher annual electricity uses on all four laundry appliances, in almost every power mode. The exception was passive standby mode on washer-dryers, where medium demand households had a slightly greater annual consumption (0.71 kWhpa) than high demand households (0.24 kWhpa).

Table 7-7 Mean annual electricity consumptions on laundry appliances by power mode and electrical demand group

Appliance type	Power mode	Mean annual electricity consumption (kWh) in the electrical demand group			
		Low (n=5)	**Medium (n=10)**	**High (n=12)**	**All (n=27)**
Iron	Active	23.74 (n=5)	43.42 (n=10)	**47.67** (n=12)	43.23 (n=27)
Washing machine	Water heating cycle	30.53 (n=5)	29.36 (n=7)	**85.04** (n=9)	53.25 (n=22)
	Washing cycle	18.67 (n=5)	14.12 (n=7)	**27.24** (n=9)	20.95 (n=22)
	Passive Standby	1.00 (n=5)	1.94 (n=7)	**2.18** (n=9)	2.07 (n=22)
Washer-dryer	Water heating cycle	0.00 (n=0)	14.72 (n=3)	**53.34** (n=3)	29.96 (n=6)
	Washing cycle	0.00 (n=0)	9.18 (n=3)	**16.60** (n=3)	8.32 (n=6)
	Heating cycle	0.00 (n=0)	29.16 (n=3)	**61.76** (n=3)	30.02 (n=6)
	Tumble cycle	0.00 (n=0)	0.30 (n=3)	**3.11** (n=3)	1.53 (n=6)
	Passive Standby	0.00 (n=0)	**0.71**(n=3)	0.24 (n=3)	0.26 (n=6)
Tumble-dryer	Heating cycle	0.00 (n=0)	35.94 (n=5)	**139.67** (n=5)	77.21 (n=10)
	Tumble cycle	0.00 (n=0)	1.02 (n=5)	**10.55** (n=5)	5.04 (n=10)
	Passive Standby	0.00 (n=0)	0.00 (n=5)	**0.07** (n=5)	0.04 (n=10)

7.2.8 Variations in annual electricity consumption on building and outdoors maintenance appliances

The average annual electricity consumptions on building and outdoors maintenance appliances between electrical demand groups are presented in Table 7-8. In general, it was observed that the annual electricity consumptions on appliance types in this category were very small and commonly had no electricity use at all. Households in the high electrical demand group were found to have higher annual electricity consumptions on vacuum cleaners (16.26 kWhpa), automatic door openers (2.06 kWhpa), indoor aquariums (55.60 kWhpa) and outdoor aquariums (83.41 kWha) all in the active power mode. These four appliance types operating in active mode can therefore be recognised as contributing to high electricity consumption.

Dwellings in the low demand group had greater annual electricity consumptions on door bells and pest alarms in the active power mode, whereas households in the medium demand group had more electricity use on security systems (alarm), plug in air fresheners and battery chargers.

Table 7-8 Mean annual electricity consumptions on building and outdoors maintenance appliances by power mode and electrical demand group

Appliance type	Power mode	Mean annual electricity consumption (kWh) in the electrical demand group			
		Low (n=5)	**Medium (n=10)**	**High (n=12)**	**All (n=27)**
Vacuum cleaner	Active	7.57 (n=8)	15.68 (n=12)	**16.26** (n=14)	11.87 (n=34)
	Off Standby	0.00 (n=8)	0.00 (n=12)	0.00 (n=14)	0.00 (n=34)
Security systems (Alarm)	Active	0.00 (n=0)	**4.35** (n=1)	2.55 (n=2)	2.58 (n=3)
Plug in air freshener	Active	0.00 (n=0)	**0.02** (n=2)	0.00 (n=0)	0.02 (n=2)
	Off Standby	0.00 (n=0)	0.00 (n=2)	0.00 (n=0)	0.00 (n=2)
Door bell	Active	**1.43** (n=1)	0.00 (n=0)	0.71 (n=1)	0.58 (n=2)
Utility meters	Active	0.00 (n=0)	0.00 (n=1)	0.00 (n=0)	0.69 (n=1)
Automatic door opener	Active	0.00 (n=0)	0.00 (n=0)	**2.06** (n=1)	0.92 (n=1)
Saw	Active	0.00 (n=0)	0.00 (n=1)	0.00 (n=1)	0.00 (n=2)
	Off Standby	0.00 (n=0)	0.00 (n=1)	0.00 (n=1)	0.00 (n=2)
Sander	Active	0.00 (n=0)	0.00 (n=0)	0.00 (n=1)	0.00 (n=1)
Sewing machine	Active	0.00 (n=1)	0.00 (n=0)	0.00 (n=0)	0.00 (n=1)
Electric lawn mowers	Active	0.00 (n=1)	0.00 (n=8)	0.00 (n=7)	0.00 (n=15)
	Off Standby	0.00 (n=1)	0.00 (n=8)	0.00 (n=7)	0.00 (n=15)
Indoor aquarium	Active	0.00 (n=0)	4.55 (n=1)	**55.60** (n=3)	33.42 (n=4)
	Off Standby	0.00 (n=0)	0.00 (n=1)	0.00 (n=3)	0.00 (n=4)

Appliance type	Power mode	Mean annual electricity consumption (kWh) in the electrical demand group			
		Low (n=5)	Medium (n=10)	High (n=12)	All (n=27)
Outdoor aquarium	Active	0.00 (n=0)	51.91 (n=1)	**83.41** (n=1)	56.39 (n=2)
	Off Standby	0.00 (n=0)	0.00 (n=1)	0.00 (n=1)	0.00 (n=2)
Battery chargers	Active	0.00 (n=0)	**6.99** (n=2)	0.05 (n=1)	5.93 (n=3)
	Off Standby	0.00 (n=0)	0.00 (n=2)	0.00 (n=1)	0.00 (n=3)
Pest alarms	Active	**3.54** (n=1)	0.00 (n=0)	1.60 (n=1)	1.37 (n=2)

7.2.9 Variations in annual electricity consumption on hygiene, beauty and leisure appliances

Table 7-9 displays the differences in average annual electricity consumption observed for hygiene, beauty and leisure appliances between electrical demand groups. It was found that households in the high electrical energy demand group consumed a larger amount of electricity on hair dryers (28.24 kWhpa) and hair straighteners (1.97 kWhpa) than low and medium electricity consumers in the active power mode. In addition, high consumers had a greater annual electricity use on massagers in passive standby mode (7.84 kWhpa). In the hygiene, beauty and leisure category these appliances can consequently be attributed to high electrical energy demand.

With the exception of electric toothbrushes, medical equipment and shavers which had higher annual consumptions by households in either the low or medium electrical demand groups, all other appliances in this category were observed to have no electricity use by all demand groups.

Table 7-9 Mean annual electricity consumptions on hygiene, beauty and leisure appliances by power mode and electrical demand group

Appliance type	Power mode	Mean annual electricity consumption (kWh) in the electrical demand group			
		Low (n=5)	Medium (n=10)	High (n=12)	All (n=27)
Electric shower	Active	0.00 (n=4)	0.00 (n=5)	0.00 (n=8)	0.00 (n=17)
Hair dryer	Active	2.07 (n=3)	5.40 (n=5)	**28.24** (n=8)	16.02 (n=16)
	Off Standby	0.00 (n=3)	0.00 (n=5)	0.00 (n=8)	0.00 (n=16)
Hair straighteners	Active	0.45 (n=1)	0.23 (n=3)	**1.97** (n=3)	0.76 (n=7)
	Off standby	0.00 (n=1)	0.00 (n=3)	0.00 (n=3)	0.00 (n=7)
Hot air styler	Active	0.00 (n=0)	0.00 (n=1)	0.00 (n=0)	0.00 (n=1)
	Off Standby	0.00 (n=0)	0.00 (n=1)	0.00 (n=0)	0.00 (n=1)
Hair clippers	Active	0.00 (n=0)	0.00 (n=1)	0.00 (n=0)	0.00 (n=1)
	Off Standby	0.00 (n=0)	0.00 (n=1)	0.00 (n=0)	0.00 (n=1)

Appliance type	Power mode	Mean annual electricity consumption (kWh) in the electrical demand group			
		Low (n=5)	Medium (n=10)	High (n=12)	All (n=27)
Shaver	Active	0.00 (n=0)	**0.18** (n=1)	0.09 (n=1)	0.13 (n=2)
	Off Standby	0.00 (n=0)	0.00 (n=1)	0.00 (n=1)	0.00 (n=2)
Massager	Active	0.00 (n=0)	0.00 (n=0)	0.00 (n=1)	0.00 (n=1)
	Passive Standby	0.00 (n=0)	0.00 (n=0)	**7.84** (n=1)	3.47 (n=1)
	Off Standby	0.00 (n=0)	0.00 (n=0)	0.00 (n=1)	0.00 (n=1)
Toothbrush	Active	**0.09** (n=1)	0.02 (n=1)	0.00 (n=0)	0.02 (n=2)
Medical	Active	**1.45** (n=1)	0.00 (n=0)	0.00 (n=0)	0.27 (n=1)

7.2.10 Summary of variations in annual appliance electricity consumption

Section 7.2 presented the average annual electricity consumptions for domestic appliance types by power mode and electrical demand group. The results indicate the appliance types which are contributing to high electrical energy demand in the study sample. From the results obtained, it could be understood that high electrical energy consumption is an outcome of higher electricity consumption on:

- In the office equipment and infotainment appliance category, desktop computers operating in the active and active/passive standby modes; laptop computers in active, active/passive standby and off standby modes; printers in active and passive standby modes; and wireless routers in active power mode.
- In the non-fixed lighting appliance category, incandescent bulbs operating in active mode.
- In the HVAC appliances category, electric fires, electric blankets, portable halogen radiators and portable oil filled radiators operating in the active mode.
- In the transportation appliances category, mobility scooters, golf trolleys and chair lifts in active power mode.
- In the catering appliances category, microwaves and kettles operating in the active mode, toasters, blenders and coffee makers in the passive standby mode, upright freezers in the non-cooling cycle and beer and wine coolers in the cooling cycle.
- In the washing appliances category, dishwashers operating in the washing and drying cycles and passive standby power modes.

- In the laundry appliances category, all laundry appliances (iron, washing machine, washer-dryer and tumble-dryer) operating in each power mode except passive standby mode for washer-dryers.
- In the building and outdoors maintenance appliances category, vacuum cleaners, automatic door openers and indoor and outdoor aquariums in the active power mode.
- In the hygiene, beauty and leisure appliances category, hair dryers and hair straighteners operating in the active power mode and massagers in the passive standby mode.

Although, the findings provide an indication of the appliance types that contribute to high electrical energy demand, the annual appliance electricity consumption figures presented conceal the underlying factors that contribute to increased electricity consumption. Therefore, in the following sections 7.3 to 7.5, the variations in ownership, power demand and use of domestic appliances between the electrical demand groups are examined. These results will establish the driving factors and consequently the potential targets to reduce electricity consumption from high demand dwellings.

7.3 Variations in ownership of domestic appliances between electrical demand groups

Figures 7-1 to 7-10, indicate the ownership rates of the different appliances monitored amongst the L27 cohort categorised by electrical demand group (See Chapter 4, Section 4.10.4.4). The ownership rate represents, as a percentage, the average household ownership of the appliance types for an electrical demand group. The appliance types are ordered from the highest to the lowest household ownerships based on the average ownership of all demand groups combined.

7.3.1 Variations in the ownership of domestic appliances by appliance category

Figure 7-1 shows that appliances belonging to the office equipment and infotainment category had the highest overall ownership amongst the L27 cohort. On average, 13.1 office equipment and infotainment appliances were found in the households. This average ownership varied between the electrical demand groups, 10.4 for low demand, 13.3 for medium demand, and 14.1 for high demand dwellings, which represented the largest disparity in ownership of any of the appliance categories.

Appliances used for catering were the second highest owned in the study. It was established that on average 6.5 cooking appliances were owned by the households. Again, the mean ownership was different for each consumer group, with high electricity users owning more (7.0) than low (6.3) and medium users (5.6).

The subsequent four appliance categories (building and outdoors maintenance, laundry, non-fixed lighting, and hygiene, beauty, and leisure) all had a similar overall average ownership total (around 2 appliances per home). With the exception of the lower ownership of non-fixed lighting appliances observed for the high demand group, all other electrical demand groups had a similar level of ownership in each appliance category.

The HVAC, transportation, and washing categories were characterised by an average appliance ownership of around 0.3 per home. In general, each electrical demand group owned a similar number of appliances in each category. However, the most obvious difference in ownership related to the washing category, it was revealed that none of the medium demand dwellings owned a dishwasher and consequently the results show that this group had an ownership rate of zero for washing appliances.

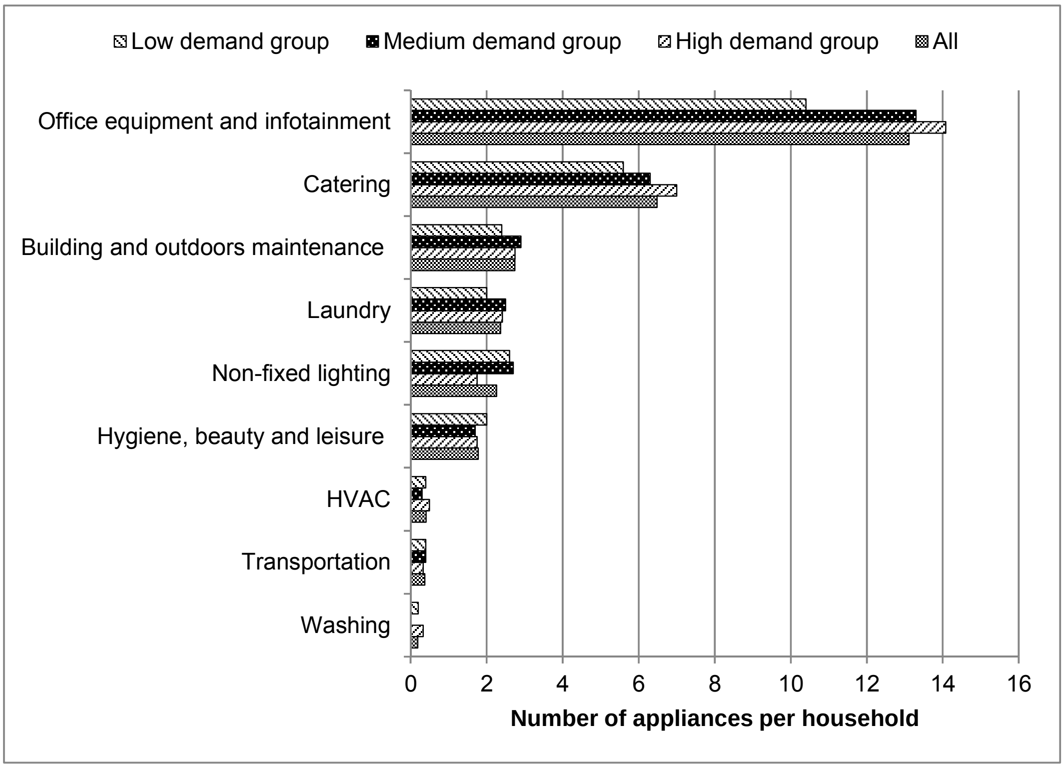


Figure 7-1 Appliance ownership rates by appliance category

By analysing the variations in appliance ownership in each appliance category, a high level indication of the types and quantities of appliances which are owned by households in the different electrical demand groups was identified. The most evident variations between the electrical demand groups related to the ownership of appliances in the office equipment and infotainment, catering, and washing categories.

In order to link appliance ownership to electricity consumption, appliance ownership at a more refined level needed to be investigated, for the reason that the broad appliance categories contain a range of appliances types all with different power demands. The appliance types owned and their power demands may vary between electrical demand groups, therefore, it was important to observe the ownership levels on an individual appliance type basis.

7.3.2 Variations in the ownership of office equipment and infotainment appliances

The ownership rates of appliances in the office equipment and infotainment category are shown in Figure 7-2. LCD televisions had the highest overall ownership rate (148%). CRT televisions were the only other type of television owned by participants in this study; however, the ownership rate was much lower at 56%. The ownership rates of LCD and CRT televisions varied between electrical demand groups. For LCD televisions the high electrical demand dwellings possessed more (192%) than medium (160%) and low demand dwellings (20%). Conversely, CRT televisions were primarily owned by low consumers (100%), compared with 60% for medium and 33% for high consumers. While all of the homes in the study possessed at least one TV, it was found that only 20% of the low demand homes owned more than one TV, compared with 80% of medium and 58.3% of high demand homes.

Telephones were widely owned by homes in all electrical demand groups. On average, 1.22 telephones were found in L27 cohort homes. Whilst there was little variation in the ownership of standard telephones between the groups, telephones with answering machines were only found in low consuming dwellings (40%).

Video consoles had a high overall ownership rate (81%). Medium consumers owned on average 0.8 and high consumers 1.17 video consoles per dwelling, however low consumers did not own any.

In relation to computer appliances, laptops had a slightly higher overall ownership rate than desktop computers (74% compared with 70%). It was found that the ownership rates of desktop and laptop computers were quite similar for both medium and high demand households. However, for the low demand group there was a large variation in ownership, as low consumers tended to own laptop (60%) rather than desktop (20%)

computers. By merging the ownerships of laptop and desktop computers it can be seen that households in the high demand group owned more computer appliances (1.75 computers per home) than those in the low (0.8) and medium demand groups (1.4). Additionally, it was found that 60% of low consuming households owned at least one computer, compared with 80% for medium consumers, whereas all high consuming homes owned a computer.

Three types of networking device were found in the L27 households. The majority of households had a wireless router (67%), followed by DSL (7%) and Ethernet hub (4%). The variation in ownership of networking devices between electrical demand groups, possibly related to the fact that low demand households owned fewer computer appliances. The DSL networking devices were owned by medium and high consumers only and the sole Ethernet hub belonged to a medium demand dwelling.

With regard to audio devices, stereo systems were the most commonly owned appliance type with an overall ownership rate of 63%. The ownership rates of this device were similar for all electrical demand groups. The next three highest ownership rates of audio devices were different types of radio, firstly, clock radios were owned by an average of 44% of the households, whereas portable analogue and portable digital radios were both possessed by 37%. Medium demand households had a higher ownership rate of clock radios (60%), than low (40%) and high demand (33%). Dwellings in the low demand group however had more analogue (80%) and digital (60%) radios than medium (30% and 50%) and high demand dwellings (25% and 17%).

The remaining audio devices had overall ownership rates of between 11% and 4%, which included MP3 docking stations, speakers, keyboards/organs, home music studios, guitar/keyboard amplifiers, personal CD players, home theatre systems and turntables. Only MP3 docking stations were owned by homes in all electrical demand groups.

In the video and recording appliance subcategory, it was found that electrical demand groups owned almost an equal number of devices per home (1 for low, 1.2 for medium and 1.08 for high), however, the ownership rates of specific appliance types varied. DVD players had the highest average ownership for all homes (56%). VCR players were the second most commonly owned device (33%). The low and high consumers had more VCR players (40% and 42%) than medium consumers (20%). The ownership of Blu-ray players was low (11%); none of the low consuming households owned a Blu-ray player, and the ownership was only 20% for medium and 8% for high demand dwellings. It was found that only households in the medium demand group possessed portable DVD players (20%) while combination DVD with VCR players were owned solely by high demand dwellings (8%).

To receive satellite, cable, digital or internet broadcasting services a range of set top boxes (STBs) were owned by the L27 homes. Digital STBs had the highest overall ownership rate (56%). The ownership rate of this device type was different for each electrical demand group, high consumers had the greatest number (75%) compared with 60% for low, and 30% for medium consumers. Conversely, households in the high demand group owned the least satellite STBs (30%) and were instead primarily possessed by low (60%) and medium (40%) users. Cable STBs had a much lower total ownership (19%) and were owned by households in the medium and high demand groups only. A single household in the high demand group owned an internet STB, contributing to an overall ownership rate of just 4%.

The average ownership rate of printers was 44%. Whilst households in the high and medium demand groups had an identical ownership rate of 50%, the low consuming households owned fewer printers (20%).

In the office accessories appliance subcategory, two appliances were found in the L27 households. Firstly, shredders had an average ownership rate of 33%, which was similar amongst all electrical demand groups. Laminators were owned by medium consumers only and had a low overall ownership rate of 4%.

A number of other appliances types with overall ownership rates of less than 11% were identified in medium and high consuming households only. Both video amplifiers and ebook readers were owned by medium and high consumers and portable hard-drives by high consumers only.

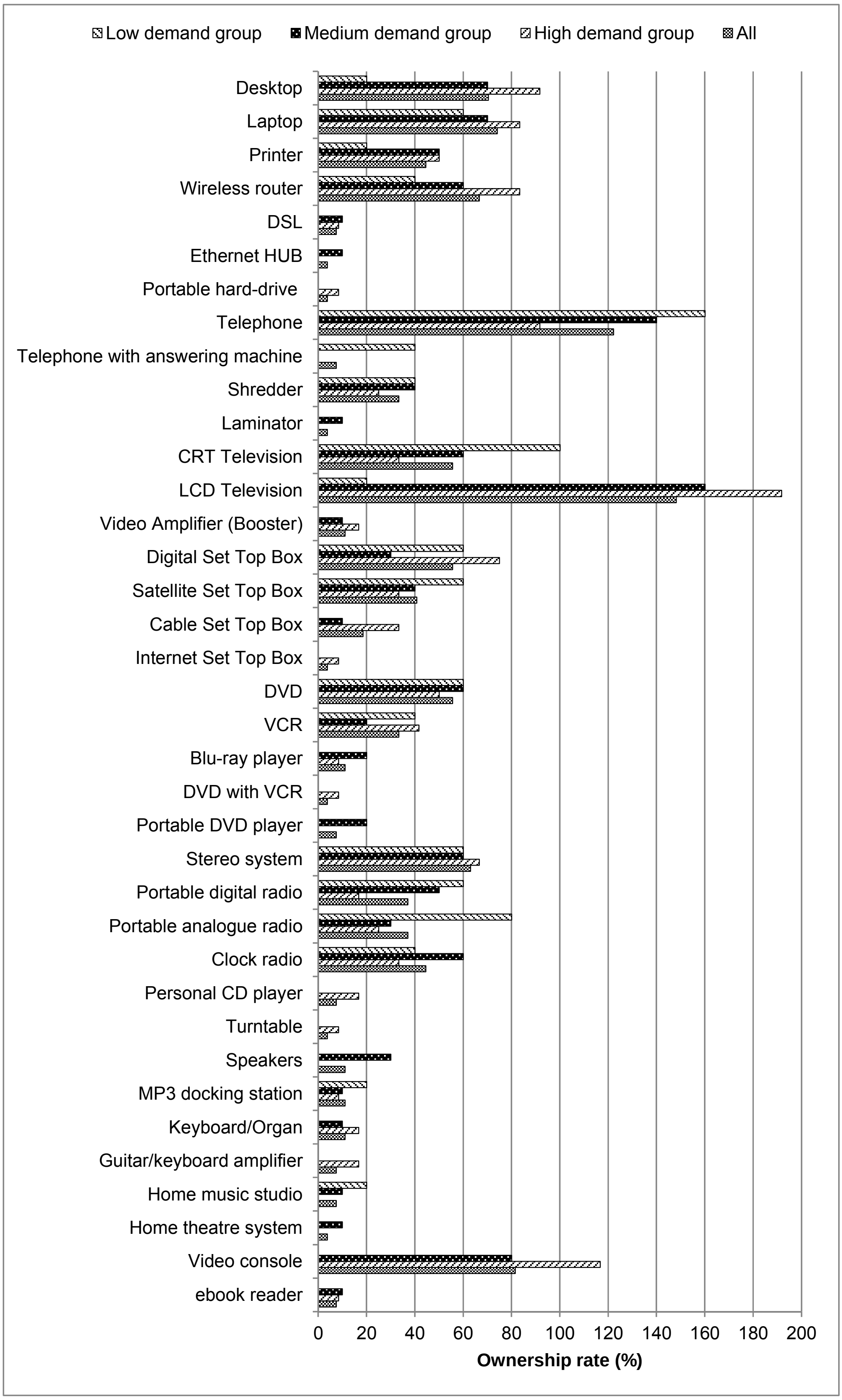


Figure 7-2 Appliance ownership rates in the office equipment and infotainment category

7.3.3 Variations in the ownership of non-fixed lighting appliances

Figure 7-3 shows that in the non-fixed lighting category the most commonly owned devices were incandescent table lamps (89%). CFL table lamps had the second highest overall ownership rate (74%). Low electrical energy users owned less table lamps with incandescent bulbs (40%) than medium (110%) and high consumers (92%), but alternatively had the highest ownership of table lamps with CFL bulbs (140%). The low demand group was also found to have the highest ownership rate of floor lamps with CFL bulbs (60%), which was much greater than medium (10%) and high demand groups (8%). The ownership of incandescent floor lamps was quite similar for all electrical demand groups, combined an ownership rate of 11% was identified. The remaining non-fixed lighting had low ownership rates of between 7% and 4%.

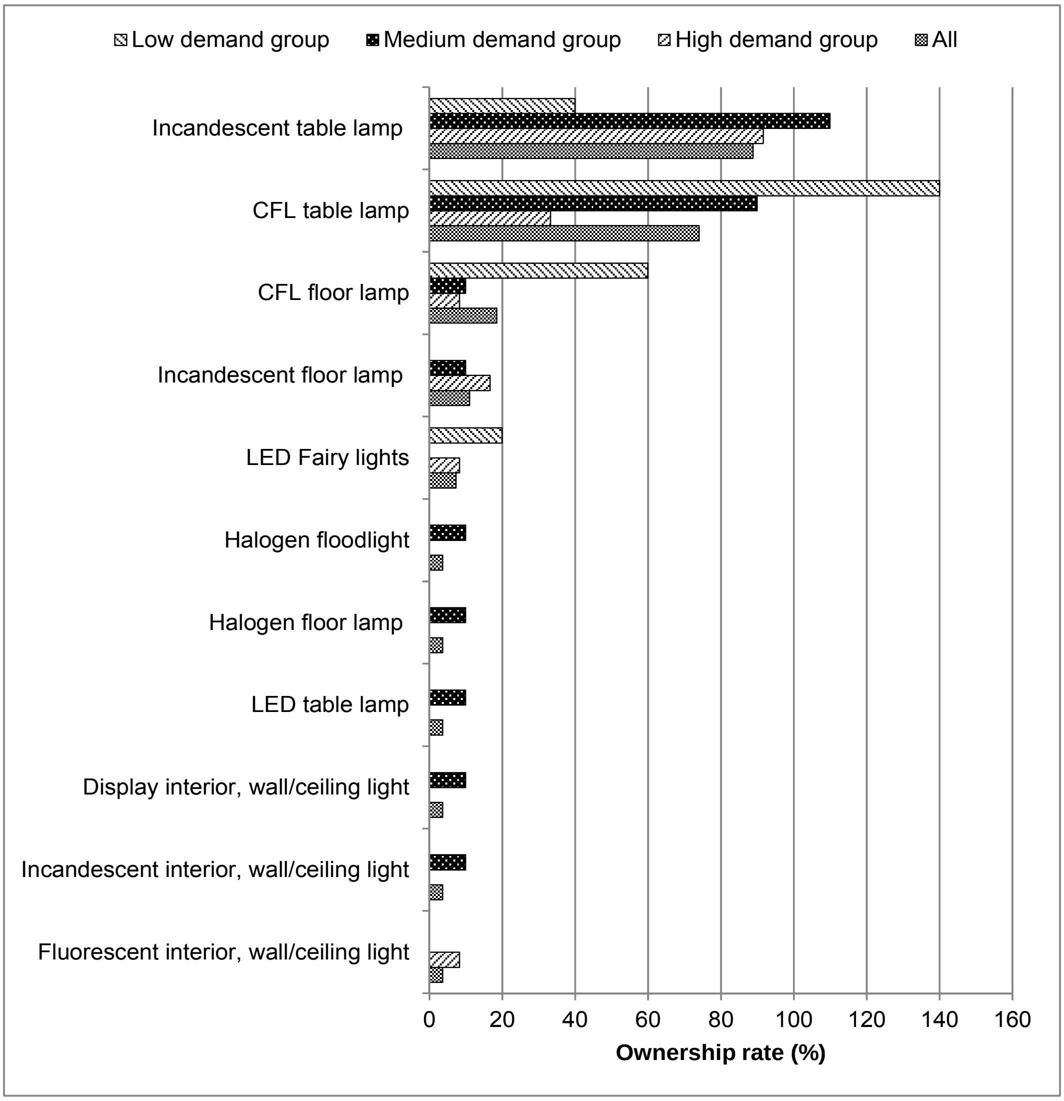


Figure 7-3 Appliance ownership rates in the non-fixed lighting category

7.3.4 Variations in the ownership of HVAC appliances

Figure 7-4 shows that desk fans were the most common HVAC appliance owned by L27 households. The overall ownership rate of desk fans was 22%. All electrical demand groups owned desk fans but the ownership rate decreased with electricity use. Desk fans were only owned by one household in each electrical demand group. The remaining appliances which are all forms of secondary space heating were owned by high electricity consuming households only. Electric fires had the highest overall ownership rate at 7%, followed by electric blankets, halogen radiators, and oil filled radiators at 4%.

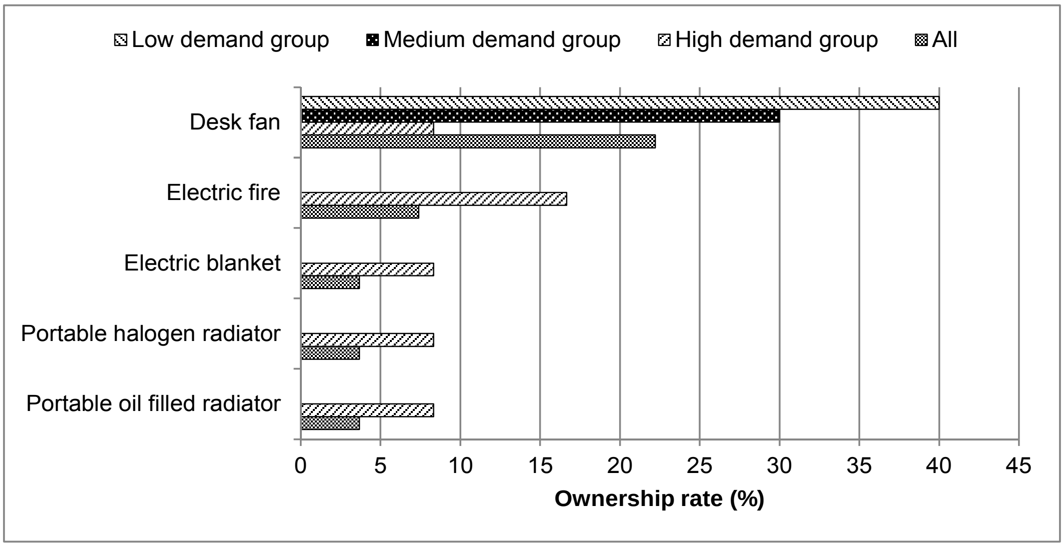


Figure 7-4 Appliance ownership rates in the HVAC category

7.3.5 Variations in the ownership of transportation appliances

Figure 7-5 indicates the ownership rates of the transportation appliances found in L27 homes. Reclining furniture had the highest overall ownership rate (15%), but was located in medium consuming households only. The second highest overall ownership identified was for mobility scooters (11%), which were owned by low and high demand dwellings only. The remaining devices had an overall ownership rate of 4%. The bath lift was located in a single low consuming dwelling and the golf trolley and chair lift in two high consuming dwellings (one device per household).

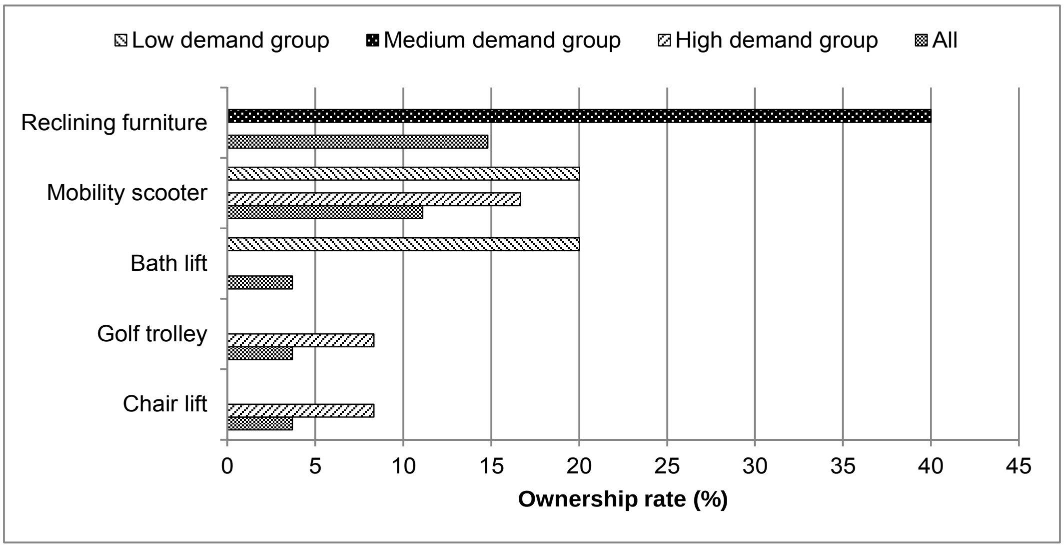


Figure 7-5 Appliance ownership rates in the transportation category

7.3.6 Variations in the ownership of catering appliances

The ownership rates of catering appliances are shown in Figure 7-6. It was found that kettles had the highest overall ownership rate (93%), which was relatively consistent for all electrical demand groups.

Toasters and Microwaves were the next most commonly owned devices with an average ownership rate of 85%. Whilst the ownership rate of toasters was similar for all demand groups (80%-92%), households in the high demand group had more microwaves (108%) than the low (60%) and medium consumers (70%).

Preservation and cooling appliances were amongst the most frequently owned in the catering appliance category. With the exception of beer and wine coolers (7%), the overall ownership rates of preservation and cooling appliances were fairly similar; refrigerator (48%); fridge-freezer (48%); upright freezer (41%); and chest freezer (37%). In relation to variations in ownership rates between electrical demand groups, it was identified that high electrical consumers owned less refrigerators (33%) than the low and medium consumers (both 60%). Households in the low demand group also owned more fridge-freezers (60%) than those in the medium (50%) and high groups (42%). It was discovered that all electrical demand groups had an almost identical ownership of upright freezers (40%-42%). The ownership of chest freezers was found to be restricted to medium and high consuming dwellings only; however, the rate of ownership was much higher amongst the medium consumers (70%) than the high consumers (25%). Beer and wine coolers were owned by medium and high consumers only.

