CRANFIELD UNIVERSITY

GEMMA OLIVER GIL

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SCHOOL OF WATER, ENERGY AND ENVIRONMENT
Energy Systems and Thermal Processes

Master of Science
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Supervisor: Dr Nazmiye Ozkan
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This thesis is submitted in partial fulfilment of the requirements for the degree of MSc

ABSTRACT

The Oxford – Milton Keynes – Cambridge (OMC) arc is one of the fastest growing regions of the United Kingdom. The connection of OMC cities via new infrastructure services is seen vital for long-term economic growth of the arc. This growth is expected to increase the arc's population by 1.9 million and create 23,000 new jobs by 2050. With world-class universities, research locations and high-tech firms, the arc's future economic growth is threatened by the absence of affordable housing and appropriate connective infrastructures. Since residential and commercial buildings account for half of UK energy use, it is important to plan new housing development in a smart way by including low carbon technologies so as to reduce demands for energy. Therefore, this thesis studies the relationship between the urban development and energy and investigates the potential of low carbon technologies and associated grid impacts for the arc's new housing development. The study considers PV panels with storage systems such as lithium nickel-cobalt-aluminium and lead-acid batteries as low carbon technologies and analyses their potential to reduce demand for energy from new housing development. Additionally, the growing use of electrical vehicles (EVs) and their impact on the grid has also been included in the investigation. The study calculates and compares the energy demand for the new housing development with and without the low carbon technologies under alternative scenarios which has been characterised as 'degree of smartness'. The results show that installing PV panels coupled with energy storage systems reduce the dwellings' demand from the grid as well as it is economically advantageous. Particular considerations about smart EV charging along with load shifting of appliances are highlighted to reduce the number of PV panels and the size of batteries to be installed.

Keywords: New housing developments, Households electrical demands, Demand side response, EVs

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LIST OF ABBREVIATIONS

BIPV	Building-Integrated Photovoltaics
DNO	Distribution Network Operators
EV	Electric Vehicle
FIT	Feed – In – Tariffs
GHG	Greenhouse Gases
Li-NCA	Lithium – Nickel Cobalt Aluminium oxide
NIC	National Infrastructure Commission
OMC	Oxford – Milton Keynes – Cambridge
PV	Photovoltaic
TSO	Transmission System Operators

1 INTRODUCTION

According to Climate Change Act 2008, the UK must reduce its greenhouse gases (GHG) emissions by 80% by 2050 (The UK government, 2018). Domestic and services buildings are the biggest energy consumers and, therefore, the ones which release more GHG in Europe (European Environment Agency, 2017). In the UK, buildings consume half of the total energy used, while transport and industry consume less than 25% each (Steemers, 2003). It is believed, though, that buildings still have a large energy efficiency potential and therefore, their energy consumption can be reduced (Astudillo et al., 2017). If new housing developments are designed efficiently with low carbon technologies future figures of energy consumption could be decreased.

Developing a sustainable urbanisation aiming to reduce buildings' GHG emissions is not easy due to the involvement of a number of actors: from the land owners and building developers to local authorities. More explicitly, the selection of new built areas is determined by local authorities and private constructors, whereas the energy and water planning is determined by utilities that look for the most economical solution (Sager-Klaus, 2016). Sustainable urban planning should include renewable energy systems, passive heating and cooling, recycling materials, reuse of water and natural ventilation, among others. All these technologies can be conveniently mixed to minimise the impact of new housing developments on the environment.

Even though there is a wide range of authors studying how energy consumption is affected by the urban form, the existing knowledge is diffuse and sectoral. There is still a gap on understanding how the morphology of a growing urban area influences its energy performance. Most of the researches are focused in quantifying the energy demand of existing areas (Ratti, Baker and Steemers, 2005), whereas insights into managing demands for energy for new housing developments are very limited. The aim of this study is to address this gap using a recently announced growth area, Oxford – Milton Keynes – Cambridge arc, as a case study.

The OMC arc is one of the fastest growing regions of the UK with an expected increase on its population of 1.9 million and 23,000 new jobs by 2050. The creation of new housing developments, services and new infrastructures to connect the OMC cities are essential for the growth of the arc. With world-class universities, research locations and high-tech firms, the arc's future economic growth is threatened by the absence of affordable housing and appropriate connective infrastructures. Securing the long-term economic success of the arc has become a national priority (NIC, 2018). This study aims to analyse the impact of new housing development on energy infrastructures using the OMC arc as a case study and assesses the potential of using low carbon technologies in new housing developments. Additionally, the uptake of EVs and their impact on the grid are included in the investigation. Using published data on electrical loads for different types of dwellings, new energy demands, specifically electricity demands, for new developments with and without low carbon technologies are quantitatively modelled. Heating demand is excluded due to data limitations. Moreover, the study considers the demand side response for EV charging, electricity storage and load shifting. Finally, it provides recommendations for reducing the energy demand and the impacts on the grid for the arc's development as well as broader implications for new housing developments.

The rest of the thesis is organised as follows: *section 2* provides a review of literature on the relation between urban planning and energy consumption and low carbon technologies that can lead to a more sustainable growth. This section also provides background information on the development of the arc. *Section 3* describes the methods to calculate energy demands for new housing development with and without low carbon technologies and EVs under alternatives scenarios which have been identified as 'degrees of smartness'. *Section 4* presents results under different scenarios studied in this thesis. These results are discussed in *section 5* by considering the demand side response for EV charging, electricity storage and loads shifting. In addition, avenues for further research are suggested in *section 5.* Finally, in *section 6*, recommendations are provided to reduce the energy consumption for new housing development and their impacts on the grid.

2 LITERATURE REVIEW

New housing development in regions intensively exploited can affect the existing infrastructure of transport, water, sewage and energy, among others (Farmani and Butler, 2014). Therefore, it is necessary to review existing literatures on the relationship between urban development and energy for new housing development. Moreover, it is also important to revise which low carbon technologies can be used to reduce the energy demand on the new housing development in the OMC arc. In contrast to low carbon technologies, EVs have a huge impact on grids because they will increase the dwellings' loads. Also, since the electrification of transport has been highlighted an important component of UK's decarbonisation strategy (Committee on Climate Change, 2018), the literature about EVs and their required charging arrangement for new housing development is also reviewed. Finally, there is a summary about the potential growth of the OMC at the end of this section.

2.1 Urban development and energy

New building construction has a huge impact on the environment, society and economy (Vilcekova, Selecka and Burdova, 2016). So, planning sustainable developments benefits all these three aspects. Although energy-saving technologies can be adopted at any phase of the buildings' life (for instance retrofitting a building with better thermal insulation or adopting heat pumps for space heating), the most significant impact is made in the design and construction phase of dwellings (Vilcekova, Selecka and Burdova, 2016).

The energy performance of new buildings depends of different factors such as different actors' decisions, types of low carbon technologies used, behaviour of occupants, etc. For example, local authorities and constructors set the location for new buildings, while architects design the buildings for the specific location. In addition, dwellings' energy efficiency depends on which technologies have engineers selected. Finally, once the building is constructed, the behaviour of its occupants plays a key role on demand for energy. All these factors affect to a greater or lesser extent to the energy demand. If urban development is not well planned, the resulting urban sprawl causes an increase in energy, soil and land consumption, which affects directly to people’s quality life (European Environment Agency, 2006). Sustainable building design is the way of finding the compromise between housing development and sustainable environment, based on economic and environmental factors (Vilcekova, Selecka and Burdova, 2016).

The design parameters of buildings are also important because if drafted well could reduce the energy consumption (Anisimova, 2011; Hachem, 2016). The notable parameters are: energy performance, building construction typology, type of neighbourhood and density.

Energy performance of a building is the ratio between the overall energy consumed by building operations assuming that the neighbourhood is fully electrified and the potential generation of electricity if all the roof surface is equipped with PV panels (Hachem, 2016). During the construction phase of buildings, adopting measures such as wall and building insulation or airtight construction would help increasing their efficiency, reducing energy consumption, and therefore, their GHG emissions up to a 75% (Hachem, 2016). There are three different types of building insulation: indoor, outdoor and integrated.

The building construction type, in particular compact structures like flats play an important role to reduce energy demand in dwellings (Anisimova, 2011). Not only type and size affect the energy consumption in dwellings, but also the community layout, the surface coverage or the density (Ko, 2014). So, the influence of urban development on energy demand depends on a mix of variables, which should be simultaneously analysed under a comprehensive framework. In urban development the weather must be considered. Passive solar heating consists of designing and orientating buildings for using solar energy to heat them. To use the building as an appropriate solar storage system, passive solar heating must be considered in very early planning processes. It must also be taken into account that some attributes that save energy when heating the buildings, does not affect the same way when the building is cooled. More compact dwellings, like flats or non-detached houses, behave efficiently wherever heating is a dominant use. For both heating and cooling purposes, a preferred orientation is very important to reduce energy consumption (Silva, 2017). Moreover, multi-family housing instead of single-family housing make urban areas more efficient in terms of energy consumption. While detached houses are the most energy intensive (Hachem, 2016), the attached houses with smaller and denser neighbourhoods have a lower energy demand (Serghides et al., 2017).

Not only the building construction type, but also how is the neighbourhood organised affect the energy demand. Type of neighbourhood, whether residential or mixed-used, the design of the streets and where is the commercial centre located respect the residential areas are parameters that highly affect the GHG emissions from transport (Hachem, 2016). The emissions related to travel depends on traffic, daily activities and the distance to destinations (Hachem, 2016). Hence, in residential areas, creating daily-need services, such as bakeries, banks or coffee shops, decreases trip needs and, therefore, energy consumption (Silva et al., 2018).

The importance of population density to save energy has been highlighted in several studies. Areas with a higher density imply less mobility and thus less energy is consumed (Nichols and Kockelman, 2014; Silva, 2017). In contrast, Hachem (2016) argues that an analysis focused only on the parameter ‘density’ would be incomplete. As a matter of fact, density slightly affects the mobility in terms of using public or private mode of transportation, but the neighbourhood design and its distance to the business centre are the ones which have a huge impact in energy consumption.

There is still a knowledge gap regarding other variables affecting the energy consumption per capita. While some authors stated that the urban form undoubtedly affects energy consumption, a case study mentioned that there is a 10% variation in energy demand between Toulouse and Berlin due to their urban planning, in particular building design and urban geometry (Ratti, Baker and Steemers, 2005). Others have found significantly different results, around a 3% variation for heating and 1% for cooling (Silva, 2017).

A case study in the city of Porto shows the energy implications of specific locations, given different densities, land uses and building compactness. It concludes that mixed-use settlements with a high density reduce the energy consumption at least 15% due to mobility (Silva et al., 2018). Nevertheless, if mobility effects are not taken into account in compact densifications, advantages such as reduced heat losses are balanced to the disadvantages of less solar and daylight radiation (Steemers, 2003).

However, more intensive use of land reduces the energy cost per capita related to its construction and maintenance by sharing infrastructures such as energy and water supply or drainage. So, expanding cities or creating big towns take advantage from economy of scale compared to dispersed urban forms (Steemers, 2003).

In the UK, electricity supply chain includes four entities: power plant owners, transmission system operators (TSO), distribution network operators (DNO) and electricity retailers. Power plant owners are responsible for the bulk electricity generation. Then, the TSO carry the bulk electricity over long distances and operate with high voltage transmission network. Next the DNO are in charge of the electricity distribution from the national transmission grid to houses and buildings. This local distribution is done by towers, cables and meters. Finally, the electricity retailers sell electricity to customers (NIST, 2014). Hence, to connect new houses to the grid, the developer does an application form where provides the exact location of meter points, relevant drawings, etc. Then the application team processes the form. To understand the requirements, the DNO interacts with the customer with the purpose of studying a design (network modelling) to identify Points of Connection and quote the minimum cost considering existing network capacity. Once both parties agree, the DNO processes the payment. Once the customer has accepted the DNO's connection offer, the construction can begin (ENA, 2014). The entire process is shown in *Figure 2-1*. It is worth to mention that the whole process does not consider finding the most sustainable solution in terms of energy saving and GHG reduction.

Figure 2-1: Process to connect new housing developments to the grid.

2.2 Review of low carbon technologies

GHG emissions of the building sector can be reduced by lowering demands as well as by increasing the use of renewable, hence low-carbon, energy sources. Sustainable buildings usually use renewable sources such as passive solar home design, photovoltaic (PV) equipment, solar thermal systems, green roofs or rain gardens (Vilcekova, Selecka and Burdova, 2016). However, peak electricity, which is strongly seasonal due to the heating demand, can be difficult to deliver with non-dispatchable renewable energies (Astudillo et al., 2017).

The use of photovoltaic solar panels as a renewable energy source has highly increased over the last decades in worldwide new building construction (Curtius, 2018). Solar PV panels produce electricity directly from solar radiation. The photovoltaic effect occurs when a semi-conductive material, usually silicon, is hit by solar radiation (Khan and Arsalan, 2016). However the direct radiation is not necessary and the PV panels still can produce electricity even with the sunlight of a cloudy day (Energy Saving Trust, 2018a). Since PV panels can be located on the buildings' rooftops, they are suitable to use for different locations just varying the incident radiation angle and orientation. More advanced systems are the building-integrated photovoltaics (BIPV) which consist of replacing conventional building materials for roofs, skylights or facades with photovoltaic materials. For dense cities, BIPV are a good option to multiply the total photovoltaic area (Curtius, 2018).

Since solar radiation fluctuates during the day and there are times when the generation from PV surpluses the demand. To take the maximum advantage of PV, surplus solar energy may be stored in batteries. Although the PV solar system is the key technology to develop an optimal system design, the storage technology is also very important (Ayeng’o et al., 2018). A typical storage system compatible with solar PV systems includes batteries, an inverter/charger, a battery management system, an energy management system and various control boards. Naturally, the storage system is charged in off-peak load and discharged during the peak consumption hours. Nevertheless, to deal with the fluctuations of PV systems output, the charging and discharging plan should be adjusted with respect to the PV system intermittencies at least every hour (Teng et al., 2013).

Several papers investigate lithium-nickel cobalt aluminium oxide (Li-NCA) and lead-acid batteries as most affordable storage technologies (Ayeng’o et al., 2018; Jaiswal, 2017; Kwiecien et al., 2017). The technology behind lead-acid batteries is mature since are used in most PV systems installed today (Ayeng’o et al., 2018). Although lead-acid batteries are cheaper to install than Li-NCA, Li-NCA batteries have a higher energy density, higher number of lifecycles and need less maintenance (Anuphappharadorn et al., 2014). Hence, Jaiswal (2017) found that Li-NCA batteries have a longer lifetime, which involve lower substitution costs. In addition, the initial investment cost is reducing due to an 8-16% pa decrease of lithium-ion price (Jaiswal, 2017).

Other researches explore the energy savings and GHG emissions reduction of more advanced thermal systems such as solar water heating (Sami et al., 2018), ground source heat pumps (Reda and Laitinen, 2015) and solar combisystems (Ž, Kirsanovs and Dzik, 2017).

A technology highly used is solar water heating systems. A field of flat plate solar collectors supply heat to a hot water storage tank. When there is not enough solar contribution, an auxiliary heater heats the water stored in the tank. To minimise the cost of this system, it is necessary to find the optimal area of the collector (Sami et al., 2018).

A ground source heat pump (GSHP) is an efficient method to produce heating, cooling and domestic hot water (Reda and Laitinen, 2015). In a GSHP, a fluid, which is a mix of water and antifreeze, circulates through a loop of pipe buried in the garden. The fluid, flowing in the borehole heat exchanger, absorbs heat from the ground. Consequently, the fluid is diverted to the evaporator where heat is transferred to a refrigerant, which is the working fluid driving the heat pump system (constituted by the previously mentioned evaporator, condenser, compressor and expansion valve). The length of the loop of pipe varies depending on the heat needed and the household size. Longer loops extract more heat from the ground although more area is required. When there are field limitations, a vertical borehole can be dig. This system has some environmental impacts since it needs electricity. However, GHSP extracts the heat from the ground which is naturally renovated (Energy Saving Trust, 2018b). Compared to other heating systems, heat pumps use less energy to heat a building. In addition, their many configurations make them suitable for use in different climatic conditions (Self, Reddy and Rosen, 2013).

Another renewable energy source for small and middle consumers is solar combisystems based on biomass pellets. Combining solar thermal collectors with pellet-based heating systems instead of burning solid fuels reduces between 19-45% of CO emissions released to the atmosphere (Ž, Kirsanovs and Dzik, 2017).

Moreover, low carbon technologies such as cogeneration can be implemented to reduce the energy consumption and GHG emissions. Installing combined heat and power (CHP) and district heating (DH) in a neighbourhood delivers energy at a higher efficiency, around 85%, and decreases the distribution and transmission losses of centralised power stations (Steemers, 2003).

Most of the English dwellings use electricity to meet the household’s electrical demand rather than for heating. In Great Britain, electric heating is more common in flats: 25% use electricity for heating purposes, in comparison with just 4% of the other types of dwellings (Ofgem, 2015). PV systems and energy storage systems reduce the dwellings’ electricity consumption from the grid, whereas all the other systems above mentioned are low carbon technologies for heating the dwellings. The purpose of this study is reducing the electrical demand of new housing developments, so, the calculations will be done using PV systems and batteries.

2.3 Electric vehicles

Since transport has a significant impact in GHG emission, nowadays electric vehicles (EVs) are an alternative option to be considered for reducing the emissions from the sector. Moreover, to make an urban area sustainable and comfortable, it should integrate electrical mobility. EVs do not produce noise pollution neither release local emissions. In a near future they might take advantage from the increased production of renewable energy. As well as they could help with the renewable energy integration because their on-board batteries could store electricity when it is generated and hence, reduce the demand of the grid at peak times (Andrenacci, Genovese and Ragona, 2017). A proper mix of renewable energy, electrical transportation and grid design are key parameters for a sustainable urban development (Silvester et al., 2013).

As the number of EVs increases, a large number of charging stations will be needed. These stations increase significantly the distribution network demand, particularly in peak hours when power congestions or voltage and current problems could appear (Qiao and Yang, 2016). Kuihua *et al.* (2012) analyse different charging scenarios (plug and charge, night charging or intelligent charging) and how their loads impact the grid. They concluded that by 2030 the EVs' charging mainly will be in two peak loads: in the morning and evening.

Paevere, Higgins and Ren (2014) studied nine different scenarios of EV penetration and their charging and discharging modes. The authors concluded that encouraging households to charge the EV in off-peak periods through pricing will effectively minimise the impacts on the grid. Moreover, it is important to highlight that the impacts on the grid due to EVs depend on their charging mode.

2.4 Oxford – Milton Keynes – Cambridge arc

The OMC arc is a set of cities and towns around 50-miles radius of London. It expands around 130 miles from Oxfordshire to Cambridgeshire, via the southeast midlands and Bedford. It also encompasses big towns such as Luton and Northampton, among others.

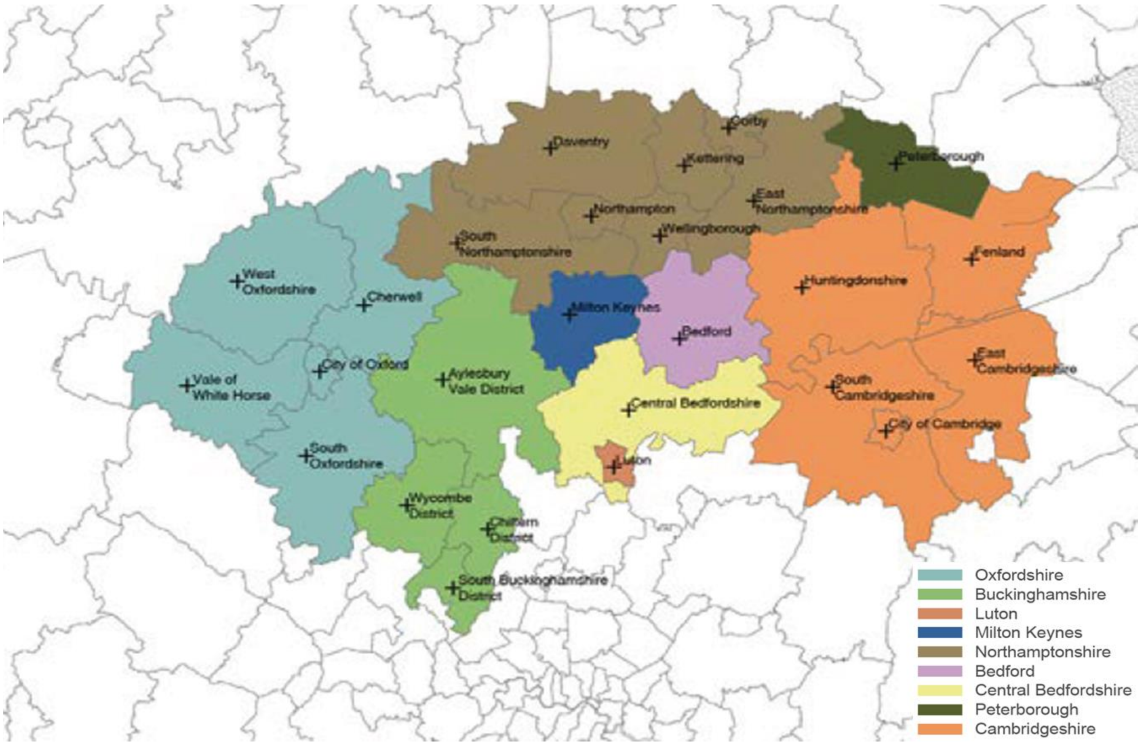


Figure 2-2: Map of the existing local government bodies across the Oxford – Milton Keynes -Cambridge arc.

Source: NIC (2018).

The National Infrastructure Commission (NIC) published a report of the arc development, where a set of recommendations were made for securing the arc's long-term economic success by proposing new places to work and live and new infrastructure. Particularly, it proposes construction of 23,000 new homes per year until 2050 that would equate to a 1.4 million people increase in the arc. Additionally, taking into account that London will not be able to meet its housing demand, these figures will become 30,000 homes per year or an increase of 1.9 million people living within the arc (NIC, 2018). The report also estimates a growth of 335,000 new jobs in the arc by 2050 (NIC, 2018).

Seven different speculative scenarios have been studied to cover the housing demand, each of them with an optimal density of 3,500 people/km^2 (NIC, 2018).

However, as the scenarios radically differ from each other, possibly a combination of them will emerge in the future.

In order to select optimal areas for new housing, several aspects must be taken into account. A concentric expansion of Luton, Cambridge or Oxford cannot be considered due to the green belt constraints of the areas. In the UK, green belt is a policy for preventing urban sprawl. It consists on a ring of countryside around main cities, where forestry, agriculture and outdoor leisure must prevail (The UK government, 2012). Instead, south Milton Keynes, south Bedford, Aylesbury Vale, Marston Vale and around Sandy and Biggleswade could be suitable areas to housing development (NIC, 2018).

3 MATERIALS AND METHODS

In this study, baseline energy demands from new housing development in the OMC arc were calculated. The baseline energy demand is a reference tool to compare energy performance before and after a change is made to a system. According to the government's report 'The Road to Zero' (DfT, 2018), new homes built in the UK would need to be fitted with an EV charging point. In addition, in the study 'Future Energy Scenarios (FES)' carried out by National Grid, predicted that 90% of the vehicle sold in the UK by 2050 will be EVs (National Grid, 2018). Therefore, for this study, base load for each type of household was obtained by adding a potential EV charging pattern to the household electricity demand.

These demands were compared with the incorporation of different low carbon technologies under alternative scenarios characterised as 'degree of smartness'. Among different low carbon technologies, PV panels and storage systems such as Li-NCA and lead-acid batteries were used to reduce the energy demands from new housing development. In addition, the study considered the demand side response with the EV charging and possible load shifting of the appliances.

The different degrees of smartness considered in this study are as follows. The first scenario examined the energy consumption by a household with an EV charging just arriving home from work. In the second scenario, it was assessed how many PV panels were needed to reduce the electricity demand. Then, the PV panels were coupled with energy storage systems. Finally, the last scenario studied the possibility of load shifting with the operation management of electrical appliances.

Figure 3-1 shows the overall flow chart for the calculation of baseline energy demand, number of PV panels, energy storage sizing, energy saving, load shifting and cost saving potentials. Firstly, baseline demands for each type of dwelling were calculated from data of an English household survey and EVs. Then, it was assumed that households charged the EV when they arrived home and only supplying the electricity to cover the average commuting distance in England. From that electricity consumption, the size of the PV system and the necessity of energy storage systems were determined. For the sizing of the PV system it was considered both, annual electricity consumption and monthly solar generation in England, whereas two different capacities of batteries were studied. Finally, load shifting was analysed to find the smartest electricity management solution for the new houses.

In addition, an economic analysis comparing the baseline scenario with a scenario with PV systems and batteries taking advantage of Economy 7 tariff was carried out.