By combining the ownerships rates of each of the preservation and cooling appliances it was found that households in the medium demand group owned more preservation and cooling appliances (2.3 per home) than those in the low (1.6) and high demand groups (1.5). On average, 1.81 preservation and cooling appliances were owned by households in the study.

The presence of electric cooking (oven and hob) was relatively high amongst the L27 households compared to other catering appliances. Overall, 44% of the dwellings had an electric oven and 19% an electric hob. The remaining households in the study used gas for cooking. The ownership rates of electric cooking appliances varied greatly between the demand groups; it was found that the low consumers did not own any electric cooking appliances, whereas high consumers owned 1 appliance per home and medium consumers 0.5 appliances per home. The ownership rates of electric ovens and electric hobs were 67% and 33% in high consuming homes compared to 40% and 10% in medium consuming homes.

All the remaining appliances can be characterised as minor cooking devices. Amongst these appliances, blenders were the only type of device that was owned by households in all electrical demand groups, the overall ownership rate was 22%, but this rate was higher for high demand dwellings (33%) and less for low (20%) and medium demand dwellings (10%). The further fourteen minor cooking appliances had overall ownership rates of less than 15%. Low consumers possessed only two of these further appliances (juicer and popcorn maker) and neither of these were owned by medium or high consumers. It was found that grill plates and coffee grinders were exclusively owned by households in the medium demand group, whereas, small ovens, food mixers, food processors, electric knifes and ice makers were owned by high consumers only.

Five of the minor cooking appliances were owned by both medium and high consuming homes, although their ownership rates varied between the groups. More deep fryers, can openers, coffee makers and steamers were possessed by medium consuming homes (30%, 20%, 10% and 10%) than high consuming homes (8%, 17%, 8% and 8%), although the opposite was the case for slow cookers where the ownership rate for high consumers was 17% compared to 10% for medium consumers.

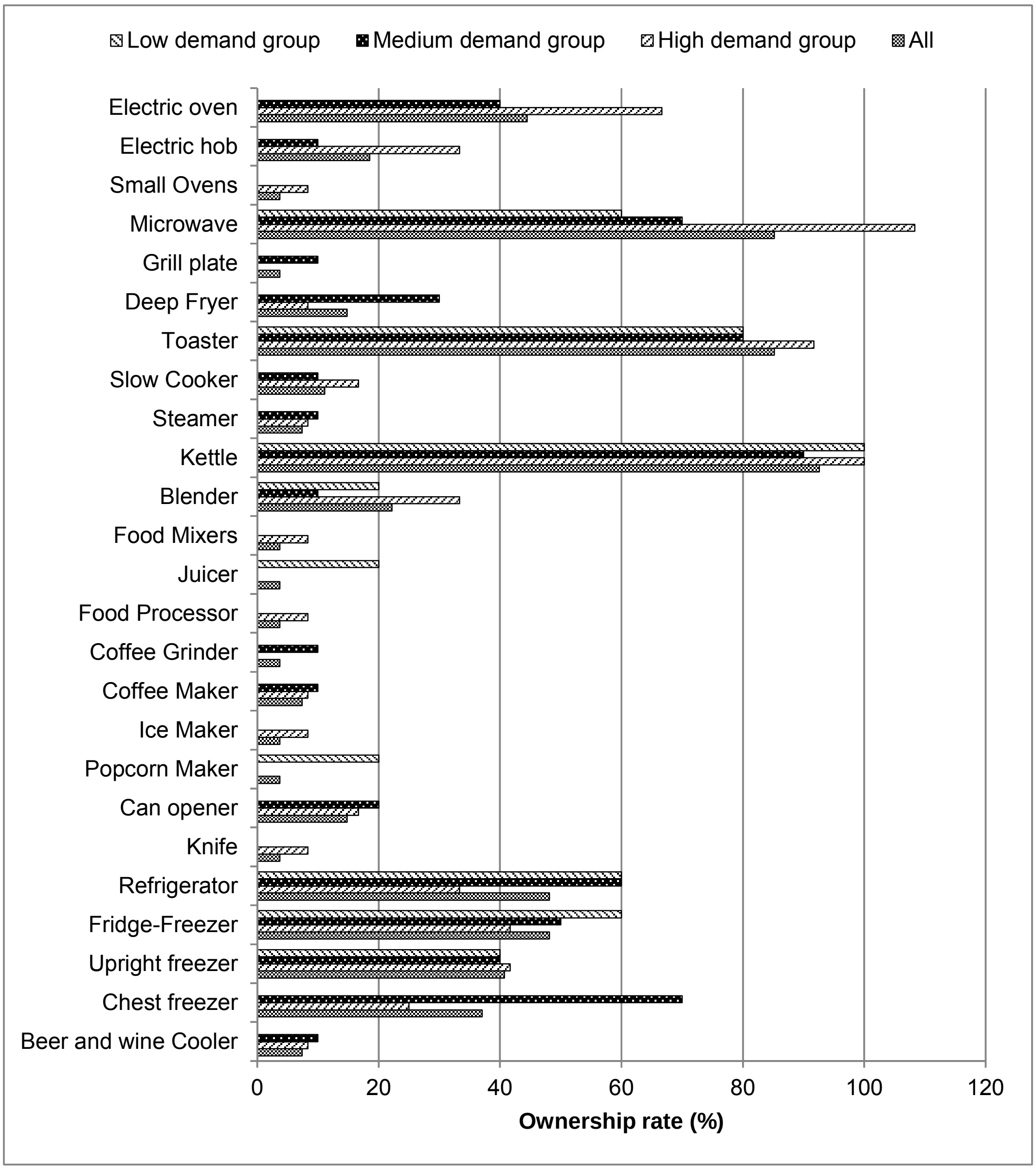


Figure 7-6 Appliance ownership rates in the catering category

7.3.7 Variations in the ownership of washing appliances

Figure 7-7 shows a low ownership rate of dishwashers across the whole L27 cohort (19%). In the sample studied, only households in the low and high demand groups owned dishwashers, with the high consumers owning more (33%) than low consumers (20%).

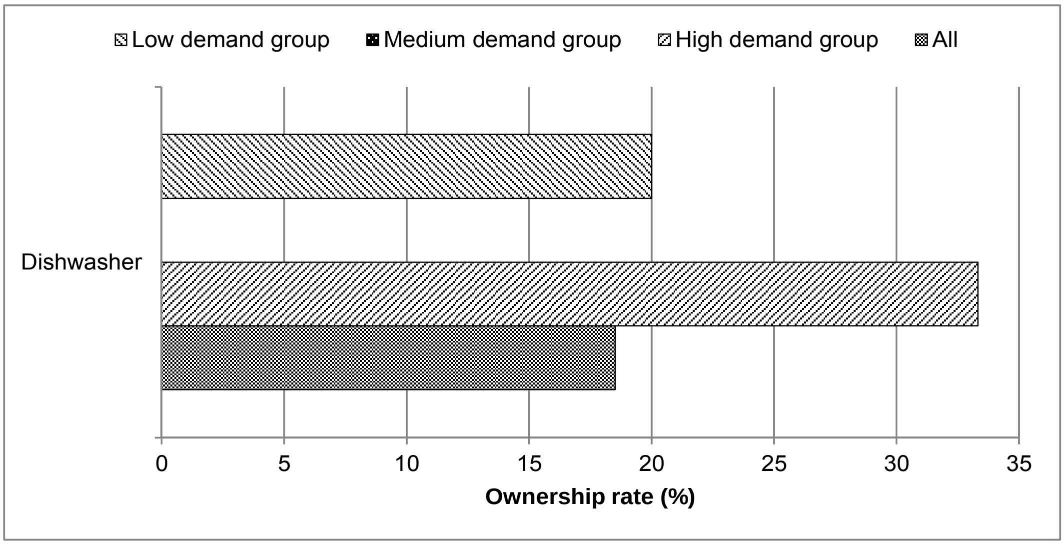


Figure 7-7 Appliance ownership rates in the washing category

7.3.8 Variations in the ownership of laundry appliances

Figure 7-8 shows that irons were the most commonly owned laundry appliance. All electrical demand groups had an ownership rate of 100% for irons (one iron per home). The combined ownership rates of clothes washing appliances (i.e. washing machine and washer-dryer) was identical for all electrical demand groups (100%); however the type of clothes washing appliance owned varied between groups. The households in the low demand group possessed only washing machines, whereas medium and high demand dwellings owned a combination of washing machines and washer-dryers. Overall, 78% of the dwellings owned a washing machine, and the remaining 22% a washer-dryer. Furthermore, 50% of the medium, and 42% of the high demand groups owned a separate tumble-dryer. Households in the low demand group did not own any electrical clothes drying appliances (i.e. tumble-dryer and washer-dryer), whereas 80% of the medium and 67% of the high demand households did. For all dwellings, the ownership rate of tumble-dryers was 37%.

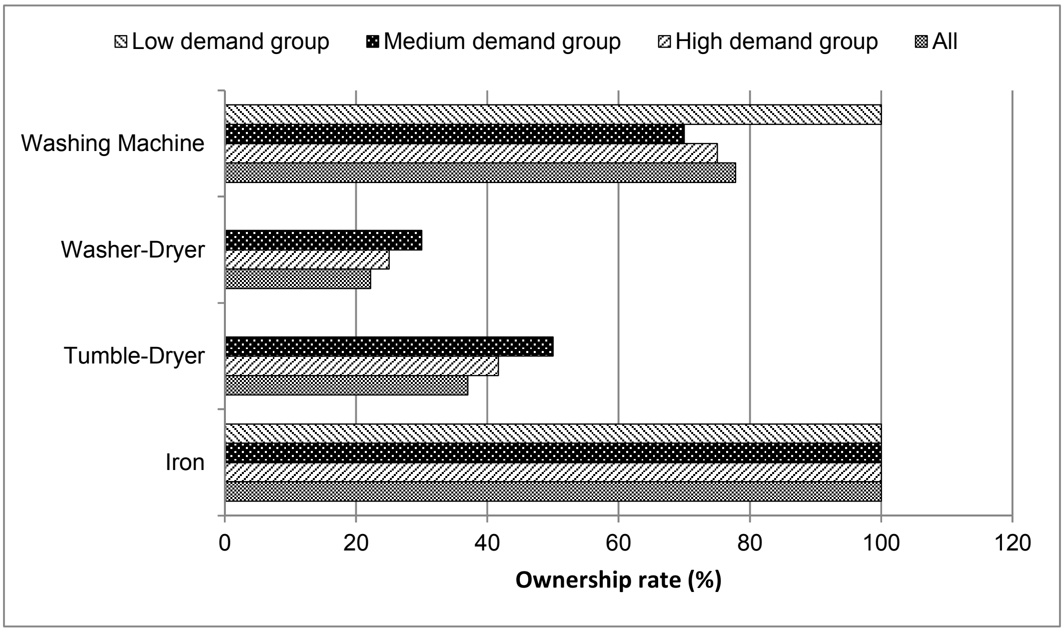


Figure 7-8 Appliance ownership rates in the laundry category

7.3.9 Variations in the ownership of building and outdoors maintenance appliances

Figure 7-9 shows that in the building and outdoors maintenance category, vacuum cleaners had the overall highest ownership rate (126%). The ownership of vacuum cleaners was greater amongst low electricity consumers than medium and high consumers. The second most commonly owned appliance was an electric lawn mower with an ownership rate of 59%. The ownership rate of this device varied significantly between the electrical demand groups from only 20% in the low consuming households, up to 80% in the medium consuming households.

All other building and outdoors maintenance appliance types found in the L27 dwellings had overall ownership rates of 15% or less. The largest difference in ownership rates for the remaining devices related to indoor aquariums; it was found that 25% of the high consuming dwellings owned this device compared with 10% of the medium consuming dwellings. None of the low demand dwellings owned an indoor aquarium.

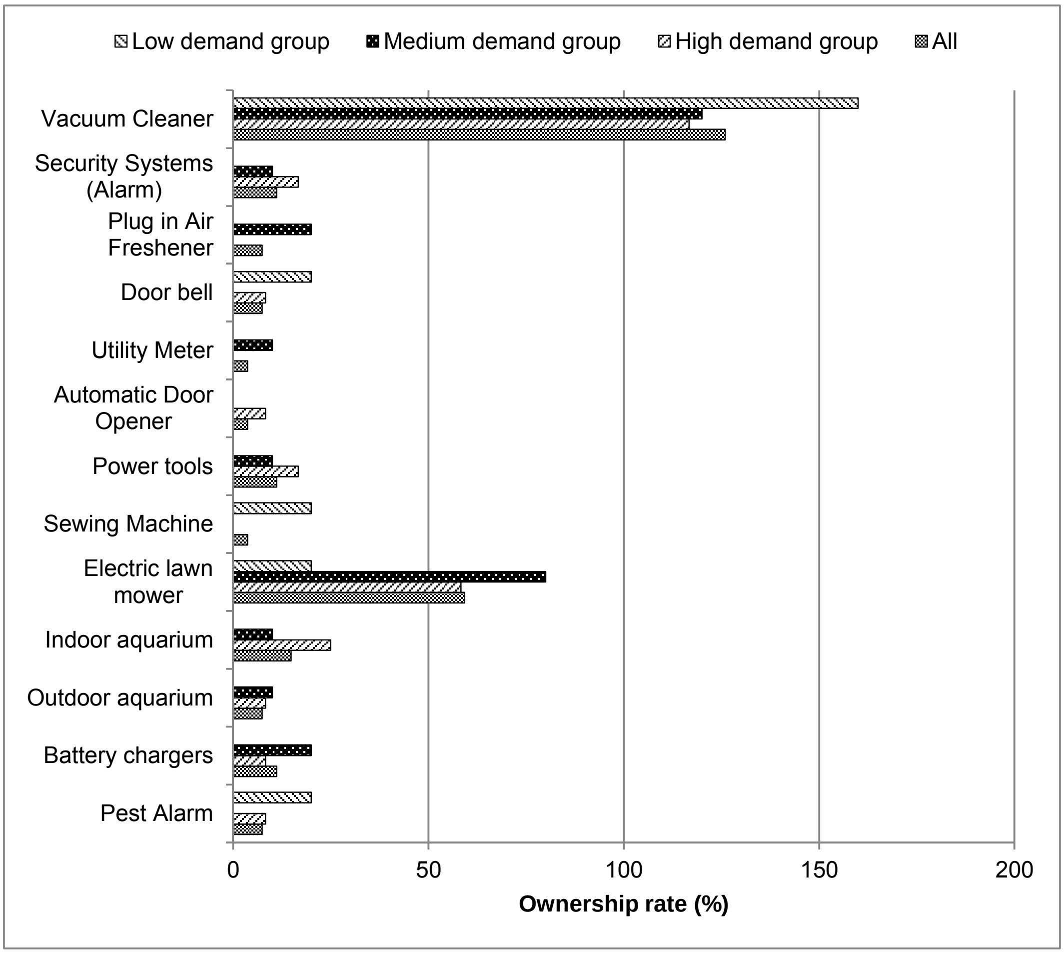


Figure 7-9 Appliance ownership rates in the building and outdoors maintenance category

7.3.10 Variations in the ownership of hygiene, beauty and leisure appliances

Figure 7-10 shows that electric showers were the most widespread hygiene, beauty and leisure appliance owned by the study's households, with an overall ownership rate of 63%. Households in the low demand group had a very high ownership rate of electric showers at 80%, compared with 67% for the high, and 50% for the medium consumers. Hair dryers were the second most commonly owned device, high consumers owned the most (67%), followed by the low (60%) and then medium consumers (50%). For all electrical demand groups, an ownership of between 20% and 30% was recorded for hair straighteners. The remaining appliances in the category had a relatively low overall ownership rate at either 7% or 4%. None of these appliances were owned by households in all electrical demand groups.

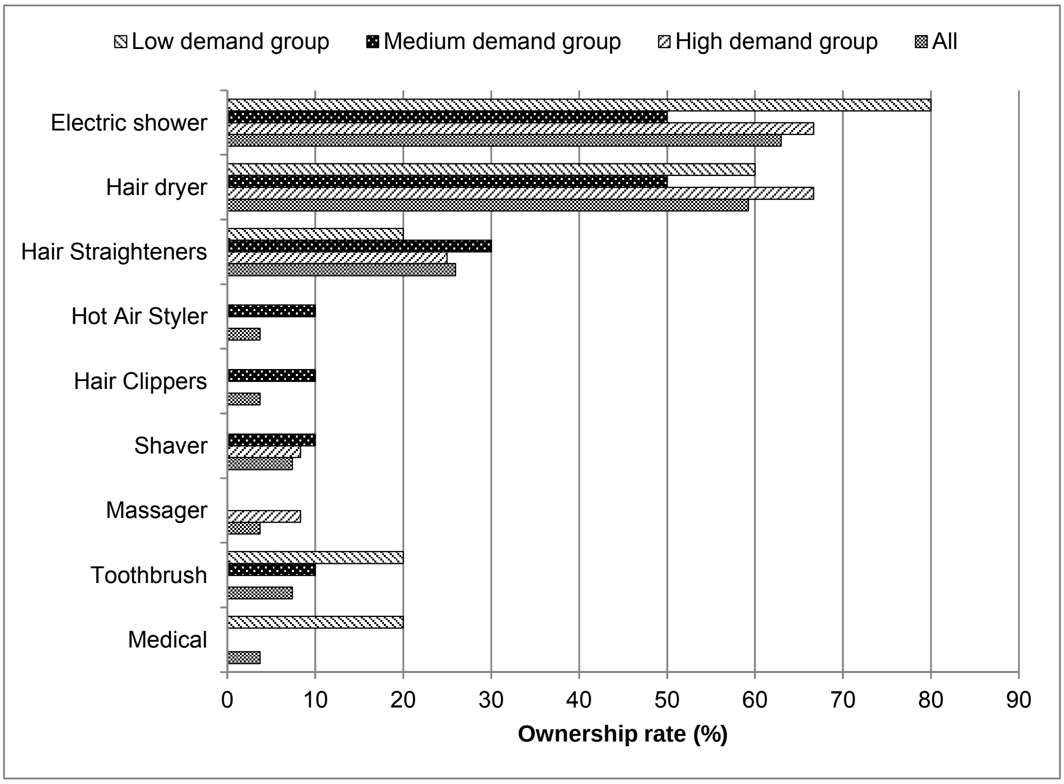


Figure 7-10 Appliance ownership rates in the hygiene, beauty and leisure category

7.3.11 Summary of variations in ownership of domestic appliances

Section 7.3 has indicated the ownership rates of appliance types for each electrical demand group. In relation to the appliance categories, high electricity consumers were found to have a higher ownership rate of appliances in the office equipment and infotainment, catering, HVAC and washing categories (Figure 7-1). By investigating further the variations in appliance ownership rates within each appliance category, it was found that with the exception of the laundry category, high electricity consumers had a higher ownership rate of some appliance types in all remaining categories. Table 7-10 provides a summary of the appliance types that households in the high electrical demand group had a higher ownership rate than low and medium demand groups.

Table 7-10 Summary of appliances types that high electrical energy demand households have a higher ownership rate than low and medium electricity consumers

Appliance category	Appliance types with a higher ownership rate by high electrical energy demand households	
Office equipment and infotainment	• LCD Television • Video console • Laptop • Desktop • Wireless router • Stereo system • Digital Set Top Box • VCR	• Cable Set Top Box • Keyboard/Organ • Video Amplifier (Booster) • Personal CD player • Turntable • DVD with VCR • Internet Set Top Box • Portable hard-drive
Non-fixed lighting	• Incandescent floor lamp	• Fluorescent interior, wall/ceiling light
HVAC	• Electric fire • Electric blanket	• Portable halogen radiator • Portable oil filled radiator
Transportation	• Golf trolley	• Chair lift
Catering	• Toaster • Microwave • Electric oven • Upright freezer • Blender	• Electric hob • Ice Maker • Knife • Food Processor • Food Mixers • Small Ovens
Washing	• Dishwasher	
Laundry	None	
Building and outdoors maintenance	• Indoor aquarium • Security Systems (Alarm)	• Power tools • Automatic Door Opener
Hygiene, beauty and leisure	• Hair dryer	• Massager

7.4 Variations in power demands of domestic appliances between electrical demand groups

This section presents results for the average power demands of appliances types in different power modes for each of the electrical demand groups. These results are appliance averages and are derived by dividing the sum of each appliance's average power demand in a specific power mode by the number of appliances monitored for each electrical demand group (See Chapter 4, Section 4.10.4.5).

The results presented demonstrate the variations in power characteristics of appliances by power mode and electrical demand group (Tables 7-11 to 7-19). The lowest average power demand shown is 0.01 Watts, therefore when 0.00 Watts is displayed; the power demand should be interpreted as less than 0.01 Watts, not that there is no power demand. Values in **bold** indicate the greatest average power demands observed for an appliance power mode. An asterisk (*) indicates that the value is based on only one monitored appliance.

7.4.1 Variations in power demands of office equipment and infotainment appliances

Table 7-11 shows average power demands for office equipment and infotainment appliances.

In the IT appliance subcategory it was observed that for computers, desktops had a higher overall power demand than laptops in both active and active/passive standby modes. Despite representing less than 1 Watt, the power demand in off standby mode was higher for laptops than desktops, which perhaps relates to the power required for the LED commonly found on a laptop charger. In general, for desktop and laptop computers the power required in each mode was similar regardless of electrical demand group. The power demand of desktop computers in active mode did slightly increase with electrical demand group and the laptops owned by medium electricity consumers had the highest power demand in the active mode.

Printers owned by high electrical energy consumers were found to have a larger power load in active mode than the low and medium consumers, despite the loads in the active standby and passive standby modes being similar for all the groups.

In relation to the three networking devices measured, it was established that wireless routers required a greater overall power demand than DSLs and Ethernet HUBs. In addition, the wireless routers owned by high demand dwellings had the highest average active power demand.

Irrespective of electrical demand group the power loads of telephones were similar, all requiring less than 3 Watts in the active mode. The power requirements of telephones with an answering machine was greater (7.34 Watts), however ownership was confined to low electrical demand households only.

In the office accessories appliance subcategory, power load measurements were obtained for shredders owned by medium and high users only. None of the shredders owned by low consumers were used during the AEUS and therefore no indication of power demand was obtained. The active power loads of shredders belonging to high consumers were greater than medium consumers. No power load data was collected for laminators as they were owned solely by medium demand dwellings and again were unused.

In the entertainment appliance subcategory, it was recognised that on average LCD televisions had a higher power demand in each mode than CRT televisions, which is perhaps related to larger screen sizes. The LCD television owned by the low demand group had a much lower active power load than those of the medium and high groups. Conversely, for CRT televisions, the highest active power loads belonged to devices owned by the low consumers. For both television types, the average passive standby and off standby modes did not vary with electrical demand group.

In relation to STBs, basic digital STBs were found to have the lowest average active power load. The highest active load was for cable STBs, followed by internet, and satellite STBs. It is evident that as a proportion of the power required in the active mode, the power load of the active standby mode was large for STBs. The digital and satellite models were the only types of STB which comparable power load data was available for all electrical demand groups. There was little variation in the active power loads of digital and satellite STBs between the electrical demand groups; however the active standby loads were much higher for the high demand group on both STB models. Cable STBs owned by high consumers had a higher active power load than those of medium consumers of almost exactly 10 Watts.

Power loads for five types of video and recording appliances were collected during the study. It was found that DVD with VCR players had the highest overall active power load of the devices monitored, followed by portable DVD, Blu-ray, DVD, and finally VCR players. From the five types of video and recording devices monitored, comparable load data for all demand groups was obtained for the DVD and VCR players only. It was observed that the average active and active standby loads of DVDs owned by low consumers was much lower than those in the other two groups, whilst the passive standby loads were similar for all groups. The power loads of each VCR player mode were almost identical for all of the electrical demand groups.

Three types of radio were measured during the study and the data demonstrated that digital radios had the highest overall power demand in both the active and active standby modes. Clock radios required the least power in the active mode, but whether the device should be classified as a radio appliance is perhaps questionable, given that its primary use is most likely as a clock. On the whole, the loads for each radio power mode did not change in relation with total electricity consumption, with the exception of the active mode of digital radios.

The power loads of MP3 docking stations were found to decrease as total electrical energy use increased. The power demand in the active standby mode was much higher for docking stations owned by the low consumers than either the medium or high consumers.

Power load data for home music studios was collected in low and medium demand dwellings only and from the results obtained it can be seen that in every power mode the required load was higher for the devices owned by the medium consumers.

The video consoles owned by high consuming households had a greater average power load in the active mode of about 10 Watts compared with medium consuming households. The passive standby load was similar for devices owned by both the medium and high demand households.

Table 7-11 Mean appliance power demands in the office equipment and infotainment category by power mode and electrical demand group

Appliance type	Power mode	Mean power demand (W) of appliance types in the electrical demand group			
		Low (n=5)	Medium (n=10)	High (n=12)	All (n=27)
IT					
Desktop	Active	91.89 (n=1)	96.75 (n=7)	**104.11** (n=11)	100.36 (n=18)
	Active/Passive Standby	**14.22** (n=1)	9.49 (n=7)	8.11 (n=11)	8.96 (n=18)
	Off Standby	0.00 (n=1)	**0.48** (n=7)	0.02 (n=11)	0.22 (n=18)
Laptop	Active	29.05 (n=3)	**35.77** (n=7)	32.48 (n=10)	33.43 (n=20)
	Active/Passive Standby	**7.58** (n=3)	3.60 (n=7)	6.86 (n=10)	5.60 (n=20)
	Off Standby	0.16 (n=3)	**0.62** (n=7)	0.46 (n=10)	0.49 (n=20)
Printer	Active	10.22 (n=1)	6.82 (n=5)	**18.35** (n=6)	14.47 (n=12)
	Active Standby	**5.22** (n=1)	3.26 (n=5)	3.48 (n=6)	3.61 (n=12)
	Passive Standby	0.31 (n=1)	0.31 (n=5)	1.10 (n=6)	0.88 (n=12)
Wireless router	Active	6.11 (n=2)	9.30 (n=6)	**11.40** (n=10)	10.34 (n=18)
DSL	Active	-	-	**6.23** (n=1)	6.23 (n=1)
Ethernet HUB	Active	-	**2.67** (n=1)	-	2.67 (n=1)
Portable hard-drive	Active	-	-	**0.24** (n=1)	0.24 (n=1)
Telephony					
Telephone	Active	1.87 (n=8)	**2.41** (n=14)	1.85 (n=11)	2.07 (n=33)
Telephone with answering machine	Active	**7.34** (n=2)	-	-	7.34 (n=2)
Office accessories					
Shredder	Active	49.87 (n=2)	56.38 (n=4)	**69.39** (n=3)	62.88 (n=9)
Laminator	Active	-	-	-	-
Entertainment					
CRT television	Active	**64.51** (n=5)	31.74 (n=6)	51.12 (n=4)	47.83 (n=15)
	Passive Standby	**5.72** (n=5)	2.18 (n=6)	3.77 (n=4)	3.60 (n=15)
	Off Standby	0.00 (n=5)	0.22 (n=6)	**0.34** (n=4)	0.15 (n=15)
LCD television	Active	71.61 (n=1)	100.30 (n=16)	**105.67** (n=18)	102.65 (n=35)
	Passive Standby	**16.35** (n=1)	8.15 (n=16)	12.35 (n=18)	10.86 (n=35)
	Off Standby	0.31 (n=1)	0.15 (n=16)	**0.34** (n=18)	0.26 (n=35)

Appliance type	Power mode	Mean power demand (W) of appliance types in the electrical demand group			
		Low (n=5)	Medium (n=10)	High (n=12)	All (n=27)
Video amplifier (booster)	Active	-	**2.01** (n=1)	1.75 (n=2)	1.84 (n=3)
Digital Set Top Box	Active	10.94 (n=3)	**13.12** (n=3)	12.83 (n=9)	12.48 (n=15)
	Active Standby	3.52 (n=3)	1.84 (n=3)	**8.74** (n=9)	6.31 (n=15)
	Passive Standby	**0.72** (n=3)	-	-	0.72 (n=3)
Satellite Set Top Box	Active	13.88 (n=3)	16.36 (n=4)	**17.47** (n=4)	16.19 (n=11)
	Active Standby	8.67 (n=3)	11.14 (n=4)	**18.69** (n=4)	11.58 (n=11)
	Passive Standby	-	-	-	-
Cable Set Top Box	Active	-	12.78 (n=1)	**22.80** (n=4)	20.80 (n=5)
	Active Standby	-	6.58 (n=1)	**22.53** (n=4)	14.55 (n=5)
	Passive Standby	-	-	-	-
Internet Set Top Box	Active	-	-	**19.00** (n=1)	19.00 (n=1)
	Active Standby	-	-	2.45 (n=1)	2.45 (n=1)
	Passive Standby	-	-	-	-
DVD player	Active	6.72 (n=3)	9.35 (n=6)	**10.62** (n=6)	9.73 (n=15)
	Active Standby	4.76 (n=3)	**10.37** (n=6)	8.25 (n=6)	8.61 (n=15)
	Passive Standby	1.20 (n=3)	1.73 (n=6)	**2.59** (n=6)	1.99 (n=15)
VCR player	Active	8.55 (n=2)	9.15 (n=2)	**9.89** (n=5)	9.31 (n=9)
	Active Standby	-	**8.02** (n=2)	7.84 (n=5)	7.90 (n=7)
	Passive Standby	**3.31** (n=2)	2.89 (n=2)	2.69 (n=5)	2.81(n=9)
Blu-ray player	Active	-	**12.10** (n=2)	-	12.10 (n=2)
	Active Standby	-	**6.56** (n=2)	-	6.56 (n=2)
	Passive Standby	-	**0.25** (n=2)	0.23 (n=1)	0.24 (n=2)
DVD with VCR	Active	-	-	**12.80** (n=1)	12.80 (n=1)
	Active Standby	-	-	**8.55** (n=1)	8.55 (n=1)
	Passive Standby	-	-	**1.75** (n=1)	1.75 (n=1)
Portable DVD player	Active	-	**12.37** (n=1)	-	12.37 (n=1)
	Active Standby	-	**10.23** (n=1)	-	10.23 (n=1)
	Passive Standby	-	**0.43** (n=1)	-	0.43 (n=1)
Stereo system	Active	11.98 (n=3)	15.23 (n=6)	**19.04** (n=8)	16.02 (n=17)
	Active Standby	**14.39** (n=3)	7.94 (n=6)	9.86 (n=8)	9.68 (n=17)
	Passive Standby	2.52 (n=3)	**7.03** (n=6)	2.49 (n=8)	4.31 (n=17)
Digital radio	Active	4.34 (n=3)	7.76 (n=5)	**9.02** (n=2)	7.58 (n=10)
	Active Standby	-	3.80 (n=5)	**4.93** (n=2)	4.08 (n=7)
	Passive Standby	1.43 (n=3)	-	**1.97**(n=2)	1.61 (n=5)
Analogue radio	Active	4.71 (n=4)	**5.49** (n=3)	5.39 (n=3)	5.21 (n=10)
	Active Standby	**5.72** (n=4)	5.28 (n=3)	2.40 (n=3)	3.95 (n=10)
	Passive Standby	**2.17** (n=4)	1.52 (n=3)	2.11 (n=3)	2.01 (n=10)
Clock radio	Active	1.54 (n=2)	**2.42** (n=6)	2.02 (n=4)	2.14 (n=12)

Appliance type	Power mode	Mean power demand (W) of appliance types in the electrical demand group			
		Low (n=5)	Medium (n=10)	High (n=12)	All (n=27)
Personal CD player	Active	-	-	**5.54** (n=2)	5.54 (n=2)
	Active Standby	-	-	**3.30** (n=2)	3.30 (n=2)
	Passive Standby	-	-	**2.96** (n=2)	2.96 (n=2)
Turntable	Active	-	-	-	-
Speakers	Active	-	**3.03** (n=3)	-	3.03 (n=3)
	Active Standby	-	**10.18** (n=3)	-	10.18 (n=3)
	Passive Standby	-	-	-	-
MP3 docking station	Active	**14.98** (n=1)	11.66 (n=1)	8.34 (n=1)	11.66 (n=3)
	Active Standby	**11.51** (n=1)	6.15 (n=1)	6.45 (n=1)	8.04 (n=3)
	Passive Standby	-	-	**3.99** (n=1)	3.99 (n=1)
Keyboard/organ	Active	-	-	-	-
Guitar/keyboard amplifier	Active	-	-	-	-
Home music studio	Active	41.77 (n=1)	**63.06**(n=1)	-	52.42 (n=2)
	Active Standby	26.02 (n=1)	**34.75** (n=1)	-	30.39 (n=2)
	Passive Standby	11.41 (n=1)	**13.71** (n=1)	-	12.56 (n=2)
Home theatre system	Active	-	**40.69** (n=1)	-	40.69 (n=1)
	Active Standby	-	-	-	-
	Passive Standby	-	**2.25** (n=1)	-	2.25 (n=1)
Video console	Active	-	93.21 (n=8)	**104.77** (n=14)	99.95 (n=22)
	Passive Standby	-	1.84 (n=8)	**2.52**(n=14)	2.28 (n=22)
ebook reader	Active	-	10.02 (n=1)	**15.09** (n=1)	12.64 (n=2)

7.4.2 Variations in power demands of non-fixed lighting appliances

Table 7-12 indicates the average power loads of different types of non-fixed lighting. It was observed that incandescent lamps owned by medium electrical energy consumers had a higher average power demand than low and high consumers. Both CFL and LED lamps were found to have a similar power rating regardless of electrical demand group. None of the high consumption dwellings owned a LED lamp and neither of the high nor low consumers owned a halogen lamp. Halogen lamps had the greatest power load of all the measured lamps, but were owned by medium demand dwellings only.