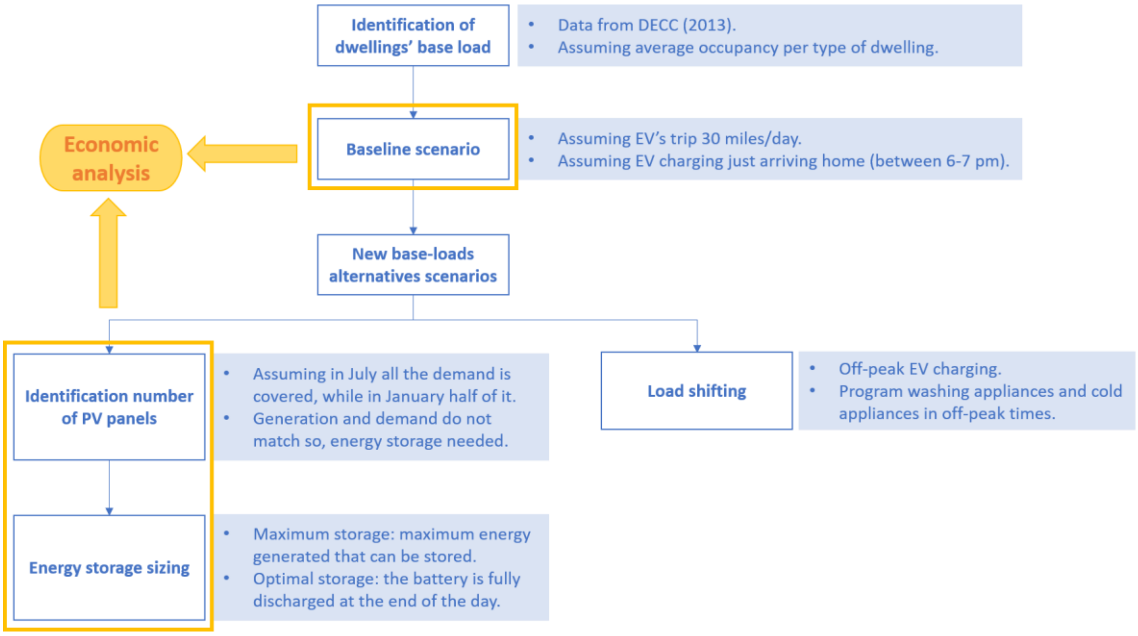


Figure 3-1: Methodology.

More details about the methodology are given in *sections 3.1 to 3.6.*

3.1 Data sources

3.1.1 Local Housing Plan for Central Bedfordshire

The Local Plan for Central Bedfordshire provides the strategic objectives and vision for the area in the period of 2015 to 2035. The objectives consist of creating a minimum of 24,000 new jobs and deliver around 39,350. See *Table 3-1*. Of these 39,350 new homes, 23,528 homes are already planned or built

(Central Bedfordshire Council, 2018). See *Table 3-2.* A range of different homes such as family homes, two-bedroom homes and apartments to buy and rent are included in the plan.

Table 3-1: Strategic objectives for Central Bedfordshire.

Housing need for Central Bedfordshire	32,000
Unmet need from Luton	7,350
Total houses to be delivered	**39,350**

Source: Central Bedfordshire Council (2018).

Table 3-2: Number of dwellings expected per type in Central Bedfordshire.

Type of commitment	**Number of dwellings expected**
Net completions April – October 2017	4,335
Existing allocations	7,742
Strategic sites (with planning permission)	6,780
Large windfall (with planning permission)	4,023
Small windfall (with planning permission)	648
Total	**23,528**

Source: Central Bedfordshire Council (2018).

Some of the locations where housing growth is planned are:

- Creating one new village to the east of Biggleswade (around 1,500 homes + around 60 hectares for employment).
- Creating up to four new villages in Marston Moretaine (5,000 homes + 40 ha for employment).
- A sustainable new extension in north of Luton (around 4,000 homes + 20 ha employment land).
- A sustainable new extension in east of Arlesey (around 2,000 homes).
- Small to medium growth in existing towns villages, but only where services can support it.
- M1 Junction 11a (around 45 hectares for employment).
- M1 Junction 13 (around 35 hectares for employment).
- RAF Henlow (130 ha of mixed use specialist employment).

3.1.2 New housing developments in England

NIC guidelines indicate total number of houses yet assessing energy demands requires an understanding of the size of new housing developments and types of dwellings going to be built. In England, the distribution of newly built dwelling types depends on the size of the site. National House Building Council (NHBC) Foundation classifies the sites according the number of new properties: from 1-10, 11-30, 31-100, 101-500 and 501-2000 (NHBC Foundation, 2018a). Since it is expected 23,000 new homes along the arc, big new housing developments are going to be built (NIC, 2018). For the purpose of this study, the distribution of 100 to 500 dwellings was selected because it was the biggest in number of new properties after the one between 501 to 2000 properties. This last one was dismissed because an 87% of the new properties were flats, and the growth in the OMC arc should not have a high density (NIC, 2018).

Table 3-3: Distribution of new built composition in England during the period 2014 – 2018.

Detached	Flat	Medium/large terraced	Semi detached	Small terraced
19%	42%	9%	20%	10%

Source: NHBC Foundation (2018b).

A guideline and an overview of the most favourable characteristics for the future English homes in 2050 can be found in NHBC Foundation (2018a). Due to a societal and demographic transition, types of new housing are arising. The typology and composition of households is changing. Some new types of dwellings should be designed for a growth of people living alone. Others will accommodate different generations of people due to an increase of the third age and the lack of affordable houses, which have driven young adults to leave their family home later. In urban areas, homes will be preferred to build vertically to use limited lands. These dwellings will have more terraces and smaller gardens than other types of households. Also, studios and micro apartments will be common between the youngest and recent graduates. Whereas in rural areas, traditional homes will prevail but with roof orientated designs for the PV panels. In addition, multigenerational homes will be built due to the household composition changing patterns (NHBC Foundation, 2018b)

3.1.3 Households base load

One of the main difficulties to predict the future energy consumption of a new housing development site is the diversity of dwellings. There are many types of dwellings available such as flat, detached, semi-detached, terraced and so on. Depending on the types of dwellings, the occupancy rate, i.e. number of people living in it and their behaviours, the energy consumption varies.

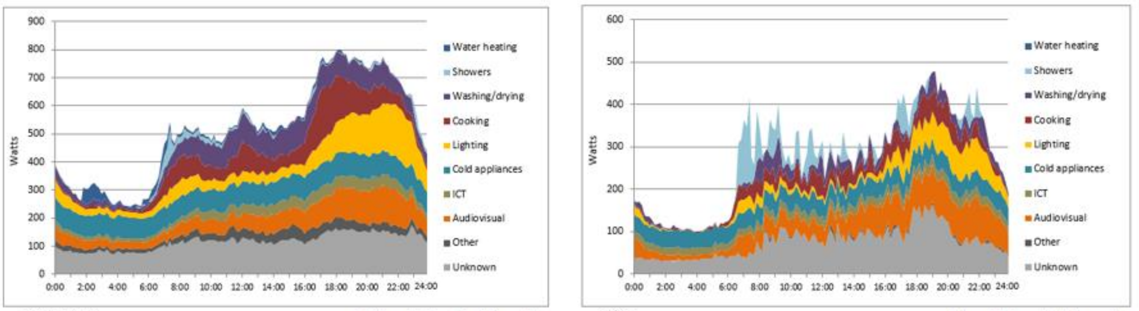
Energy consumption data was obtained from a survey of 251 households, carried out by the Department of Energy and Climate Change (DECC) that was undertaken from May 2010 to July 2011 in England. The DECC monitored electricity consumption by each household at every 10 minutes interval. Data about type of household as well as the daily energy consumption profile obtained is therefore used in this study.

Of all the dwelling types analysed in DECC (2013), bungalows is the only type that does not match with the future English homes prediction of NHBC Foundation (2018a) neither the actual distribution of new dwellings in England of NHBC Foundation (2018b). Hence, for the purpose of this study, this kind of homes was not considered.

Figure 3-2 shows the different electricity consumption profiles by different loads such as water heating or lighting. Detached houses consume slightly more electricity during the day than the average, with the greatest share in lighting at night compared to the other types of dwellings. However, flats have lower electricity profiles than the others. In general, the evening peak is evident for all dwelling types, with the largest share of electricity used for cooking in the early evening. In the later evening, the biggest share of electricity corresponds to lighting and audio-visual.

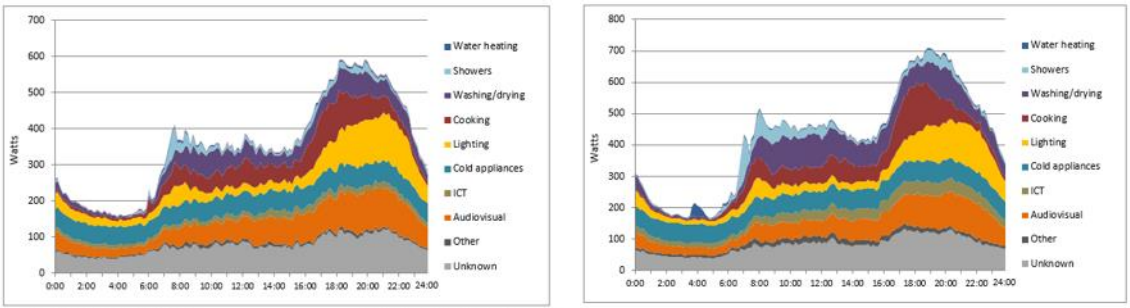
Small terraced dwellings consume more electricity than semi-detached houses. Note that this data is coming from a survey with different size of samples.

Moreover, in this study variables such as occupancy or floor area have not been taken into account.



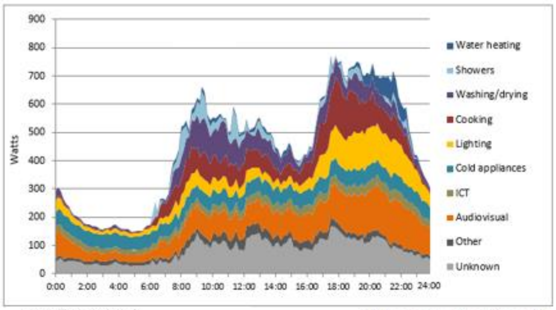
Detached 48 Households matched the conditions

Flat 5 Households matched the conditions



Medium/large terraced 45 Households matched the conditions

Semi detached 63 Households matched the conditions



Small terraced 18 Households matched the conditions

Figure 3-2: Daily electricity profiles with the different loads per type of dwelling.

Source: *DECC (2013).*

Figure 3-3 shows the electricity consumption per each type of dwelling. This figure shows that the peak consumption takes place between 18:00 and 19:00 h for all the types.

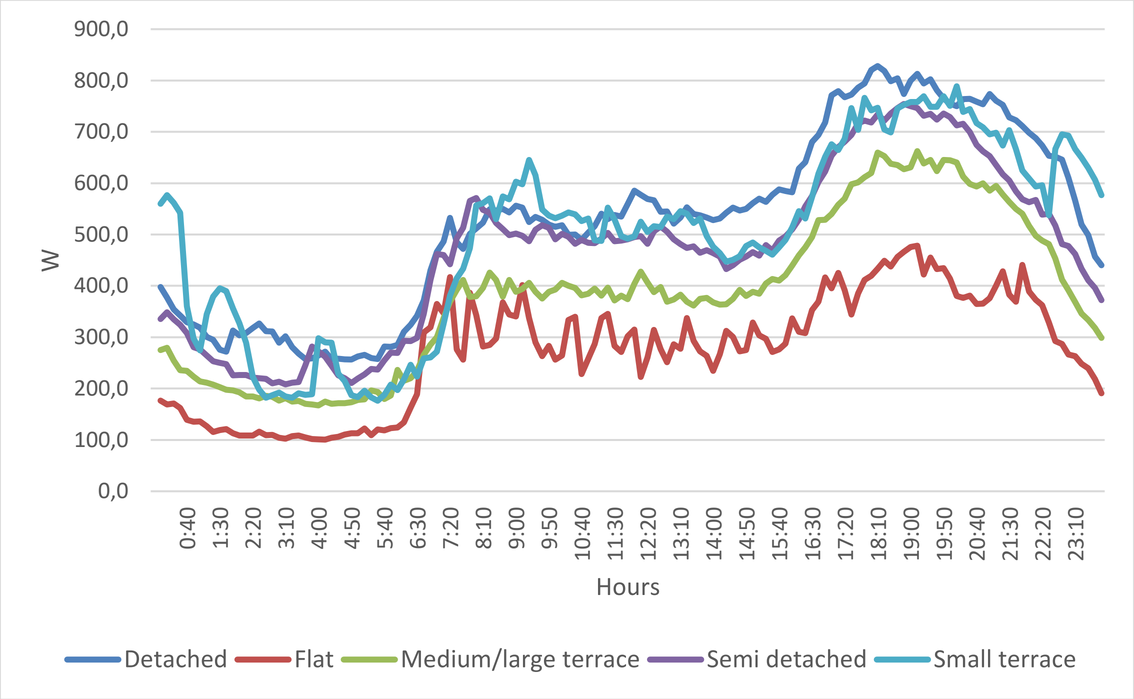


Figure 3-3: Electricity use profile through the day for different households that took part in the study.

Source: DECC (2013).

3.2 Baseline scenario: charging just arriving home

Given the need for electrification of transport to decarbonise UK energy system and the Government's plans to install an EV charging point for each new home, it was assumed that each new dwelling will own an electric vehicle. In order to obtain total electricity load for each household type in this study, the load for each EV should be added. Depending on the size, model and autonomy of the EV, the capacity of the battery varies. Small cars like Smart Fortwo or BMW i3 have batteries of 16.5 and 22 kWh, respectively. While medium cars such as Nissan Leaf hold a 40 kWh-battery, bigger cars like Tesla S are equipped with 100 kWh-batteries. For the purpose of this study, Nissan Leaf was chosen to develop all the scenarios because it was the most commonly bought in UK during the first quarter of 2018 (Department for Transport, 2018).

It was assumed that there was no necessity to fully charge the battery every day since the average commuting trip in England is around 10.9 miles while shopping and leisure trips are 4 and 8.6 miles, respectively (Department for Transport, 2017). On this basis, this study considered that on average a car runs 30 miles a day, which includes commuting and other short distance trips.

This study also assumed that every home is equipped with a 7 kW charger, which will become a standard among households in 2050 (National Grid, 2018). Therefore, for instance, charging the Nissan Leaf with 40-kWh battery (168 miles reach) it will take 7.5 hours (Nissan, 2018).

While in the UK drivers charge the EV during the day at different locations, the most common group, a 35%, charges at home and typically between 17:00 and 20:00 h (Jennings, Parkin and Del Maestro, 2018). In the baseline scenario it was assumed that people do not charge the EV at work, but they charge it just when arriving home. It was supposed that people plug in the EV to charge at 18:00 h. Assuming that an EV runs 30 miles a day and knowing that it consumes 23.8 kWh/100 miles, the daily charging time with a 7-kW charger is one hour. See (3-1). So, the EV was charged from 18:00 to 19:00 h, matching with the home peak demand.

$$\frac{30\,miles}{day}\cdot\frac{23.8\,kWh}{100\,miles}\cdot\frac{1}{7kW}=\frac{1h}{day} \qquad \textbf{(3-1)}$$

Hence, the baseline demand was obtained by adding to the 10-minute load profile data from *Figure 3-3,* the EV charging requirement of 7 kW between the time period of 18:00 to 19:00 h.

3.3 Solar energy generation

To select a proper size of a PV system, ideally it is necessary to know the voltage requirements, the appliance’s power and the time of use.

In 2016, the average floor area of a English newly built house was 104 m^2 (ONS, 2016). For this case study it was assumed a maximum of 25% of the rooftop could hold PV panels, which means a 26-m^2 surface area. The PV panel ‘the N310K Photovoltaic Module HIT® BLACK of Panasonic’ was chosen for this study. Its module area is 1.67 m^2 with a rated power of 310 Wp (Watt peak capacity) and a 19.1-module efficiency (Panasonic, 2017).

However, the PV system performance depends of different factors like geographical location, array orientation and inclination and shade effects, among other factors. The most significant one is the location, basically the latitude. The further the location is from the equator, the less irradiation there is. The best orientation to obtain the maximum yield for PV solar panels for Bedfordshire is facing directly the south. The further the PV panels are from a southerly orientation, the less effective they are, although 45 degrees either way can still supply more than 90% of the electricity because of the south orientation. Shade effects from objects adjacent the PV system can impact significantly its output, even if the degree of shading is small (MCS, 2012).

In this section, the PV array size for each type of dwelling was calculated in two different ways: considering the annual and the daily profile consumption. Hence, both results were compared, and the best methodology was pointed. It is considered the best methodology the one that takes more advantage of the solar radiation and have a smaller system, which involve a lower investment cost. For these calculations it was assumed that the householders charge the EV when they arrive home as outlined *section 3.2*.

3.3.1 Sizing PV array based on annual electricity consumption

The size of the PV array was calculated from the annual electricity consumption per household type with the following equation.

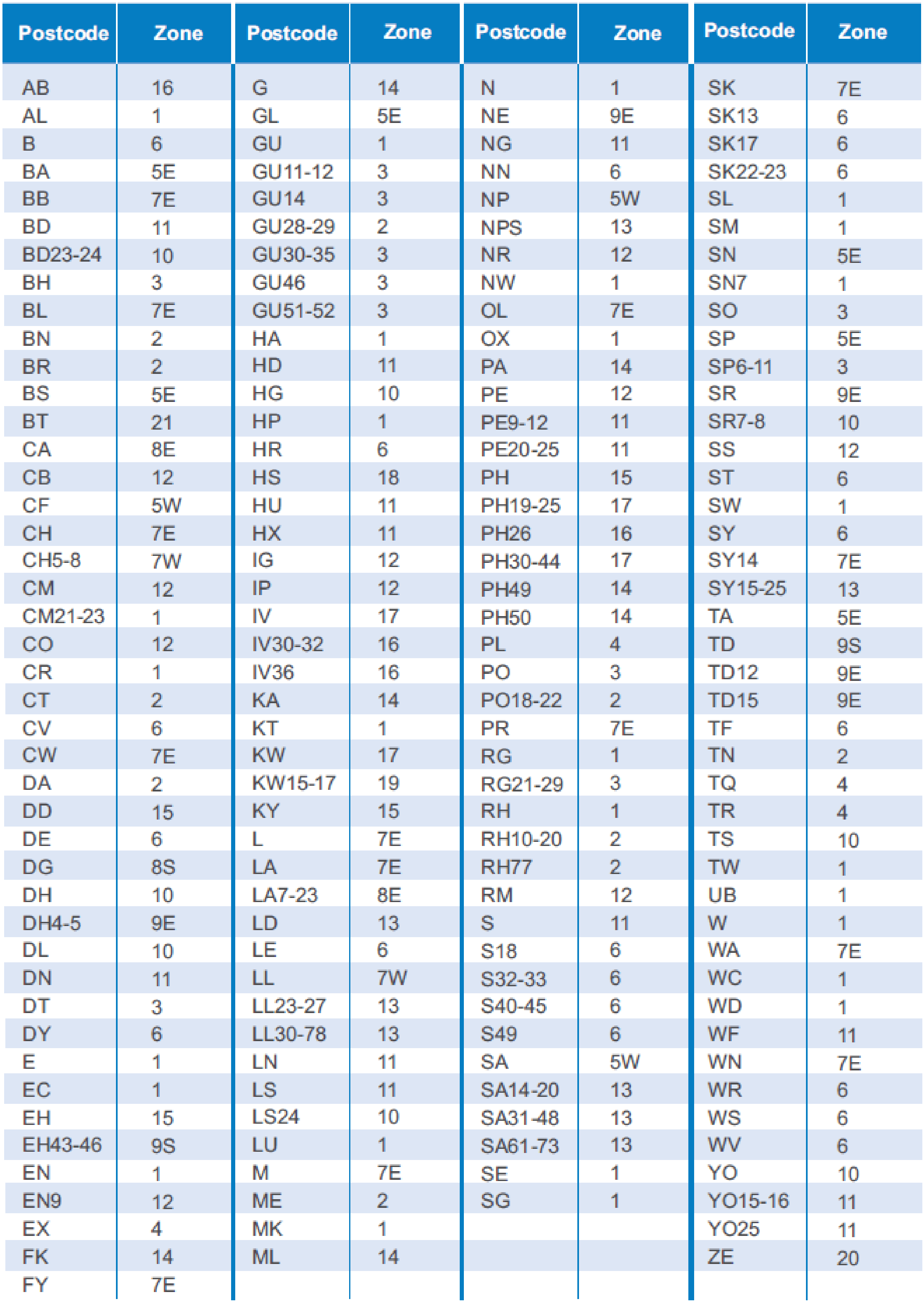
$$Annual\ AC\ output\ (kWh) = kWp \cdot Kk \cdot SF \tag{3-2}$$

Where kWp is the electric rating of the system in kWh. Kk (kWh/kWp) is a factor considering the location and the orientation of the panels. SF (Shading Factor) determines how much of the solar irradiance could be blocked by objects in the horizon during different daytimes. It can vary between 1 and 0.

Firstly, the final electrical rating of the system can be obtained by knowing the electrical rating of a specific PV panel (0.31 kWp) and multiplying it per the number of PV panels (n_{PV}). Secondly, looking for the postcode of Biggleswade, Marston Moretaine, North Luton and Arlesey in *Table 3-4*, zone 1 was determined for Central Bedfordshire in *Figure 3-4*. *Table 3-5* indicated the potential outputs for zone 1 depending on the orientation and the inclination of the PV array. Optimum and minimum outputs are in dark green and dark red, respectively. Assuming that the array was fully orientated to the South, the Kk factor was 985 kWh/kWp. Finally, since this case study was estimating new housing areas for Central Bedfordshire, it was assumed a SF value of 1. However, when planning specific homes, a potential for shading must be considered.

Lastly, knowing the annual consumption per each type of household it was possible to obtain the number of PV panels (n_{PV}) required. And therefore, the size of the PV system and the electricity generated per each type of household can also be determined.

Table 3-4: Postcodes and zone in UK.



Postcode	Zone	Postcode	Zone	Postcode	Zone	Postcode	Zone
AB	16	G	14	N	1	SK	7E
AL	1	GL	5E	NE	9E	SK13	6
B	6	GU	1	NG	11	SK17	6
BA	5E	GU11-12	3	NN	6	SK22-23	6
BB	7E	GU14	3	NP	5W	SL	1
BD	11	GU28-29	2	NPS	13	SM	1
BD23-24	10	GU30-35	3	NR	12	SN	5E
BH	3	GU46	3	NW	1	SN7	1
BL	7E	GU51-52	3	OL	7E	SO	3
BN	2	HA	1	OX	1	SP	5E
BR	2	HD	11	PA	14	SP6-11	3
BS	5E	HG	10	PE	12	SR	9E
BT	21	HP	1	PE9-12	11	SR7-8	10
CA	8E	HR	6	PE20-25	11	SS	12
CB	12	HS	18	PH	15	ST	6
CF	5W	HU	11	PH19-25	17	SW	1
CH	7E	HX	11	PH26	16	SY	6
CH5-8	7W	IG	12	PH30-44	17	SY14	7E
CM	12	IP	12	PH49	14	SY15-25	13
CM21-23	1	IV	17	PH50	14	TA	5E
CO	12	IV30-32	16	PL	4	TD	9S
CR	1	IV36	16	PO	3	TD12	9E
CT	2	KA	14	PO18-22	2	TD15	9E
CV	6	KT	1	PR	7E	TF	6
CW	7E	KW	17	RG	1	TN	2
DA	2	KW15-17	19	RG21-29	3	TQ	4
DD	15	KY	15	RH	1	TR	4
DE	6	L	7E	RH10-20	2	TS	10
DG	8S	LA	7E	RH77	2	TW	1
DH	10	LA7-23	8E	RM	12	UB	1
DH4-5	9E	LD	13	S	11	W	1
DL	10	LE	6	S18	6	WA	7E
DN	11	LL	7W	S32-33	6	WC	1
DT	3	LL23-27	13	S40-45	6	WD	1
DY	6	LL30-78	13	S49	6	WF	11
E	1	LN	11	SA	5W	WN	7E
EC	1	LS	11	SA14-20	13	WR	6
EH	15	LS24	10	SA31-48	13	WS	6
EH43-46	9S	LU	1	SA61-73	13	WV	6
EN	1	M	7E	SE	1	YO	10
EN9	12	ME	2	SG	1	YO15-16	11
EX	4	MK	1			YO25	11
FK	14	ML	14			ZE	20
FY	7E						

Source: MCS (2012).