Table 7-12 Mean appliance power demands in the non-fixed lighting category by power mode and electrical demand group

Lighting type	Power mode	Mean power demand (W) of appliance types in the electrical demand group			
		Low (n=5)	Medium (n=10)	High (n=12)	All (n=27)
Incandescent	Active	41.95 (n=2)	**61.14** (n=14)	48.09 (n=14)	53.64 (n=30)
CFL	Active	11.78 (n=10)	11.30 (n=10)	**14.63** (n=5)	12.28 (n=25)
LED	Active	**3.67** (n=1)	3.44 (n=1)	-	3.55 (n=2)
Halogen	Active	-	**820.15** (n=1)	-	820.15 (n=1)

7.4.3 Variations in power demands of HVAC appliances

The power demands of a range of HVAC devices are displayed below in Table 7-13. With the exception of desk fans, it was not possible to compare the power loads of any of the remaining HVAC devices because they were owned by households in the high electrical demand group only. With respect to desk fans which were possessed by the low and medium consumers, an almost identical power was required by the devices owned in both groups. In general, the power load data for HVAC devices was based on a single appliance and therefore should be treated with care.

Table 7-13 Mean appliance power demands in the HVAC category by power mode and electrical demand group

Appliance type	Power mode	Mean power demand (W) of appliance types in the electrical demand group			
		Low (n=5)	Medium (n=10)	High (n=12)	All (n=27)
Desk fan	Active	31.26 (n=2)	**33.02** (n=3)	-	32.14 (n=5)
Electric fire	Active	-	-	**642.29** (n=2)	642.29 (n=2)
Electric blanket	Active	-	-	**5.70** (n=1)	5.70 (n=1)
Portable halogen radiator	Active	-	-	**1317.86** (n=1)	1317.86 (n=1)
Portable oil filled radiator	Active	-	-	**1293.42** (n=1)	1293.42 (n=1)

7.4.4 Variations in power demands of transportation appliances

Table 7-14 shows the power demands of the transportation devices monitored in the L27 study. The power loads of transportation appliances between electrical demand groups were not compared because all the devices in the category were owned by one electrical demand group only.

Table 7-14 Mean appliance power demands in the transportation category by power mode and electrical demand group

Appliance type	Power mode	Mean power demand (W) of appliance types in the electrical demand group			
		Low (n=5)	Medium (n=10)	High (n=12)	All (n=27)
Reclining furniture	Active	-	**37.78** (n=4)	-	37.78 (n=4)
Mobility scooter	Active	-	-	**20.27** (n=2)	20.27 (n=2)
Bath lift	Active	-	-	-	-
Golf trolley	Active	-	-	**18.06** (n=1)	18.06 (n=1)
Chair lift	Active	-	-	**6.25** (n=1)	6.25 (n=1)

7.4.5 Variations in power demands of catering appliances

Table 7-15 shows average power loads for the catering appliances measured in the study. The variations in average power loads for the catering appliances amongst the electrical demand groups are outlined using the subcategories; major cooking, minor cooking and preservation and cooling.

In the major cooking subcategory, no power load data was collected for either the electric ovens or electric hobs because they were not possible to monitor as the appliances were wired directly into the mains electricity.

In the minor cooking subcategory the power loads of microwaves in both the active and passive standby modes decreased as overall electricity consumption increased. Power demand data collected from deep fryers owned by medium and high electricity consumers showed that those owned by medium consumers had a larger average active power load than those of high consumers. However, the average figure for the medium consumers' deep fryers was based on a single sample.

With regard to the power loads of toasters it was seen that whilst the active power loads for low and high electricity users' toasters were practically identical, those owned by medium consumers were lower. Interestingly, it was evident that some of the toasters owned by high electricity consumers appeared to have an additional passive standby mode, which on average demands a continuous load of 1.09 Watts.

The active power loads of kettles were found to increase with higher total electricity use, with the kettles owned by high electricity consumers requiring an average load almost 400 Watts greater than those owned by low consumers.

Can openers were the only other minor cooking appliance for which power load data was collected for more than one electrical demand group. The results showed that a similar active power demand was required for the device regardless of whether it was possessed by either the medium or high consumers.

Power load data was obtained for five types of preservation and cooling appliance. Chest freezers had the highest power load in the cooling cycle, followed closely by fridge-freezers, upright freezers and refrigerators. The lowest cooling cycle load was for the beer and wine coolers. It was found that overall fridge-freezers and upright freezers both had a small power draw of a few Watts in the non-cooling cycle.

With regard to variations in the power loads of preservation and cooling devices between the electrical demand groups, firstly, it was observed that refrigerators owned by low electrical energy consumers had a much higher power load in the cooling cycle than medium or high consumers. Secondly, the cooling cycle load of fridge-freezers was seen to decrease as total electricity use increased. Fridge-freezers owned by the low consumers also had a higher power load in the non-cooling cycle than medium or high consumers. The upright freezers of medium electrical demand dwellings required a greater power load in the cooling cycle than those of high and low consuming dwellings. The non-cooling cycle load of upright freezers was quite low for all demand groups, but was slightly higher for those appliances owned by the high consumers. Chest freezers were owned by medium and high electricity consumers only and the power load results showed that on average those belonging to high consumers required a greater load in the cooling cycle than those of the medium consumers.

Table 7-15 Mean appliance power demands in the catering category by power mode and electrical demand group

Appliance type	Power mode	Mean power demand (W) of appliance types in the electrical demand group			
		Low (n=5)	Medium (n=10)	High (n=12)	All (n=27)
Major cooking					
Electric oven	Active	-	-	-	-
Electric hob	Active	-	-	-	-
Minor cooking					
Small ovens	Active	-	-	-	-
Microwave	Active	**969.92** (n=3)	792.79 (n=7)	892.75 (n=13)	872.39 (n=23)
	Passive Standby	**7.13** (n=3)	2.39 (n=7)	2.29 (n=13)	3.04 (n=23)
Grill plate	Active	-	**1455.36** (n=1)	-	1455.36 (n=1)
Deep fryer	Active	-	**2276.64** (n=3)	1954.31 (n=1)	2061.76 (n=4)

Appliance type	Power mode	Mean power demand (W) of appliance types in the electrical demand group			
		Low (n=5)	Medium (n=10)	High (n=12)	All (n=27)
Toaster	Active	**1081.91** (n=4)	967.76 (n=8)	1080.51 (n=11)	1046.44 (n=23)
	Passive Standby	-	-	**1.09** (n=11)	1.09 (n=11)
Slow cooker	Active	-	-	**121.29** (n=2)	121.29 (n=2)
Steamer	Active	-	**620.28** (n=1)	-	620.28 (n=1)
Kettle	Active	2279.73 (n=5)	2546.11 (n=9)	**2643.50** (n=12)	2539.58 (n=26)
Blender	Active	-	-	**566.29** (n=4)	566.29 (n=4)
	Passive Standby	-	-	**0.60** (n=4)	0.60 (n=4)
Food mixer	Active	-	-	**40.82** (n=1)	40.82 (n=1)
Juicer	Active	-	-	-	-
Food processor	Active	-	-	-	-
Coffee grinder	Active	-	-	-	-
Coffee maker	Active	-	-	-	-
	Passive Standby	-	-	**0.41** (n=1)	0.41 (n=1)
Ice maker	Active	-	-	-	-
Popcorn maker	Active	-	-	-	-
Can opener	Active	-	**46.32** (n=2)	45.05 (n=2)	45.37 (n=4)
Knife	Active	-	-	-	-
Preservation and cooling					
Refrigerator	Cooling cycle	**105.66** (n=3)	72.65 (n=6)	82.66 (n=4)	83.34 (n=13)
	Non-cooling cycle	0.00 (n=3)	0.00 (n=6)	0.00 (n=4)	0.00 (n=13)
Fridge-freezer	Cooling cycle	**98.64** (n=3)	90.23 (n=5)	90.00 (n=5)	92.05 (n=13)
	Non-cooling cycle	**9.56** (n=3)	1.90 (n=5)	2.16 (n=5)	3.81 (n=13)
Upright freezer	Cooling cycle	72.26 (n=2)	**105.11** (n=4)	85.33 (n=5)	88.35 (n=11)
	Non-cooling cycle	0.50 (n=2)	0.45 (n=4)	**1.86** (n=5)	1.17 (n=11)
Chest freezer	Cooling cycle	-	89.53 (n=7)	**95.87** (n=3)	92.70 (n=10)
	Non-cooling cycle	-	0.00 (n=7)	0.00 (n=3)	0.00 (n=10)
Beer and wine cooler	Cooling cycle	-	-	**77.05** (n=1)	77.05 (n=1)
	Non-cooling cycle	-	-	0.00 (n=1)	0.00 (n=1)

7.4.6 Variations in power demands of washing appliances

Table 7-16 shows the average power loads of dishwashers in different power modes for each of the electrical demand groups. There is no dishwasher power data for the medium electrical demand group because none of the medium consumer households in the L27 cohort owned a dishwasher. It can be seen that the highest power demand for a dishwasher occurs during the drying cycle and the results showed that dishwashers owned by low consumers had a higher average power load in this mode than high consumers. Conversely, it was found that the dishwashers owned by high consumers had a greater power demand in the washing cycle.

In the passive standby mode, the high consumers' dishwashers were discovered as having a continuous average power load of 1.05 Watts. This means that even when the dishwashers were not performing their main function (i.e. washing or drying), some power draw was occurring consequently resulting in additional electricity use. Due to only one appliance being monitored in both the washing and drying cycles for the low electrical demand group, caution should be applied regarding it's representativeness of the average dishwasher owned by a low consuming dwelling.

Table 7-16 Mean appliance power demands in the washing category by power mode and electrical demand group

Appliance type	Power mode	Mean power demand (W) of appliance types in the electrical demand group			
		Low (n=5)	**Medium (n=10)**	**High (n=12)**	**All (n=27)**
Dishwasher	Washing cycle	17.64 (n=1)	-	**45.28** (n=4)	38.37 (n=5)
	Drying cycle	**2355.06** (n=1)	-	2068.27 (n=4)	2139.97 (n=5)
	Passive Standby	0.00 (n=1)	-	**1.05** (n=4)	0.84 (n=5)

7.4.7 Variations in power demands of laundry appliances

The laundry appliances' average power loads are shown in Table 7-17. The average active power demand of an iron increased in relation to overall electrical demand. Whilst the power active load of irons owned by medium consumers (1321.79 Watts) was only slightly higher than those of low consumers (1300.81 Watts), high consumers' irons had a much higher active power demand of 1632.60 Watts.

The washing machines owned by medium electrical energy consumers had a lower average power load for both the water heating and washing cycles than low and high consumers. There was little variation in the average power demands required in all washing machine modes between the low and high electrical consumers.

None of the low electrical energy consumers in the L27 cohort owned either a washer-dryer or tumble dryer, and therefore there is no indication of the power demands of such devices for this group. With regard to the five washer-dryer power modes identified, the average power requirement in each mode was similar between medium and high demand dwellings, with the exception of the heating cycle in the clothes drying phase, where washer-dryers owned by high consumers had a greater power draw than those of medium consumers. For standalone tumble-dryers the power demand in the heating cycle was also higher for devices owned by high consumers rather than medium. A similar power load was evident in the tumble cycle for both electrical demand groups.

A small power load of less than 1 Watt was apparent in the passive standby mode for all laundry devices. This result demonstrates that laundry devices consume electricity even when they are not performing their main function. The power required in the passive standby mode probably relates to an electronic display or LED lights on the control panel.

Table 7-17 Mean appliance power demands in the laundry category by power mode and electrical demand group

Appliance type	**Power mode**	**Mean power demand (W) of appliance types in the electrical demand group**			
		Low (n=5)	**Medium (n=10)**	**High (n=12)**	**All (n=27)**
Iron	Active	1300.81 (n=5)	1321.79 (n=10)	**1632.60** (n=12)	1480.31 (n=27)
Washing machine	Water heating cycle	2091.39 (n=5)	2010.95 (n=7)	**2118.18** (n=9)	2084.32 (n=21)
	Washing cycle	**85.26** (n=5)	67.86 (n=7)	79.38 (n=9)	77.58 (n=21)
	Passive Standby	0.31 (n=5)	0.46 (n=7)	**0.49** (n=9)	0.50 (n=21)
Washer-dryer	Water heating cycle	-	2016.34 (n=3)	**2087.65** (n=3)	2052.00 (n=6)
	Washing cycle	-	78.63 (n=3)	**84.21** (n=3)	81.42 (n=6)
	Heating cycle	-	1997.41 (n=3)	**2114.97** (n=3)	2056.19 (n=6)
	Tumble cycle	-	82.36 (n=3)	**85.33** (n=3)	83.84 (n=6)
	Passive Standby	-	**0.47**(n=3)	0.20 (n=3)	0.34 (n=6)
Tumble-dryer	Heating cycle	-	1640.93 (n=5)	**2250.85** (n=5)	2115.32 (n=10)
	Tumble cycle	-	**139.42** (n=5)	137.61 (n=5)	138.02 (n=10)
	Passive Standby	-	0.00 (n=5)	**0.03** (n=5)	0.02 (n=10)

7.4.8 Variations in power demands of building and outdoors maintenance appliances

Table 7-18 displays the active power loads of the monitored appliances in the building and outdoors maintenance category. Vacuum cleaners were the only devices owned by households in all electrical demand groups and had the greatest overall active power load. By comparing the average power loads of vacuum cleaners, it was identified that although little variation existed between the demand groups, the power required did increase with overall annual electricity consumption.

The calculated active power loads for the other appliances were primarily established from one sample for each electrical demand group. These appliances were owned by a maximum of two groups. Disparities in the active power loads between the medium and high consumer groups were recognised for the devices saws, electric lawn mowers, indoor and outdoor aquariums. The differences possibly relate to the low sample sizes but for the indoor and outdoor aquariums may also indicate the size of the pump and filters installed and whether the aquarium is a heated for tropical rather than cold water fish.

Table 7-18 Mean appliance power demands in the building and outdoors maintenance category by power mode and electrical demand group

Appliance type	Power mode	Mean power demand (W) of appliance types in the electrical demand group			
		Low (n=5)	Medium (n=10)	High (n=12)	All (n=27)
Vacuum cleaner	Active	1037.29 (n=8)	1074.28 (n=12)	**1113.41** (n=14)	1083.60 (n=34)
Security systems (Alarm)	Active	-	**4.97** (n=1)	3.48 (n=2)	3.97 (n=3)
Plug in air freshener	Active	-	**6.20** (n=2)	-	6.20 (n=2)
Door bell	Active	0.82 (n=1)	-	**0.98** (n=1)	0.90 (n=2)
Utility meters	Active	-	**2.12** (n=1)	-	2.12 (n=1)
Automatic door opener	Active	-	-	**2.85** (n=1)	2.85 (n=1)
Saw	Active	-	**976.95** (n=1)	329.40 (n=1)	653.17 (n=2)
Sander	Active	-	-	**317.22** (n=1)	317.22 (n=1)
Sewing machine	Active	-	-	-	-
Electric lawn mowers	Active	-	**860.35** (n=8)	719.80 (n=7)	813.50 (n=15)
Indoor aquarium	Active	-	5.19 (n=1)	**55.59** (n=3)	42.99 (n=4)
Outdoor aquarium	Active	-	59.76 (n=1)	**114.83** (n=1)	87.29 (n=2)
Battery chargers	Active	-	4.56 (n=2)	**13.35** (n=1)	10.42 (n=3)
Pest alarms	Active	2.02 (n=1)	-	**2.20** (n=1)	2.11 (n=2)

7.4.9 Variations in power demands of hygiene, beauty and leisure appliances

Table 7-19 shows the average power demands of the hygiene, beauty and leisure appliances. The majority of the power loads for the devices were based on a single sample appliance and only hair dryers, hair straighteners, shavers and electric toothbrushes were owned by households in more than one electrical demand group.

The results show that hair dryers owned by medium electrical energy consumers had the highest active power load of the three groups. Whilst the average power load of high consumers' hair dryers was less, the hair dryers owned by low consumers had a much lower power demand, about one third of that of the medium consumers'. It was found that the power loads of hair straighteners were similar for the low and medium demand groups, but was much higher for those belonging to the high consumers.

Shavers were owned solely by households in the medium and high demand groups. Although the active power demands are estimated based on one appliance per group, it was observed that the power demands were comparable for both groups.

The results demonstrated that electric toothbrushes owned by households in the low and medium demand groups had virtually identical electrical power loads of less than 1 Watt. It was not possible to compare with households in the high demand group because none owned an electric toothbrush in this study.

Table 7-19 Mean appliance power demands in the hygiene, beauty and leisure category by power mode and electrical demand group

Appliance type	Power mode	Mean power demand (W) of appliance types in the electrical demand group			
		Low (n=5)	**Medium (n=10)**	**High (n=12)**	**All (n=27)**
Electric shower	Active	-	-	-	-
Hair dryer	Active	566.97 (n=3)	**1478.32** (n=5)	1105.19 (n=8)	1097.05 (n=16)
Hair straighteners	Active	61.67 (n=1)	64.32 (n=3)	**135.06** (n=3)	104.37 (n=7)
Hot air styler	Active	-	-	-	-
Hair clippers	Active	-	**8.30** (n=1)	-	8.30 (n=1)
Shaver	Active	-	1.48 (n=1)	**3.13** (n=1)	2.31 (n=2)
Massager	Active	-	-	**203.05** (n=1)	203.05 (n=1)
	Passive Standby	-	-	**10.79** (n=1)	10.79 (n=1)
Toothbrush	Active	0.91 (n=1)	**0.93** (n=1)	-	0.92 (n=2)
Medical	Active	**0.83** (n=1)	-	-`	0.83 (n=1)

7.4.10 Summary of variations in power demands of domestic appliances

Section 7.4 has demonstrated the variations in average power demands of domestic appliances in each power mode in relation to electrical demand group. Table 7-20 provides a summary of the appliance power modes which had the greatest power demand when owned by high electricity consumers.

Table 7-20 Summary of appliance power modes which had the greatest power demand when owned by high electricity consumers

Appliance categories	**Power modes**			
Office equipment and infotainment				
Desktop	A			
Printer	A		PS	
Wireless router	A			
DSL	A			
Portable hard-drive	A			
Shredder	A			
CRT Television				OS
LCD Television	A			OS
Digital Set Top Box		AS		
Satellite Set Top Box	A	AS		
Cable Set Top Box	A	AS		
Internet Set Top Box	A			
DVD	A		PS	
VCR	A			
DVD with VCR	A	AS	PS	
Stereo system	A			
Portable digital radio	A	AS	PS	
Personal CD player	A	AS	PS	
MP3 docking station			PS	
Video console	A		PS	
ebook reader	A			
Non-fixed lighting				
CFL	A			
HVAC				
Electric fire	A			
Electric blanket	A			
Portable halogen radiator	A			
Portable oil filled radiator	A			

Appliance categories	Power modes									
Transportation										
Mobility scooter	A									
Golf trolley	A									
Chair lift	A									
Catering										
Toaster			PS							
Slow cooker	A									
Kettle	A									
Blender	A		PS							
Food mixers	A									
Coffee maker			PS							
Upright freezer					NC					
Chest freezer						C				
Beer and wine cooler						C				
Washing										
Dishwasher			PS				W			
Laundry										
Iron	A									
Washing machine			PS					WH		
Washer-dryer							W	WH	H	T
Tumble-dryer			PS						H	
Building and outdoors maintenance										
Vacuum cleaner	A									
Door bell	A									
Utility meter	A									
Automatic door opener	A									
Sander	A									
Indoor aquarium	A									
Outdoor aquarium	A									
Battery chargers	A									
Pest Alarm	A									
Hygiene, beauty and leisure										
Hair straighteners	A									
Shaver	A									
Massager	A		PS							

Note: (A) Active; (AS) Active standby; (PS) Passive standby; (OS) Off standby; (NC) Non-cooling cycle; (C) Cooling cycle; (W) Washing cycle; (WH) Water heating cycle; (H) Heating cycle; (T) Tumble cycle.

7.5 Variations in daily use of domestic appliances between electrical demand groups

This section presents average daily appliance use figures, which provide an indication of the extent that appliances were used in different power modes by electrical demand groups. The appliance use averages were calculated by dividing the sum of total daily use for a given appliance type by the number of homes in the electrical demand group (See Chapter 4, Section 4.10.4.6). The use figures therefore incorporate the appliance ownership rates presented in section 7.3. Values in **bold** indicate the longest average daily use observed for an appliance power mode.

7.5.1 Variations in daily use of office equipment and infotainment appliances

Table 7-21 shows average daily usages for the office equipment and infotainment appliances measured in the L27 study. The variations amongst the electrical demand groups in the number of hours of operation of these appliances in the different power modes are discussed using the subcategories; IT, telephony, office accessories and entertainment.

In the IT subcategory it was observed that in general devices owned by high electricity consumers had a longer daily duration of use in all power modes. None of the appliances owned by low electricity consumers had a longer daily use in any of the power modes than appliances owned by the other two groups. Printers in the active and passive standby modes, and active DSL and Ethernet hubs were the only appliances and power modes that medium demand dwellings had a greater duration of use than those in the high electrical demand group.

In the telephony subcategory two types of device were monitored. It was found that telephones decreased their daily usage as total annual electricity consumption increased. It was observed that telephones owned by households in the low consumption group had almost double the number of hours of active operation per day than those in the medium or high consumption groups. The ownership of telephones with answering machines were confined to the low electrical demand group only and therefore the daily use of such devices in the other two groups was zero hours compared with 9.60 hours for the low demand group.

In the office accessories subcategory, it was identified that while the average daily use of shredders in the active mode was low for all electrical demand groups, the duration of use decreased with total annual electricity consumption. All electrical demand groups had a usage of zero hours per day on laminators, although it should be noted that this device was possessed by medium demand dwellings only.

In the entertainment subcategory, it was recognised that older CRT televisions owned by low electricity consumers had a greater active daily duration of use than those owned by medium or high consumers. Conversely, newer LCD televisions were operated in the active mode for longer by high consumers. Both television types were left in passive standby mode for a longer duration each day by medium electricity consumers.

In relation to STBs, basic digital STBs belonging to high electrical demand dwellings were found to have a higher active mode daily use. However, low consuming dwellings' digital STBs were observed to remain in the standby power modes for a longer period of time each day. In addition, cable and internet STBs were also found to be operated in the active power mode for a greater number of hours per day by high demand dwellings. Medium demand dwellings however had a larger average active standby usage on cable STBs. Moreover, medium electricity consumers had the highest duration of use on satellite STBs in the active mode.

Average daily duration of use data was collected for five types of video and recording appliance. It was found that DVD players owned by households in the high consumption group had longer operative hours in the active and active standby modes, while those owned by households in the medium consumption group had longer use in the passive standby mode. The electrical demand group with the highest average duration of use on VCR players varied between all of the power modes; low electricity consumers had a greater active power mode use, medium consumers a greater active standby use, and high consumers a greater passive standby use. Blu-ray players were found to be used for more hours each day in the active and passive standby modes by medium demand dwellings. Additionally, households in the medium demand group operated portable DVD players in the active mode for a greater duration each day. Finally, it was observed that high consumers tended to leave their combination DVD with VCR players in the passive standby mode for longer.

The number of hours that stereo systems were operational in their different power modes varied between the electrical demand groups. Low electricity consumers' devices functioned in the active, passive and off standby modes for a longer duration than similar devices owned by medium or high consumers. Stereo systems owned by medium consumers had a greater usage in the active standby power mode.

Three different types of radio were monitored during the study and the data demonstrated that digital radios owned by dwellings in the medium electrical demand group had on average the highest usage in both the active and active standby modes. Low consumers' digital radios had a greater use in the passive standby mode. The electrical demand group which had the longest usage on analogue radios varied between each of the power modes, low consuming households had a greater use in the active, medium consuming households in the active and off standby, and high consuming households in the passive standby modes. Clock radios possessed by households in the medium demand group were found to have a much higher daily duration of use in the active power mode, compared with those in either the low or high demand groups.

From the remaining audio devices monitored it was seen that personal CD players had a higher average active usage when owned by medium demand dwellings and a higher usage in the standby modes when owned by high demand dwellings. Speakers owned by medium consumers had a longer daily use in the active and active standby modes. MP3 docking stations possessed by high consumers had a higher usage in the active and passive standby modes. Home music studios measured in the low electrical demand group had a greater average duration of use in the active, active standby and passive standby power modes. With the exception of the active standby mode, which had an identical number of hours of daily use between all electrical demand groups, the further power modes of home theatre systems were all found to have a higher duration of use when owned by medium electricity consumers.

Video consoles in this study were found to be operated for a longer period of time each day in the active power mode by households in the medium demand group, and in the passive standby mode by households in the high demand group.

Table 7-21 Mean appliance daily use in the office equipment and infotainment category by power mode and electrical demand group

Appliance type	Power mode	Mean usage (hours per day) of appliance types in the electrical demand group			
		Low (n=5)	Medium (n=10)	High (n=12)	All (n=27)
IT					
Desktop	Active	0.31 (n=1)	1.76 (n=7)	**3.00** (n=11)	2.04 (n=18)
	Active/Passive Standby	1.08 (n=1)	5.51 (n=7)	**10.45** (n=11)	6.89 (n=18)
	Off Standby	0.00 (n=1)	3.43 (n=7)	**6.36** (n=11)	4.10 (n=18)
Laptop	Active	0.78 (n=3)	1.74 (n=7)	**1.93** (n=10)	1.65 (n=20)
	Active/Passive Standby	0.77 (n=3)	0.14 (n=7)	**1.25** (n=10)	0.75 (n=20)
	Off Standby	1.46 (n=3)	3.43 (n=7)	**9.36** (n=10)	5.70 (n=20)
Printer	Active	0.00 (n=1)	**0.09** (n=5)	0.00 (n=6)	0.04 (n=12)
	Active Standby	0.06 (n=1)	0.17 (n=5)	**0.38** (n=6)	0.23 (n=12)
	Passive Standby	1.32 (n=1)	**3.16** (n=5)	1.70 (n=6)	2.02 (n=12)
	Off Standby	0.00 (n=1)	5.87 (n=5)	**6.44** (n=6)	4.69 (n=12)

Appliance type	Power mode	Mean usage (hours per day) of appliance types in the electrical demand group			
		Low (n=5)	Medium (n=10)	High (n=12)	All (n=27)
Wireless router	Active	6.06 (n=2)	12.52 (n=6)	**19.93** (n=10)	14.62 (n=18)
DSL	Active	0.00 (n=0)	**2.00** (n=1)	0.00 (n=1)	0.88 (n=2)
Ethernet HUB	Active	0.00 (n=0)	**2.40** (n=1)	0.00 (n=0)	0.89 (n=1)
Portable hard-drive	Active	0.00 (n=0)	0.00 (n=0)	0.00 (n=1)	0.00 (n=1)
Telephony					
Telephone	Active	**33.39** (n=8)	17.42 (n=14)	15.07 (n=11)	21.11 (n=33)
Telephone with answering machine	Active	**9.60** (n=2)	0.00 (n=0)	0.00 (n=0)	1.78 (n=2)
Office accessories					
Shredder	Active	**0.03** (n=2)	0.01 (n=4)	0.00 (n=3)	0.06 (n=9)
Laminator	Active	0.00 (n=0)	0.00 (n=1)	0.00 (n=0)	0.00 (n=1)
Entertainment					
CRT television	Active	**3.04** (n=5)	2.06 (n=6)	0.99 (n=4)	1.75 (n=15)
	Passive Standby	0.59 (n=5)	**2.58** (n=6)	0.89 (n=4)	1.48 (n=15)
	Off Standby	**17.26** (n=5)	5.61 (n=6)	2.70 (n=4)	6.31 (n=15)
LCD television	Active	1.46 (n=1)	4.46 (n=16)	**5.10** (n=18)	4.45 (n=35)
	Passive Standby	0.06 (n=1)	**6.72** (n=16)	4.56 (n=18)	4.79 (n=35)
	Off Standby	3.25 (n=1)	8.01 (n=16)	**10.63** (n=18)	8.86 (n=35)
Video amplifier (booster)	Active	0.00 (n=0)	**2.40** (n=1)	2.00 (n=2)	1.78 (n=3)
Digital Set Top Box	Active	4.03 (n=3)	0.91 (n=3)	**6.39** (n=9)	3.90 (n=15)
	Active Standby	**1.11** (n=3)	0.98 (n=3)	0.90 (n=9)	0.97 (n=15)
	Passive Standby	**1.28** (n=3)	0.00 (n=3)	0.00 (n=9)	0.22 (n=15)
	Off Standby	**4.65** (n=3)	0.05 (n=3)	2.85 (n=9)	2.09 (n=15)
Satellite Set Top Box	Active	2.19 (n=3)	**6.00** (n=4)	4.22 (n=4)	4.55 (n=11)
	Active Standby	**7.53** (n=3)	2.64 (n=4)	0.00 (n=4)	2.30 (n=11)
	Passive Standby	0.00 (n=3)	0.00 (n=4)	0.00 (n=4)	0.00 (n=11)
	Off Standby	0.00 (n=3)	0.00 (n=4)	**1.35** (n=4)	0.60 (n=11)
Cable Set Top Box	Active	0.00 (n=0)	0.87 (n=1)	**4.24** (n=4)	2.04 (n=5)
	Active Standby	0.00 (n=0)	**1.51** (n=1)	0.12 (n=4)	0.06 (n=5)
	Passive Standby	0.00 (n=0)	0.00 (n=1)	0.00 (n=4)	0.00 (n=5)
	Off Standby	0.00 (n=0)	0.00 (n=1)	0.00 (n=4)	0.00 (n=5)

Appliance type	Power mode	Mean usage (hours per day) of appliance types in the electrical demand group			
		Low (n=5)	Medium (n=10)	High (n=12)	All (n=27)
Internet Set Top Box	Active	0.00 (n=0)	0.00 (n=0)	**0.11** (n=1)	0.05 (n=1)
	Active Standby	0.00 (n=0)	0.00 (n=0)	**0.60** (n=1)	0.29 (n=1)
	Passive Standby	0.00 (n=0)	0.00 (n=0)	0.00 (n=1)	0.00 (n=1)
	Off Standby	0.00 (n=0)	0.00 (n=0)	0.00 (n=1)	0.00 (n=1)
DVD player	Active	0.00 (n=3)	0.14 (n=6)	**0.63** (n=6)	0.33 (n=15)
	Active Standby	0.00 (n=3)	0.03 (n=6)	**0.18** (n=6)	0.09 (n=15)
	Passive Standby	0.00 (n=3)	**3.15** (n=6)	1.22 (n=6)	1.63 (n=15)
	Off Standby	**9.57** (n=3)	6.57 (n=6)	7.54 (n=6)	8.12 (n=15)
VCR player	Active	**4.78** (n=2)	0.65 (n=2)	0.07 (n=5)	1.12 (n=9)
	Active Standby	0.00 (n=2)	**1.82** (n=2)	0.46 (n=5)	0.86 (n=9)
	Passive Standby	4.78 (n=2)	2.15 (n=2)	**7.09** (n=5)	4.91 (n=9)
	Off Standby	0.00 (n=2)	0.00 (n=2)	0.00 (n=5)	0.00 (n=9)
Blu-ray player	Active	0.00 (n=0)	**0.12** (n=2	0.00 (n=1)	0.05 (n=3)
	Active Standby	0.00 (n=0)	0.00 (n=2)	0.00 (n=1)	0.00 (n=3)
	Passive Standby	0.00 (n=0)	**4.40** (n=2)	0.00 (n=1)	1.63 (n=3)
	Off Standby	0.00 (n=0)	0.00 (n=2)	**1.99** (n=1)	0.89 (n=3)
DVD with VCR	Active	0.00 (n=0)	0.00 (n=0)	0.00 (n=1)	0.00 (n=1)
	Active Standby	0.00 (n=0)	0.00 (n=0)	0.00 (n=1)	0.00 (n=1)
	Passive Standby	0.00 (n=0)	0.00 (n=0)	**1.67** (n=1)	0.74 (n=1)
	Off Standby	0.00 (n=0)	0.00 (n=0)	0.00(n=1)	0.00 (n=1)
Portable DVD player	Active	0.00 (n=0)	**0.08** (n=1)	0.00 (n=0)	0.03 (n=1)
	Active Standby	0.00 (n=0)	0.00 (n=1)	0.00 (n=0)	0.00 (n=1)
	Passive Standby	0.00 (n=0)	0.00 (n=1)	0.00 (n=0)	0.00 (n=1)
	Off Standby	0.00 (n=0)	0.00 (n=1)	0.00 (n=0)	0.00 (n=1)
Stereo system	Active	**0.87** (n=3)	0.08 (n=6)	0.07 (n=8)	0.22 (n=17)
	Active Standby	0.26 (n=3)	**1.70** (n=6)	0.03 (n=8)	0.67 (n=17)
	Passive Standby	**4.11** (n=3)	0.67 (n=6)	1.95 (n=8)	1.88 (n=17)
	Off Standby	**3.90** (n=3)	1.90 (n=6)	0.07 (n=8)	1.41 (n=17)
Digital radio	Active	0.03 (n=3)	**0.43** (n=5)	0.05 (n=2)	0.19 (n=10)
	Active Standby	0.00 (n=3)	**4.27** (n=5)	0.03 (n=2)	1.59 (n=10)
	Passive Standby	**4.76** (n=3)	0.00 (n=5)	0.17 (n=2)	0.96 (n=10)
	Off Standby	0.01 (n=3)	0.00 (n=5)	**1.07** (n=2)	0.48 (n=10)

Appliance type	Power mode	Mean usage (hours per day) of appliance types in the electrical demand group			
		Low (n=5)	Medium (n=10)	High (n=12)	All (n=27)
Analogue radio	Active	**0.23** (n=4)	0.20 (n=3)	0.05 (n=3)	0.15 (n=10)
	Active Standby	0.01 (n=4)	**2.00** (n=3)	0.01 (n=3)	0.78 (n=10)
	Passive Standby	0.69 (n=4)	3.95 (n=3)	**3.98** (n=3)	3.22 (n=10)
	Off Standby	0.00 (n=4)	**1.95** (n=3)	0.24 (n=3)	0.85 (n=10)
Clock radio	Active	9.53 (n=2)	**13.03** (n=6)	7.67 (n=4)	10.11 (n=12)
Personal CD player	Active	0.00 (n=0)	**0.01** (n=0)	0.00 (n=2)	0.01 (n=2)
	Active Standby	0.00 (n=0)	0.07 (n=0)	**0.60** (n=2)	0.31 (n=2)
	Passive Standby	0.00 (n=0)	1.58 (n=0)	**3.10** (n=2)	2.00 (n=2)
	Off Standby	0.00 (n=0)	**0.01** (n=0)	0.00 (n=2)	0.00 (n=2)
Turntable	Active	0.00 (n=0)	0.00 (n=0)	0.00 (n=1)	0.00 (n=1)
	Off Standby	**4.77** (n=0)	0.00(n=0)	0.00 (n=1)	0.88 (n=1)
Speakers	Active	0.00 (n=0)	**0.10** (n=3)	0.00 (n=0)	0.04 (n=3)
	Active Standby	0.00 (n=0)	**2.38** (n=3)	0.00 (n=0)	0.88 (n=3)
	Passive Standby	0.00 (n=0)	0.00 (n=3)	0.00 (n=0)	0.00 (n=3)
	Off Standby	0.00 (n=0)	0.00 (n=3)	0.00 (n=0)	0.00 (n=3)
MP3 docking station	Active	0.01 (n=1)	0.01 (n=1)	0.01 (n=1)	0.01 (n=3)
	Active Standby	0.01 (n=1)	0.01 (n=1)	**1.09** (n=1)	0.49 (n=3)
	Passive Standby	0.00 (n=1)	0.00 (n=1)	**0.90** (n=1)	0.40 (n=3)
	Off Standby	0.00 (n=1)	0.00 (n=1)	0.00 (n=1)	0.00 (n=3)
Keyboard/organ	Active	0.00 (n=0)	0.00 (n=1)	0.00 (n=2)	0.00 (n=3)
Guitar/keyboard amplifier	Active	0.00 (n=0)	0.00 (n=0)	0.00 (n=2)	0.00 (n=2)
Home music studio	Active	**0.07** (n=1)	0.05 (n=1)	0.00 (n=0)	0.03 (n=2)
	Active Standby	**0.26** (n=1)	0.11 (n=1)	0.00 (n=0)	0.09 (n=2)
	Passive Standby	**1.06** (n=1)	0.01 (n=1)	0.00 (n=0)	0.20 (n=2)
	Off Standby	0.00 (n=1)	**0.13** (n=1)	0.00 (n=0)	0.05 (n=2)
Home theatre system	Active	0.00 (n=0)	**0.40** (n=1)	0.00 (n=0)	0.15 (n=1)
	Active Standby	0.00 (n=0)	0.00 (n=1)	0.00 (n=0)	0.00 (n=1)
	Passive Standby	0.00 (n=0)	**0.34** (n=1)	0.00 (n=0)	0.12 (n=1)
	Off Standby	0.00 (n=0)	**1.36** (n=1)	0.00 (n=0)	0.50 (n=1)
Video console	Active	0.00 (n=0)	**1.45** (n=8)	0.75 (n=14)	0.90 (n=22)
	Passive Standby	0.00 (n=0)	3.70 (n=8)	**6.76** (n=14)	4.66 (n=22)
	Off Standby	0.00 (n=0)	1.41 (n=8)	**3.38** (n=14)	2.17 (n=22)

Appliance type	Power mode	Mean usage (hours per day) of appliance types in the electrical demand group			
		Low (n=5)	Medium (n=10)	High (n=12)	All (n=27)
ebook reader	Active	0.00 (n=1)	0.01 (n=1)	0.01 (n=1)	0.01 (n=1)
	Off Standby	0.00 (n=0)	**2.39** (n=1)	1.98 (n=1)	1.77 (n=2)

7.5.2 Variations in daily use of non-fixed lighting appliances

Table 7-22 indicates the average daily use of different types of non-fixed lighting for each electrical demand group. It was observed that incandescent lamps owned by high electrical energy consumers had a higher active average duration of use than low and medium consumers who both had a similar daily usage. For CFL, LED and halogen lighting types, households in the medium demand group had the longest daily usage in the active power modes.