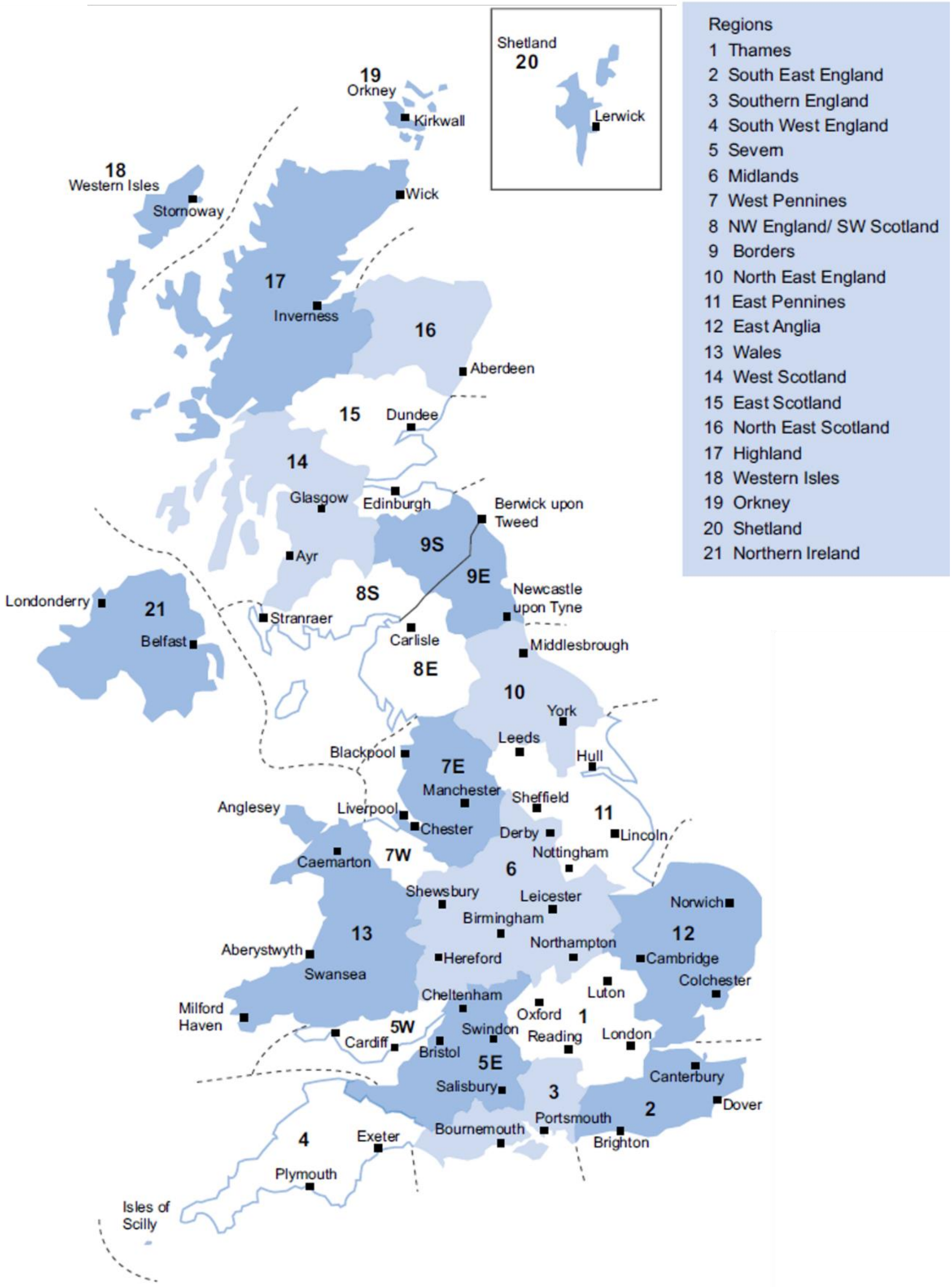
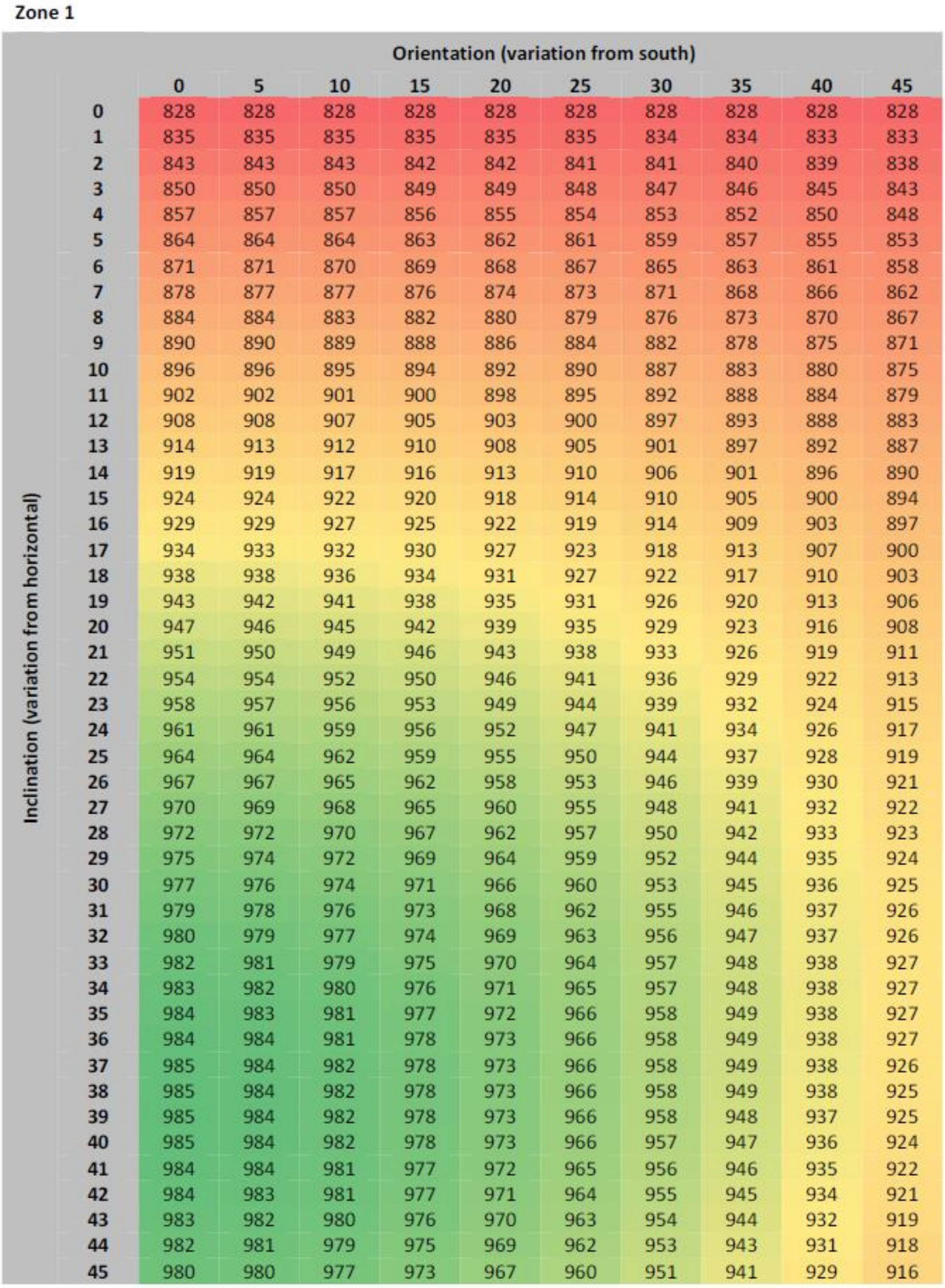


Figure 3-4: Map of UK zones.

Source: MCS (2012).

Table 3-5: Kk table for Central Bedfordshire (zone 1).



Zone 1

	Orientation (variation from south)									
Inclination (variation from horizontal)	0	5	10	15	20	25	30	35	40	45
0	828	828	828	828	828	828	828	828	828	828
1	835	835	835	835	835	835	834	834	833	833
2	843	843	843	842	842	841	841	840	839	838
3	850	850	850	849	849	848	847	846	845	843
4	857	857	857	856	855	854	853	852	850	848
5	864	864	864	863	862	861	859	857	855	853
6	871	871	870	869	868	867	865	863	861	858
7	878	877	877	876	874	873	871	868	866	862
8	884	884	883	882	880	879	876	873	870	867
9	890	890	889	888	886	884	882	878	875	871
10	896	896	895	894	892	890	887	883	880	875
11	902	902	901	900	898	895	892	888	884	879
12	908	908	907	905	903	900	897	893	888	883
13	914	913	912	910	908	905	901	897	892	887
14	919	919	917	916	913	910	906	901	896	890
15	924	924	922	920	918	914	910	905	900	894
16	929	929	927	925	922	919	914	909	903	897
17	934	933	932	930	927	923	918	913	907	900
18	938	938	936	934	931	927	922	917	910	903
19	943	942	941	938	935	931	926	920	913	906
20	947	946	945	942	939	935	929	923	916	908
21	951	950	949	946	943	938	933	926	919	911
22	954	954	952	950	946	941	936	929	922	913
23	958	957	956	953	949	944	939	932	924	915
24	961	961	959	956	952	947	941	934	926	917
25	964	964	962	959	955	950	944	937	928	919
26	967	967	965	962	958	953	946	939	930	921
27	970	969	968	965	960	955	948	941	932	922
28	972	972	970	967	962	957	950	942	933	923
29	975	974	972	969	964	959	952	944	935	924
30	977	976	974	971	966	960	953	945	936	925
31	979	978	976	973	968	962	955	946	937	926
32	980	979	977	974	969	963	956	947	937	926
33	982	981	979	975	970	964	957	948	938	927
34	983	982	980	976	971	965	957	948	938	927
35	984	983	981	977	972	966	958	949	938	927
36	984	984	981	978	973	966	958	949	938	927
37	985	984	982	978	973	966	958	949	938	926
38	985	984	982	978	973	966	958	949	938	925
39	985	984	982	978	973	966	958	948	937	925
40	985	984	982	978	973	966	957	947	936	924
41	984	984	981	977	972	965	956	946	935	922
42	984	983	981	977	971	964	955	945	934	921
43	983	982	980	976	970	963	954	944	932	919
44	982	981	979	975	969	962	953	943	931	918
45	980	980	977	973	967	960	951	941	929	916

Source: MCS (2012).

3.3.2 Sizing PV array based on daily electricity consumption profile

In this method, the amount of electricity needed to cover the daily demand was calculated.

Figure 3-5 shows the daily solar radiation for different months in England. This kind of curves give the solar radiation per area (W/m^2). So, once the size of the PV array is known, the solar output can be determined.

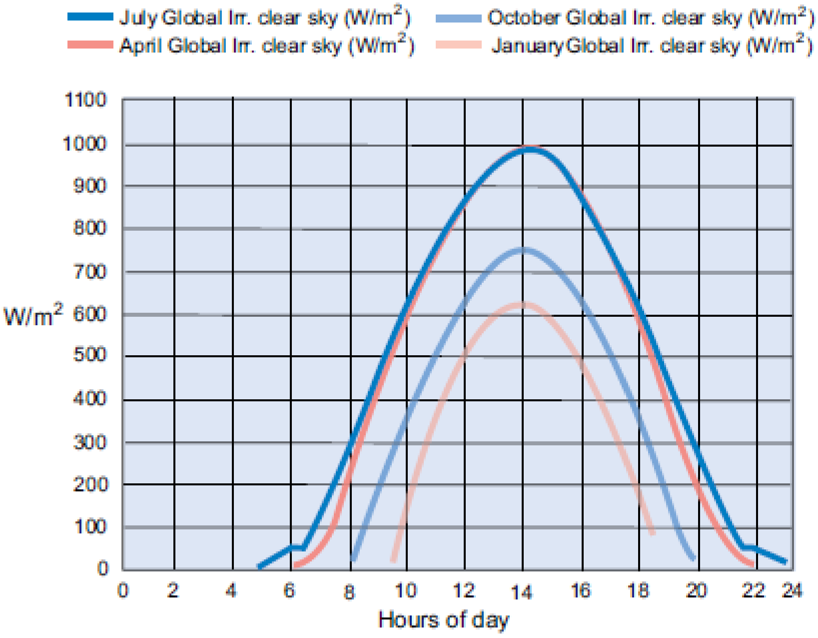


Figure 3-5: Typical daily and annual insolation curves.

Source: MCS (2012).

For the purpose of this study, the most representative insolation curves, January and July, were considered. It should be noted that there is not much solar radiation variation between the months of April, May, June, July and August. There is also similarity between the insolation curves of January, November and December (Burnett, Barbour and Harrison, 2014).

In this scenario, the size of the PV array was determined by the months in which there is more generation. So, in July, the generation must cover the total demand, whereas the generation in January just need to supply half of the dwelling's electricity demand. The generic model for the calculation of energy demand that is fulfilled by solar PV is given in equations (*3-3* and *3-4*). All the variables depend on $i = 10\, min$.

July insolation curve was multiplied by the area of PV array and its efficiency ($\eta = 0.185$) until it was covered the dwelling's electricity demand:

$$July_{gen,i}\ [W] \cdot\ area_{PV} \cdot \eta \geq D_i(dwelling)[W] \tag{3-3}$$

While for January, the generation supplied just half of the demand:

$$January_{gen,i}\ [W] \cdot\ area_{PV} \cdot \eta \geq \frac{1}{2} D_i(dwelling)[W] \tag{3-4}$$

From the area of the PV array and the efficiency, the number of PV panels (n_{PV}) can be obtained. Once n_{PV} was selected, it must accomplish both equations for each type of dwelling.

3.4 Sizing of storage system

Several factors influence the overall design of energy storage system, including the dwelling's required electricity storage capacity, its cost and the battery technology and type. When the PV array is the only source for charging the battery, the output of the solar system should be between the minimum and maximum recommended charge rates by the manufacturer.

To dimension the storage system, first, the power of the July generation, January generation and electricity demand for each type of dwelling was converted to energy. In other words, the area under the curves was calculated.

$$July_{energy,i}\ [kWh] = July_{gen,i}\ [W] \cdot 10\ min \cdot \frac{60s}{1min} \cdot \frac{1\ kWh}{3600000\ J} \cdot \tag{3-5}$$

$$January_{energy,i}\ [kWh] = January_{gen,i}\ [W] \cdot 10\ min \cdot \frac{60s}{1min} \cdot \frac{1\ kWh}{3600000\ J} \cdot \tag{3-6}$$

$$D_i(dwelling)[kWh] = D_i(dwelling)[W] \cdot 10\ min \cdot \frac{60s}{1min} \cdot \frac{1\ kWh}{3600000\ J} \cdot \tag{3-7}$$

It was considered July as a reference for sizing the battery, since it is when the highest generation is produced. Subtracting the consumption from the generation and doing its cumulative, the maximum size of the battery is given.

$$Capacity_i\ [kWh] = July_{energy,i}\ [kWh] - D_i(dwelling)[kWh]\ \cdot \tag{3-8}$$

$$Battery_{max}\ [kWh] = \sum_{i=0}^{n} Capacity_i\ [kWh] \tag{3-9}$$

Equation (3-9) gives the overall amount of energy that can be stored during a day, which has been defined as ‘Maximum storage’. However, Nge et al. (2019) recommended that the battery charges and discharges fully every day. Thus, it was defined the ‘Optimal storage’, in which at the end of the day the battery is empty.

$$Battery_{opt}\ [kWh] = \sum_{i=0}^{n} (Capacity_i\ [kWh] - Capacity_n\ [kWh]) \tag{3-10}$$

3.5 Demand side response

Demand side response allows households to make informed decisions concerning the electricity consumption. Load shifting is one of the techniques used in demand-side management. It consists of moving the highest consumption loads to another time. It does not lead to a reduction in net electricity consumed. It simply implies changing when it is consumed rather than how much it is consumed. It can be reached through rescheduling activities, switching off unnecessary appliances or switching to onsite generation. From the household electricity survey conducted by DECC, the source of the energy consumption for individual appliance can be known. See *Figure 3-2*. Therefore, the energy consumption by appliances was assessed for possible load shifting. In addition, the feasibility of charging the EV in off-peak hours was analysed.

3.6 Economic analysis of alternative demand patterns

A cost analysis was conducted to compare the monthly electricity costs associated with the baseline scenario versus a scenario with PV and storage system taking advantage of Economy 7 tariffs.

Table 3-6 shows the electricity prices used for the analysis. Electricity price in Standard tariff does not differ whether is day or night, whereas in the Economy 7 tariffs electricity consumed during the 7 hours of night time is cheaper than during day time. The standing chargers cover fixed cost regarding the electricity supply. These costs include keeping dwellings connected to the electricity grid, carrying out meter readings, maintenance and other related charges. In addition, part of the standing charge will cover government initiatives for helping vulnerable homes and decreasing carbon emissions. Commonly, if households select a plan with high standing charges, it is likely they will pay less per unit of energy. If they do not pay standing charges, electricity price is likely to be higher (SSE, 2018). For the purpose of this study it was selected a ‘Pay as you go’ tariffs for both scenarios.

Table 3-6: Electricity prices for Standard and Economy 7 tariffs.

Tariff	Day (p/kWh)	Night (p/kWh)	Standing charge (p/day)
Standard	14.45	14.45	30.41
Economy 7	15.19	7.67	32.03

Source: SSE (2018).

It can be noticed that prices of electricity used are from SSE, which is the DNO of the study area of Central Bedfordshire.

Regarding the smartest scenario, dwellings can be eligible to receive Feed in Tariffs (FIT) payments due to installation of PV panels. These can be:

- Generation tariff: the energy supplier will pay 3.93 p/kWh of electricity generated. Once the system has been registered, the tariff levels are guaranteed for the period of the tariff (up to 20 years).
- Export tariff: the energy supplier will pay 5.24 p/kWh for 50% of electricity generated, which is an estimation of the electricity exported to the grid.

In *Table 3-7*, cost and warranty of the low carbon technologies used in this study are summarised.

Table 3-7: Prices and warranty of different components.

Component	**Price (*) (£)**	**Warranty (years)**	**Installation (£)**
N310K Photovoltaic Module HIT® BLACK of Panasonic	450	25	500
Powervault 3 8.2 kWh	6,095	10	N/A
Powervault 3 12.3 kWh	8,050	10	N/A

(*) All prices include 5% VAT

Source: Panasonic (2017); Powervault (2018) and Solar Trade Association (2017).

It must be noted that the installation cost includes the capital cost of the installation. For the energy storage systems, the installation costs are included in the price of the device.

Although the cost of current energy storage systems are high, prices are expected to fall in the future (Energy Saving Trust, 2018c).

Finally, the depreciation of the scenario with PV and storage system taking advantage of Economy 7 tariffs was calculated. Powervault 3 batteries can offer over 6,000 cycles and are estimated to last 13 years (Powervault, 2017). So, since the PV panels have a warranty of 25 years and the electricity batteries are expected to last 13 years, during a 25-year period, the energy storage system must be replaced once.

Basically, the depreciation consisted of breaking down the total installation costs into its constituents: PV panels and storage systems and by knowing the monthly electricity cost, compute whether the investment is profitable during the 25-years period.

Note that for this analysis a discount rate of 4% was used. According to Hay (2016), 4% as a discount rate in simple payback is a good assumption, since the energy savings in the future are valued similarly as the energy savings in the present.

4 RESULTS

First of all, the results of the baseline scenario are presented. Then, it follows the results of solar generation for both cases based on annual and daily electricity consumption. Next, both capacities for the storage system (maximum and optimal) are presented. Afterwards, the demand side response is analysed. Finally, a cost analysis of the different scenarios is presented before the determination of the impacts on the grid of OMC arc.

4.1 Baseline scenario: charging just arriving home

Figure 4-1 shows the daily base load profile with an EV for all types of household. It can be seen from the figure that charging the EV just when arriving home stresses the grid since it matches with the peak demand.

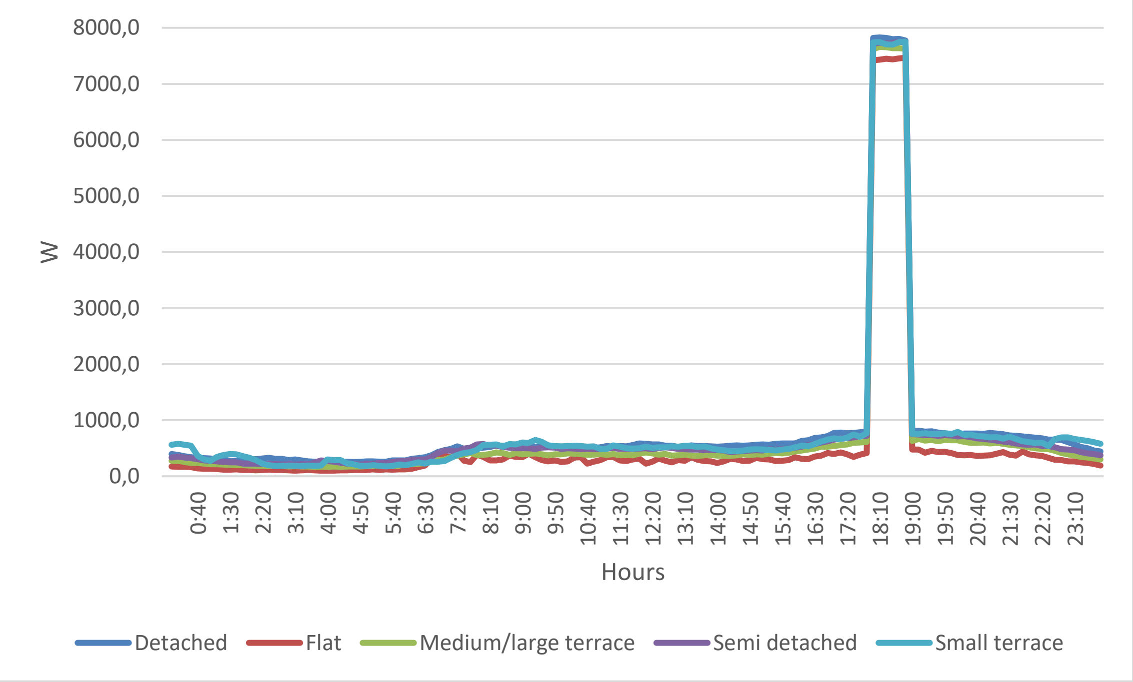


Figure 4-1: Base load demand per all household types with an EV.

4.2 Solar energy generation

4.2.1 Sizing PV array based on annual electricity consumption

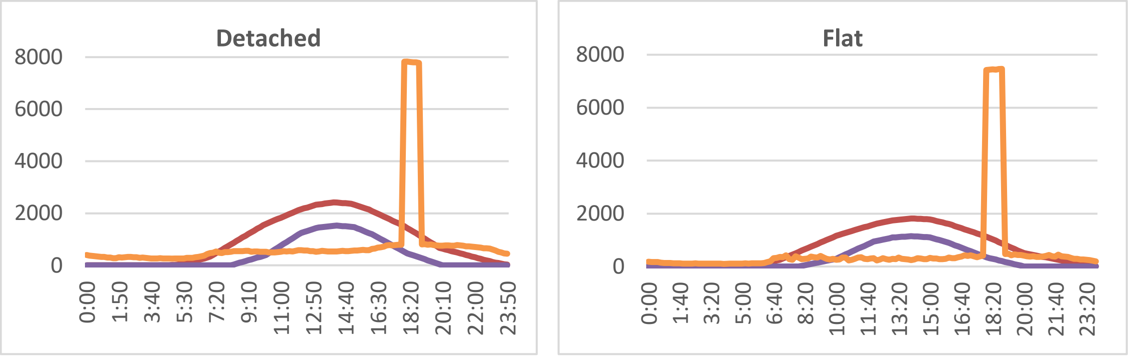
Table 4-1 shows the size of the PV system for different households calculated from the annual electricity demand. This scenario is not a smart choice since the PV array is oversized. The oversized array is due to a calculation method that considers the annual demand must be covered per PV panels, without considering seasonal and daily radiation. In addition, PV arrays of *Table 4-1* occupy more than 25% of the rooftop assumed in *section 3.3*.

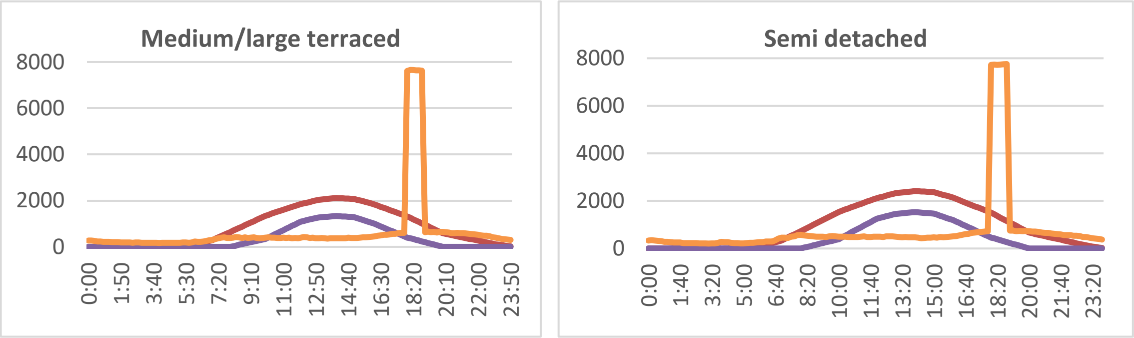
Table 4-1: PV array output and size.

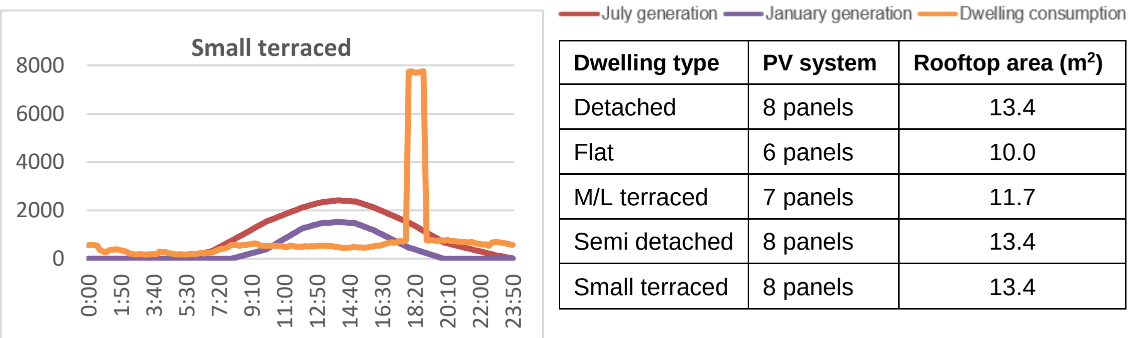
Type of household	**Annual output (kWh)**	**Number of PV panels**	**Roof area needed (m^2)**
Detached	7173	24	40.08
Flat	4969	17	28.39
Medium/ large terrace	5930	20	33.40
Semi detached	6654	22	36.74
Small terrace	6912	23	28.41

4.2.2 Sizing PV array based on daily electricity consumption profile

Figure 4-2 shows the daily generation and consumption for each type of dwelling. Each graph consists of PV array size including number of PV panels and rooftop area, the overall daily consumption including household and EV demands, and daily generation for the most representative months: January and July. For all the cases, the PV system was developed to cover the whole demand in July and half of it in January.







Dwelling type	PV system	Rooftop area (m^2)
Detached	8 panels	13.4
Flat	6 panels	10.0
M/L terraced	7 panels	11.7
Semi detached	8 panels	13.4
Small terraced	8 panels	13.4

*Energy consumption in W during a day

Figure 4-2: Daily energy generation and consumption profiles for dwellings.