Table 7-22 Mean appliance daily use in the non-fixed lighting category by power mode and electrical demand group

Lighting type	Power mode	Mean usage (hours per day) of appliance types in the electrical demand group			
		Low (n=5)	Medium (n=10)	High (n=12)	All (n=27)
Incandescent	Active	0.28 (n=2)	0.25 (n=14)	**0.89** (n=14)	0.55 (n=30)
	Off Standby	9.17 (n=2)	**14.05** (n=14)	12.84(n=14)	12.87 (n=30)
CFL	Active	0.84 (n=10)	**2.07** (n=10)	0.61 (n=5)	1.24 (n=25)
	Off Standby	**12.59** (n=10)	6.77 (n=10)	6.69 (n=5)	8.38 (n=25)
LED	Active	0.13 (n=1)	**0.27** (n=1)	0.00 (n=1)	0.15 (n=3)
	Off Standby	0.00 (n=1)	**2.12** (n=1)	0.00 (n=1)	1.13 (n=3)
Halogen	Active	0.00 (n=0)	**0.27** (n=1)	0.00 (n=0)	0.15 (n=1)
	Off Standby	0.00 (n=0)	**2.12** (n=1)	0.00 (n=0)	1.13 (n=1)

7.5.3 Variations in daily use of HVAC appliances

The average daily use of a range of HVAC devices are displayed below in Table 7-23. It was observed that apart from desk fans, all other appliances types in this category were used more by the high consumers than the low or medium consumers. This is due to the fact that with the exception of desk fans all other HVAC devices were owned by households in the high demand group only. The average daily duration of use of desk fans in the active power mode was found to decrease with overall annual electricity consumption.

Table 7-23 Mean appliance daily use in the HVAC category by power mode and electrical demand group

Appliance type	Power mode	Mean usage (hours per day) of appliance types in the electrical demand group			
		Low (n=5)	**Medium (n=10)**	**High (n=12)**	**All (n=27)**
Desk fan	Active	**0.18** (n=2)	0.07 (n=3)	0.00 (n=1)	0.07 (n=6)
	Off Standby	**3.79** (n=2)	0.38 (n=3)	0.00 (n=1)	0.91 (n=6)
Electric fire	Active	0.00 (n=0)	0.00 (n=0)	**0.16** (n=2)	0.07 (n=2)
	Off Standby	0.00 (n=0)	0.00 (n=0)	**1.03** (n=2)	0.46 (n=2)
Electric blanket	Active	0.00 (n=0)	0.00 (n=0)	**0.36** (n=1)	0.16(n=1)
	Off Standby	0.00 (n=0)	0.00 (n=0)	**1.64** (n=1)	0.73 (n=1)
Portable halogen radiator	Active	0.00 (n=0)	0.00 (n=0)	**0.05** (n=1)	0.02 (n=1)
	Off Standby	0.00 (n=0)	0.00 (n=0)	**1.95** (n=1)	0.87 (n=1)
Portable oil filled radiator	Active	0.00 (n=0)	0.00 (n=0)	**0.09** (n=1)	0.04 (n=1)
	Off Standby	0.00 (n=0)	0.00 (n=0)	**1.62** (n=1)	0.72 (n=1)

7.5.4 Variations in daily use of transportation appliances

Table 7-24 shows the daily use of the transportation devices monitored in the L27 study. The five different appliance types monitored in the category were owned by households in one demand group only. Therefore for each appliance type, two of the electrical demand groups had a usage of zero hours per day. Medium electricity consumers had a higher average daily duration of use in the active and off standby modes on reclining furniture. High electricity consumers' average use on mobility scooters, golf trolleys and chair lifts was longer than the other demand groups.

Table 7-24 Mean appliance daily use in the transportation category by power mode and electrical demand group

Appliance type	Power mode	Mean usage (hours per day) of appliance types in the electrical demand group			
		Low (n=5)	**Medium (n=10)**	**High (n=12)**	**All (n=27)**
Reclining furniture	Active	0.00 (n=0)	**0.38** (n=4)	0.00 (n=0)	0.16 (n=4)
	Off Standby	0.00 (n=0)	**2.00** (n=4)	0.00 (n=0)	0.83 (n=4)

Appliance type	Power mode	Mean usage (hours per day) of appliance types in the electrical demand group			
		Low (n=5)	Medium (n=10)	High (n=12)	All (n=27)
Mobility scooter	Active	0.00 (n=1)	0.00 (n=0)	**0.15** (n=2)	0.07 (n=3)
	Off Standby	0.00 (n=1)	0.00 (n=0)	**3.01** (n=2)	1.40 (n=3)
Bath lift	Active	0.00 (n=1)	0.00 (n=0)	0.00 (n=0)	0.00 (n=1)
	Off Standby	**4.78** (n=1)	0.00 (n=0)	0.00 (n=0)	0.89 (n=1)
Golf trolley	Active	0.00 (n=0)	0.00 (n=0)	**1.99** (n=1)	0.89 (n=1)
	Off Standby	0.00 (n=0)	0.00 (n=0)	0.00 (n=1)	0.00 (n=1)
Chair lift	Active	0.00 (n=0)	0.00 (n=0)	**1.98** (n=1)	0.88 (n=1)
	Off Standby	0.00 (n=0)	0.00(n=0)	**0.01** (n=1)	0.01 (n=1)

7.5.5 Variations in daily use of catering appliances

Table 7-25 shows average daily uses of the catering appliances measured in the study. The variations in use amongst the electrical demand groups are outlined using the subcategories; major cooking, minor cooking and preservation and cooling.

In the major cooking subcategory, no use data was collected for either the electric ovens or electric hobs because they were not possible to monitor as the appliances were wired directly into the mains electricity.

In the minor cooking subcategory it was found that half of the appliances (small ovens, grill plate, food mixer, juicer, food processor, coffee grinder, ice maker, pop maker and knife) had no variation in the daily number of hours of use between any of the electrical demand groups. In fact these devices had a usage of zero hours per day in all power modes.

However, it was observed that some of the devices had differences in use between electrical demand groups. Kettles owned by low electricity consumers had a higher average active use than those owned by medium and high consumers. The usage data collected from toasters showed that those owned by medium consumers had a larger average daily use in the active and passive standby modes than those of low and high consumers. In addition, slow cookers were also operated by medium consumers for a longer duration each day. The daily use of microwaves in the active and passive standby was found to increase as total annual electricity consumption of the dwellings also increased. Furthermore, high consumers were noted as using steamers in the active mode for a longer duration each day. In addition, blenders and coffee grinders owned by high consumers were also left in passive standby mode longer.

Duration of use data was obtained for five types of preservation and cooling appliance. With regard to variations in the use of these appliances between the electrical demand groups, firstly, it was observed that refrigerators owned by low electrical energy consumers had a longer duration of operation in both the cooling and non-cooling cycles compared with medium and high consumers. Secondly, the cooling cycle hours of fridge-freezers was greater for high consumers, whereas low consumers' fridge-freezers were operated in the non-cooling cycle for longer each day. Additionally, the same pattern of usage was also evident for the cooling and non-cooling cycles of upright freezers. The average daily hours of use of chest freezers in the cooling and non-cooling cycles owned by the medium electricity consumers were found to be more than double either of the other two electrical demand groups. Finally, beer and wine coolers possessed by high electrical demand dwellings had a higher daily duration of use in the cooling cycle, while those belonging to medium consumers had a greater number of hours use in the non-cooling cycle.

Table 7-25 Mean appliance daily use in the catering category by power mode and electrical demand group

Appliance type	Power mode	Mean usage (hours per day) of appliance types in the electrical demand group			
		Low (n=5)	**Medium (n=10)**	**High (n=12)**	**All (n=27)**
Major cooking					
Electric oven	Active	-	-	-	-
Electric hob	Active	-	-	-	-
Minor cooking					
Small ovens	Active	0.00 (n=0)	0.00 (n=0)	0.00 (n=1)	0.00 (n=1)
	Off Standby	0.00 (n=0)	0.00 (n=0)	0.00 (n=1)	0.00 (n=1)
Microwave	Active	0.09 (n=3)	0.11 (n=7)	**0.12** (n=13)	0.11 (n=23)
	Passive Standby	7.92 (n=3)	8.19 (n=7)	**12.90** (n=13)	10.82 (n=23)
	Off Standby	**15.80** (n=3)	5.72 (n=7)	7.20 (n=13)	7.87 (n=23)
Grill plate	Active	0.00 (n=0)	0.00 (n=1)	0.00 (n=0)	0.00 (n=1)
	Off Standby	0.00 (n=0)	0.00 (n=1)	0.00 (n=0)	0.00 (n=1)
Deep fryer	Active	0.00 (n=0)	0.00 (n=3)	0.00 (n=1)	0.00 (n=4)
	Off Standby	0.00 (n=0)	**0.80** (n=3)	0.58 (n=1)	0.56 (n=4)
Toaster	Active	0.03 (n=4)	**0.04** (n=8)	0.03 (n=11)	0.03 (n=23)
	Passive Standby	0.00 (n=4)	**2.40** (n=8)	0.02 (n=11)	0.90 (n=23)
	Off Standby	**13.71** (n=4)	5.88 (n=8)	12.81 (n=11)	10.41 (n=23)

Appliance type	Power mode	Mean usage (hours per day) of appliance types in the electrical demand group			
		Low (n=5)	**Medium (n=10)**	**High (n=12)**	**All (n=27)**
Slow cooker	Active	0.00 (n=0)	**0.06** (n=1)	0.00 (n=2)	0.02 (n=3)
	Off Standby	0.00 (n=0)	**0.06** (n=1)	0.00 (n=2)	0.02 (n=3)
Steamer	Active	0.00 (n=0)	0.00 (n=1)	**0.01** (n=1)	0.00 (n=2)
	Off Standby	0.00 (n=0)	0.00 (n=1)	**1.99** (n=1)	0.88 (n=2)
Kettle	Active	**0.22** (n=5)	0.19 (n=9)	0.19 (n=12)	0.19 (n=26)
	Off Standby	18.42 (n=5)	**23.44** (n=9)	21.12 (n=12)	21.32 (n=26)
Blender	Active	0.00 (n=1)	0.00 (n=1)	0.00 (n=4)	0.00 (n=6)
	Passive Standby	0.00 (n=1)	0.00 (n=1)	**2.00** (n=4)	0.88 (n=6)
	Off Standby	0.00 (n=1)	0.00 (n=1)	0.00 (n=4)	0.00 (n=6)
Food mixer	Active	0.00 (n=0)	0.00 (n=0)	0.00 (n=1)	0.00 (n=1)
	Off Standby	0.00 (n=0)	0.00 (n=0)	0.00 (n=1)	0.00 (n=1)
Juicer	Active	0.00 (n=1)	0.00 (n=0)	0.00 (n=0)	0.00 (n=1)
	Off Standby	0.00 (n=1)	0.00 (n=0)	0.00 (n=0)	0.00 (n=1)
Food processor	Active	0.00 (n=0)	0.00 (n=0)	0.00 (n=1)	0.00 (n=1)
	Off Standby	0.00 (n=0)	0.00 (n=0)	0.00 (n=1)	0.00 (n=1)
Coffee grinder	Active	0.00 (n=0)	0.00 (n=1)	0.00 (n=0)	0.00 (n=1)
	Off Standby	0.00 (n=0)	0.00 (n=1)	0.00 (n=0)	0.00 (n=1)
Coffee maker	Active	0.00 (n=0)	0.00 (n=1)	0.00 (n=1)	0.00 (n=2)
	Passive Standby	0.00 (n=0)	0.00 (n=1)	**0.89** (n=1)	0.89 (n=2)
	Off Standby	0.00 (n=0)	0.00 (n=1)	0.00 (n=1)	0.00 (n=2)
Ice maker	Active	0.00 (n=0)	0.00 (n=0)	0.00 (n=1)	0.00 (n=1)
Popcorn maker	Active	0.00 (n=1)	0.00 (n=0)	0.00 (n=0)	0.00 (n=1)
	Off Standby	0.00 (n=1)	0.00 (n=0)	0.00 (n=0)	0.00 (n=1)
Can opener	Active	0.00 (n=0)	0.00 (n=2)	0.00 (n=2)	0.00 (n=4)
	Off Standby	0.00 (n=0)	2.41 (n=2)	**4.00** (n=2)	2.67 (n=4)
Knife	Active	0.00 (n=0)	0.00 (n=0)	0.00 (n=1)	0.00 (n=1)
Preservation and cooling					
Refrigerator	Cooling cycle	1.94 (n=3)	**4.10** (n=6)	2.38 (n=4)	2.88 (n=13)
	Non-cooling cycle	9.96 (n=3)	**10.27** (n=6)	4.98 (n=4)	7.84 (n=13)
Fridge-freezer	Cooling cycle	5.62 (n=3	4.56 (n=5)	**5.93** (n=5)	5.37 (n=13)
	Non-cooling cycle	**8.71** (n=3)	7.38 (n=5)	4.03 (n=5)	6.14 (n=13)

Appliance type	Power mode	Mean usage (hours per day) of appliance types in the electrical demand group			
		Low (n=5)	**Medium (n=10)**	**High (n=12)**	**All (n=27)**
Upright freezer	Cooling cycle	2.53 (n=2)	4.48 (n=4)	**5.46** (n=5)	4.58 (n=11)
	Non-cooling cycle	**7.02** (n=2)	4.25 (n=4)	3.74 (n=5)	4.50 (n=11)
Chest freezer	Cooling cycle	0.00 (n=0)	**10.64** (n=7)	3.91 (n=3)	5.68 (n=10)
	Non-cooling cycle	0.00 (n=0)	**4.78** (n=7)	1.63 (n=3)	2.49 (n=10)
Beer and wine cooler	Cooling cycle	0.00 (n=0)	0.54 (n=1)	**0.69** (n=1)	0.51 (n=2)
	Non-cooling cycle	0.00 (n=0)	**1.86** (n=1)	1.30 (n=1)	1.27 (n=2)

7.5.6 Variations in daily use of washing appliances

Table 7-26 shows the average daily use of dishwashers in each power mode for the electrical demand groups. There was zero usage for the medium electrical demand group as none of the medium consumption households in the L27 cohort owned a dishwasher. For the operational power modes, it was observed that dishwashers owned by low electricity consumers were used on average for a longer duration in the washing cycle mode; whereas high consumers' dishwashers were used for longer in the drying cycle mode. In addition, the dishwashers owned by high consumers were found to function in the passive standby mode for a greater duration (7.13 hours) than those owned by the low consumers (3.96 hours) each day.

Table 7-26 Mean appliance daily use in the washing category by power mode and electrical demand group

Appliance type	Power mode	Mean usage (hours per day) of appliance types in the electrical demand group			
		Low (n=5)	**Medium (n=10)**	**High (n=12)**	**All (n=27)**
Dishwasher	Washing cycle	**0.75** (n=1)	0.00 (n=0)	0.43 (n=4)	0.31 (n=5)
	Drying cycle	0.04 (n=1)	0.00 (n=0)	**0.07** (n=4)	0.04 (n=5)
	Passive Standby	3.96 (n=1)	0.00 (n=0)	**7.13** (n=4)	3.64 (n=5)

7.5.7 Variations in daily use of laundry appliances

The laundry appliances' average daily usages in each power mode are shown in Table 7-27. The average daily use of irons was greatest for the medium demand dwellings (0.09 hours), followed by the high (0.08 hours) and then low demand (0.05 hours).

Washing machines owned by the high electrical energy consumers were found to be operated for a longer duration in all of the power modes each day. In the operational modes (water heating and washing cycles) both the low and medium electrical energy consumers were identified as having a similar average daily use. When active, the washing cycle accounted for the greatest proportion of the daily use for washing machines owned by all electrical demand groups. In addition, the average number of hours that washing machines were left in the passive standby modes was observed to increase with overall electricity consumption.

In relation to the five washer-dryer power modes, with the exception of the passive standby mode, the average daily duration of use in each power mode increased with total annual electricity consumption. The number of hours in the passive standby mode was highest for the medium demand group, followed by the high demand. As none of the low electrical energy consumers in the L27 cohort owned a washer-dryer, the hours of use for all power modes were recorded as zero. The washing cycle was again accountable for the largest duration of use for both the medium and high demand dwellings' washer-dryers whilst in operation.

For tumble-dryers the average number of hours used daily on the operational power modes (heating and tumble cycles) increased with electrical demand group. Medium demand dwellings' tumble dryers spent about 1 hour longer each day in the passive standby mode than those owned by the high demand dwellings. The number of hours that tumble dryers were operated in all power modes for low consumers was zero, for the reason that none of the dwellings owned such an appliance. The operational power mode which had the longest duration of use varied between the medium and high demand groups. On average the duration of the heating cycle of tumble dryers owned by medium consumers was larger than the tumble cycle, whereas for high consumers the opposite was observed.

Table 7-27 Mean appliance daily use in the laundry category by power mode and electrical demand group

Appliance type	Power mode	Mean usage (hours per day) of appliance types in the electrical demand group			
		Low (n=5)	**Medium (n=10)**	**High (n=12)**	**All (n=27)**
Iron	Active	0.05 (n=5)	**0.09** (n=10)	0.08 (n=12)	0.08 (n=27)
Washing machine	Water heating cycle	0.04 (n=5)	0.04 (n=10)	**0.11** (n=12)	0.07 (n=27)
	Washing cycle	0.60 (n=5)	0.57 (n=10)	**0.94** (n=12)	0.74 (n=27)
	Passive Standby	8.86 (n=5)	11.58 (n=10)	**12.21** (n=12)	11.36 (n=27)
Washer-dryer	Water heating cycle	0.00 (n=0)	0.02 (n=3)	**0.07**(n=3)	0.04 (n=6)
	Washing cycle	0.00 (n=0)	0.32 (n=3)	**0.54** (n=3)	0.28 (n=6)
	Heating cycle	0.00 (n=0)	0.04 (n=3)	**0.08** (n=3)	0.04 (n=6)
	Tumble cycle	0.00 (n=0)	0.01 (n=3)	**0.10** (n=3)	0.05 (n=6)
	Passive Standby	0.00 (n=0)	**4.12** (n=3)	3.24 (n=3)	2.07 (n=6)
Tumble-dryer	Heating cycle	0.00 (n=0)	0.06 (n=5)	**0.17** (n=5)	0.10 (n=10)
	Tumble cycle	0.00 (n=0)	0.02 (n=5)	**0.21** (n=5)	0.10 (n=10)
	Passive Standby	0.00 (n=0)	**7.33** (n=5)	6.35 (n=5)	5.54 (n=10)

7.5.8 Variations in daily use of building and outdoors maintenance appliances

Table 7-28 displays the average number of hours per day that the monitored appliances in the building and outdoors maintenance category were used by the different electrical demand groups. Vacuum cleaners were the only devices in this category that were owned by households in all electrical demand groups. The active duration of use on vacuum cleaners was however found to be similar for all electrical demand groups.

Households in the low electrical demand group were observed to have a higher active usage on door bells and pest alarms compared to the other demand groups. Whereas medium demand dwellings had a greater use on security systems, plug in air fresheners, utility meters, outdoor aquariums and battery chargers. High electrical energy consumers on average used only automatic door openers and indoor aquariums in the active power mode for longer than their low and medium demand counterparts.

Table 7-28 Mean appliance daily use in the building and outdoors maintenance category by power mode and electrical demand group

Appliance type	**Power mode**	**Mean usage (hours per day) of appliance types in the electrical demand group**			
		Low (n=5)	**Medium (n=10)**	**High (n=12)**	**All (n=27)**
Vacuum cleaner	Active	0.02 (n=8)	0.04 (n=12)	0.04 (n=14)	0.03 (n=34)
	Off Standby	**5.37** (n=8)	3.25 (n=12)	2.98 (n=14)	3.59 (n=34)
Security systems (Alarm)	Active	0.00 (n=0)	**2.40** (n=1)	2.01 (n=2)	1.78 (n=3)
Plug in air freshener	Active	0.00 (n=0)	**0.01** (n=2)	0.00 (n=0)	0.01 (n=2)
	Off Standby	0.00 (n=0)	**0.05** (n=2)	0.00 (n=0)	0.02 (n=2)
Door bell	Active	**4.78** (n=1)	0.00 (n=0)	1.99 (n=1)	1.77 (n=2)
Utility meters	Active	0.00 (n=0)	**2.40** (n=1)	0.00 (n=0)	0.89 (n=1)
Automatic door opener	Active	0.00 (n=0)	0.00 (n=0)	**1.98** (n=1)	0.88 (n=1)
Saw	Active	0.00 (n=0)	0.00 (n=1)	0.00 (n=1)	0.00 (n=2)
	Off Standby	0.00 (n=0)	1.86 (n=1)	**1.99** (n=1)	1.57 (n=2)
Sander	Active	0.00 (n=0)	0.00 (n=0)	0.00 (n=1)	0.00 (n=1)
Sewing machine	Active	0.00 (n=1)	0.00 (n=0)	0.00(n=0)	0.00 (n=1)
Electric lawn mowers	Active	0.00 (n=1)	0.00 (n=8)	0.00 (n=7)	0.00 (n=16)
	Off Standby	0.00 (n=1)	0.85 (n=8)	**1.99** (n=7)	1.20 (n=16)
Indoor aquarium	Active	0.00 (n=0)	2.40 (n=1)	**2.74** (n=3)	2.13 (n=4)
	Off Standby	0.00 (n=0)	0.00 (n=1)	**1.45** (n=3)	0.67 (n=4)
Outdoor aquarium	Active	0.00 (n=0)	**2.38** (n=1)	1.99 (n=1)	1.77 (n=2)
	Off Standby	0.00 (n=0)	0.00 (n=1)	0.00 (n=1)	0.00 (n=2)
Battery chargers	Active	0.00 (n=0)	**4.20** (n=2)	0.01 (n=1)	1.56 (n=3)
	Off Standby	0.00 (n=0)	0.60 (n=2)	**1.98** (n=1)	1.10 (n=3)
Pest alarms	Active	**4.80** (n=1)	0.00 (n=0)	1.99 (n=1)	1.78 (n=2)

7.5.9 Variations in daily use of hygiene, beauty and leisure appliances

Table 7-29 shows the average daily usage of hygiene, beauty and leisure appliances. In general, it was observed that there was very little variation in the number of hours that appliances in this category were operated in the active power mode between any of the electrical demand groups. Low demand dwellings had an increased duration of use in the active mode on the appliance type’s toothbrush and medical, medium demand dwellings on shavers, and higher demand on hair dryers and hair straighteners. These latter two appliance types when owned by low consumers spent on average a greater amount of time in the off standby power mode, in comparison to those owned by households in the other two demand groups. Massagers were not operated in the active or off standby power modes by any of the electrical demand groups, although such devices possessed by high consuming dwellings had a greater average passive standby use of 1.99 hours per day compared with zero for the low and medium consuming dwellings.

Table 7-29 Mean appliance daily use in the hygiene, beauty and leisure category by power mode and electrical demand group

Appliance type	Power mode	Mean usage (hours per day) of appliance types in the electrical demand group			
		Low (n=5)	**Medium (n=10)**	**High (n=12)**	**All (n=27)**
Electric shower	Active	-	-	-	-
Hair dryer	Active	0.01 (n=3)	0.01 (n=5)	**0.07** (n=8)	0.04 (n=16)
	Off Standby	**9.51** (n=3)	4.65 (n=5)	3.06 (n=8)	4.78 (n=16)
Hair straighteners	Active	0.02 (n=1)	0.01 (n=3)	**0.04** (n=3)	0.02 (n=7)
	Off standby	**4.75** (n=1)	2.21 (n=3)	0.09 (n=3)	1.75 (n=7)
Hot air styler	Active	0.00 (n=0)	0.00 (n=1)	0.00 (n=0)	0.00 (n=1)
	Off Standby	0.00 (n=0)	0.00 (n=1)	0.00 (n=0)	0.00 (n=1)
Hair clippers	Active	0.00 (n=0)	0.00 (n=1)	0.00 (n=0)	0.00 (n=1)
	Off Standby	0.00 (n=0)	0.00 (n=1)	0.00 (n=0)	0.00 (n=1)
Shaver	Active	0.00 (n=0)	**0.34** (n=1)	0.08 (n=1)	0.16 (n=2)
	Off Standby	0.00 (n=0)	0.00 (n=1)	**1.92** (n=1)	0.85 (n=2)
Massager	Active	0.00 (n=0)	0.00 (n=0)	0.00 (n=1)	0.00 (n=1)
	Passive Standby	0.00 (n=0)	0.00 (n=0)	**1.99** (n=1)	0.88 (n=1)
	Off Standby	0.00 (n=0)	0.00 (n=0)	0.00 (n=1)	0.00 (n=1)
Toothbrush	Active	**0.28** (n=1)	0.05 (n=1)	0.00 (n=0)	0.07 (n=2)
Medical	Active	**4.78** (n=1)	0.00 (n=0)	0.00 (n=0)	0.88(n=1)

7.5.10 Summary of variations in daily use of domestic appliances

Section 7.5 has demonstrated the differences in average daily use of domestic appliances in each power mode in relation to electrical demand group. Table 7-30 provides a summary of the appliance power modes which had the longest daily use when owned by high electricity consumers.

Table 7-30 Summary of appliance power modes which had the longest daily use when owned by high electricity consumers

Appliance categories	**Power modes**				
Office equipment and infotainment					
Desktop	A	AS*	PS	OS	
Laptop	A	AS*	PS	OS	
Printer		AS		OS	
Wireless router	A				
LCD Television	A			OS	
Digital Set Top Box	A				
Satellite Set Top Box				OS	
Cable Set Top Box	A				
Internet Set Top Box	A	AS			
DVD	A	AS			
VCR			PS		
Blu-ray player				OS	
DVD with VCR			PS		
Portable digital radio				OS	
Portable analogue radio			PS		
Personal CD player		AS	PS		
MP3 docking station		AS	PS		
Video console			PS	OS	
Non-fixed lighting					
Incandescent	A				
HVAC					
Electric fire	A			OS	
Electric blanket	A			OS	
Portable halogen radiator	A			OS	
Portable oil filled radiator	A			OS	
Transportation					
Mobility scooter	A			OS	
Golf trolley	A				
Chair lift	A			OS	
Catering					
Microwave	A		PS		
Steamer	A			OS	
Blender			PS		
Coffee maker			PS		
Can opener				OS	
Fridge-freezer					C

Appliance categories	Power modes								
Upright freezer				C					
Beer and wine cooler				C					
Washing									
Dishwasher		PS			D				
Laundry									
Washing machine		PS				W	WH		
Washer-dryer						W	WH	H	T
Tumble-dryer								H	T
Building and outdoors maintenances									
Automatic door opener	A								
Saw			OS						
Electric lawn mowers			OS						
Indoor aquarium	A		OS						
Hygiene, beauty and leisure									
Hair dryer	A								
Hair straighteners	A								
Shaver			OS						
Massager		PS							

Note: (A) Active; (AS) Active standby; (PS) Passive standby; (OS) Off standby; (C) Cooling cycle;(D) Drying; (W) Washing cycle; (WH) Water heating cycle; (H) Heating cycle; (T) Tumble cycle.
* The values for the active standby mode for computers represent a combined active/passive standby mode

7.6 Uncertainty in results presented in Chapter 7

The main uncertainty in the results presented in Chapter 7 relates to the range of months in which the domestic appliances were monitored in the L27 homes. The L27 homes were monitored for periods of around one month between 11th July 2011 and 14th December 2011, thus spanning summer, autumn and winter. Whilst little seasonal variation has previously been identified for domestic electrical appliances (EST 2012), some of the appliances for which results are presented in this chapter clearly have strong seasonality in usage and thus electricity consumption. This is likely to be applicable to all of the HVAC appliance results, as well as for the lawn mower, washer-dryer and tumble dryer. The electricity consumption and hours of use for the non-fixed lighting appliances will also be affected by seasonal variation. The magnitude of the imprecision is however likely to be negated by the fact that both the mean electricity consumption and usage values are calculated based on a sample of homes in each electrical demand group that were collected spanning all three seasons (i.e. the months of appliance monitoring for the low demand group spanned the summer to winter period).

In relation to the results for appliance power demand, reasonable confidence can be placed on those results calculated with a large sample of appliances, however care should be taken over those based on single or few appliance samples. In addition, the results for hours of use per day can be considered more reliable for those appliances which the usage does not relate to occupant operation (e.g. refrigerator, fridge-freezer, indoor aquarium etc.).

A second source of uncertainty relates to the sampling error in the low, medium and high electrical demand group sample sizes. Using the software G*Power (Faul et al. 2007) the sampling error was estimated at 43.8% for the low demand, 31% for the medium demand and 28.3% for the high demand groups at the 95% confidence interval. These results are significantly higher than the typically acceptable margin of between 4% and 8%, meaning that should another equally sized random sample of dwellings been drawn from the population the results could vary. In the combined sample of homes (n=27) the sampling error is reduced to 18.9%, but still higher than would be desirable.

Further research is required on a larger sample size to validate the electricity consumption, ownership, power demand and use values presented in Chapter 7.

7.7 Chapter 7: Summary

This chapter has described the variations in annual appliance electricity consumption between electrical demand groups. It has also investigated the three factors that are responsible for variations in annual appliance electricity consumption: appliance ownership; power demands in each power mode; and duration of use in each power mode. The results relating to these three factors have been presented individually in this chapter, but in Chapter 8, Section 8.4, these will be combined to explain why variations in annual electricity consumption on domestic appliances occurred between the electrical demand groups. An overview of the key results in this chapter are:

- High electrical energy consumption results from a range of domestic appliances operated in various power modes. These appliances span the entire appliance categories investigated (see section 7.2.10).
- The high electrical demand group had higher ownership rates of particular domestic appliance types compared with the low and medium electrical demand groups (see section summary 7.3.11).

- Some domestic appliance types owned by households in the high electrical demand group had higher average electrical power demands in certain power modes compared with those owned by households in the low or medium demand groups (see section summary 7.4.10).
- Households in the high electrical demand group were found to use certain appliance types for a longer duration each day compared to those in the low or medium demand group (see section summary 7.5.10).

Chapter 8

Discussion

8.1 Introduction

This chapter summarises the findings that emerged from the research presented in this thesis in relation to the research questions proposed in Chapter 4. The discussion starts with a description of the main findings from the analysis undertaken on the skewed electricity distributions of the L315 and L27 cohorts and their changes in demand overtime (section 8.2). A summary of the socio-economic, technical and appliance related factors contributing to high electrical energy demand identified in the odds ratio analysis are then outlined (section 8.3). The key findings from the Appliance Electricity Use Survey (AEUS) assessing the impact of ownership, power demand and use of different domestic appliances on high electricity use are presented (section 8.4). Finally, opportunities to reduce the electricity use of high electrical energy consumers in the UK domestic sector are offered with consideration of the research findings (section 8.5). The current findings are compared with results from earlier research and relevant literature.

8.2 Discussion 1: The skewed electricity distribution and changes in demand over time

To answer the following research questions, an analysis of the electricity use of the L315 and L27 cohorts was undertaken using data collected from the 4M LIL electricity meter reading and 4M energy supplier annual electricity use follow ups. In addition, the reasons expressed by the occupants of the L27 homes in the AEUS unstructured interviews are considered.

1. Does a sample of UK households demonstrate that large variations in electrical energy demand exist between homes?
2. Is the electricity consumption of a sample of UK households with high electrical energy demand increasing over time?

Chapter 5 presented the results which address research questions 1 and 2. This included analyses of the annual electricity use distributions of the L315 and L27 household samples and the changes in annual electricity use of the low, medium and high demand groups of the L315 and L27 samples over time.

In this research, large variations in annual electricity consumption were observed amongst households in both the L315 and L27 samples. In 2009, the lowest annual electricity use of the L315 homes was 259 kWh and the highest was 25,587 kWh. The lowest annual electricity consumption of the L27 homes was 1,355 kWh and the highest was 9,627 kWh.

It was found that the electricity demands of the two cohorts were highly skewed towards high electrical energy consumers. The highest consuming 27% of the L315 dwellings used more electricity than the remaining households combined. The high electricity demand group of the L315 homes not only accounted for more than half (57%) of the electricity used by the sample in 2009 (1,895 kWh/day), but used three times more electricity than the low demand group (499 kWh/day) and double that of the medium demand group (930 kWh/day). In addition, the collective annual electricity use of the ten highest demand L27 homes used more electricity than the remaining seventeen homes combined.

These results support the observations of previous UK electricity use studies that concluded that a skewed electricity distribution towards high electricity consumers in the domestic sector exists (Coleman et al. 2012; DECC 2011; Summerfield et al. 2010; Firth et al. 2008; Summerfield et al. 2007; Zimmermann et al. 2012). The skewed electricity consumption distribution evident in this current study is similar to those reported elsewhere. Summerfield et al. (2007) identified that the high energy group in their study of fourteen dwellings in Milton Keynes in 2005 used an identical 57% of the electricity supplied to all of the homes, and the group's consumption was three times greater than the low energy and double that of the middle energy groups.

Previous studies have also recognised that the electricity demands of the highest consuming domestic properties are not only larger, compared with others, but are also increasing over time (Summerfield et al. 2010; Firth et al. 2008; Summerfield et al. 2007). The current study investigated this phenomenon using the annual electricity consumption data of the L315 and L27 cohorts. The year-on-year percentage changes in mean electricity consumption of the three electricity demand groups were examined from 2007 to 2009 for the L315 and 2007 to 2011 for the L27 cohorts. In this research, conflicting results were obtained for the two samples; the L315's high demand group reduced mean electricity use by 3.9%, whereas the L27's high demand group increased mean electricity use by 16.6%. Although a definitive empirical result regarding the trend in electricity use of high electricity consumers over time cannot be drawn, the results gained do have some implications for consideration.

Firstly, with the exception of the L315's low demand group, the mean annual electricity consumption of all other electricity demand groups for both the L315 and L27 cohorts fluctuated between increasing and decreasing electricity use over time. This result is important as it highlights the need to study the changes in electricity use of domestic buildings longitudinally. For example, the mean electricity demand of the L315's high demand group reduced by 13.1% from 2007 to 2008, but subsequently increased by 10.6% between 2008 and 2009. In this case, by observing the changes in demand between only two consecutive years, the conclusion could be that the high demand group are either greatly decreasing or increasing electricity use, rather than over a three year period the electricity use is relatively stable. This concern could be drawn when considering the 5.1% increase in electricity use for the high energy group observed by Firth et al. (2008) over a two year monitoring period. For this reason, although the L27 cohort was much smaller than the L315, the conflicting results attained, cannot be disregarded, as the changes in electrical demand were observed over a five year compared to three year period.

Secondly, a possible issue of sample size was evident in the contradictory results offered by the L315 and L27 cohorts. As the L27 was a sub sample of the L315, it might have been anticipated that similar changes in annual electricity use would have been observed for the three demand groups in both samples. In reality, comparing the overall changes in electricity demand between 2007 and 2009 for the same electrical demand group in each sample, it was found that whilst the results for the low electrical demand group were quite similar (L315= +43.6%; L27= +40.1%), the results for the medium (L315= +3%; L27= -1.7%) and high electrical demand groups (L315= -3.9%; L27= +18.3%) were not. The L315 cohort is currently the largest sample of UK properties for which the changes in electrical demand over time have been reported. As the results from this cohort do not support the claim that high consumers are increasing electricity use with time, the findings of previous studies (Summerfield et al. 2010; Firth et al. 2008; Summerfield et al. 2007) as well as the L27 using much smaller sample sizes (between 14 and 72 dwellings), should be treated with care. Substantial research is required to generate statistically representative long-term trends in electricity use for the whole UK housing stock, particularly if it is to be supported by monitored data rather than by the results of technical models.

The results of the L315 homes indicated that high electricity consumers might be slightly reducing electricity demand over time, opposing the suggestions of previous researchers (Summerfield et al. 2010; Firth et al. 2008; Summerfield et al. 2007). Although, the decrease in electrical demand between 2007 and 2009 observed was not statistically significant, the general trend in electricity use for the group was in decline. Apart from the effects of study duration and sample size previously mentioned, distinct contextual factors of the earlier studies may have contributed to this different outcome: Summerfield et al.'s (2010; 2007) conclusions were drawn based on monitoring data collected from low-energy dwellings in Milton Keynes Energy Park, whilst Firth et al.'s (2008) sample of homes were modestly sized social housing which were only occupied from 1–3 years before monitoring began.

The low-energy dwellings investigated by Summerfield et al. (2010; 2007) had higher standards of energy performance than were required by the building regulations when built in the late 1980s. Although, these homes may not be classifiable as low-energy by current building standards, the sample examined were unique new build properties, excluding the older UK housing stock. The occupants choosing to live in a new low energy home may also vary in characteristics (e.g. higher incomes, young urban professionals) and attitudes (e.g. energy conscious) to the general population, which might have carried implications for the results obtained.

The Milton Keynes homes were initially monitored for electricity use in 1990 and a follow up study was undertaken in 2005-2007. The conclusion that high consuming dwellings are increasing electricity demand over time was established based on an observed increase in electricity use between 1990 and 2005-2007 for the homes that were classified as high consumers in 1990. During the fifteen year period, the authors did not record changes in the dwelling and occupant characteristics, as well as the ownership of electrical appliances. Therefore a comparison of the electricity use of the homes in 1990 and 2005-2006 was perhaps like comparing two very different types of dwellings.

The period investigated by Summerfield et al. (2010; 2007) also coincided with a significant expansion in the electricity used to power domestic appliances (DECC 2012). The results attained may indicate that households in the high energy group were more inclined to purchase and use appliances compared to the low and middle energy groups, thereby explaining the increased electricity use observed. However, at present the annual growth in appliance electricity use appears to be slowing (DECC 2012), associated with improvements in technical efficiency and improved occupant behaviour, therefore, it could be that the previous trends in electricity use observed amongst high consumers between 1990 and 2005-2007 are no longer suitable to describe the current situation.

Firth et al. (2008) conceded in their study of modestly sized social housing that it would be unwise to draw sweeping conclusions from the analysis undertaken and make strong statements concerning policies to reduce the CO_2 emissions in the UK housing stock. This acknowledgment was due to the distinct group of occupants residing in the dwellings and a suggestion that changes in electricity use could well have been because the houses were relatively new and the occupants were still in the process of furnishing their new homes with new or replacement appliances.

Although the current study found conflicting evidence that high electricity consumers are increasing their electrical energy demand over time, perhaps more worryingly both the L315 and L27 cohorts identified that the low and medium demand groups were increasing consumption with time. The 38.7% increase between 2007 and 2009 for the L315's low demand group was statistically significant at the 5% level. Despite the lack of statistical significance for some of the group trends, overall it would appear that the groups are contracting variances in electricity use, but rather than the ideal situation where high consumers reduce their consumption to a lower level, instead the low and medium demand dwellings are becoming higher electricity consumers. The observed increase in electricity use by the low demand group was consistent with earlier research: Summerfield et al. (2010) recorded a 34.4% increase in mean electricity use from 6.4 kWh/day in 1990 to 8.6 kWh/day in 2005-2007; Firth et al. (2008) found a 67.9% mean increase from 1,170 kWh to 1,964 kWh per annum; and Summerfield et al. (2007) stated a 20.6% growth in mean electricity use from 6.3 kWh in 1990 to 7.6 kWh per day in 2005.

The overarching message of the current analysis has been to reaffirm the impact of the skewed distribution of domestic electricity use towards high electrical energy consumers. Unfortunately, a conclusive experimental result was not obtained to confirm that high electricity users are also increasing their electricity demand over time. Despite the lack of statistical power for the L27 cohort, the current analysis has provided insights into the changes in electricity use of two samples of UK homes over a three and five year time period. The results obtained strongly establish the need for a future longitudinal study of the changes in electricity use of a statistically representative sample of UK households, linked to modifications in the social, technical and behavioural characteristics of the homes.

The findings from both samples also demonstrate that the trends in electricity use of the three electrical demand groups varied in percentage of increase and decrease over time. These results question the common use of average values to present national trends in domestic electricity use and for the development of energy policy. It could therefore be beneficial if future electricity-related statistics were stratified by the overall electricity consumption of the dwellings.

Given that the most effective means of reducing energy and CO_2 emissions from the residential sector need to urgently be identified, the results showing the impact of the skewed distribution of electricity use towards high consumers supports previous recommendations that energy policy and energy research, might target those parts of the housing stock where electricity use is highest.

Table 8-1 provides a summary of the key findings relating to research questions 1 and 2.

Table 8-1 Summary of key findings: Research questions 1 and 2

Key findings
▪ A skewed electricity distribution towards high electricity consumers in the domestic sector exists. ▪ Large variations in annual electricity consumption were observed amongst households in both the L315 and L27 samples. ▪ The electricity demands of the two cohorts were highly skewed towards high electrical energy consumers. ▪ The highest consuming 27% of the L315 dwellings used more electricity than the remaining households combined. ▪ The collective annual electricity use of the ten highest demand L27 homes used more electricity than the remaining seventeen homes combined. ▪ The high electricity demand group of the L315 homes not only accounted for more than half (57%) of the electricity used by the sample in 2009 (1,895 kWh/day), but used three times more electricity than the low demand group (499 kWh/day) and double that of the medium demand group (930 kWh/day). ▪ Conflicting results were obtained from the two samples assessing whether high electricity consumers are increasing electrical energy demand over time. ▪ The L315's high demand group reduced mean electricity use by 3.9% between 2007 and 2009. ▪ The L27's high demand group increased mean electricity use by 16.6% between 2007 and 2011. ▪ With the exception of the L315's low demand group, the mean annual electricity consumption of all other electricity demand groups for both the L315 and L27 cohorts fluctuated between increasing and decreasing electricity use over time. This result highlights the need to study changes in electricity use of domestic buildings longitudinally. ▪ Low and medium demand dwellings are becoming higher electricity consumers over time. Both the L315 and L27 cohorts identified that the low and medium demand groups were increasing consumption with time. ▪ The results obtained strongly establish the need for a future longitudinal study of the changes in electricity use of a statistically representative sample of UK households, linked to modifications in the social, technical and behavioural characteristics of the homes. ▪ The results question the common use of average values to present national trends in domestic electricity use and for the development of energy policy. It might be beneficial if future electricity-related statistics were stratified by the overall electricity consumption of the dwellings. ▪ The results support previous recommendations that energy policy and energy research might target those parts of the housing stock where electricity use is highest.

8.3 Discussion 2: The socio-economic, technical and appliance related factors contributing to high electrical energy demand

The effects of the socio-economic, technical and appliance related characteristics of UK homes on the probability of being a high electricity consumer were investigated using an odds ratio analysis to answer the following research question:

3. Which socio-economic, technical and appliance factors contribute to high electrical energy demand in a sample of UK households?

The odds ratios (OR) obtained are a representation of the likelihood that a household will have a high electrical energy demand, given an exposure to a specific socio-economic, technical or appliance related characteristic. The ORs can also be used to compare the change in probability of a household being a high electricity consumer based on a change in the household characteristics, for example, if the number of occupants increases from two to three.

Chapter 6 presented the results of the odds ratio analysis which addresses research question 3.

8.3.1 Socio-economic characteristics

In this study, the influence of nine socio-economic characteristics were explored: number of occupants; presence of children; number of teenagers; age, employment status, education level and national statistics socio-economic classification of the household representative person (HRP); tenure; and annual household income.

The number of occupants residing in a dwelling was established to increase the probability of a dwelling being a high electricity consumer. In comparison to two occupant households, single occupant homes are significantly less likely to be high electrical energy consumers, whereas, homes with three or more occupants are more than twice as likely to be high users. The positive relationship observed between the number of occupants and domestic electricity consumption is consistent with a wide number of previous studies (Zhou & Teng 2013; Kavousian et al. 2013; Brounen et al. 2012; Ndiaye & Gabriel 2011; Leahy & Lyons 2010; Baker & Rylatt 2008; Druckman & Jackson 2008; Yohanis et al. 2008; Summerfield et al. 2007; Tso & Yau 2007; Bartiaux & Gram-Hanssen 2005; Genjo et al. 2005; Gram-Hanssen et al. 2004; Parker 2003; Halvorsen & Larsen 2001; Tiwari 2000; Haas 1997). Specifically, Leahy & Lyons (2010) also established that households occupied by only one person, consume significantly less electricity than households with two or more occupants.

The increased likelihood of high electrical energy demand amongst houses with more occupants might result from an increased use of multiple appliances and lights at the same time. In addition, homes with larger numbers of occupants may have a greater appliance stock attributed to the fact that households with more than two occupants are likely to comprise children and teenagers who tend to have a wider ownership of IT and entertainment appliances as well as multiple ownership of some appliances such as TVs and computers. It was observed in the OR results that both the total number of electrical appliances owned, along with the ownership of IT and entertainment appliances specifically, has a significant positive effect on the probability of being a high electricity consumer.

Furthermore, a greater household size may affect the use of some appliances, like washing machines, tumble dryers, dishwashers and electric showers. Households with more occupants will understandably generate more dirty laundry and dishes each week and require more showers for personal hygiene. Although, the OR results attained in this study show no clear impact of the loads of dishwashing per week, the loads of clothes washing and drying, as well as the number of electric showers per week increased the chance of high electricity consumption at various weekly usage levels.

Two factors associated with the total number of occupants were the presence of children and number of teenagers. Compared to homes without any children, the significant OR results showed that those with at least one child are more than twice as likely to be high electricity consumers. The OR results also indicated that households with teenagers living in them are significantly more likely to be high electrical energy consumers than those without any. Dwellings with either one or two teenagers are more than three times more likely to be high consumers than dwellings with no teenagers.

The presence of children and its significant positive influence on electricity consumption has previously been identified by McLoughlin et al. (2012), Brounen et al. (2012), Wiesmann et al. (2011) and Nielsen (1993). In addition, the significantly increased electricity consumption amongst homes with teenagers has been reported in number of earlier studies (Bartusch et al. 2012; Bartiaux & Gram-Hanssen 2005; Gram-Hanssen et al. 2004).

The higher probability of high electrical energy consumption amongst residential buildings with children and teenagers can probably be attributed to many of the potential factors mentioned for the number of occupants, such as the increased ownership and use of specific domestic appliances. Wiesmann et al. (2011) and Nielsen (1993) also believe this to be the case, stating that older children watch more television, use personal computers, and are frequent users of gaming devices.

In addition, children and teenagers are perhaps less conscious of the electricity they use because they have no association with the energy bill and are also disconnected from the financial implications of a higher electrical energy demand. This lack of knowledge possessed by children and teenagers might therefore manifest itself in higher electricity consumption compared to adult only homes.

The OR results for the age of the Household Representative Person (HRP), which is the age of the highest income earner in the household, indicated that only dwellings with a HRP over 65 years old are significantly less likely to be high electricity consumers. All other HRP age bands are just as likely to be high consumers as those with a HRP aged between 36 and 50.

In line with the current findings, previously, Leahy & Lyons (2010) found that household electricity use decreases significantly with a HRP aged over 64 years old. Yohanis et al. (2008) identified those dwellings with HRPs older than 65 years old use the smallest amount of electricity and Kavousian et al. (2013) revealed that HRPs older than 55 have lower electricity consumption.

The lower probability of dwellings with a HRP over 65 years old being high consumers might be attributed to the fact that the occupants could be retired and may have less disposable income than working families. Consistent with this suggestion, it was also noted in the OR results that dwellings with a retired HRP are significantly less likely to be high consumers than those with an employed HRP. In addition, households with a HRP over 65 probably have fewer occupants as any children have grown up and moved on. McLoughlin et al. (2012) stated the reverse as a reason for higher consumption amongst homes with middle aged HRPs. Moreover, houses with an older HRP may well own less electrical appliances, in particular those associated with a younger generation, such as video consoles and computers. Interestingly, Yohanis et al. (2008) claims that the HRP also dictates a household's energy using behaviour, which has an influence on the electricity consumption. Thereby, dwellings with fewer occupants maybe more inclined to consistently follow the energy efficient behaviour encouraged by a HRP.

The current result counters Zhou & Teng (2013)'s assertion that households with HRPs older than 50 years old consume more electricity than other HRP age ranges because old people generally stay at home longer than young people. The variation in result may relate to the significant cultural differences in the mobility and lifestyles of older people in the UK and China.

The employment status of the HRP was only found to affect the likelihood of a dwelling being a high consumer if the HRP was retired. Homes with a retired HRP are significantly less likely to have high electrical energy demand than those with an employed HRP. Earlier research studies (McLoughlin et al. 2012; Leahy & Lyons 2010; Baker & Rylatt

2008; Yohanis et al. 2008; Cramer et al. 1985) however have consistently found that the employment status of the HRP has no significant effect on domestic electricity use.

The reduced probability of high consumption among houses with a retired HRP can be explained using many of the same reasons suggested for the effect observed for households with a HRP over 65 years old. It should be noted that although Yohanis et al. (2008) did not find any significant effect of the HRP's employment status on electricity consumption, it was observed that homes that were occupied during the day by retired people had generally smaller electricity consumptions than homes unoccupied during the day.

The education level of the HRP was established to have no effect on the probability of a household being a high electricity consumer. Households with a HRP with an education below degree level are similarly likely to be high consumers as those with a HRP with a degree education or higher. This finding is coherent with the results published by Bedir et al. (2013), McLoughlin et al. (2012), and Leahy & Lyons (2010). This result is perhaps understandable as there is no obvious link between education level and domestic electricity use.

It could be suggested that households with a HRP with a degree education or higher may have a greater electricity demand because a degree level education could elevate their socio-economic classification and consequent income earning potential resulting in less need to be energy efficient. This may well be the case in the work undertaken by Zhou & Teng (2013) in China, which recognised that families with higher education have higher electricity consumption.

At the same time, a higher level education could be associated with a broader desire for knowledge, whereby the occupants of homes with a HRP with a degree education or higher might be more aware of energy and environmental issues and take action to reduce their electricity demand.

Any possible effect of HRP education level on electricity use might also be degraded by the likely mixed education levels amongst adults and children residing in the same home.

The current result also varies from the conclusions of Gram-Hanssen et al. (2004) which state that mean domestic electricity consumption decreases significantly with the level of education in Denmark. Households that were occupied by family members with a long education appeared to use significantly less electricity than households occupied by family members with no further education than primary school. This alternative finding could relate to the fact that the current study only investigated two stages of education, above or below degree level and should a more refined representation of education level, including primary and high school have been introduced a different result may have possibly emerged.

The National Statistics Socio-economic Classification of the HRP has no clear influence on the likelihood of high domestic electricity demand. All socio-economic classifications of the HRP were similarly likely to be high consumers. This outcome on one hand is consistent with the findings of Leahy & Lyons (2010) who reported that socio-economic status does not significantly affect electricity use, but on the other hand, contrary to McLoughlin et al. (2012) and Cramer et al. (1985) who observed that the social group of the HRP does have a significant effect on electricity use.

Specifically, McLoughlin et al. (2012) and Cramer et al. (1985) revealed that the HRP's socio-economic classification has a negative effect on total electricity consumption, with higher professionals consuming more electricity than lower professionals. The previous researchers established that the former tend to live in larger dwellings and have a greater number of electrical appliances, suggesting a possible income effect.

This current finding is therefore perhaps unexpected, as it could be hypothesised that the HRPs' occupation would be indicative of the annual household income, which was shown in the OR analysis to affect the likelihood of being a high electrical energy consumer. This relationship may not have emerged however, because households may have multiple incomes such that two occupants working in routine occupations could earn as much as one occupant working in a managerial occupation.

The way in which occupants occupy their dwelling does not affect the possibility of being a high electricity user. All dwelling tenure types: own house outright, buying house with mortgage and rented or rent free, are just as likely to be high or low consumers. Other earlier studies have also concluded that tenure type has no significant effect on electricity use (Bedir et al. 2013; Kavousian et al. 2013; Leahy & Lyons 2010; Tso & Yau 2007).

However, some studies have previously observed a significantly higher consumption in privately owned houses (Hamilton et al. 2013; Wiesmann et al. 2011; Yohanis et al. 2008). Hamilton et al. (2013) determined that owner occupied dwellings use 25% more electricity than rented houses. Yohanis et al. (2008) established that privately owned houses have a significantly higher electricity demand profile than rented homes. The authors credited the effect to the fact that in Northern Ireland the majority of rented accommodation is social housing, rented by lower income families. This previous finding is however less applicable to the current study as the case study city of Leicester has a large stock of privately rented houses (22.7%) (ONS 2010).

In addition, Wyatt (2013) observed that council housing and housing association homes have the lowest average consumption of electricity and owner-occupied households the highest, whilst, privately rented homes are in the middle. The author states that tenure is likely to be correlated with wealth and that rented properties are generally smaller than privately owned dwellings. Unfortunately, the present study was unable to distinguish between social and privately rented homes and therefore no indication of whether any effect on the probability of high electricity consumption was established. Hamilton et al. (2013) did however find that electricity demand of private rental dwellings was very similar to social rentals. Furthermore, the low number of homes (16 dwellings) in this current study with electric heating as their primary form of heating possibly mitigated for the differences in floor area between tenure types as suggested.

Contrary to the other studies, Ndiaye & Gabriel (2011) identified a higher electricity use in rented rather than owned houses. The authors attributed this effect to utility bills being included in the rent, so renters do not necessary pay the extra cost associated with excessive electricity consumption and have less incentive to save energy. Although, this may be the case in Canada, in the UK with the exception of student rentals, the vast majority of occupants of both social and private rental properties are responsible for the payment of their energy bill perhaps explaining the variation in findings.

Households with a higher annual income are more likely to be high electrical energy users. Households with an annual income between £20,000 and £50,000 and greater than £50,000 are significantly more likely to be high consumers than those earning less than £20,000. This finding agrees with a large number of previous studies that have also concluded that electrical energy consumption increases with income (Zhou & Teng 2013; Bedir et al. 2013; Carlson et al. 2013; Wyatt 2013; Wiesmann et al. 2011; Louw et al. 2008; Yohanis et al. 2008; Santamouris et al. 2007; Summerfield et al. 2007; Bartiaux & Gram-Hanssen 2005; Genjo et al. 2005; Gram-Hanssen et al. 2004; Halvorsen & Larsen 2001; Tiwari 2000; Lam 1998; Haas 1997; Cramer et al. 1985; Parti & Parti 1980).

The increased likelihood of high electrical energy demand amongst houses with higher annual incomes might result from an increased ownership and use of domestic electrical appliances due to greater financial freedom to initially purchase and continue to pay for the energy required to power their use. This suggestion is also raised by Carlson et al. (2013), Yohanis et al. (2008), Santamouris et al. (2007) and Haas (1997).

In addition, households with a higher income are perhaps also more inclined to purchase new and high end appliances. Whilst the energy performance of appliances has increased in recent years, hinting that occupants with newer appliances should achieve a reduction in electricity use, this potential saving has widely been offset by an increase in the size of appliances, for example LCD TVs and American style fridge-freezers. These larger ‘power hungry’ appliances tend to be higher end devices with higher price tags, which are consequently more likely to be purchased by households with a high income and therefore may explain a greater chance of high electricity consumption.

Moreover, families with higher annual incomes more commonly have larger homes. If these dwellings are electrically heated this would explain the higher electricity consumption observed, although this is unlikely to be the case in this instance as there are few electrically heated dwellings in this study. A larger home does nonetheless increase the potential number and size of appliances that can be owned by a household, for example, bigger kitchens may have the additional space required to accommodate a dishwasher or a separate tumble dryer, which are both shown in this study to increase the probability of high consumption. Also, larger homes almost certainly have more lights and a consequent increased potential for electricity use.

Yohanis et al. (2008) proposes that households with larger incomes also have a greater number of occupants. Whilst on the surface this suggestion may seem rational as these homes have greater finances to support having more children, in reality, the opposite trend appears to be occurring in the UK, where richer families have fewer children and poorer families more.

8.3.2 Technical characteristics

In this study, the effects of ten technical characteristics were investigated: dwelling type; the period in which the dwelling was built; the number of bedrooms; the number of floors; the total floor area; presence of electric space heating; presence of fixed electric heating; presence of portable electric heating; presence of electric water heating; and proportion of low-energy lighting.

With the exception of mid-terrace dwellings, which are significantly less likely to have a high electricity use than semi-detached properties, all other dwelling types are equally likely to have a high electrical energy demand. Similarly, Kavousian et al. (2013) and Baker & Rylatt (2008) found no significant correlation between electricity consumption and dwelling type.

The finding that mid-terrace dwellings having a lower probability of high consumption perhaps relates to a smaller floor area compared to other dwelling types, particularly semi-detached and detached homes. A smaller floor area will reduce space heating requirements, but is only relevant in this case if the dwelling is electrically heated, additionally, mid-terrace properties have less exposed walls than other dwelling types, which should reduce electric heating demand. A smaller floor area will also restrict the number and size of domestic appliances owned.

The floor area of mid-terrace homes is also commonly smaller than end-terrace dwellings, which in addition have a greater potential for extensions to the floor area. Whilst flats are often regarded as having small floor areas, the growth of modern apartment buildings in the UK, associated with the regeneration of cities has led to larger more desirable flats, which offer comparable floor areas with terrace properties.

Furthermore, flats frequently have electric rather than gas fuelled heating, increasing the dwelling type's potential for high consumption.

The smaller space offered by mid-terrace properties might also dictate the family composition and number of occupants that live in this dwelling type. Compared to semi-detached homes, which are typically family homes with children and teenagers, mid-terrace homes may be occupied by young and elderly couples. The profile of the building occupants has previously been identified as a possible reason for variations in electricity use between dwelling types by Wyatt (2013). A greater number of occupants were earlier observed to increase the probability of high electricity consumption.

The period in which a dwelling was built has no significant influence on the likelihood of being a high electricity consumer. Homes constructed before 1900, between 1945 and 1990, and after 1990 are just as likely to be high consumers as those homes built between 1900 and 1944. A non-significant effect of dwelling age has also been reported by Hamilton et al. (2013), Kavousian et al. (2013), and Tso & Yau (2007).

Earlier studies which have identified that older homes use more electricity primarily attribute the effect to increased heat loss associated with less insulation (Leahy & Lyons 2010; Parker 2003) and less efficient appliances (Brounen et al. 2012; Parker 2003). Other studies that found modern homes to have a higher electrical energy demand suggest that increased presence of air conditioning (Chong 2012), a higher wiring capacity in newly built houses (Halvorsen & Larsen 2001) and a greater use of appliances (Halvorsen & Larsen 2001) are responsible factors.

In the current study, greater heat loss associated with less insulation was mitigated as the number of electrically heated homes in the study sample was low. Moreover, none of the homes in the study used air conditioning reflecting the overall situation in the UK building stock. For these two primary reasons, the effect of building age on the likelihood of high electricity consumption may not have emerged in the current research.

The number of bedrooms a dwelling possesses was established to have no significant effect on the probability of being a high electrical energy consumer. Houses with one, two or more than four bedrooms are equally likely to be high consumers as houses with three bedrooms.

This finding is different from previous studies which have found both a significant and positive relationship (Hamilton et al. 2013; Carter et al. 2012; McLoughlin et al. 2012; Baker & Rylatt 2008; Yohanis et al. 2008), and a significant and negative relationship between the number of bedrooms and domestic electricity consumption (Bedir et al. 2013).

This variation in finding may relate to the lack of electrically heated homes in the current sample. Houses with more bedrooms probably have a greater total floor area and require more heating; however this will only affect the probability of high consumption for homes with electric space heating. In addition, compared to other rooms in a home, bedrooms in general have fewer electrical appliances and are occupied for a shorter duration reducing any effect of additional bedroom lights.

The number of floors was also found to not increase the probability of a household being a high electricity consumer. Dwellings with either one or one and a half floors were just as likely to be high consumers as those dwellings with two or more floors. In an earlier study undertaken by Bartusch et al. (2012), it was similarly confirmed that the number of stories does not represent any statistically significant variance in annual electricity consumption.

This result could reflect that floor area varies little between homes with one and two or more floors and instead multi-storey homes simply have a reduced footprint area. Moreover, in UK homes, floors above the ground floor are traditionally bedrooms, which were previously shown to have no effect on the probability of high consumption.

Homes with a floor area greater than 100 m^2 were significantly more likely to be high electricity consumers than dwellings with a floor area between 50 and 100 m^2. No significant difference in probability was identified between homes less than 50 m^2 and 50 to 100 m^2.

Previous research studies have also found that dwellings with a larger floor area have higher electricity consumption (Zhou & Teng 2013; Carlson et al. 2013; Hamilton et al. 2013; Kavousian et al. 2013; Wyatt 2013; Wiesmann et al. 2011; Baker & Rylatt 2008; Yohanis et al. 2008; Summerfield et al. 2007; Bartiaux & Gram-Hanssen 2005; Filippini & Pachauri 2004; Gram-Hanssen et al. 2004; Halvorsen & Larsen 2001; Nielsen 1993). In general, earlier research has attributed the influence of floor area on electricity consumption to a greater demand for space heating and cooling, because larger houses require more electric heating in the winter and cooling in the summer.

In this instance, this explanation is insufficient due to both the low penetration of electrically heated and non-existent air conditioned homes in the study cohort. Therefore, the increased probability of high consumption may relate to the fact that larger homes have more space for additional electrical appliances and more lights. This suggestion however is contrary to Genjo et al. (2005)'s results which determined that total floor area has a very small influence on the electricity consumption for lighting and appliances. Another possible reason could be that larger homes probably contain a greater number of occupants and have a higher wealth, both of which have been shown to effect high electrical energy demand.

Dwellings for which electric space heating is the primary form of heating are significantly more likely to be high electricity consumers than those households using other fuel types. Earlier results by other researchers also consistently agree that there is a significant and positive effect of the use of an electric space heating system on electricity use (Bedir et al. 2013; Kavousian et al. 2013; Bartusch et al. 2012; Ndiaye & Gabriel 2011; Leahy & Lyons 2010; Baker & Rylatt 2008; Larsen & Nesbakken 2004; Halvorsen & Larsen 2001).

This result is unsurprising and easy to understand. As space heating accounts for about 60% of the total energy use in a domestic property (DECC 2012), if this service is provided by electricity, rather than say gas, the likelihood of being a high electricity consumer should clearly be greatly increased.

Two forms of secondary electric space heating for dwellings were also investigated. Households with a fixed electric heater were found to be just as likely to be high electrical energy consumers as those homes without. However, dwellings owning a portable electric heater are significantly more likely to be high electrical energy users.

Larsen & Nesbakken (2004) estimated the electricity consumption of households owning portable electric heaters and also found a significant increase in electricity consumption.

The variation in impact of fixed and portable electric heaters on high consumption may highlight differences in their use by building occupants and occupants' preferred system of choice for providing supplementary heating. Fixed electric heaters are most commonly found in a dwelling's living or family space, which is an area almost certainly heated by the primary heating system, thereby reducing the system's utility. By comparison, portable electric heaters offer freedom to heat areas of the home that are not covered by the primary heating system, such as conservatories, and the option to heat individual rooms or spaces of the home, as opposed to using the main central heating.

Homes heating water using electricity are also significantly more likely to be high consumers. Several other studies have observed a significant positive influence of the use of electric hot water heating systems on the electrical energy demand of residential buildings (Kavousian et al. 2013; McLoughlin et al. 2012; Ndiaye & Gabriel 2011; Leahy & Lyons 2010; Baker & Rylatt 2008; Tso & Yau 2003; Larsen & Nesbakken 2004).

The result obtained reflects the fact that water heating represents on average 6% of electricity use in UK dwellings (DECC 2012), and therefore dwellings with electric water heating have an elevated potential for electricity consumption. It should be noted that some of the households that reported using an electric immersion heater or instant electric water heater, also stated they had a gas fuelled boiler. The portion of water heating undertaken by each method is not known.

Whilst the rate of water use in a home will dictate the total electricity required to maintain a sufficient hot water supply, as identified by Bedir et al. (2013), Baker & Rylatt (2008), and Larsen & Nesbakken (2004), households with an electric immersion heater will periodically consume electricity irrespective of hot water use, as a result of the water stored in the immersion tank cooling down and requiring reheating, thereby increasing the probability of high consumption.

A significant energy-efficiency strategy imposed under the European Union's 2005 Eco-Design Directive (EU 2005), is the phasing out of inefficient incandescent and halogen lighting between 2009 and 2012; thereby 'encouraging' households to use low-energy lamps instead. However, it would appear that regardless of the portion of low-energy lamps installed, no clear reduction in the probability of high consumption is achieved.

Bartiaux & Gram-Hanssen (2005) likewise determined that there is no significant correlation between having low-energy lights and electricity consumption. While Kavousian et al. (2013) and Bedir et al. (2013) concluded that the use of energy-efficient lights is correlated with lower electrical energy consumption.

As lighting accounts for less than a fifth of total electricity use in an average UK household (EST 2011), it is not perhaps unreasonable to expect a weak impact of low-energy lighting on electricity demand.

8.3.3 Appliance characteristics

In the OR study, the effects of two components of appliance electricity consumption on the likelihood of high electrical energy demand were investigated: appliance ownership and use. Specifically, the total appliance ownership level and the ownership levels of particular appliance categories and appliance types were observed. In addition, the use of a selection of specific appliance types by householders was explored.