As can be seen from *Figure 4-2*, the peak generation is very high on midday when the load is also trivial. The maximum load occurs in the evening, which means that it is very difficult to cover directly the load with the PV array output. So, energy generated during the midday should be stored in batteries for the evening demand.

The proper way to calculate the size of a PV array is by knowing the daily consumption and generation. As can be seen in *Table 4-1*, if just the annual electricity consumption is considered, it results in a bigger PV system compared to the results of the *Figure 4-2*.

4.3 Sizing of storage system

However, installing only PV panels is not a good option because the peak of generation and consumption do not match. Even though, the PV system can supply all the energy needed by a dwelling and the EV, this energy may be stored until it can be used. Another option that could be considered is that all the electricity generated is fed in to the grid and electricity is purchased from the grid when there is a peak in demand. This option does not look very smart since the dwellings are supplying electricity to the grid when it is not needed and are demanding electricity when the grid is under stress. In addition, buying electricity during the peak hours is more expensive than during the night.

Since all type of households and EV have the peak demand at 18:00 h, batteries must store electricity from the beginning of the generation (between 10:00 and 13:00 h depending on the battery size) to 18:00 h. For all the types of dwellings displayed in *Figure 4-2,* there are two different capacities for the storage system: the maximum and the optimal (see *Figure 4-3* and *Figure 4-4).* The optimal system does not store electricity from one day to another. Instead the stored electricity is fully discharged at the end of the day. While the maximum one can store all the energy generated that is not used during the day. Hence, at night it still has electricity stored.

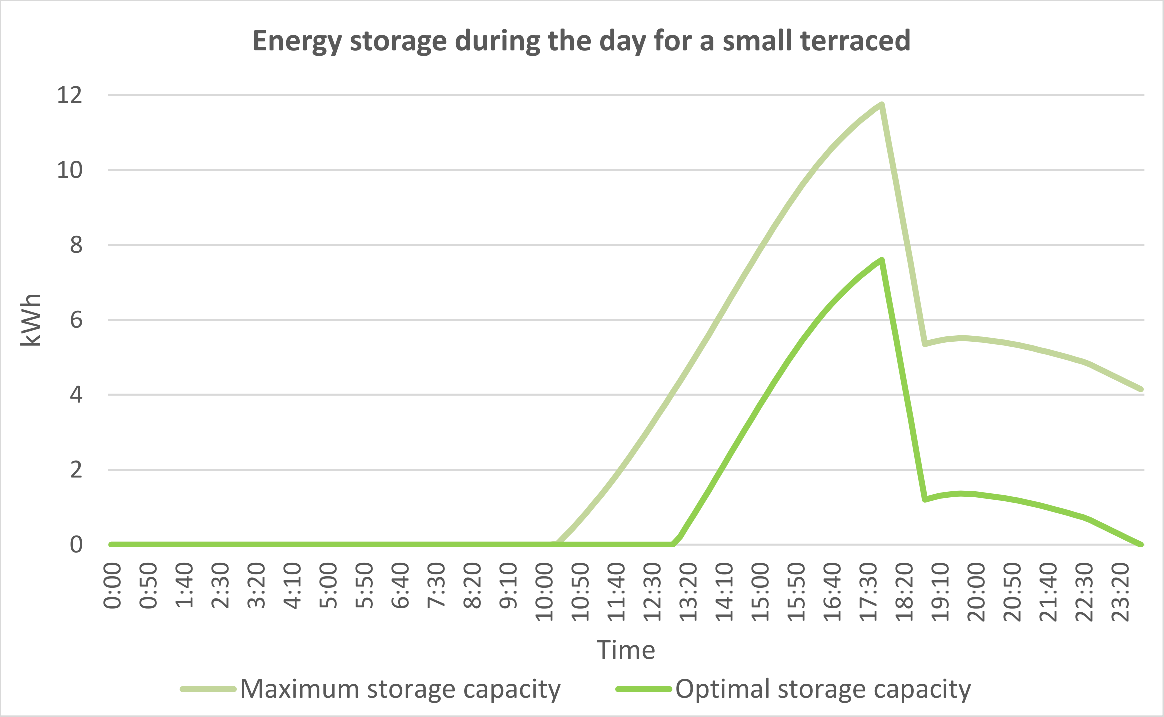


Figure 4-3: Maximum and optimal capacity for the energy storage system for a detached dwelling.

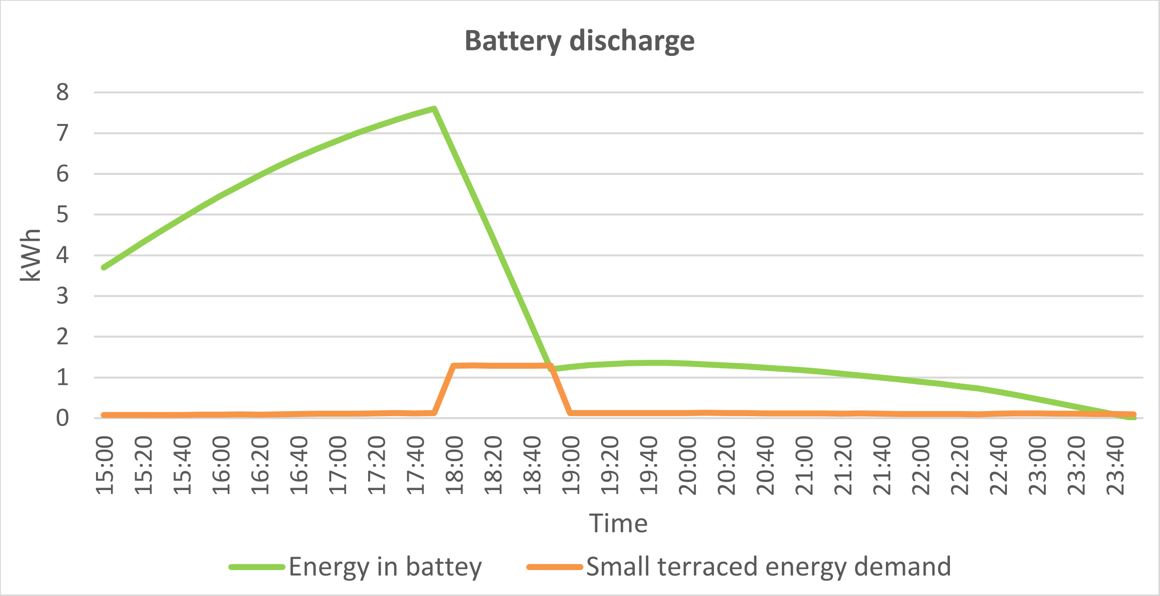


Figure 4-4: Discharge of the optimal storage system vs. small terraced consumption during the day.

Figure 4-2 and *Figure 4-4* have similar patterns for all types of dwellings. *Table 4-2* displays the capacity of the batteries needed for each type of dwelling.

Table 4-2: Storage system capacity (in kWh) per type of dwelling.

Detached	Flat	Medium/large terraced	Semi detached	Small terraced
7.72	10.28	11.12	12.04	7.60

4.4 Demand side response

In *Figure 3-3* it can be observed that the evening peak load is around three times higher than the night baseload. Analysing the data from *Figure 3-3*, it may be a potential shift of the peak load since during the evening apart from lighting and cooking also washing appliances and cold appliances are used. Nowadays, all these devices are programmable and can be set when to switch them on. For instance, if washing machines, dishwashers and tumble driers are programmed in off-peak hours instead of on peak hours, at least 8% of the dwelling's peak demand (around 57 W per household) will be shifted.

If the EV is charged in off-peak hours, there are two possible options: buying the cheaper electricity needed at night from the grid or charging it from the energy storage system. For the first option, the size of PV panels can be smaller than the one of *Figure 4-2. Table 4-3* shows different sizes of PV arrays and batteries (in kWh) for covering the dwellings demand when the EV is charged from the grid at night. These results have been obtained using the same methodology outlined in *sections 3.3.2* and *3.4.*

Table 4-3: Size of PV system and energy storage for each dwelling when EV is charged from the grid during the night.

Detached	Flat	Medium/large terraced	Semi detached	Small terraced
5 panels	3 panels	4 panels	4 panels	5 panels
2.1 kWh	0.98 kWh	1.54 kWh	1.97 kWh	2.04 kWh

4.5 Economic analysis of alternatives demands

In this section, the monthly electricity costs associated with the baseline scenario are compared to the costs of a scenario with PV panels and storage system taking advantage of Economy 7 tariffs. The low carbon technologies analysed in this section are based on the daily consumption profile.

Table 4-4 displays average cost of the electricity with a standard tariff during a month when dwellings do not use PV panels and batteries.

Table 4-4: Monthly cost of electricity without low carbon technologies assuming standard tariff.

Dwelling type	Grid consumption (kWh)	Cost (£)
Detached	609.22	97.46
Flat	422.06	70.41
Medium/large terraced	503.62	82.20
Semi detached	565.13	91.09
Small terraced	587.01	94.25

Table 4-5 and *Table 4-6* show FIT received for the solar generation and electricity bills payed respectively, for each type of dwelling in July.

Table 4-5: Electricity generated in July and payments received from FIT.

Dwelling type	Generation (kWh)	Generation tariff (£)	Export tariff (£)
Detached	715.70	28.13	18.75
Flat	536.80	21.10	14.06
Medium/large terraced	626.27	24.61	16.41
Semi detached	715.70	28.13	18.75
Small terraced	715.70	28.13	18.75

Table 4-6: Electricity purchased from the grid during day and night in July.

Dwelling type	Day (kWh)	Cost (£)	Night (kWh)	Cost (£)
Detached	244.77	37.18	56.81	14.29
Flat	214.49	32.58	22.19	11.63
Medium/large terraced	227.10	34.50	36.31	12.71
Semi detached	229.09	34.80	47.84	13.60
Small terraced	240.62	36.55	51.35	13.87

Table 4-7 displays the July's electricity bill for each type of household. This was calculated by subtracting the generation and export money from the cost of day and night electricity.

Table 4-7: Cost of the electricity in July with low carbon technologies.

Detached	Flat	Medium/large terraced	Semi detached	Small terraced
£4.59	£9.05	£6.19	£1.52	£3.54

Similarly for January, *Table 4-8* and *Table 4-9* show the money received and payed respectively, for each type of household in January.

Table 4-8: Electricity generated in January and payments received from FIT.

Dwelling type	Generation (kWh)	Generation tariff (£)	Export tariff (£)
Detached	304.64	11.97	7.98
Flat	228.48	8.98	5.99
Medium/large terraced	266.56	10.48	6.98
Semi detached	304.64	11.97	7.98
Small terraced	304.64	11.97	7.98

Table 4-9: Electricity purchased from the grid during day and night in January.

Dwelling type	Day (kWh)	Cost (£)	Night (kWh)	Cost (£)
Detached	375.96	57.11	65.48	14.95
Flat	297.22	45.15	28.69	12.13
Medium/large terraced	332.87	50.56	43.89	13.30
Semi detached	356.28	54.12	56.51	14.26
Small terraced	370.44	56.27	60.01	14.53

Hence, *Table 4-10* displays the January's electricity bill for each type of household

Table 4-10: Cost of the electricity in January with low carbon technologies.

Detached	Flat	Medium/large terraced	Semi detached	Small terraced
£52.11	£42.31	£46.40	£48.43	£50.85

Comparing *Table 4-4* with *Table 4-7* and *Table* 4-10, it can be seen that using low carbon technologies reduce significantly monthly bills. In July, the maximum reduction is for semi-detached with 98.33% and the minimum is an 87.15% off in flats. Even though the reduction in January is smaller compared to July, it is still considerable. The maximum savings are for semi-detached with a 46.83% off and the minimum are 39.91% off of the monthly bill for flats.

In addition, if all (or almost all, depending on the battery size) the electricity needed during the day is purchased the previous night and stored in the battery, the maximum advantage from the FIT can be obtained. Almost all dwellings, except detached and small terraced in January, can purchase electricity only during the night, which is the cheapest rate. Hence, in July more money from FIT is obtained than the amount spent for purchasing the electricity. *Table 4-11* shows the amount of money received by FIT in July and the final cost of electricity in January.

Table 4-11: Money received after paying the electricity bills for the months of July and January.

	Detached	Flat	Medium/large terraced	Semi detached	Small terraced
July	£13.82	£7.08	£10.89	£15.71	£14.56
January	-£32.99	-£19.96	-£21.37	-£21.64	-£31.73

Note that in July all the numbers are positive because the money received due to FIT is higher than the electricity purchased from the grid. Whereas in January is the opposite. More electricity is purchased than the money received with FIT. Hence, FIT payments reduce the January's electricity bill, but the negative sign of *Table 4-11* means that each dwelling must pay that amount of money for the electricity purchased.

The depreciation of the installation was calculated from the cost of all the devices (*Table 3-7*) and the cost of the electricity with and without low carbon technologies (*Table 4-4,* Table *4-7* and *Table 4-10*). Considering *Figure 3-5,* where the solar generation for different months of the year can be seen, the yearly cost of using low carbon technologies was obtained by doing an average between the costs of January and July. Finally, savings are obtained by subtracting the yearly average cost of using low carbon technologies to the yearly costs of a dwelling without them. *Table 4-12* summarises the savings of using low carbon technologies.