8.3.3.1 Appliance ownership

The total number of electrical appliances a household owns appears to play a very important role in whether a household will be a high electrical energy user. It was found that households owning more than thirty electrical appliances were significantly more likely to be high consumers than those owning less than thirty. A large significant increase in the likelihood of high electricity consumption was observed for homes owning more than thirty-six appliances.

A significant and positive effect of the total number of appliances owned on domestic electricity demand has also been acknowledged by several previous authors (Bedir et al. 2013; Carlson et al. 2013; Wiesmann et al. 2011; Genjo et al. 2005; Halvorsen & Larsen 2001; Tiwari 2000; Nielsen 1993)

The effect of varying appliance ownership levels in different appliance categories on the probability of high consumption was also studied. The results showed that households possessing four or more IT appliances are significantly more likely to have high electrical energy consumption than those without any.

Dwellings with three or more telephony appliances were observed to have a significantly higher probability of high electricity use.

Households owning more than five entertainment appliances are much more likely to have a high electrical energy demand than those with five or less.

The ownership of three or more HVAC appliances also resulted in a significant increase in the probability of being a high electricity user.

Dwellings with any major electrical cooking device are twice as likely to be high consumers in comparison to houses with major cooking appliances using alternative fuel types.

The results also demonstrated that households possessing more preservation and cooling appliances have an increased chance of being a high electricity consumer. Homes owning two or more preservation and cooling appliances are significantly more likely to be high consumers than those owning zero or one appliance.

Additionally, the ownership of a washing appliance has a significant effect; households owning one washing appliance are almost 4 times more likely to be a high consumer than households without any.

Households owning three or more laundry appliances are significantly more likely to be high electrical energy consumers than those owning either one or two laundry appliances.

Compared to homes owning zero or one building and outdoors maintenance appliances, homes owning three, or more than five appliances, are around 5 times more likely to be high consumers.

Whilst the effect of owning more hygiene, beauty and leisure appliances was not entirely clear, the results showed that homes owning two appliances had double the probability of high electricity demand compared to households with zero.

The ownership of minor cooking appliances was the only appliance category studied which had no significant effect on the likelihood of high electricity consumption. Households owning three or less and more than seven minor cooking appliances were similarly likely to have high electrical energy consumption as homes owning between four and six appliances.

Whilst ownership of electrical appliances alone will not directly affect the electricity consumption of a domestic building, the number and types of appliances owned by a household is clearly important as it will define the physical infrastructure in which electricity consumption can occur. Simply, the greater number of appliances owned, the more opportunities that exist for electricity use. This was clear for both the total number of appliances owned as well as the ownership of appliances in specific appliance categories.

The non-significant effect identified for the ownership of minor cooking appliances on high electricity consumption may indicate that the energy use of commonly owned small appliances, like kettles, microwaves, and toasters is quite similar regardless of the overall total electricity consumption of a dwelling, and supplementary devices, like slow cookers, food processors and bread makers, are infrequently used by occupants and therefore consume little or no additional electricity.

The impact of owning a series of specific appliance types on the probability of high electrical energy consumption was also undertaken as part of the OR analysis. In the IT appliance category the effect of owning desktop and laptop computers was examined. The results showed that households owning two or three desktop computers are significantly more likely to be high electricity consumers. The ownership of one desktop computer had no clear effect. In relation to laptop computers, it was observed that as ownership level increases, so does the likelihood of high electrical energy demand.

The significant effect of the ownership of desktop and laptop computers on electricity consumption has previously been acknowledged by Zhou & Teng (2013), McLoughlin et al. (2012), Baker & Rylatt (2008), and Bartiaux & Gram-Hanssen (2005). In particular, Zhou & Teng (2013) determined that households that own a desktop computer consume approximately 10% more electricity.

The increased likelihood of high electrical energy demand may result from the fact that desktop computers have a relatively high annual electricity use (166 kWh) in an average UK home (Zimmermann et al. 2012). In addition, the ownership of a desktop or laptop computer almost certainly increases the ownership level of other compatible IT appliances, like printers, scanners and routers, all of which will further contribute to a higher total household electricity use.

In the entertainment appliance category, the effect of television ownership on high electricity use was observed. Households owning three or more TVs have a significantly increased likelihood of high consumption. However, homes with one or two TVs are equally likely to be high consumers.

Several earlier studies have consistently agreed that homes with a TV have significantly higher electricity consumption than those without (Kavousian et al. 2013; McLoughlin et al. 2012; Baker & Rylatt 2008; Bartiaux & Gram-Hanssen 2005; Genjo et al. 2005; Larsen & Nesbakken 2004; Parti & Parti 1980). Specifically, Larsen & Nesbakken (2004) estimated that households with a TV consume an additional 1,301 kWh per year.

The greater probability of high electrical energy consumption amongst residential buildings with more than three televisions can probably be attributed to the use of multiple TVs at the same time by different occupants. Also, households with more than two televisions may use the additional devices for purposes other than just watching TV, such as a display screen for a video games console or desktop computer, therefore the increased ownership of TVs is also linked with an increased ownership of other electrical appliances which are also increasing overall electricity demand.

The similar probability of high consumption for homes owning either one or two televisions might indicate that homes with two TVs simply split their normal usage between devices rather than increasing use. This however would imply that similar power requirements exist for both TVs. Alternatively, a second TV with lower power consumption may even offer the opportunity for households to reduce the likelihood of high electrical energy demand by transferring some of their regular TV use from their high consuming main TV to the lower energy consuming second device.

The choice of the main television screen type was also observed to have a significant impact on the likelihood of high consumption. Homes owning a plasma screen are more likely to be high electricity users than homes with a LCD screen. No variation in probability however was identified between houses with CRT and LCD screens. This finding is perhaps explained by the higher operational power demand of plasma screen TVs (245.6 Watts), compared with CRT (57 Watts) and LCD (96.9 Watts) (Zimmermann et al. 2012). In addition, the reduced probability of high consumption among homes with a CRT as opposed to a plasma screen TV could highlight a possible income effect as CRT TVs are no longer manufactured indicating that the household has not recently replaced their main television. Also, the ownership of an older style CRT screen may well be associated with older or retired residents which have been found to have a lower likelihood of being high electricity consumers.

Furthermore, the size of the main television was found to have a significant influence on the possibility that a dwelling will have high electrical energy demand. Households with a main television 40” or larger are much more likely to be high electricity consumers than those owning a TV 32” or less. Households with a TV between 32” and 39” are similarly possible to have high electrical demand as homes with a TV up to 32”. The increased likelihood of high electricity use amongst homes with a main television 40” or larger may relate to the higher operational power load. Also larger TVs generally have a higher purchase price, which may indicate that the homes possessing TVs 40” or larger have a greater wealth, which was previously shown to positively affect high consumption.

In the preservation and cooling appliance category, the impact of ownership of refrigerators, fridge-freezers, upright freezers and chest freezers on the probability of high electrical energy demand was studied. The OR results showed that owning an upright freezer was the only preservation and cooling appliance to significantly increase the likelihood of a dwelling being a high electricity user. The significant effect of ownership of upright freezers on electricity demand has not been studied by earlier researchers, however, extensive research has been undertaken exploring the influence of refrigerators, fridge-freezers and chest freezers (Zhou & Teng 2013; Kavousian et al. 2013; Carter et al. 2012; McLoughlin et al. 2012; Leahy & Lyons 2010; Bartiaux & Gram-Hanssen 2005; Genjo et al. 2005; Larsen & Nesbakken 2004; Gram-Hanssen et al. 2004; Halvorsen & Larsen 2001; Parti & Parti 1980). The majority of previous research has established that these three preservation and cooling appliances increase the electricity use of domestic buildings.

The current result therefore shows with the exception of upright freezers that whilst owning a preservation and cooling appliance almost certainly increases a dwelling's electricity use, they are not responsible for driving the highest consumptions. This finding may relate to the fact that preservation and cooling appliances are both essential and commonly owned domestic appliances, which overall contribute to a similar baseline electricity use. For example, the non-significant effect of owning a fridge-freezer is probably because households not owning the device, simply own a refrigerator and chest freezer which in total consume a similar amount of electricity.

The influential effect of the ownership of upright freezers could indicate that this device is a supplementary preservation and cooling appliance thereby increasing the probability of high consumption. In addition, households requiring the ability to store large quantities of frozen food may have larger families. The number of occupants residing in a dwelling has been identified to influence high electrical energy demand.

In the washing appliance category, the effect of owning a dishwasher on high electricity consumption was estimated. Houses with a dishwasher are four times more likely to have high electricity use than those not owning the device. The significant relationship between the ownership of a dishwasher and increased electricity demand has consistently been established by previous researchers (McLoughlin et al. 2012; Leahy & Lyons 2010; Bartiaux & Gram-Hanssen 2005; Genjo et al. 2005; Gram-Hanssen et al. 2004; Larsen & Nesbakken 2004; Halvorsen & Larsen 2001; Parti & Parti 1980). Explicitly, McLoughlin et al. (2012) determined that dishwashers were the largest contributors to household electricity consumption. In addition, Leahy & Lyons (2010) established that having a dishwasher increases electricity consumption by over 9 kWh per week. Similarly, Larsen & Nesbakken (2004) added that those households with a dishwasher use 2,015 kWh more electricity per year.

The increased likelihood of high electricity consumption amongst homes owning a dishwasher relates to the additional electricity consumption, around 294 kWh per year in the average UK home (Zimmermann et al. 2012), resulting from automating rather than manually dishwashing. Also, households that wash dishes by hand, with the exception of homes with electric water heating, do not consume any electricity for this task as the hot water is probably provided by a gas fuelled boiler. Furthermore, as a dishwasher is a non-essential appliance, dwellings choosing to own the device may have higher household incomes or have a greater number of occupants generating more washing than is deemed acceptable to manually clean. Both of these socio-economic characteristics were also observed to increase the likelihood of high consumption.

In the laundry appliance category, the consequence of households owning a washing machine, washer-dryer and tumble dryer on the likelihood of high electricity use was investigated. It was found that only the ownership of a tumble dryer increased the probability of high electrical demand. Homes with a washing machine or washer-dryer were similarly likely to be high consumers as those not owning the appliances.

The high impact of the ownership of a tumble dryer on electrical energy demand has been the focus of extensive research (McLoughlin et al. 2012; Leahy & Lyons 2010; Bartiaux & Gram-Hanssen 2005; Larsen & Nesbakken 2004; Gram-Hanssen et al. 2004; Parker 2003; Parti & Parti 1980). Specifically, Leahy & Lyons (2010) established that households owning a tumble dryer consume over 9 kWh more electricity per week. Similarly, Larsen & Nesbakken (2004) found that households with a tumble dryer use 2,338 kWh more electricity per year. McLoughlin et al. (2012) and Parker (2003) added that the ownership of a tumble dryer was one of the three largest contributors to domestic electricity consumption.

The increased probability of high consumption amongst dwellings with a tumble dryer can be attributed to the additional electricity use required for drying clothes, which for the average UK home equates to 394 kWh per annum (Zimmermann et al. 2012). Furthermore, the ownership of a tumble dryer might also be associated with family size and composition; households with children and teenagers that have larger quantities of dirty laundry may use a tumble dryer to accelerate the laundry task. The number of occupants and presence of children and teenagers were previously found to have a significant impact on the probability of high electrical energy consumption.

The non-significant effect of ownership of washing machines and washer-dryers on high electricity use probably relates to the fact that they are commonly owned appliances and households which do not own a washing machine instead own a washer-dryer or vice-versa. Both appliance types have a similar average annual electricity use in UK homes, 166 kWh for a washing machine and 243 kWh for a washer-dryer (Zimmermann et al. 2012), thereby their effect on high electricity consumption is balanced.

Finally, in the hygiene, beauty and leisure appliance category, the ownership of electric showers was found to significantly increase the likelihood of high electricity consumption. The impact of a dwelling having an electric shower has not previously been acknowledged by researchers.

Although used for a short time, as electric showers are likely to have the highest power consumption (typically 7 - 11 kW) of any household electrical end-use, it is perhaps understandable that dwellings with at least one electric shower should have a greater likelihood of high electrical energy demand, compared to those without any electric showers. Also, households without an electric shower probably heat the hot water used for showering with a gas fuelled boiler, thereby further limiting electricity consumption.

8.3.3.2 Appliance use

The number of appliances owned by a household only partially reflects the effects of domestic appliances on household electricity consumption. It is also necessary to consider the duration of appliance use by the building occupants. Previously, Bedir et al. (2013) established that that the frequency of use of appliances (including IT, entertainment, HVAC, washing and laundry appliances) explains 37% of the variance in electricity consumption between domestic buildings, however, it has been acknowledged by previous researchers (Bedir et al. 2013; Sanquist et al. 2012; Bartiaux & Gram-Hanssen 2005; Cramer et al. 1985) that little research has been undertaken to assess the influence of the use of appliances on the total electrical energy demand of residential buildings.

In the IT appliance category, the impact of the hours of use for the main desktop and laptop computer during the week and at the weekend on high electricity consumption was studied. The OR results revealed that the working hours of the main desktop computer had little influence on the probability of high electricity consumption. Only households using their main computer for more than four hours each day at the weekend have an increased likelihood of high consumption. The working hours of the main laptop computer during the week however has a significant effect on high consumption. Dwellings operating their main laptop for more than two hours per day are more likely to be high consumers. Conversely, the usage of laptop computers at the weekend had no clear impact on the probability of high electrical energy use.

Earlier research by Sanquist et al. (2012) determined a strong correlation between the use of desktop computers and the annual electrical energy demand of households and suggested that the use of IT appliances in a household may be a manifestation of higher disposable income.

The current findings regarding the effect of the use of desktop and laptop computers compare well with the ownership results for the same appliances. The ownership results showed that only households owning two or more desktop computers had an increased likelihood of high consumption, so the little impact of the working hours for the main desktop computer alone was in line with these earlier results. The unclear relationship between the use of both desktop and laptop computers and the likelihood of high electricity consumption may also be attributed to the variations in power demands of different models of desktop and laptop computer and the proportion of time in which the appliances are defined as working but are actually operating in either active or active standby power modes.

In the entertainment appliance category, the effect of daily use of the main television during the week and at the weekend was observed. The findings indicated that the duration of use has no influence on the likelihood that a dwelling will have high electricity consumption. Previously, Sanquist et al. (2012) established a significant effect between television use and domestic electricity consumption and observed that this impact is higher in larger households which tend to own and use more televisions.

The lack of influence of the occupants' use of the main television is consistent with both the earlier OR results that observed that an ownership level of three or more TVs was required to affect high electricity consumption and the statement of Sanquist et al. (2012) that higher TV ownership has a greater effect on electricity consumption. In addition, the absence of effect of the use of the main TV could relate to variations in the power consumptions of the main TV in different homes, dictated by the TV type and size. Whereby, a lower powered smaller CRT TV could have a higher number of working hours but have less electricity use, than a higher powered larger plasma screen TV used for a shorter duration.

In the major cooking appliance category, the working hours of the electric oven and hob during the week and at the weekend, and the consequent impact on the likelihood of high electricity consumption was estimated. The findings demonstrated that the number of hours an electric oven is used for each day has no obvious effect on the probability of high electricity use. Similar results were obtained for the effect of the working hours of the electric hob. Only households using an electric hob between one and two hours each day both during the week and at the weekend were found to have an increased likelihood of high consumption, compared to those using the hob for between half an hour and one hour per day.

This result is perhaps unexpected as the OR result for electric cooking demonstrated a significant effect on the likelihood of high electrical energy use in residential buildings. The current finding may be explained by the variable power demands of different oven and hob types. Also, the current results do not take into account the specific cooking activities of the occupants. To elaborate, the working hours do not reflect the number of electric hobs used (normally up to four) or the temperature settings chosen, these additional factors will have a significant effect on the electricity consumed over the duration of time specified. The same lack of specific behavioural information also applies to the use of the electric oven.

In the washing appliance category, the impact on the probability of high electrical energy consumption by the number of loads of dishwashing undertaken per week and the temperature selected was examined. Overall, the OR results showed that the likelihood of high electricity consumption was unaffected by the amount of dishwashing and the temperature settings chosen by the occupants. Earlier research however, has shown a significant correlation between the duration and frequency of use of a dishwasher and electricity demand (Bedir et al. 2013; Bartiaux & Gram-Hanssen 2005).

The current conflicting results relating to the loads of dishwashing each week could be attributed to the fact that, frequency of use, rather than duration of use was observed. The quantity of dishwashing loads may not be indicative of the actual operative hours of a dishwasher. Occupants undertaking more loads of dishwashing on a quick wash setting may use less electrical energy than those using the dishwasher less but on an intensive wash setting. Furthermore, the number of loads of dishwashing does not stipulate the temperature chosen to wash the dishes. Households operating the dishwasher more but at a cooler washing temperature could feasibly use less electricity than in the contrary situation.

Regarding the unclear effect of the choice of dishwasher temperature settings on the probability of high consumption, a possible explanation may again relate to the lack of information about the occupants' operation of the dishwasher, as the impact of a higher temperature setting may be negated by less use. Also, the temperature settings data are probably subject to self-report error, for a couple of reasons, firstly, occupants may use multiple temperature settings, therefore does the temperature indicated reflect an average or the most recent temperature used. Secondly, dishwashers can have very diverse programming interfaces, some may stipulate the temperature in ^{o}C, but others numerically on a scale from 1 to 5, or even descriptively, “hot”, “cold” or “economy”, the latter classifications will make it difficult for the occupants to report the exact temperature without referring to the user manual.

In the laundry appliance category, the effect of the number of loads of clothes washing and drying each week, and the occupants' chosen temperature of clothes washing on the likelihood of a dwelling having a high electrical energy demand was observed. The findings indicate that on the whole as households do more clothes washing, their probability of being a high consumer increases. The same statement applies to the loads of clothes drying per week in the summer but only households undertaking four or more loads of drying per week in the winter demonstrated an increased chance of high consumption. The temperature selected for clothes washing had no clear impact on the likelihood of high electricity use.

In the research undertaken by Bedir et al. (2013), Sanquist et al. (2012), and Bartiaux & Gram-Hanssen (2005), a significant influence of the use of laundry appliances, both washing machines and tumble dryers, on domestic electricity demand has been discovered. In addition, Bedir et al. (2013) also reported a significant correlation between the number of hot (90 ^{o}C) and cold washes (30 ^{o}C) and total electricity use.

The current finding that a higher use of laundry appliances results in a greater probability of high consumption is widely consistent with expectations. However, the results specifically established that only summer and high winter use (three or more times per week) of clothes drying appliances affect the probability of high consumption. This may reveal that whilst some winter use of drying appliances is quite common in UK homes, summer use is much less so, therefore dwellings choosing to use a tumble dryer or washer-dryer in the summer, rather than drying laundry outside, are much more likely to be high consumers.

The unimportant effect of the temperature of clothes washing on the likelihood of high consumption can be explained with the same reasons suggested for the temperature of dishwashing, which includes a lack of specific occupant use data and self-report errors.

In the hygiene, beauty and leisure appliance category, households taking more than twenty-one electric showers each week were found to have a significantly increased probability of high electricity use. This result can almost certainly be attributed to the high power demand of electric showers (typically 7 - 11 kW). Moreover, the number of electric showers is likely to be correlated with the number of occupants residing in a dwelling and whether the family composition includes children and teenagers, of which both factors have been shown to have a significant effect on the likelihood of high electrical energy demand.

Finally, the reliability of the self-report data provided by the building occupants is an overarching concern for all of the appliance use results presented in this section. The accuracy of the appliance use data may be affected by both the occupants' inability to report their usage reliably but also by intentionally adjusting their actual usage to appear more energy efficient. For example, the participants of the survey may have understated their actual main television working hours because they did not want to feel judged or reveal their actual behaviour to the researchers. Also given the energy related nature of the 4M LIL appliance survey, the participants could have been aware of the underlying motives of the researchers and may have chosen to report more energy efficient behaviours, such as, washing laundry at a cooler temperature (e.g. 30 ^{o}C).

Table 8-2 provides a summary of the key findings relating to research question 3.

Table 8-2 Summary of key findings: Research question 3

Key findings
Socio-economic characteristics ▪ Households with more occupants have a greater probability of high electrical energy consumption. ▪ Households with children are more likely to be high electricity consumers. ▪ Households with teenagers have an increased probability of high electrical energy use. ▪ Households with a HRP over 65 years old are less likely to be high electricity consumers. ▪ Households with a retired HRP are less likely to have high electrical energy demand. ▪ The education level of the HRP has no effect on the probability of high electricity consumption. ▪ The National Statistics Socio-economic Classification of the HRP has no influence on the likelihood of high electricity demand. ▪ Tenure type does not affect the possibility of being a high electricity user. ▪ Households with a higher annual income are more likely to be high electrical energy users. **Technical characteristics** ▪ Mid-terrace dwellings are less likely to have a high electrical energy use. ▪ The period in which a dwelling was built has no influence on the likelihood of being a high electricity consumer. ▪ The number of bedrooms a dwelling possesses has no effect on the probability of high electricity use. ▪ The number of floors a dwelling possesses has no influence on the probability of high electricity use. ▪ Dwellings with a floor area greater than 100 m^2 are more likely to have high electrical energy demand. ▪ Dwellings for which electric space heating is the primary form of heating are more likely to be high electricity consumers. ▪ Dwellings with a fixed electric heater are just as likely to be high electrical energy consumers as those without. ▪ Dwellings with a portable electric heater are more likely to be high electrical energy users. ▪ Dwellings with electric water heating have a greater probability of high electricity consumption. ▪ The proportion of low-energy lighting installed does not reduce the probability of high electricity consumption. **Appliance characteristics: Ownership** ▪ Households owning more than thirty electrical appliances are more likely to be high electricity consumers. ▪ Households owning four or more IT appliances are more likely to be high electricity consumers. ▪ Households owning three or more telephony appliances are more likely to be high electricity consumers. ▪ Households owning more than five entertainment appliances are more likely to be high electricity consumers.

- Households owning three or more HVAC appliances are more likely to be high electricity consumers.
- Households owning any major electrical cooking appliance are more likely to be high electricity consumers.
- Households owning two or more preservation and cooling appliances are more likely to be high electricity consumers.
- Households owning one washing appliance are more likely to be high electricity consumers.
- Households owning three or more laundry appliances are more likely to be high electricity consumers.
- Households owning three or more than five building and outdoors maintenance appliances are more likely to be high electricity consumers.
- Households owning two hygiene, beauty and leisure appliances are more likely to be high electricity consumers.
- The ownership level of minor cooking appliances has no effect on the likelihood of high electricity consumption.
- Households owning two or three desktop computers are more likely to be high electricity consumers.
- Households owning one or more laptop computers are more likely to be high electricity consumers.
- Households owning three or more TVs are more likely to be high electricity consumers.
- Households with a plasma screen as their main TV are more likely to be high electricity consumers than those with a LCD screen.
- Households with a main television 40” or larger are more likely to be high electricity consumers than those owning a TV 32” or less.
- The ownership of an upright freezer is the only preservation and cooling appliance to increase the likelihood of a dwelling being a high electricity consumer.
- Households with a dishwasher are more likely to be high electricity consumers.
- The ownership of a tumble dryer is the only laundry appliance to increase the likelihood of a dwelling being a high electricity consumer.
- Households with an electric shower are more likely to be high electricity consumers.

Appliance characteristics: Use

- The working hours of the main desktop computer for a weekday has no effect on the likelihood of a dwelling being a high electricity consumer.
- Households using their main desktop computer for more than four hours each day at the weekend are more likely to be high electricity consumers.
- Households using their main laptop computer for more than two hours per day during weekdays are more likely to be high electricity consumers.
- The working hours of the main laptop computer at the weekend has no effect on the likelihood of a dwelling being a high electricity consumer.
- The working hours of the main TV for a weekday and at the weekend has no effect on the likelihood of a dwelling being a high electricity consumer.

- The working hours of an electric oven for a weekday and at the weekend has no effect on the likelihood of a dwelling being a high electricity consumer.
- Households using an electric hob between one and two hours each day both on a weekday and at the weekend are more likely to be high electricity consumers.
- The number of loads of dishwashing per week has no clear effect on the likelihood of a dwelling being a high electricity consumer.
- The temperature selected for dishwashing has no effect on the likelihood of a dwelling being a high electricity consumer.
- In general, the more clothes washing that is undertaken each week, the greater the likelihood a dwelling will have a high electrical energy demand.
- The temperature selected for clothes washing has no effect on the likelihood of a dwelling being a high electricity consumer.
- The more clothes drying that is undertaken each week in summer, the greater the likelihood a dwelling will have a high electrical energy demand.
- Households undertaking four or more loads of drying each week in the winter are more likely to be high electricity consumers.
- Households taking more than twenty-one electric showers each week are more likely to be high electricity consumers.

8.4 Discussion 3: The contributions of ownership, power demand and usage of domestic appliances to high electrical energy demand

The contributions of ownership, power demand and use of electrical appliances in UK homes on high electricity consumption were studied using the data collected in the Appliance Electricity Use Survey (AEUS) conducted with the L27 sample. The analysed data were used to answer the following research question:

4. To what extent do the ownership, power demand and use of different domestic appliances contribute to high electrical energy demand in a sample of UK households?

Chapter 7 presented for the three electrical demand groups, the mean electricity consumption for each appliance type, as well as, the mean ownership, power demand and use values for a range of appliance types individually. In the next sections, these three components of appliance electricity consumption will be combined to help explain the higher electricity use on certain appliance types for the high electrical demand group. Addressing these underlying factors are opportunities for demand reduction for high electricity consumers.

8.4.1 Office equipment and infotainment appliances

In the office equipment and infotainment appliances category, dwellings with a high electrical energy demand were found to have higher mean annual electricity consumptions on IT, office accessories and entertainment appliances than low and medium demand dwellings.

The high electricity consumers' higher mean annual electricity consumption on IT appliances was recognised to relate to greater electricity uses on: desktop computers operating in the active and active/passive standby modes; laptop computers in active, active/passive standby and off standby modes; printers in active and passive standby modes; and wireless routers in active power mode.

The results for the average power loads and daily duration of use of these appliances for high electrical energy consuming dwellings compared with low and medium consuming dwellings revealed the underlying reasons for the larger electricity uses on these specific appliances.

In relation to desktop computers, it was found that whilst operating in the active mode, desktop computers owned by high electricity consumers have both a higher power demand and a longer duration of use each day. In the active/passive standby mode, the higher electricity use for desktop computers is explained by an extended daily functioning period. The greater operational hours of high consumers' desktop computers in active and active/passive standby modes may also be connected to the higher ownership rate of desktop computers, which will enable simultaneous use of the appliance type by multiple occupants and potentially increase the standby electricity use when not in use.

Regarding laptop computers, the higher electricity consumptions in active, active/passive standby and off standby modes by high electricity consumers can all be attributed to a longer average duration of operation each day. The mean power loads in these modes for laptop computers were lower for high electricity consuming dwellings than either low or medium consuming dwellings. The greater daily functioning period of laptop computers in the three power modes might be connected with the higher ownership level observed for high electricity consumers.

The larger electricity consumption in active standby mode for printers owned by high electricity consumers was found to be related to a longer duration of operation each day. Conversely, the higher electricity use in passive standby mode is associated with a greater average power load compared with low and medium electricity consuming dwellings.

Concerning wireless routers, the higher electricity consumption in active mode can be ascribed to an extended duration of usage each day and a greater power demand when operational. The longer hours of operation is also possibly related to a higher ownership rate of wireless routers amongst high electrical energy consuming dwellings.

In the office accessories appliance subcategory, the higher average annual electricity consumption by high consumers was associated with a greater electricity use on shredders in active power mode. Shredders owned by high electricity consumers were found to have both a greater working power load and daily duration of usage by residents in the active mode.

The higher mean annual electricity consumption on entertainment appliances by high electrical energy consumers was found to result from a wide combination of greater appliance electricity consumptions in different power modes. Specifically, LCD TVs operating in active, passive standby and off standby modes; digital and internet STBs in active and active standby modes; cable STBs in active mode; DVD players in active and active standby modes; VCR and DVD with VCR players in passive standby mode; analogue radios in passive standby mode; personal CD players in active standby and passive standby modes; MP3 docking stations in active standby and passive standby modes; video consoles in passive and off standby modes; and ebook readers in active mode.

A closer examination of the power characteristics and usage of high consumers' LCD TVs revealed that the higher electrical energy use in active and off standby modes was associated with both greater power loads and duration of operation. For passive standby, the greater electricity use by high consuming dwellings was related to a higher power load compared with medium electricity consumers. It should be noted that LCD TVs owned by low electricity consumers had a greater power demand in the passive standby mode than high consumers, but their TVs functioned much less in this power mode. Therefore, compared to low electricity consumers, the additional electricity used in passive standby mode by high consumers is related to an extended duration of operation. The longer daily hours of operation of LCD TVs by high electrical energy consumers could be associated with the higher ownership rate observed.

In relation to set top boxes, the increased electricity used on digital STBs by high consumers in active mode is owed to a longer daily usage by the building occupants, whereas, for the active standby power mode this is related to a higher average power load required by the appliance. For cable STBs, the greater electricity used by high consumers on this appliance compared with low consumers is simply related to the fact that none of the low electrical energy demand dwellings owned the appliance and therefore used no electricity at all. In comparison with medium electricity consumers, the greater active power mode consumption of high electrical energy consumers could be attributed to a longer average daily usage by the residents, as well as, a larger operational power load. Regarding internet STBs the higher electricity consumption by high consumers was the result of low and medium demand dwellings owning none of this appliance type.

Concerning video and recording appliances, the higher average annual electricity consumption on DVD players in active mode by high consumers was found to relate to both a greater in use power demand as well as increased usage by the residents of high consuming dwellings. The larger active standby electricity consumption was associated with an extended daily functioning period only. VCR and combination DVD with VCR players were both observed to have a higher passive standby electricity use when possessed by high electrical energy consumers. For VCR players this resulted from the appliance type being operational in the power mode for longer each day, whereas, DVD with VCR players were owned by high consumers only.

With regard to audio devices, the larger electricity consumption of high consumers' analogue radios in passive standby mode was recognised to result from the device functioning in this power mode for a longer duration per day. The higher electricity use by personal CD players owned by high electricity consumers simply related to the fact that low and medium demand dwellings did not own this type of device. In relation to MP3 docking stations, it was found that whilst operating in the active standby mode, MP3 docking stations owned by high electricity consumers have a longer duration of use each day. In passive standby mode, high consumers' appliances have both a greater power load and function for an extended period of time.

The additional electricity used by high electrical energy consumers on video consoles in passive and off standby power modes was explained by a larger power load and increased daily duration of operation compared with video consoles owned by medium consumers. Low electrical energy demand dwellings had no electricity on video consoles as they did not own this device.

The higher active power mode electricity consumption of ebook readers owned by high rather than medium electricity consumers can be attributed to a greater operational power demand when used by the dwelling occupants. Again, low electrical energy demand dwellings had a zero ownership for this appliance type and therefore used no electricity.

8.4.2 Non-fixed lighting appliances

In the non-fixed lighting appliance category, high electrical energy consuming households were observed to have higher mean annual electricity consumptions on old fashioned incandescent bulbs than low and medium consuming homes. This finding was in spite of the fact that medium electricity consuming dwellings had both a higher ownership rate of incandescent bulbs, which on average had a greater in use power demand of around 61 Watts compared to 53 Watts in high consuming dwellings. The increased electricity use on incandescent bulbs by high consumers therefore related to a longer period of usage by the occupants each day.

High electrical energy consuming dwellings also had the lowest ownership rate of low-energy bulbs (CFL and LED), which might help explain the extended duration of occupant usage of incandescent bulbs. In addition, the CFL bulbs installed in high electrical energy demand dwellings were found to have a greater active operational power load than those in low and medium demand dwellings. This finding may indicate that when high consumers upgrade to low-energy bulbs, they tend to choose higher powered and thus energy consuming options. This could be associated with a concern for reduced lighting performance compared to old style incandescent bulbs (Crosbie & Baker 2010).

The lower ownership of low-energy lighting evident amongst high electricity consuming dwellings may further point towards a wider reduced willingness of high consumers to transition to lower energy consuming technologies, which in addition to contributing to a larger lighting electricity use, could have wider implications for appliance electricity demands.

The results obtained for non-fixed lighting should however be treated with care when considering potential policies for reducing the energy demand of high consumers as the amount of lighting use by fixed lamps is not known. Consequently, the higher operational hours of non-fixed incandescent lighting by high consumers may be associated with a reduced usage on fixed sources compared with low and medium consumers. Increasing the ownership rate of low-energy bulbs used in non-fixed lighting in high electrical energy demand dwellings could potentially achieve electricity savings.

8.4.3 HVAC appliances

In the HVAC appliances category, dwellings with a high electrical energy demand were found to have higher average annual electricity consumptions on electric fires, electric blankets, portable halogen radiators and portable oil filled radiators than low and medium demand dwellings.

In all cases, the higher electricity use was due to the fact that only high consuming households owned these appliance types. In general, the HVAC appliances examined also had a high functioning power demand, meaning that even low occupant usage could result in noteworthy additional electricity consumption.

8.4.4 Transportation appliances

In the transportation appliances category, the higher mean annual electricity consumption by high electrical energy consumers was found to result from greater appliance electricity consumptions on mobility scooters, golf trolleys and chair lifts.

The latter two appliances were owned by high electrical energy demand dwellings only and therefore all of the electricity consumed on these appliances contributed directly to a higher overall electricity consumption. Mobility scooters however were owned by both low and high electricity consuming households. The results for the average power load and daily duration of use for the mobility scooters showed that the greater electricity use by high consumers was associated with a longer duration of use by the occupants in the active mode. It was not possible to compare the power requirements, as mobility scooters owned by low electricity consumers were not used and therefore no power data were obtained.

8.4.5 Catering appliances

In the catering appliances category, dwellings with a high electrical energy demand were found to have higher mean annual electricity consumptions on only a limited number of minor cooking and preservation and cooling appliances compared to low and medium demand dwellings.

Regarding minor cooking appliances, high electricity consumers used a greater amount of electricity on microwaves and kettles operating in the active mode and toasters, blenders and coffee makers in the passive standby mode. Concerning preservation and cooling appliances, high electrical energy demand homes consumed more electricity on upright freezers in the non-cooling cycle and beer and wine coolers in the cooling cycle.

The results for the average power loads and daily duration of use of these appliances established the underlying drivers for the larger electricity uses by high electricity users on these specific appliances.

With regard to minor cooking devices, the larger electricity consumption of high consumers' microwaves in active mode was recognised to result from a longer duration of use by the occupants each day. The increased usage by high consumers may be a consequence of the greater ownership rate of microwaves amongst high consuming homes. Conversely, the higher active electricity use by kettles related to a greater operational power demand. In relation to toasters, the higher passive standby consumption was due to both a greater in use power demand as well as increased usage by the residents of high consuming dwellings. This result should however be treated with some care as only one toaster in the monitoring study had a passive standby mode, which may perhaps have been connected with a technical issue with the device. Normally toasters function in active or off standby modes only. The higher electricity use on blenders and coffee makers in the passive standby power mode was due to an increased functioning period in high electrical demand dwellings. It was not possible to compare the power requirements, as blenders and coffee makers owned by low and medium electricity consumers were not used and therefore no power data were obtained.

Concerning the preservation and cooling appliances, the higher electricity consumption by high electrical energy consuming households on upright freezers functioning in the non-cooling cycle was found to relate to a greater electrical power demand. The additional electricity used on beer and wine coolers in the cooling cycle referred to both a higher appliance power demand and a longer period of operation in the power mode each day.

8.4.6 Washing appliances

In the washing appliances category, high electrical energy consuming households were seen to have higher average annual electricity consumptions on dishwashers in both the washing and drying cycles and passive standby power modes than low and medium electricity consumers.

The increased electricity consumption compared to medium consumers related to the fact that none of the medium demand homes in the study owned a dishwasher and therefore recorded zero electricity use for the appliance type. In contrast with dishwashers owned by low electrical energy demand households, high consumers' dishwashers had a greater in use power requirement for the washing cycle, a longer operating duration in the drying cycle and both a larger power demand and increased operating period for the passive standby mode.

8.4.7 Laundry appliances

In the laundry appliances category, the monitoring results revealed that high electrical energy consumers had higher annual electricity consumptions on all four laundry appliances studied compared with low and medium electrical energy consumers. With the exception of passive standby mode for washer-dryers, high electricity consumers consumed more electricity in every power mode on the laundry appliances.

Specifically, in relation to irons, the increased electricity consumption used by high consuming dwellings was found to be related to a greater average power demand in the active mode when operated by the building occupants.

For washing machines, the results indicated that the additional electricity used by devices owned by high demand homes was due to larger power loads in the water heating cycle and passive standby modes, coupled with longer functioning periods in the water heating and washing cycle modes and passive standby mode.

Concerning high electricity consumers' washer-dryers, the findings established that the greater electricity consumptions in the water heating, washing, heating and tumble cycle modes could all be attributed to both larger in use power demands and extended operating durations.

As regards to tumble dryers owned by high electrical energy consumers, the higher electricity consumption in the heating cycle mode can be recognised to result from both a higher operational power demand and longer average duration of operation each day. For the tumble cycle the increased electricity use could be attributed to a greater daily functioning period, whereas, for the passive standby mode, the additional electricity use was due to a higher average power demand.

It should be noted that the increased electricity consumption on washer-dryers and tumble dryers by high electrical energy demand households in comparison with low consumers related to the fact that none of the low electrical energy consuming households in the study owned these devices.

The reason for the longer average duration of operation each day by high consumers' washing machines, washer-dryers and tumble dryers in certain power modes is unclear and may relate to both occupant and appliance related factors. A possible explanation could be that occupants of high demand dwellings use these specific laundry appliances more often (i.e. undertake more loads of washing and drying) or choose settings which take longer to finish (i.e. intensive rather than rapid wash). Alternatively, the laundry appliances owned by high consumers tend to take longer to complete similar washing and drying tasks (i.e. appliance operational design) compared with laundry appliances owned by low and medium electrical energy demand dwellings.

8.4.8 Building and outdoors maintenance appliances

In the building and outdoors maintenance appliances category, dwellings with a high electrical energy demand were found to have higher average annual electricity consumptions on vacuum cleaners, automatic door openers and indoor and outdoor aquariums than low and medium demand dwellings.

From these appliances, vacuum cleaners were the only device owned by households in all three electrical demand groups. A closer examination of the power characteristics and usage revealed that vacuum cleaners owned by high consumers had a higher average electrical energy use in the active power mode, which was the result of a greater operational power demand.

Automatic door openers were owned by high electrical energy consuming households only, therefore all electricity consumed by this device directly contributed to a greater overall electricity use compared to low and medium consuming homes.

Indoor and outdoor aquariums were owned by medium and high electricity consuming households only. High electrical demand dwellings were observed to have increased electricity consumptions in the active power mode for both indoor and outdoor aquariums. In relation to indoor aquariums the higher electricity use related to a greater in use power demand and operating duration each day. For outdoor aquariums however this additional consumption was the result of a higher functioning power load.

8.4.9 Hygiene, beauty and leisure appliances

In the hygiene, beauty and leisure appliances category, high electricity consumers were observed to have higher mean annual electricity consumptions than low and medium consumers on hair dryers and hair straighteners in the active power mode and massagers in the passive standby mode.

The results for the average power load and daily duration of use for hair dryers showed that the greater electricity consumption by high consumers was associated with a longer duration of use by the occupants. In relation to hair straighteners, the increased electricity use could be attributed to both a higher operational power requirement and a greater usage by the householders. Massagers however were owned by high electrical energy demand dwellings only and therefore all of the electricity consumed on this appliance contributed directly to a higher overall electricity consumption, in comparison to low and medium demand homes.

8.4.10 Overview of the contributions of ownership, power demand and usage of domestic appliances to high electrical energy demand

Linking the data on ownership, power demand and usage of electrical appliances in high consuming households has established the appliance related factors contributing to high electrical energy consumption. The analysis has identified for the stock of appliances on which high consumers use more electricity the contributing drivers and thereby the potential methods for energy demand reduction. The results have shown that high electricity consumers have greater electricity consumptions on a broad range of appliance types spanning the appliance categories investigated. Moreover, the increased electricity consumptions on these appliances were found to relate to a combination of all three drivers of appliance electricity consumption: ownership, power demand and usage.

In relation to appliance ownership, high electrical energy consuming households owned a series of appliances that were not possessed by low and/or medium consuming homes. Consequently, any electricity used by these appliances directly contributed to the increased electrical energy demand of high consuming homes. These additional appliances could be broadly described as unessential (e.g. automatic door opener, massager) or special use (e.g. chair lift, golf trolley) devices, perhaps offering an explanation as to why they were not commonly owned by low and medium demand dwellings also. In fact, by observing appliance ownership rates more widely (See Chapter 7, Section 7.3), it could be seen that high consumers owned many devices that low and medium consumers did not (e.g. electric knifes, ice makers, food mixers etc.), but these were unused and therefore made no contribution to the electricity consumptions of the high demand dwellings.

Additionally, high electricity consumers were discovered to have higher ownership rates on a number of appliance types that were owned by households in all three electrical demand groups (e.g. desktop and laptop computers, LCD TVs, wireless routers, etc.) This increased ownership rate may explain the longer mean daily usage of some appliances by the occupants of high demand households, as the additional appliances enable the use of two or more similar appliances simultaneously.

The higher ownership rates of specific appliances in high electrical energy demand households may well relate to the wider socio-economic and technical characteristics of high consuming dwellings. The earlier OR results showed that households with more occupants were more likely to be high consumers and in line with this finding may be expected to have a greater number of appliances. In addition, households with more occupants probably have children and teenagers residing in them, who tend to have a wider ownership of IT and entertainment appliances, as well as multiple ownership of some appliances such as TVs and computers. High electrical consuming dwellings were also revealed to have larger annual household incomes which could be associated with a greater financial freedom to purchase additional appliances. Furthermore, high electrical demand dwellings are inclined to have larger floor areas than low and medium demand dwellings meaning there is also added space for more appliances.

Regarding appliance power demand, some domestic appliances owned by high electrical energy consuming households were observed to have greater power requirements in a range of power modes when compared with similar appliances owned by low and medium consuming households. For example, high consumer’s LCD TVs had a larger average active power demand of 105.67 Watts than low (71.61 Watts) and medium consumer’s (100.30 Watts) LCD TVs. Accordingly, these greater power demands mean that high consumer's appliances use more electricity if the duration of use by the building occupants is identical.

The higher operational power demands of high consumer's appliances maybe associated with appliance size; larger appliances (e.g. 32" TV compared with a 40" TV) tend to have greater power demands. Therefore, the current results may indicate that high electrical energy consumers more frequently own bigger appliances. In addition, appliance power demand is often related to appliance age, with older devices having greater power loads than newer ones. These findings may suggest that high consuming dwellings less frequently replace their existing appliances with newer more energy efficient models. It should be noted that a drive towards more efficient appliance design has however been greatly degraded by increasing appliance size, meaning older 'less-efficient' appliances are actually in fact more efficient. Moreover, the greater power demands of high consumers' appliances may well be explained by the occupants' operational behaviour. The occupants of high demand dwellings may simply choose higher power demand settings, such as, washing at a higher temperature, which will have a direct impact on the power requirements of the appliance.

Finally, a number of appliances owned by high electricity demand households had longer durations of operation each day in different power modes than low and medium consumer's equivalent appliances. The longer duration of operation observed can be explained by a series of diverse factors. Firstly, a longer active power mode usage may indicate that high consumers simply use their appliances more. For example, high consuming dwelling's desktop computers were used on average three hours per day compared with 0.31 hours in low consuming and 1.76 hours in medium consuming dwellings. The average hours of operation in all power modes is probably related to appliance ownership rates as households with more appliances have an increased potential for electricity use due to simultaneous usage. Also, high consuming dwellings have been shown to have higher household incomes and more occupants, which probably include children and teenagers. These socio-economic characteristics can be hypothesised to increase appliance usage because there are more people to use multiple appliances at the same time and the higher household income may mean that the households do not need to be energy efficient.

Secondly, a longer active appliance operating period could be attributed to the occupants of high consuming homes choosing less efficient settings on their appliances, such as, intensive rather than economy washing cycles on a dishwasher or washing machine.

Thirdly, it was observed that some of the high consumers' appliances functioned in the standby power modes (active, passive and off standby) for a greater period of time each day, perhaps demonstrating that occupants of high consuming dwellings are less energy conscious.

Fourthly, the longer operating periods could be the result of ownership of less efficient appliances, which require an increased operating period to complete similar household tasks. For example, less efficient washing machines may take longer to wash clothes to the same standard as an energy efficient appliance.

Table 8-3 provides a summary of the key findings relating to research question 4. The table summarises the appliance related factors contributing to high electrical energy demand in a sample of UK households and consequently the opportunities for energy demand reduction.

Table 8-3 Summary of key findings: Research question 4

Key findings
Office equipment and infotainment appliances **IT appliances** ▪ High consumers' increased electricity use on desktop computers in active mode relates to a higher power demand and duration of use. ▪ High consumers' increased electricity use on desktop computers in active/passive standby mode relates to an extended functioning period. ▪ High consumers' increased electricity use on laptop computers in active, active/passive standby and off standby modes relates to a longer duration of operation each day. ▪ High consumers' increased electricity use on printers in active standby mode relates to a longer duration of operation each day ▪ High consumers' increased electricity use on printers in passive standby mode relates to a greater average power load. ▪ High consumers' increased electricity use on wireless routers in active mode relates to an extended duration of usage each day and a greater power demand when operational. **Office accessories appliances** ▪ High consumers' increased electricity use on shredders in active mode relates to a greater working power load and daily duration of usage. **Entertainment appliances** ▪ High consumers' increased electricity use on LCD TVs in active and off standby modes relates to both greater power loads and duration of use. ▪ High consumers' increased electricity use on LCD TVs in passive standby mode relates to a greater power load. ▪ High consumers' increased electricity use on digital STBs in active mode relates to a longer daily usage. ▪ High consumers' increased electricity use on digital STBs in active standby mode relates to a higher power load. ▪ High consumers' increased electricity use on cable STBs in active mode relates to a longer daily usage and larger operational power load. ▪ High consumers' increased electricity use on internet STBs in active and active standby modes was the result of low and medium consumers' not owning this appliance type.

- High consumers' increased electricity use on DVD players in active mode relates to both a greater in use power demand and increased usage.
- High consumers' increased electricity use on DVD players in active standby mode relates to an extended daily functioning period.
- High consumers' increased electricity use on VCR players in passive standby mode relates to a longer duration of use.
- High consumers' increased electricity use on DVD with VCR players in passive standby mode was the result of low and medium consumers' not owning this appliance type.
- High consumers' increased electricity use on analogue radios in passive standby mode relates to a longer functioning duration.
- High consumers' increased electricity use on personal CD players in active standby and passive standby modes was the result of low and medium consumers' not owning this appliance type.
- High consumers' increased electricity use on MP3 docking stations in active standby mode relates to a longer duration of use.
- High consumers' increased electricity use on MP3 docking stations in passive standby mode relates to both a greater power load and extended functioning period.
- High consumers' increased electricity use on video consoles in passive standby and off standby modes relates to a larger power load and increased duration of operation.
- High consumers' increased electricity use on ebook readers in active mode relates to a greater operational power demand.

Non-fixed lighting

- High consumers' increased electricity use on incandescent bulbs related to an extended duration of usage.

HVAC appliances

- High consumers' increased electricity use on electric fires in active mode was the result of low and medium consumers' not owning this appliance type.
- High consumers' increased electricity use on electric blankets in active mode was the result of low and medium consumers' not owning this appliance type.
- High consumers' increased electricity use on portable halogen radiators in active mode was the result of low and medium consumers' not owning this appliance type.
- High consumers' increased electricity use on portable oil filled radiators in active mode was the result of low and medium consumers' not owning this appliance type.

Transportation appliances

- High consumers' increased electricity use on mobility scooters in active mode relates to a longer duration of use.
- High consumers' increased electricity use on golf trolleys in active mode was the result of low and medium consumers' not owning this appliance type.
- High consumers' increased electricity use on chair lifts in active mode was the result of low and medium consumers' not owning this appliance type.

Catering appliances

Minor cooking

- High consumers' increased electricity use on microwaves in active mode relates to a longer duration of use.

- High consumers' increased electricity use on kettles in active mode relates to a greater operational power demand.
- High consumers' increased electricity use on toasters in passive standby mode relates to both a greater in use power demand and longer duration of operation.
- High consumers' increased electricity use on blenders in passive standby mode relates to a longer duration of use.
- High consumers' increased electricity use on coffee makers in passive standby mode relates to a longer duration of use.

Preservation and cooling appliances

- High consumers' increased electricity use on upright freezers in the non-cooling cycle relates to a greater electrical power demand.
- High consumers' increased electricity use on beer and wine coolers in the cooling cycle relates to a higher power demand and longer period of operation.

Washing appliances

- High consumers' increased electricity use on dishwashers in the washing cycle relates to a greater electrical power demand.
- High consumers' increased electricity use on dishwashers in the drying cycle relates to a longer operating duration.
- High consumers' increased electricity use on dishwashers in the passive standby mode relates to both a greater electrical power demand and increased operating period.

Laundry appliances

- High consumers' increased electricity use on irons in the active mode relates to a greater electrical power demand.
- High consumers' increased electricity use on washing machines in the water heating cycle relates to a greater electrical power demand and longer functioning period.
- High consumers' increased electricity use on washing machines in the washing cycle relates to a longer functioning period.
- High consumers' increased electricity use on washing machines in the passive standby mode relates to a greater electrical power demand and longer functioning period.
- High consumers' increased electricity use on washer-dryers in the water heating, washing, heating and tumble cycles all relate to a greater electrical power demand and longer functioning period.
- High consumers' increased electricity use on tumble dryers in the heating cycle relates to a greater electrical power demand and longer functioning period.
- High consumers' increased electricity use on tumble dryers in the tumble cycle relates to a greater functioning period.
- High consumers' increased electricity use on tumble dryers in the passive standby mode relates to a greater electrical power load.

Building and outdoors maintenance appliances

- High consumers' increased electricity use on vacuum cleaners in active mode relates to a greater operational power demand.
- High consumers' increased electricity use on automatic door openers in active mode was the result of low and medium consumers' not owning this appliance type.

- High consumers' increased electricity use on indoor aquariums in active mode relates to a greater in use power demand and longer duration of operation.
- High consumers' increased electricity use on outdoor aquariums in active mode relates to a greater in functioning power demand.

Hygiene, beauty and leisure appliances

- High consumers' increased electricity use on hair dryers in active mode relates to a longer duration of use.
- High consumers' increased electricity use on hair straighteners in active mode relates to a greater in use power demand and longer duration of operation.
- High consumers' increased electricity use on massagers in passive standby mode was the result of low and medium consumers' not owning this appliance type.

8.5 Facilitating energy saving from high electrical energy demand households

A motivation for undertaking the research presented in this thesis was to identify opportunities to reduce CO_2 emissions from high electrical energy consuming households. This motivation directed the final research question:

5. What policy recommendations can be established from the research findings?

It is believed that the findings obtained in this research might be used to help inform potential UK energy policies aimed at reducing the electricity consumptions of high demand homes, as well as directing future research in this area. The following sections suggest possible methods of energy demand reduction for high demand households in light of the socio-economic, technical and appliance related drivers of high electrical energy consumption established in this research. It should be noted however that this study has focused on relatively small numbers of dwellings (315 and 27) and it is accepted that it would be unwise to draw sweeping conclusions from the analysis or to make strong statements concerning policies to reduce the CO_2 emissions in the UK housing stock.

8.5.1 Scope of energy saving recommendations

Before outlining potential opportunities to reduce the electricity demand of high demand households, it is essential to define the scope of the potential energy saving recommendations that will be made. It was observed in this research that a broad range of socio-economic, technical and appliance related factors contribute to high electrical energy demand in UK homes. However, the methods of demand reduction described in the subsequent sections will focus on opportunities associated with the ownership, power demand and usage of electrical appliances only. This boundary has been established for a number of reasons, firstly, without the implementation of unrealistic and drastic policies (for example, limiting the number of children, capping household incomes or restricting the maximum floor area of new build homes or extensions) there is very little that can be done to address the socio-economic and technical building characteristics influencing high consumption. Although, it is noted that more efficient electric space and water heating systems and reduced occupant use of these systems could potentially achieve energy savings in high electrical demand dwellings. Secondly, the effects of these socio-economic and technical characteristics ultimately manifest themselves in appliance ownership and use, therefore rather than attempting to address the underlying factors instead the recommendations will suggest how to mitigate the resultant impacts on electricity use.

Another important point to acknowledge before providing energy saving recommendations is that domestic electricity use is an essential part of everyday life and electrical appliances, lighting, space and water heating have transformed the way people live and created possibilities to improve their quality of life. Therefore, the methods aimed at reducing the electricity consumptions of high demand homes described in the following sections will be realistic and accept that the electricity used by households is the effect of supplying services to the building occupants. However, by addressing high demand dwellings specifically, it could be argued that these households use more electricity than what is essential to maintain an acceptable standard of life and it has been demonstrated in the current research that the electricity consumed by high consuming dwellings does not always provide a useful purpose (e.g. standby) and the appliances owned can be more efficient (e.g. greater power demand in active mode), which presents a genuine opportunity to reduce household electricity consumption.

The findings from this research suggest that the electricity consumption of high demand dwellings can be reduced in two main ways. Firstly, technical improvements can be made to increase the energy efficiency of electrical appliances by decreasing the power required to deliver given services or functions. Secondly, by motivating more energy efficient behaviour amongst the occupants of high demand homes, which includes influencing both occupants' operational (e.g. reducing standby power demand) and purchasing behaviours (e.g. buying more energy efficient appliances). In the following sections these technical and behavioural opportunities will be considered in more detail.

8.5.2 Technical opportunities to reduce electricity use and CO_2 emissions from high electrical energy demand households

The results of this research has identified that a key opportunity for reducing the electricity consumption of high consumers is through improvements in appliance energy efficiency by decreasing the power required in different power modes. Table 8-3 provided a summary of the specific appliances and power modes in which high consumers have a greater power demand than low and medium consumers and are therefore a priority in terms of reducing the energy consumption of this group.

To reduce the power demands of appliances, manufacturers should be required to continually drive down the power requirements of their devices both in use and in standby modes. In 2010, the UK introduced a series of minimum energy performance standards (MEPS) to improve the energy efficiency of appliances (Defra 2009b), which is clearly a step in the right direction but continuous improvement is still required in this area in line with the development and availability of new technology. The MEPS established a set of power requirements for a range of appliances for active and standby modes. Manufacturers are also required to comply with the European eco-design requirements for standby and off-mode, which produced MEPS for standby power in 2009 (Defra 2009b). The results from this study highlight that an extension of the range of appliances for which MEPS are required could clearly be beneficial.

MEPS as a policy does however have limitations, most evident is that to actually see a reduction in power demand, building occupants have to replace their existing appliances with new ones. The replacement of some appliances in the UK is very slow and therefore the potential energy reductions of MEPS will take time to come to fruition. Also, manufacturers could choose to bypass the MEPS by designing single function devices that are always in active mode, rather than having to ensure that all power modes of their appliances comply.

Another key opportunity for reducing the electricity demand of high consumers identified in this research is to reduce the duration of operation of appliances. Table 8-3 provided a summary of the specific appliances and power modes in which high consumers have a longer duration of operation than low and medium consumers. Whilst reducing the wasted energy consumption associated with standby power modes is essential, it is harder to state that the hours of operation in active mode should be reduced because it is associated with a service or function for the occupants. Although it is not evident in this study, it is highly likely that some of the active mode usage of appliances is being wasted as the service provided is not actually being used by the occupants (e.g. the TV is on but no one is actually watching it). Therefore, a number of technical solutions can be recommended to reduce the duration of operation of appliances in both active and standby modes.

The introduction of automatic power down functions which allows appliances to automatically enter a standby power mode after a period without operational use could help reduce wasted electricity associated with the active power mode. Policies enforcing the introduction of automatic power down functions already exist for computers, TVs and

STBs (Defra 2009b) but this research advocates that power down functions should also be announced for other domestic appliances.

Moreover, the current research has identified that the duration of time spent in standby modes by some appliances also contributes to high electricity consumption and therefore a similar power down function from active standby or passive standby to off standby mode would clearly be beneficial.

Power down functions should however be a default setting on new appliances rather than an option that the occupants need to select. This will ensure that at least initially the solution may achieve energy savings; of course, this technical intervention will be vulnerable to the occupants disabling the function in order to maintain existing patterns of appliance operation.

This study found that the electricity used in active standby, passive standby and off standby modes by some domestic appliances contributed to high electricity consumption. It could be imagined that occupants may be less likely to disconnect their appliances from the mains supply due to difficulties accessing the mains supply switch (i.e. the mains switch is behind a cupboard or too low or too high). A possible solution could be for manufacturers to introduce an easily accessible mains off switch on the appliance itself, which will similarly cut the power to the device. Equally, better consideration for where mains sockets are located when designing or refurbishing homes or the introduction of a centrally located master switch which cuts the power supply to all appliances in a home or room could be alternative solutions.

A lack of plug sockets in the participants' homes appeared to be a possible reason for appliances being left in active or standby modes. Dwellings in this study were observed to have many more appliances than mains sockets and were therefore using multi-socket extension leads to power appliances. The impact was that if one of the devices on the extension lead was deemed essential to be permanently on (e.g. wireless router), it was not then possible for the occupants to switch off the mains supply and therefore all other appliances were also powered. Although it sounds counter intuitive, a possible recommendation to reduce standby power could be to increase the number of mains sockets available in domestic buildings or ensure that all multi-socket extension leads sold in the UK have individual switches for each socket.

Standby power modes also provide occupants with the convenience of faster starting times for their appliances and the same functioning condition as when previously used (i.e. software still open and running on computers). Perhaps, if manufacturers could improve the speed at which appliances start and are ready to be used by the occupants, as well as, automatically reinstating previous software and files, occupants may be more inclined to power down their devices to off standby or mains off conditions.

Furthermore, it is not always evident from just observing appliances that they are consuming electricity (e.g. a red standby light or display). This lack of visual connection might contribute to occupants leaving their appliances in standby modes for longer simply because they are unaware that the appliance is still consuming electricity. Therefore better appliance design 'eco-design' or 'user-centred design' (Casamayor & Su 2013; Tang & Bhamra 2012) coupled with more standardised display screens and controls (Meier & Nordman 2002), which provide visual cues could encourage occupants to turn appliances off.

Previous research (Coleman et al. 2012; De Almeida et al. 2008; Vowles et al. 2001) has identified that occupants leave their appliances in standby mode due to concerns with losing appliance settings. As suggested in the earlier research, a possible solution could be for appliances to utilise non-volatile memory components, which store the information about the chosen settings even when the appliance is not powered. Thereby, occupants are able to disconnect appliances from the mains supply without concern for the loss of settings. The benefit of appliances having non-volatile memory components would however need to be effectively communicated to occupants, as some appliances already contain such components but occupants are still worried about losing settings based on the legacy of their experiences with past appliances (e.g. VCR players).

8.5.3 Behavioural opportunities to reduce electricity use and CO2 emissions from high electrical energy demand households

As noted in the previous sections, reducing the power demand of appliances in active and standby modes presents a real opportunity to reduce the electricity consumptions of high electricity consumers. However, the availability of more energy efficient appliances is only beneficial if they are purchased by consumers to replace the old inefficient appliances in their homes. Therefore, integrating energy efficiency into appliance purchasing decisions is essential. This research supports a number of existing and potential policies that are or could be used to encourage households to buy more energy efficient appliances.

Mandatory energy labelling introduced by the European Commission (EC 2010) coupled with voluntary energy labelling schemes, such as Energy Star or the Energy Saving Trust's Recommended are the cornerstone of policy in this area and are important for communicating the energy efficiency of appliances to consumers. Continued promotion of these labelling schemes is clearly essential to increase understanding of their purpose and meaning amongst the general public as well as to encourage households to choose more efficient appliances. It is however recommended that a consistent approach is developed for labelling schemes as there are evident variations between existing schemes, including differences in the range of ratings (e.g. A to G or A+++ to D), the number of levels of rating and colour schemes used. These inconsistencies could lead to confusion and misinterpretation by consumers and degrade the usefulness of the information provided.

At present, energy labelling is only used for some electrical appliances (i.e. preservation and cooling, laundry, washing, major cooking and HVAC appliances, and specifically televisions). As the current research has identified that appliances which are currently not covered by energy labelling schemes contribute to high electrical energy demand, it is recommended that mandatory energy labelling should be extended to address further appliance types.

In addition, energy labelling currently displays the energy efficiency of appliances whilst in active mode only. Given the findings that standby consumption is an important contributory factor to high electricity demand; it would be useful if energy labels could be modified to show the efficiency of appliances in standby modes as well. This would not only give consumers a better picture of the actual efficiency of the appliances that they are purchasing but also ensure that manufacturers are not excluding consideration for the power demands of their devices in standby mode in favour of efficient performance in active mode.

In order to encourage the purchase of energy efficient appliances, it is clear that information about the availability and benefits of such appliances are communicated to the general public. Ironically, the dissemination of this information probably has to occur through mass media channels (i.e. via infotainment appliances) to have a significant impact on purchasing decisions. It can be imagined that this information probably needs to come from multiple sources; on one hand advertising from manufacturers is essential but can be construed as simply a marketing technique, on the other hand independent reviews from consumer organisations (e.g. Which or Energy Saving Trust) have the benefit of impartiality but tend to lack mass media impact and therefore the information is only available for those consumers specifically searching for it.

An alternative policy for stimulating consumers to purchase energy efficient appliances could be to offer fiscal incentives, such as reduced value added tax (VAT). Price is a central factor in any purchase decision and a comparably favourable price for efficient appliances in the market may increase customers' likelihood to buy. This however may not be applicable for reducing the electricity consumption of high demand homes because they have been identified to have greater household incomes and therefore price might not be such an important factor. De Almeida et al. (2008) has also highlighted that reducing the price of energy efficient appliances may even have a negative effect as consumers associate price with quality and consequently a cheaper price might reduce desirability. Furthermore, a cheaper initial purchase price might simply result in a rebound effect, where occupants invest the financial savings in other energy consuming activities or operate the appliance for a longer duration.

On a broader level, it is clear that wider societal change has to occur to modify the underlying motivations for purchasing decisions. While more efficient appliances are being developed by manufacturers, consumers are degrading their value by purchasing larger more energy intensive appliances and rather than replacing existing inefficient appliances are instead choosing to keep and power both the new and old appliance. Therefore, policymakers not only need to consider how to encourage energy efficiency, but need to draw attention to sufficiency. In other words, consumers need to assess whether they require two of the same appliance powered in their home or require a TV which is much larger than their previous one. Whilst promoting energy efficiency amongst society is clearly important, it may be necessary in future to consider how to develop social stigma attached to wasting energy.

In addition to policy makers encouraging wider social change and energy efficiency in residential buildings, increased public knowledge and awareness delivered through campaigns will be essential to reduce the duration of operation of appliances in active and standby modes in high electrical demand households. Ultimately it is the behaviour of the occupants of high consuming homes that influence the period of time a device is used for and whether or not it is left in standby power mode. Motivating occupants to change their behaviours is extremely complex but the first step in this process has to be to increase awareness of energy efficiency but more specifically the electricity consumption attributable to specific domestic appliances both overall and for active and standby modes. This will enable occupants to make informed decisions about the behavioural modifications that they should take in their homes.

Chapter 9

Conclusions

9.1 Introduction

This study aimed to improve knowledge and understanding of the socio-economic, technical and appliance related factors affecting high electrical energy consumption in UK homes, with a particular focus on appliance electricity consumption. The research presented in this thesis used both quantitative and qualitative data. Quantitative data were collected by the use of energy monitoring, self-reported surveys and administered surveys. Qualitative data were collected by unstructured household interviews. The methods of data collection were applied during individual studies, as part of a larger research programme called 4M: ‘Measurement, Modelling, Mapping and Management 4M: an Evidence Based Methodology for Understanding and Shrinking the Urban Carbon Footprint’.

This chapter presents a brief summary of key findings from this thesis in relation to the study’s research aim and objectives (section 9.2). This is followed by a description of the thesis’ contributions to knowledge (section 9.3) and finally, limitations of the research are outlined along with recommendations for future research (sections 9.4 and 9.5).

9.2 Main findings

9.2.1 Variations in electricity consumption of UK homes and changes in demand overtime

The first objective of this thesis was to explore the variations in electricity consumption of a sample of UK homes and examine their change in electricity demand over time. This led to the following research questions being identified:

1. Does a sample of UK households demonstrate that large variations in electrical energy demand exist between homes?

2. Is the electricity consumption of a sample of UK households with high electrical energy demand increasing overtime?

The current research found that a skewed electricity distribution towards high electricity consumers in the domestic sector indeed exists. Large variations in annual electricity consumption were observed amongst households in both the L315 and L27 samples and the electricity demands of the two cohorts were highly skewed towards high electrical energy consumers. Specifically, the highest consuming 27% of the L315 dwellings used more electricity than the remaining households combined and the collective annual electricity use of the ten highest demand L27 homes used more electricity than the remaining seventeen homes. Furthermore, the high electricity demand group of the L315 homes not only accounted for more than half (57%) of the electricity used by the sample in 2009 (1,895 kWh/day), but used three times more electricity than the low demand group (499 kWh/day) and double that of the medium demand group (930 kWh/day).

Conflicting results were however obtained from the two household samples with regard to whether high electricity consumers are increasing electrical energy demand over time. The L315's high demand group reduced mean electricity use by 3.9% between 2007 and 2009, whereas, the L27's high demand group increased mean electricity use by 16.6% between 2007 and 2011.

Of particular note, with the exception of the L315's low demand group, the mean annual electricity consumption of all other electricity demand groups for both the L315 and L27 cohorts fluctuated between increasing and decreasing electricity use over time. This result highlights the need for future research to study the changes in electricity use of domestic buildings longitudinally.

The analysis also revealed that low and medium demand dwellings are becoming higher electricity consumers over time. Both the L315 and L27 cohorts identified that the low and medium demand groups were overall increasing consumption with time.

The current results strongly establish the need for a future longitudinal study of the changes in electricity use of a statistically representative sample of UK households, linked to modifications in the social, technical and behavioural characteristics of the homes. The findings also question the common use of average values to present national trends in domestic electricity use and for the development of energy policy. It might be beneficial if future electricity-related statistics were stratified by the overall electricity consumption of the dwellings.

The results support previous recommendations that energy policy and energy research might target those parts of the housing stock where electricity use is highest.

9.2.2 The socio-economic, technical and appliance related factors contributing to high electrical energy demand in UK homes

This thesis set two complementary objectives to identify the underlying socio-economic, technical and appliance related characteristics that affect the likelihood that a household will be a high electrical energy consumer, and to establish the contributions of appliance ownership, power demand and usage to high domestic electricity use. In line with these objectives, the following research questions were defined:

3. Which socio-economic, technical and appliance factors contribute to high electrical energy demand in a sample of UK households?
4. To what extent do the ownership, power demand and use of different domestic appliances contribute to high electrical energy demand in a sample of UK households?

The results of the odds ratio (OR) analysis and Appliance Electricity Use Survey (AEUS) in this thesis suggest that high electricity consumption in domestic buildings is related to a combination of the socio-economic characteristics of the building occupants, technical characteristics of the dwelling and the ownership, power demand and use of electrical appliances.

Regarding the socio-economic characteristics of the building occupants, the OR analysis found that households with: more occupants, children, teenagers, and higher annual household incomes are more likely to be high electrical energy consumers. Families with a HRP over 65 years old or a retired HRP are however less likely to have high electrical energy demand.

In relation to the technical characteristics of the dwellings, the OR results established that domestic buildings with: a floor area greater than 100 m^2, electric space heating as the primary form of heating, secondary portable electric heating, and electric water heating have a greater probability of high electricity consumption. Mid-terrace dwellings were less likely to have a high electrical energy use.

The OR study also investigated the likelihood of a household having high electricity consumption based on their ownership and usage of electrical appliances. The findings showed that households owning more than 30 appliances have an increased probability of high electrical energy demand.

More specifically, households owning: 4 or more IT appliances, 3 or more telephony appliances, more than 5 entertainment appliances, 3 or more HVAC appliances, any major electrical cooking appliance, 2 or more preservation and cooling appliances, 1 washing appliance, 3 or more laundry appliances, 3 or more than 5 building and outdoors maintenance appliances, or 2 hygiene, beauty and leisure appliances are more likely to be high electricity consumers.

With respect to the ownership of specific appliance types, the OR results demonstrated that household owning: 2 or 3 desktop computers, 1 or more laptop computers, 3 or more TVs, a plasma screen as their main TV, a main TV 40" or larger, an upright freezer, dishwasher, tumble dryer, or electric shower have a greater likelihood of having high electricity use.