Table 4-12: Bill savings of using low carbon technologies in a year.

Detached	Flat	Medium/large terraced	Semi detached	Small terraced
£1,054.50	£767.67	£923.53	£1057.50	£1027.94

Deducting these savings from the initial investment for the installation, all types of dwellings recuperate the investment in 25 years. *Table 4-13* presents the profit for each type of dwelling after 25 years.

Table 4-13: Profit of using PV panels and energy storage systems.

Detached	Flat	Medium/large terraced	Semi detached	Small terraced
£706.59	£513.76	£618.36	£708.27	£688.77

4.6 New growth of the OMC arc in Central Bedfordshire

The new housing developments in the regions of east of Biggleswade, the four new villages in Marston Moretaine, north of Luton and east of Arlesey will have a great impact on the grid.

Assuming that the households' distribution will be the same as the one displayed in *Table 3-3,* the overall impact on the grid if new housing developments do not use low carbon technologies is shown in *Table 4-14* and *Table 4-15.*

Table 4-14: Electricity demands for the new housing areas of Biggleswade and Marston Moretaine without installing low carbon technologies.

	East of Biggleswade		**4 new villages in Marston Moretaine**	
	Nº of homes	**Consumption (kwh/day)**	**Nº of homes**	**Consumption (kwh/day)**
Detached	285	5,600.93	950	18,669.77
Flat	630	8,577.25	2,100	28,590.85
Medium/large terraced	135	2,193.20	450	7,310.65
Semi detached	300	5,469.00	1,000	18,229.99
Small terraced	150	2,840.37	500	9,467.89
Total	**1,500**	**25,983.19**	**5,000**	**86,610.63**

Table 4-15: Electricity demands for the new housing areas of Luton and Arlesey without installing low carbon technologies.

	North of Luton		**East of Arlesey**	
	Nº of homes	**Consumption (kwh/day)**	**Nº of homes**	**Consumption (kwh/day)**
Detached	760	14,935.81	380	7,467.91
Flat	1,680	22,872.68	840	11,436.34
Medium/large terraced	360	5,848.52	180	2,924.26
Semi detached	800	14,583.99	400	7,292.00
Small terraced	400	7,574.31	200	3,787.15
Total	**4,000**	**65,815.31**	**2,000**	**32,907.66**

Whereas, from the figures of *Table 4-6* and Table *4-9* it is obtained the electricity purchased in day and night of July and January, respectively, when low carbon technologies are used. Summing the day and night consumption of electricity, the overall electricity purchased using PV panels and energy storage systems is obtained. *Table 4-16* and *Table 4-17* display the impact on the grid in July when low carbon technologies are used.

Table 4-16: Electricity demand for the new housing areas of Biggleswade and Marston Moretaine when low carbon technologies are installed in July.

	East of Biggleswade		**4 new villages in Marston Moretaine**	
	Nº of homes	**Consumption (kwh/day)**	**Nº of homes**	**Consumption (kwh/day)**
Detached	285	2,772.59	950	9,241.97
Flat	630	4,809.95	2,100	16,033.16
Medium/large terraced	135	1,147.11	450	3,823.69
Semi detached	300	2,679.97	1,000	8,933.23
Small terraced	150	1,412.76	500	4,709.19
Total	**1,500**	**12,822.37**	**5,000**	**42,741.24**

Table 4-17: Electricity demands for the new housing areas of Luton and Arlesey when low carbon technologies are installed in July.

	North of Luton		**East of Arlesey**	
	Nº of homes	**Consumption (kwh/day)**	**Nº of homes**	**Consumption (kwh/day)**
Detached	760	7,393.57	380	3,696.79
Flat	1,680	12,826.53	840	6,413.26
Medium/large terraced	360	3,058.95	180	1,529.48
Semi detached	800	7,146.58	400	3,573.29
Small terraced	400	3,767.35	200	1,883.68
Total	**4,000**	**34,192.99**	**2,000**	**17,096.50**

Similarly for January, *Table 4-18* and *Table 4-19* show the impact on the grid in January when low carbon technologies are used.

Table 4-18: Electricity demand for the new housing areas of Biggleswade and Marston Moretaine when low carbon technologies are installed in January.

	East of Biggleswade		4 new villages in Marston Moretaine	
	Nº of homes	**Consumption (kwh/day)**	**Nº of homes**	**Consumption (kwh/day)**
Detached	285	4,058.40	950	13,528.00
Flat	630	6,623.33	2,100	22,077.77
Medium/large terraced	135	1,640.73	450	5,469.10
Semi detached	300	3,994.74	1,000	13,315.81
Small terraced	150	2,082.82	500	6,942.74
Total	**1,500**	**18,400.03**	**5,000**	**61,333.42**

Table 4-19: Electricity demands for the new housing areas of Luton and Arlesey when low carbon technologies are installed in January.

	North of Luton		East of Arlesey	
	Nº of homes	**Consumption (kwh/day)**	**Nº of homes**	**Consumption (kwh/day)**
Detached	760	10,822.40	380	5,411.20
Flat	1,680	17,662.22	840	8,831.11
Medium/large terraced	360	4,375.28	180	2,187.64
Semi detached	800	10,652.65	400	5,326.32
Small terraced	400	5,554.19	200	2,777.10
Total	**4,000**	**49,066.74**	**2,000**	**24,533.37**

Comparing the impact on the grid when low carbon technologies are used (*Table 4-16,Table* 4-17,*Table* 4-18 *and Table 4-19*) with when they are not (*Table 4-14* and *Table 4-15*), in the months with more solar generation such as July, the electricity consumption from the grid could be reduced up to 51% for implementing low carbon technologies like PV panels and energy storage systems. In the coldest months like January, the impact on the grid could be reduced up to 28% if low carbon technologies are used.

5 DISCUSSION

Analysing the data from DECC (2013), it follows the same conclusion as obtained in Thompson *et al.* (2014) that the energy profile at peak hours remains the same during all the days in a week, no matter if they are working days or weekends.

On the one hand, the baseline scenario, which consists of charging the EV just arriving home, over-stresses the grid. From a household point of view, it is not relevant charging the EV at 7 kW in an hour or spending more time with a lower charging power since the price of electricity during daytime is the same. But from the grid point of view, it is necessary to distribute the EV's demand during time as much as possible to lower the peak because it would face runaway peak demand to manage. Hence, this scenario is not a smart option. Fortunately, diversity of demand exists, people have different routines and they arrive home at different times. Kuihua *et al.* (2012), after assessing different scenarios on charging modes conclude that by 2030 the main EV charging load will take place in the morning or in the evening, just before or after the household peak load that does not consider EVs. National Grid (2018) forecasts that only one in five dwellings would charge the EV at peak hours. In addition, there is also diversity of charging places, not all the EV owners are charging the EV at home, some charge it at workplace while others at public charging points (Jennings, Parkin and Del Maestro, 2018).

On the other hand, the demand side response scenario studies to plug in the EV to the grid at night, taking advantage of tariffs such as Economy 7. Nevertheless, it is likely that the uptake of EVs will rise the use of night tariffs in residential areas and, therefore, increasing the electricity consumption during the night. Pimm, Cockerill and Taylor (2018) proved that staggering in bands the prices of off-peak times will help to offset the rebound effect where new peaks might emerge on the grid. Anyway, this approach may be not applicable in areas where all dwellings have energy storage systems or EVs and further research will be needed.

Installing PV panels in new dwellings of the arc to reduce electricity costs go along with the requirement of the State of California where new built homes after January 1, 2020 will include PV systems (Chediak, Gopal and Eckhouse, 2018). The results show that PV systems need energy storage devices to balance the intermittency of solar energy and matching the energy generation with the consumption. These findings are in line to the findings of Eller and Gauntlett (2017) and Nge *et al.* (2019), who underline that PV systems need energy storage devices to rise security of supply and boost decarbonisation of the energy system. Hence, it is recommended installing stationary batteries in the new housing developments of the OMC arc. This is a trend that can be also observed in other countries. In Germany, by 2030, households could have installed 2-GWh capacity of energy storage systems (Klingler, 2017). This increase in the installations of energy storage systems can be accelerated with the decrease of battery prices predicted by Energy Saving Trust (2018a). In any case, some battery brands like Powervault are already making this possible with the use of second-life batteries from EVs.

Torres *et al.* (2014) by using linear programming arrived at the same conclusions of this study in terms of scheduling the PV generation, the battery storage and the electricity consumed from the grid. Furthermore, the strategy proposed in this thesis and checked with the economic analysis of charging the battery during off-peak hours and discharging it during peak period is similar to the findings of Nottrott, Kleissl and Washom (2013).

However, the scenarios presented above do not maximise revenue or energy efficiency. They only lead the way to follow for making new housing developments smarter from its planning phase. Nge *et al.* (2019) proposes an energy management system, based on the method of Lagrange multipliers. This maximises the total revenue for the PV array and the energy storage system, which is connected to the grid and use different electricity tariffs depending on time.

With the economic analysis it has been proved that dwellings which purchase the maximum amount of electricity at the most cost-effective price (during the night) could get the most benefits. This is in line with the findings of Adika and Wang (2014). Nevertheless, frequent cycling of the energy storage systems reduces their charging capacity (Feng, Gooi and Chen, 2015), which is not covered in this study. Angenendt *et al.* (2018) presents a forecast-based strategy to improve the life of the batteries. In addition, their methodology of one-day forecasts leads to an extra 12% reduction of the costs.

To calculate the economic analysis and the depreciation of the PV panels and energy storage systems, the actual electricity price was used. This approach does not consider that the rise of electricity could be double in the next two decades according to forecast published in the ‘Future Energy Scenarios (FES)’ report by National Grid (2018). So, the benefits of using low carbon technologies would increase, while the payback of the system would decrease. By any means, other assumptions in the electricity price might lead to different results. Regarding also the economic analysis, it considers the cost of all the devices used as low carbon technologies and their installation costs, but it did not take into account the costs related to maintenance. Further research on this topic should be done, as well as a more detailed economic analysis considering the consumption of all the months instead of the consumption of the two most representative months: January and July. Due to time constraints, the economic aspects of savings from low carbon technologies are not repeated for the growth of Central Bedfordshire. This may also be another point for future research.

The results presented in this thesis have been obtained by analysing published data from an English household study developed by Department of Energy and Climate Change (DECC, 2013). The energy profiles were categorised per type of dwelling. This is in accordance with Steemers (2003) who stated that there is a significant variation between the energy demand of different building types. Thus, an average load profile was assumed for each type of household, without taking into account occupancy. However, Yao and Steemers (2005) stated that part of the energy demand is related to the households’ behaviour. So, electricity consumption has a big relationship with people’s habits and might be influenced by season. Further research on electricity profiles for each dwelling type considering its occupancy and peoples' habits should be done.

Specifically, the results for the baseline scenario show that each flat needs 6 PV panels that occupy 10 m^2 of the rooftop. Whereas in the demand side response scenario, 3 PV panels are enough to supply the electricity for a single flat. So, the roof area to hold the PV panels for each flat would be 5 m^2. Future research should study the rooftop area for new blocks of flats and assess if all the PV panels needed fit on the roof. In cases where block encompasses many flats it is possible that the number of PV panels per flat might be reduced.

The overall analysis presented in this work, looks at different dwellings' types energy use but not necessarily to the urban form where these dwellings will be settled. Future research must be done to take into account urban form in terms of variables such as the garden size, the orientation of the building, etc (Hachem, 2016; Ko, 2014; Silva, 2017).

Finally, the sensitivity of the results to the assumptions of this thesis, in terms of yearly average consumption per dwelling, PV panels orientation and economic analysis, is not explored. Thus, further work in this aspect should be done.

6 CONCLUSIONS

In new housing development, dwellings must have microgeneration with a storage system. The uptake of EVs rises the dwelling’s electricity demand and therefore, the stress on the grid. Low carbon technologies, such as PV panels coupled with electricity batteries, counteract the effect of EVs on the grid as well as help to decarbonise the energy system.

Storage systems support the grid when it is under stress and help to make the most of solar energy. They reduce the demand from the grid by storing free solar electricity, but also, they help to reduce energy bills by storing cheap off-peak electricity from the grid. Moreover, households can take advantage of feed-in tariffs, which basically consist of payments that they receive for generating and exporting solar energy to the grid. However, the amount of energy savings and size of the components vary depending on types of dwellings, as well as their payback.

Smart EV charging along with load shifting of appliances may reduce the number of PV panels and the size of batteries to be installed. From the data analysed, 8% of the dwellings’ peak load can be shifted since during the evening washing appliances and cold appliances are used.

Hence, for the future housing development of the OMC arc it is recommended the use of low carbon technologies like PV panels and batteries to reduce up to 51% the impacts on the grid in the months of higher solar generation such as July. However, future research on the impact of electricity consumption depending on the dwellings’ occupancy and the urban form must be done.

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