The OR findings for the usage of appliances showed that households using: their main desktop computer for more than 4 hours each day at the weekend, their main laptop computer for more than 2 hours each day during weekdays, an electric hob between 1 and 2 hours each day both on a weekday and at the weekend, undertaking more loads of clothes washing each week, undertaking more clothes drying each week in the summer, 4 or more loads of clothes drying each week in the winter; and more than 21 electric showers each week are more likely to be high electricity consumers.

The AEUS undertaken with the L27 households provided a further detailed analysis of the contributions of appliance ownership, power demand and usage to increased electricity consumption on electrical appliances in high demand households. A comprehensive summary of the findings can be found in Table 8-3. The appliance factors identified also present the opportunities for energy demand reduction in high consuming households.

Broadly, the results showed that the increased electricity used by high consumers on particular appliances compared to low and medium consumers relates to a combination of greater power demands and longer durations of operation in specific appliance power modes. In some circumstances, ownership alone was identified as the most important factor as certain appliances were owned by high electrical energy consuming households only.

9.2.3 Opportunities to reduce high electrical energy demand in UK homes

Another objective of this thesis was to provide recommendations to support policy aimed at reducing electricity use from high electrical energy consuming households in the UK. It is accepted that the current research has focused on a relatively small number of dwellings and therefore it would be unwise to draw sweeping conclusions or to make strong statements concerning energy policy. With this limitation in mind, this objective prompted the research question:

5. What policy recommendations can be established from the research findings?

In spite of the range of socio-economic, technical and appliance related drivers of high electrical energy consumption established in this research, the opportunities for demand reduction described in this thesis were associated with the ownership, power demand and usage of electrical appliances only. This was because without the implementation of unrealistic and drastic policies there is little that can be done to address the socio-economic and technical building characteristics influencing high consumption, with the exception of increasing the efficiency of electric space and water heating systems and reducing occupants' use of these systems. Also, the effects of the socio-economic and technical characteristics ultimately manifest themselves in appliance ownership and use, therefore rather than attempting to address the underlying factors, instead the recommendations provided focused on how to mitigate the resultant impacts.

The findings from this research suggest that the electricity consumption of high demand dwellings can be reduced in two main ways. Firstly, technical improvements can be made to increase the energy efficiency of electrical appliances by decreasing the power required to deliver services or functions. Secondly, by motivating more energy efficient behaviour amongst the occupants of high demand homes, which includes influencing both occupants' operational (e.g. reducing standby power demand) and purchasing behaviours (e.g. buying more energy efficient appliances).

The current research established for the L27 households the specific appliances and power modes in which high consumers have a greater power demand and longer duration of operation than low and medium consumers and are therefore a priority in terms of reducing the electricity consumption of the high electrical demand group (Table 8-3). Considering the small sample size analysed, it is not clear whether policies targeting these specific appliances and power modes in high consuming homes more widely in the UK domestic sector would achieve similar energy savings.

The empirical findings of this study directly support the introduction of minimum energy performance standards (MEPS) to reduce the power demands of electrical appliances in high consuming households. Although MEPS already exist for some appliance types, a number of appliances identified to be contributing to high electricity consumption in the L27 households are currently exempt from this policy. Therefore, an extension of the range of appliances for which MEPS are required, as well as continuous improvement in line with the development of new technology would clearly be beneficial.

Another key opportunity for reducing the electricity demand of high consumers supported by the findings of this study is to reduce appliances' duration of operation.

This research also supports an extension and promotion for existing mandatory and voluntary energy labelling schemes as appliances which are currently not subject to such schemes were found to contribute to high electrical energy demand. Furthermore, energy labels only display the energy efficiency of appliances when active. Given the findings that standby consumption is an important contributory factor to high electricity demand it would be valuable if energy labels could be modified to show this additional information.

More generally, the literature and professional judgement of the author, after undertaking this study, suggest that to reduce the electricity consumption of high consuming households the following technical solutions may be beneficial:

- Automatic power down functions from active and standby power modes.
- Introduction of an easily accessible mains off switch on appliances.
- Better consideration for the location of mains sockets when designing or refurbishing domestic buildings.
- Introduction of a centrally located master switch which cuts the power supply to all appliances in a home or room.
- Increase the sockets available in domestic buildings.
- Ensure that all multi-socket extension leads sold in the UK have individual switches for each socket.
- Faster appliance starting times from mains off.
- Appliances that automatically reinstate the previously used condition (e.g. computers automatically opening software and files).
- Improved appliance design to raise occupants' awareness that an appliance is functioning in active or standby modes.
- Use non-volatile memory components in appliances, which store information about chosen settings when the appliance is not powered.

The availability of more energy efficient appliances is however only beneficial if they are purchased by households to replace inefficient appliances. Therefore, in the authors view, integrating energy efficiency into appliance purchasing decisions is essential. In order to encourage the purchase of energy efficient appliances, information about the availability and benefits of such appliances are communicated to the general public.

An alternative policy for stimulating consumers to purchase energy efficient appliances could be to offer fiscal incentives (e.g. reduced VAT). However, as high electrical energy demand homes were found to have greater household incomes, price might not play an important role in the appliance purchasing decisions of these households.

9.3 Contributions to knowledge

The primary contribution to knowledge from this thesis is the improved understanding of the socio-economic, technical and appliance related drivers of high electrical energy consumption in UK homes. In addition, this thesis has provided a detailed analysis of the contributions of ownership, power demand and use of electrical appliances to high electricity use in UK homes. These findings have enabled the development of a list of specific appliances and power modes which should be targeted to reduce the electricity consumption of high consuming dwellings. For each appliance power mode the thesis has specified whether the power demand and/or occupants' usage needs to be addressed in order to achieve energy savings.

Despite previous knowledge of the large variations in electricity consumptions of UK homes and the skewed electricity distribution towards high electricity consumers, this thesis adds to the debate regarding whether high electricity consuming households are in fact increasing demand over time as conflicting results were obtained from the two household samples investigated in this thesis. This research further revealed that low and medium demand dwellings are becoming higher electricity consumers with time.

A significant contribution has also been made in terms of the provision of detailed "real world" appliance electricity monitoring data from UK homes. This dataset contains measurements from around 800 electrical appliances across a broad range of domestic appliance categories.

9.4 Limitations

The limitations of this research have been outlined throughout this thesis, both in the methodology chapter and at the end of each results chapter, these include the use of different sources of energy data and treatments, missing data, the use of self-reported data, potential errors in data analysis, in particular related to the classification of power measurements into appliance power modes, generalisation of the results beyond the existing household samples studied and the constrained availability of monitoring equipment meaning some electrical appliances in the study's households were unmeasured.

The first limitation, as discussed in detail, in Chapter 5, Section 5.4 is that the conclusions drawn in relation to the variations in annual electricity use and changes in demand over time for both the L315 and L27 cohorts are subject to uncertainties inherent in the different sources of energy data used (4M LIL electricity meter reading data and 4M energy supplier annual electricity use data), normalisation treatments applied, as well as some missing energy data for dwellings. These uncertainties mean that the reliability of the results and conclusions obtained from this work, particularly the changes in demand over time are questionable. Whilst the overall trends in electricity use of the three electrical demand groups identified are likely to be accurate, the magnitudes of the changes in electricity use year-on-year are subject to inaccuracy.

The use of self-reported data in the odds ratio analysis discussed in Chapter 6, Section 6.6, is also a possible limitation for the conclusions regarding the socio-economic, technical and appliance related factors contributing to high electrical energy demand in UK homes. The ability and willingness of the general public to accurately report the information requested by the LIL household survey and LIL domestic household survey is debateable.

The classification of power measurements into power modes is another limitation and source of uncertainty in the results and conclusions obtained for the appliance factors, specifically power demand and use, influencing high electrical energy demand. The thresholds of power modes were established based on the researcher's instinct and familiarity with the data whilst observing X Y scatter graphs; however the differentiation between power modes was sometimes difficult as there were only small variations in power loads between modes. The uncertainty associated with the classification of power measurements could have led to an over or under estimation of the electricity consumption and hours of operation results.

A major and overarching limitation of the current research presented in this thesis is that the results and conclusions are obtained based on small sample sizes. Tests for the sampling error in the 315 and 27 dwelling sample sizes showed that should a similar sample have been drawn from the population, it is possible that the results would have varied. This means that the results and conclusions are thus unlikely to be representative of the wider population of Leicester and UK homes. This reduces the ability to generalise the research findings beyond the current work and to reliably devise potential policies for achieving electricity savings from high demand households.

Another limitation is the duration of electricity monitoring periods used in this research. Whilst the 4M LIL electricity meter reading was undertaken over a period of one year, the Appliance Electricity Use Survey (AEUS) had a short monitoring period of around four weeks in each home. The results from the AEUS were therefore likely to have been effected by seasonal variation and infrequent influences on occupancy. This limitation would have an effect on the conclusions relating to the influence of appliance related factors on high electrical energy demand obtained from the L27 households.

Finally, the constrained number of smart meter plugs meant that some electrical appliances in the L27 households were unmeasured. This practical limitation possibly led to an underestimation of the electricity consumption and hours of operation of certain domestic appliances in the electrical demand groups. This limitation will have an impact on the results and conclusions drawn from the AEUS undertaken in the L27 homes.

9.5 Further work

The limitations and constrained scope of this thesis do however provide future research opportunities using both the existing dataset collected during this study, as well as for the wider research community to better understand and confirm the results arising from this research. The author of this thesis believes that the following potential directions could offer valuable further research in this area.

9.5.1 Further work using the existing dataset

The detailed appliance monitoring data collected in this thesis from around 800 electrical appliances across a broad range of domestic appliance categories, offers the opportunity for many further research directions that were beyond the scope of the current work. The main avenues of future work using the existing dataset could include, but are not limited to:

- Assess the potential of electricity demand shifting. The dataset could be used to quantify the potential for shifting electricity demand associated with domestic appliances, such as reducing periods of peak demand and creating more even demand for electricity, which will be easier to meet using low carbon power generation.
- Develop a high-resolution electricity demand model for domestic appliances. The dataset could be used to produce an minutely domestic appliance electricity demand sub-model for use in building performance simulation, combining the ownership, time of use and appliance power demand data collected.
- Generate appliance electricity demand profiles. The dataset could be used to produce 24 hour appliance demand profiles at 1 minute intervals for an average day each month. The profiles could be broken down by appliance category (office equipment and infotainment, catering, washing etc.). A profile could be produced for all L27 households, for all days, weekdays and weekend days, and by low, medium and high demand groups.
- Understand baseload electricity demand. Baseload electricity demand is the minimum electricity consumption used throughout a day. Determining the appliances that contribute to this load, will help to understand how it can be reduced.

- Understand more about electricity used in standby modes. Finding out which domestic appliance types consume most electricity in standby mode will help to identify which appliances should be targeted for potential demand reduction policies, but also for better appliance design by manufacturers.
- Identify patterns of simultaneous appliance use in homes. The dataset could be used to establish if patterns of appliance use exist. Are some appliances types used together, always following each other or at a specific time each day.
- Investigate how external environmental conditions affect appliance use. Linking the existing dataset to secondary weather data for the monitored periods would allow an investigation of how appliance electricity use varies with external environmental conditions, and which appliances are used more or less.

9.5.2 Further work for the wider research community

To better understand and confirm the results arising from this research, further work in this area is recommended that can be undertaken by the wider research community. The main areas in which future research would be beneficial to further the work undertaken in this thesis include:

- A longitudinal study of the changes in electricity use of UK homes. The current study found that during the three and five year periods investigated, the mean annual electricity consumptions of the electrical demand groups fluctuated. This result highlights the need for future research to study the changes in electricity use of domestic buildings longitudinally. A future longitudinal study of the changes in electricity use of a statistically representative sample of UK households, linked to modifications in the social, technical and behavioural characteristics of the homes would be highly desirable. At the UK scale, this would require a sample size of at least 600 households to achieve the typically acceptable margin of error (4%). The number of households required would however increase based on the number of additional stratifications applied for social, technical and behavioural characteristics of the homes. Ideally, the data would be collected from homes with smart meters installed in order to ensure the accuracy of the data used in the analysis (i.e. not from estimated energy bills). This electricity data could potentially be accessed from the energy supplier using a mandate signed by the householder.
- A study of the factors affecting electricity use in UK homes. Whilst the current odds ratio analysis has provided the most detailed investigation of the socio-economic, technical and appliance related factors affecting high electricity use in UK domestic buildings to date, further regression analyses undertaken on a

larger statistically representative sample of UK homes would be useful to validate the findings of the current study. Such a study would ideally link electricity consumption data collected from smart meters, with publically available information regarding the socio-economic characteristics of the occupants and technical information about the dwelling (e.g. Homes Energy Efficiency Database (HEED), National Energy Efficiency Data Framework (NEED), Energy Saving Trust database, etc.). A further nationally representative survey regarding the ownership and use of appliances would greatly complement the work. The RCUK Centre for Energy Epidemiology at University College London (UCL) is currently leading such work for the UK domestic sector (Oreszczyn et al. 2013).

- A detailed and longitudinal appliance electricity monitoring study. This thesis has presented an exploratory study of the variations in appliance electricity consumption in a small sample of 27 UK homes with a monitoring period of around only 4 weeks per home. Further work in this area should look to both increase the sample size used (min. 600 homes) and duration of monitoring undertaken (min. one year). This would allow for seasonal variations and infrequent influences in occupancy to be accounted for in the results. The Household Electricity Survey (Zimmerman et al. 2012) has started to provide some further appliance electricity use results for UK homes, albeit only 26 of the 251homes have been monitored for a whole year and the remainder for only 1 month. The delivery of such a project is now constrained primarily on budget, rather than the availability of reliable appliance monitoring systems and the willingness of the general public to be involved.

- Testing interventions in homes. This research established a series of potential technical and behavioural interventions that could be implemented to reduce the electricity consumption of high demand households. Further research may attempt to intervene in a sample of high electricity consuming households to investigate whether it is actually possible to reduce the energy demand of this group. An intervention should be multifaceted replacing existing inefficient electrical appliances and attempting to modify the occupants' appliance operational behaviours.

- Qualitative interviews with high demand households. Some of the factors which contribute and explain high electricity consumption in domestic buildings probably extends beyond the information that can be gathered by quantitative data only, as was the case in this thesis. To explore high electrical energy demand more fully, qualitative interviews exploring attitudes and values of occupants of these homes and the underlying stories behind appliance use could develop our understanding of this energy use group further.

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Appendices

This section contains background and supportive information that are relevant to this study and have been referred to within the thesis chapters. The contents are as follows:

Appendix A: 4M Domestic appliance survey

Appendix B: AEUS recruitment letter and acceptance form

Appendix C: AEUS participant information pack

Appendix D: AEUS installation form

Appendix A 4M Domestic appliance survey

This questionnaire is completely confidential. Should you have any comments, please write them down here.

Your electricity supplier is ____________.

Your gas supplier is ____________.

Please return your completed questionnaire, as soon as possible – **by 19 January if feasible** – using the stamped and addressed envelope provided.

Thanks again for your participation.

The information you provide will be held securely by Loughborough University. No one will be identified in the results of the study. Your personal details will not be passed to other people or organisations. The research will be carried out in accordance with the Data Protection Act and Loughborough University and its partners have strict ethics procedures to control how the research is carried out and used.

Ref: <reference number>

Living in Leicester

Domestic Appliances Survey

This survey asks about electrical appliances in your home and how you use them. Instructions are provided at the beginning of each section; there are three in total. Any information you provide will be treated in confidence.

If you have any questions, please contact Dr Liyan Guo or Dr David Allinson at 01509 223643 or email L.Guo@lboro.ac.uk.

Many thanks for your help.

Section A. How many appliances in your home?

Listed below are common domestic appliances. Please indicate the **number** of each appliance you have that are used regularly, including any that may be in a cupboard, storage room, shed or garage. Fill in “0” for any appliances you do not have.

A1. Cold Appliances

Refrigerators	
Fridge-freezers	
Upright freezers	
Chest freezers	

OTHER cold appliances such as small drink coolers, please specify:

____

____

A2. Entertainment

Traditional CRT televisions *	
Flat panel LCD televisions	
Flat panel Plasma televisions	
Video Cassette Recorders	
Set-top boxes for TVs	
DVD players/recorders	
Digital TV recorders (DTR)	
Digital radios	
Hi-fi systems/Music centres	
Home cinema/Home theatre	
Record players	
Play station/Game consoles	

* CRT (cathode-ray tube) TV is the ordinary type, before flat screen TVs.

OTHER home entertainment equipment, please specify:

____

____

____

____

____

____

____

Section C. How old and what size is your appliance?

Please provide information about the **size** and **age** of your appliances, based on your best estimation. If you do not know the size, please provide both the brand and model if possible (often found on the front cover of the machine or in the manual).

Appliances		Size	(*If size unknown*) Model & Brand	Age
1^{st} TV				____years
2^{nd} TV				____years
3^{rd} TV				____years
4^{th} TV				____years
Refrigerator	1^{st}			____years
	2^{nd}			____years
Fridge-freezer	1^{st}			____years
	2^{nd}			____years
Upright freezer	1^{st}			____years
	2^{nd}			____years
Chest freezer	1^{st}			____years
	2^{nd}			____years
Washer dryer				____years
Tumble dryer				____years
Washing machine				____years
Dishwasher		Full size / Compact *(please circle)*		____years

Note: Information on style, height, length etc may help us estimate the size.

B3. During a typical week (Mon – Sun), how many hours are the computers turned on for?

	Monitor Type (*please circle*)	Hours per Day	
		Weekday	Weekend
1st desk-top pc	CRT/LCD/plasma	_____hours	_____hours
2nd desk-top pc	CRT/LCD/plasma	_____hours	_____hours
3rd desk-top pc	CRT/LCD/plasma	_____hours	_____hours
1st laptop		_____hours	_____hours
2nd laptop		_____hours	_____hours
3rd laptop		_____hours	_____hours

B4. Regardless of gas or electric cooker, please fill in below:

- On a typical weekday (Mon – Fri), on average the oven is on for about _____hours; the hob is on for about _____hours;
- On Sat and Sun, on average the oven is on for about __hours per day; the hob is on for about _____hours per day.

B5. Do you normally unplug or switch off at the wall socket the following appliances when they are not in use? (*please circle*)

TVs	No/Yes/NA	Set-top boxes	No/Yes/NA
VCRs	No/Yes/NA	Game consoles	No/Yes/NA
DVD players	No/Yes/NA	Desk-top PCs	No/Yes/NA
Digital TV recorders	No/Yes/NA	Laptops	No/Yes/NA
Audio equipment	No/Yes/NA	Printers	No/Yes/NA
Broadband modem	No/Yes/NA	Wireless router	No/Yes/NA

A3. Laundry and Cleaning

Washing machines	
Tumble dryers	
Washer dryers	
Dishwashers	
Irons	
Vacuum cleaners	

OTHER electric appliances for laundry or for home cleaning, please specify:

A4. Kitchen Appliances **

Electric kettles	
Pop-up toasters	
Sandwich toasters	
Electric deep fat fryers	
Electric steamers	
Slow cookers	
Electric health grills	
Electric bread makers	
Electric ice-cream makers	
Electric hot drink makers	
Electric Juicers	
Food processors	
Electric blenders/mixers	
Cooker hoods	

** Please note that oven, hob and microwave were included in the initial Living in Leicester Survey.

OTHER cooking appliances, please specify:

A5. Computers and Communications

Desk-top computers	
Laptop computers	
All-in-one multi-function printers	
Other printers	
Scanners	
Copiers	
Facsimile machines	
Telephone/answering machines	
Mobile phones	
Broadband modem/routers	

OTHER computer or communication appliances, please specify:

______
______
______
______
______
______
______

A6. Miscellaneous Appliances

Home security systems	
Hair styling equipment	
Electric towel rails	
Electric blanket	
Hot tub/Spa/Jacuzzi	
Heated pool	
Power tools	
Dehumidifier	
Extractor fans	
Ceiling fans/Portable fans	
Air-conditioning	

Please list any **OTHER** appliances which are regularly used but not included in the list, e.g. fish tanks, items in conservatory, cupboards, garden sheds or garages (exclude gardening tools since they were included in the initial survey):

______
______
______
______
______

Section B. How do you use your appliances?

Please provide an estimate of usage for each appliance below.
Write 'NA' if you do not have this appliance in your household.

B1. During a typical week (Mon – Sun), how many loads of laundry and dishwashing are done in your home?

	Loads per Week	Temperature
Clothes Washing	____Loads	____℃
Dishwashing	____Loads	____℃
Clothes Dryer	____Loads per week in summer ____Loads per week in winter	

B2. During a typical week (Mon – Sun), how many hours are the TVs, audio-video equipment or game consoles turned on for?

	Type (*please circle*)	Hours per Day	
		Weekday	Weekend
1st TV	CRT / LCD / plasma	____hours	____hours
2nd TV	CRT / LCD / plasma	____hours	____hours
3rd TV	CRT / LCD / plasma	____hours	____hours
4th TV	CRT / LCD / plasma	____hours	____hours
VCR		____hours	____hours
DVD player		____hours	____hours
Home cinema		____hours	____hours
Video game		____hours	____hours

Appendix B AEUS recruitment letter and acceptance form

Living in Leicester

energy travel garden

<First> <Surname>
<Address1>
<Address2>
<Address3>
<PostCode>

17th June 2011

Dear <Title> <Surname>

Greetings from the Living in Leicester Research Team at Loughborough University.

As you may remember, we have conducted several activities as follow ups of the on-going Living in Leicester study including a Domestic Appliances Survey, Meter Readings, and the collection of temperature sensors (HOBOs). We are happy to let you know that with your cooperation so far the Living in Leicester study is proving to be a great success.

Following on from the success of these previous activities, we are again looking for your help in a further study to measure the electricity used by individual appliances in your home. In return for your help, we will share the results of your own house by producing a personalised report specially designed for every participant. A £20 Love2shop voucher will be offered for your time and inconvenience. Please see the Information Sheet for more details about the study.

If you are interested in taking part, simply fill in the enclosed form and return it in the stamped addressed envelope provided. Your earliest reply is much appreciated.

Rory Jones and Liyan Guo, both working for the Living in Leicester study, will be undertaking this activity. If you have any questions please contact Rory or Liyan by telephone on (01509) 223643, or email: R.V.Jones@lboro.ac.uk.

Thank you in anticipation. As always, your support is vital to the success of this study.

Yours sincerely

RJones

Mr Rory Jones **Dr. Liyan Guo**
Department of Civil and Building Engineering
Loughborough University

dmu.ac.uk DE MONTFORT UNIVERSITY LEICESTER Loughborough University The University Of Sheffield. Newcastle University

Living in Leicester – Follow up Activity Information Sheet

What is the purpose of this activity?

To measure the electricity used by individual appliances in your home by using some state of the art gadgets.

What will the activity involve?

We simply fit a small box between the plug and the socket for each electrical appliance (as shown in the picture). This will measure the electricity used. At the end of the study we would like to ask a few questions.

How long will it take?

The whole study will last for a maximum of one month. But the total time commitment from you will be around 3 hours. This will comprise of:

- Installation of monitoring equipment (2 hours at the beginning).
- Interview and collection of monitoring equipment (1 hour at the end).

For the period between the beginning and the end of this activity, the equipment will just run in the background and does not require you to do anything.

If at any point you no longer wish to partake then you are able to withdraw.

What will I get out of it?

You will receive a unique report which integrates the measurement results from your own house and tailored advice from experts. A £20 Love2shop voucher, accepted at 20,000 popular UK stores including Argos, Debenhams, and Waterstone's, will be offered for your time and inconvenience.

Can anyone participate?

Any household with an Internet connection can participate.

I am interested in being part of this activity, what should I do now?

Please return the enclosed form in the stamped addressed envelope provided, as soon as possible, and we will be in contact soon.

The information and measurement data you provide will be held securely by Loughborough University. No one will be identified in the results of the study. Your personal details will not be passed to other people or organisations. The research will be carried out in accordance with the Data Protection Act. Loughborough University and its partners have strict ethics procedures to control how the research is carried out and used.

Living in Leicester – Follow up Activity

Returning Form

Upon receipt of your form, we would like to telephone you to tell you more about the study and to answer any questions you may have. We will also arrange a convenient time and date to install the equipment in your home during the phone call.

Reference number: **<serial>**

Please tick the relevant box and provide your telephone number, email and the most convenient time to contact you. Then, post back using the stamped addressed envelope provided.

☐ Yes, I am interested in being part of this activity.
Please call me with more details.

Name: ____________________

Please contact me on: (telephone number) ____________________

(Email) ____________________

Between: (time) ________ **and** ________ **Monday to Friday**

☐ No, I am not interested.

If you have any questions please contact us by telephone on (01509) 223643, or email: R.V.Jones@lboro.ac.uk.

Appendix C AEUS participant information pack

Participant Information Sheet

Living in Leicester: Appliance measurement follow up activity

Thank you for welcoming us into your home and for your interest in this study. We had a great response, and we will be returning to many homes in Leicester over the coming months to complete this activity.

Before we install any equipment in your home, we would like you to take a few minutes to read this information sheet. Feel free to ask us if there is anything that is not clear or if you would like more information.

What is the purpose of the study?

To measure the electricity used by individual appliances in your home by using some energy plugs.

What will the activity involve?

We will fit energy plugs between the plug and the socket for each electrical appliance in your home, which will measure the electricity used. The energy plugs will then communicate wirelessly with a small data storage device which will be placed in your home. This device will need to be powered and connected to the internet for the duration of the study. The data collected will then be sent securely over the internet to the Living in Leicester Research Team at Loughborough University.

In addition, a device will be attached around the mains electrical cable of your home's electricity meter. This will measure the amount of electricity used in your home.

At the end of the study we will ask a few questions about your views on energy use in households.

Who is doing this research?

This follow up activity is part of the continuing Living in Leicester study. Mr Rory Jones and Dr Liyan Guo, both working for the Living in Leicester study, will be undertaking this activity with you.

What will I be asked to do and how long will it take?

The whole study will last for about one month. But the total time commitment from you will be around 3 hours. This will comprise of:

- Installation of monitoring equipment (about 2 hours at the beginning).
- Interview and collection of monitoring equipment (about 1 hour at the end).

For the period between the beginning and the end of this activity, the equipment will just run in the background and does not require you to do anything.

Once I take part, can I change my mind?

Yes, you can withdraw at any time, for any reason and you will not be asked to explain your reasons for withdrawing. Please contact either Rory or Liyan using the contact details given below, if you wish to withdraw from the study at any point. They will arrange a time with you to collect the equipment.

Will my taking part in this study be kept confidential?

All the information and measurement data collected during the course of the research will be held securely by Loughborough University. No one will be identified in the results of the study. Your personal details will not be passed to other people or organisations. The research will be carried out in accordance with the Data Protection Act.

What will happen to the results of the activity?

Findings from this study will help us understand how people live across Leicester and to generate ideas about how to make our city better. The results will be used in one or more of the following sources; Living in Leicester reports; a PhD thesis; scientific papers in peer reviewed academic journals; presentations at academic and professional conferences and seminars. Anonymity and confidentiality will be in place in all cases. However, should you wish, you can get the results of your own house.

What do I get for participating?

You will receive a unique report which integrates the measurement results from your own house and tailored advice from experts. At the end of the study, a £20 Love2shop voucher, accepted at 20,000 popular UK stores including Argos, Debenhams, and Waterstone's, will be offered for your time and inconvenience.

What if I am not happy with how the research was conducted?

Loughborough University has strict ethics procedures to control how this research will be carried out and used. The University has a policy relating to Research Misconduct and Whistle Blowing which is available online at

http://www.lboro.ac.uk/admin/committees/ethical/Whistleblowing(2).htm.

Contact information

If at any time during the study you have any questions or you wish to withdraw from the study. Please telephone Rory or Liyan on (01509) 223643 or email: R.V.Jones@lboro.ac.uk

Safety Instructions for Energy Plugs and Extension Leads

The energy plugs that we will leave in your home today are **very safe** and **compliant with European standards for electrical appliances**. We have also double checked that all the energy plugs and extension leads are safe; by completing a PAT test on each and every one of them. All of the plugs and extension leads display a green sticker which shows they have passed this test and are **certified for use under the electrical safety guidelines of Loughborough University**.

When we setup the plugs and extension leads in your home, we will ensure this is done in line with the recommended normal operation guidelines for the equipment. We advise that you do not move or change the setup of the energy plugs or extension leads during the study.

However, in the case of portable appliances (e.g. laptops, irons, vacuum cleaners), you are free to move these around your home with their assigned energy plug as you wish. But before you do so, we recommend that you read the normal operation guidelines provided below.

Feel free to ask us any questions if there is anything which is not clear.

General things you should know

1. In the event of malfunction or damage to an energy plug or extension lead. You should disconnect from the mains supply socket, only if it is safe to do so, and notify Rory Jones or Liyan Guo using the contact details given below.
2. If it is not safe to remove the energy plug or extension from the mains supply socket. You should first switch off the mains supply from the fuse box. If you do not know how to do this, we would be happy to show you now.
3. You should not attempt to open, disassemble, crush, puncture, or short external power sockets or plug pins on the energy plugs or extension leads.
4. You should not clean the energy plugs or extension leads.
5. You should not overload the extension leads provided.

Normal operation guidelines for energy plugs

You can move the energy plugs attached to portable devices around your home as you wish, but you should ensure that the energy plugs are:

1. plugged into a suitable single phase AC mains supply via a socket.
2. connected to a wall or floor mains socket only where it is not difficult to remove from the socket.
3. used indoors only.
4. used at a temperature between 5°C and 40°C.
5. not used in bathrooms (maximum relative humidity of 80% for temperatures up to 31°C decreasing linearly to 50% relative humidity at 40°C).
6. used with a mains supply voltage with fluctuations of up to +/- 10% of the nominal voltage.

Contact Information

In the event of malfunction or damage to an energy plug or extension lead or you require further assistance or support. Please telephone Rory or Liyan on **01509 223643 or 07796 550498** or email: **R.V.Jones@lboro.ac.uk**

Residents can obtain further information relating to the operation of the energy plugs from the manufacturer's technical specification and setup guide documents available from:

http://www.plogginternational.com/docs/TechnicalSpecificationV02.pdf

http://www.plogginternational.com/docs/EO-ZIGBEE-SETUP%20v2011.pdf

CE

DECLARATION OF CONFORMITY

Manufacturer's Name: Energy Optimizers Limited

Manufacturer's Address: Estate Road One, South Humberside Industrial Estate, Grimsby DN31 2TA United Kingdom

Equipment Description: Single Phase, plug-in electricity meter with wireless connection to a PC

Equipment Model Designation: Plogg-Blu

Application of Council Directive: 72/23/EEC on the harmonization of the laws related to Member States relating to electrical equipment designed for use within certain voltage limits, as amended by: Council Directive 93/68/EEC and

Council Directive 89/336/EEC on the approximation of the laws related to Member States relating to electromagnetic compatibility, as amended by Council Directive 93/68/EEC.

Referenced Safety Standards:	Referenced EMC Standards:
EN 61010-1: 2001	EN 301 489-17 v1.2.1 (2002-08) EN 301 489-1 v1.6.1 (2005-09) EN 61326-2-1: 2006 EN 61326-1:2006 (Class B)

File ref: TRL 08SAF1 1148 and SU 3736/8587

I, the undersigned, hereby declare the equipment specified above conforms to the above Directive(s) and Standard(s)

Signature

Printed Name Shaun Merrick

Title: General Manager

3

Informed Consent Form

(to be completed after the participant information sheet and the safety instructions for energy plugs and extension leads have been read)

The purpose and details of this study have been explained to me. I understand that this study is designed to further scientific knowledge and that all procedures have been approved by the Loughborough University Ethical Advisory Committee.

I have read and understood the information sheet, safety instructions for energy plugs and extension leads, and this consent form.

I have had an opportunity to ask questions about my participation.

I understand that I am under no obligation to take part in the study.

I understand that I have the right to withdraw from this study at any stage for any reason, and that I will not be required to explain my reasons for withdrawing.

I understand that all the information I provide will be treated in strict confidence and will be kept anonymous and confidential to the researchers unless (under the statutory obligations of the agencies which the researchers are working with), it is judged that confidentiality will have to be breached for the safety of the participant or others.

It has been explained that the monitoring equipment used in this study will affect the electricity consumption in my home.

I agree to participate in this study.

Your name: ______________________________ (please print)

Your signature: ______________________________ Date: ..../......./.......

Researcher's name: ______________________________ (please print)

Researcher's Signature: ______________________________ Date: ..../......./.......

Living In Leicester Participant Copy ☐

Living in Leicester Project Copy ☐ *Household serial number:*

Living in Leicester

Thank you for helping us with the latest activity!

We will be back on the: at:

to collect the monitoring equipment and ask you some questions.

We will call you a few days before to make sure this appointment is still ok.

If you need to change this appointment or you have any questions please contact Rory or Liyan at:

Department of Civil and Building Engineering, Loughborough University, LE11 3TU
Telephone: (01509) 223643 or 07796 550498
Email: R.V.Jones@lboro.ac.uk

Living in Leicester

Thank you for helping us with the latest activity!

We will be back on the: at:

to collect the monitoring equipment and ask you some questions.

We will call you a few days before to make sure this appointment is still ok.

If you need to change this appointment or you have any questions please contact Rory or Liyan at:

Department of Civil and Building Engineering, Loughborough University, LE11 3TU
Telephone: (01509) 223643 or 07796 550498
Email: R.V.Jones@lboro.ac.uk

Appendix D AEUS installation form

Installation Form

To be completed by researchers.

To be signed by both the researcher and the occupant.

Household serial number:

Energy plug serial (e.g. 234)	Location (e.g. kitchen)	Appliance (e.g. TV)	Extension lead? (Yes/No and serial)

Storage device with USB dongle	**Please tick**	**Location**	**Extension lead?**
Zotac ZBox			

Current transducer type	**Please tick**	**Location of meter cupboard (e.g. inside house, cupboard under stairs)**
Energy plug with CT		
Current clamp		

Any advice given to participants (e.g. failed visual inspections)

Occupant's name: ______________________________

Occupant's signature: ______________________________ Date: ……./……./…….

Researchers' names: Rory Jones

Researchers' Signatures: ______________________________ Date: ……./……./…….

A copy should then be sent to Prof. Kevin Lomas.