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Investigation of temporal mismatch of the energy consumption and local energy generation in the domestic environment

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This thesis is submitted in partial fulfilment

of the requirements of De Montfort University

for the award of Doctor of Philosophy

December 2014

DECLARATION

No part of the material described in this thesis has been submitted for the award of any other degree or qualification in this or any other university or college of advanced education.

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ACKNOWLEDGEMENTS

I wish to express my deep gratitude to my supervisory team: Dr. Chi Biu Wong and Prof. Philip Moore for their supervision, wise guidance, continuous encouragement, immense support and valuable comments since the first day I set about my PhD study throughout the progress of my research study and the writing of this thesis. My supervisory team spared no efforts in providing what is the best for my research. Their support did not stop at the scientific supervision but extended to facilitate many administrative issues. I highly appreciate all what they have done for me.

I would like also to thank Dr. Xi Chen, Dr. Seng Chong and Mrs Wai-Ling Cheng in the mechatronics research group for their kindness and support.

My genuine thanks are to Eng. Walid Shahin the director of the National Energy Research Centre in Amman/Jordan. Very sincere thanks to Eng. Firass Alawneh and Eng. Laith Basha for their outstanding support in providing the data of the PV farm from the National Energy Research Centre in Amman/Jordan, which was a key factor for the success of this research.

Words cannot express enough my very grateful to my family in particular my wife Arwa for her patient and continuous encouragement throughout my study, for the times she backed me in the family being the mother and father at the same time. Many thanks and love to my daughter and sons for their love and support during this very hard period for them. Their prayers and blessings were no doubt the true reason behind any success I have realized in my life.

Many thanks and appreciation to my friends at DMU; Mr. Mahmoud Elbasir, Mr.Abdu Hamed Ealaskri, Mr.Abdul Basset Ghndi, Mr. Maher Al-Jaber, Mr. Abdulala Al-Thahery, and Osama Kayyali for their friendship and support. Many thanks and appreciation to my friends in Jordan Prof.Omar Badran, Dr.Youssef Al-Toss, Dr. Rashad Rusres, Mr. Maen Haddadin, Mr. Monther Kanan, and Mr. Kaled Aref for their friendship and support.

Abstract

Conventional energy sources are not only finite and depleting rapidly, but are a major source of global warming because they are key contributors of greenhouse gases to the atmosphere. Renewable energy sources are one important approach to these challenges.

Distributed micro-generation energy sources are expected to increase the diversity of energy sources for the grid, but also increase the flexibility and resilience of the grid. Furthermore, it could reduce the domestic energy demand from the grid by enabling local consumption of energy generated through renewable sources. The most widely installed renewable energy generation systems in domestic environments, in UK, are based on solar power. However, there is a common recurring issue related to output intermittency of most promising renewable energy generation methods (e.g. solar and wind), resulting in a temporal energy mismatch between local energy generation and energy consumption. Current state-of-the-art technologies/solutions for tackling temporal energy mismatch rely on various types of energy storage technologies, most of which are not suitable for the domestic environments because they are designed for industrial scale application and relatively costly. As such energy storage system technologies are generally not deemed as economically viable or attractive for domestic environments.

This research project seeks to tackle the temporal energy mismatch problem between local PV generated energy and domestic energy consumption without the need for dedicated energy storage systems; without affecting the householders comfort and/or imposing operational burdens on the householders.

Simulation has been chosen as the major vehicle to facilitate much of the research investigation although data collated from related research projects in the UK and Jordan have been used in the research study.

Solar radiation models have been established for predicting the solar radiation for days with clear-sky for any location at any time of the year. This model has achieved a correlation factor of 0.99 in relating to the experimental data-set obtained from National Energy Research Centre Amman/Jordan. Such a model is an essential component for supporting this research study, which has been employed to predict the amount of solar power that could be obtained in different locations and different day(s) of the year.

A Domestic Energy Ecosystem Model (DEEM) has been established, which is comprised of two sub-models, namely “PV panels” and “domestic energy consumption” models. This model can be configured with different parameters such as power generation capacity of the photovoltaic (PV) panels and the smart domestic appliances to model different domestic environments. The DEEM model is a vital tool for supporting the test, evaluation and validation of the proposed temporal energy mismatch control strategies.

A novel temporal energy mismatch control strategy has been proposed to address these issues by bringing together the concepts of load shifting and energy buffering, with the support of smart domestic appliances. The ‘What-if’ analysis approach has been adopted to facilitate the study of ‘cause-effect’ under different scenarios with the proposed temporal energy mismatch control strategy.

The simulation results show that the proposed temporal energy mismatch control strategy can successfully tackle the temporal energy mismatch problem for a 3 bedroom semi-detached house with 2.5kWp PV panels installed, which can utilise local generated energy by up to 99%, and reduce the energy demand from the grid by up to 50%.

Further analysis using the simulation has indicated significant socio-economic impacts to the householders and the environment could be obtained from the proposed temporal energy mismatch control strategy. It shows the proposed temporal energy mismatch control strategy could significantly reduce the annual grid energy consumption for a 3 bedrooms semi-detached house and produce significant carbon reductions.

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LIST OF ABBREVIATIONS AND ACRONYMS

AC	Alternating Current
AC&R	Air Conditioning and Refrigeration
ACORD	Appliance Coordination
CAES	Compressed Air Energy Storage
CHP	Combined Heat and Power
DEEM	Domestic Energy Ecosystem Model
DEMS	Domestic Energy Management System
DER	Distributed Energy Resources
DSM	Demand Side Management
EPSRC	Engineering and Physical Sciences Research Council
EMS	Energy Management Systems
EU	European Union
GHG	Greenhouse Gas
GTST	Goal Tree-Success Tree
HAN	Home Area Network
HEMS	Home Energy Management System
HOMER	Hybrid Optimization Model for Electric Renewable
HRES	Hybrid Renewable Energy Systems
ICT	Information and Communication Technologies
IDEF	Integration Definition
IDEF0	Integration Definition for Function Modelling
Li-ion	Lithium-ion
M2M	Machine-to-Machine
MPE	Mean Percentage Error

MLD	Master Logic Diagram
NA	Non-urgent Appliances
NERC	National Energy Research Centre
OO	Object-oriented
PCMs	Phase Change Materials
PHS	Pumped Hydro Storage
PV	Photovoltaic
PV-GSM	PV Power Generation System
RMSE	Root Mean Square Error
SDA	Smart Domestic Appliances
SMES	Super capacitors Magnetic Energy Storage
SOA	State- Of -the –Art
SSM	Supply Side Management
TAM	Technology Acceptance Model
TES	Thermal Energy Storage
TSB	TSB Banking Group
V2G	Vehicle-to-Grid

LIST OF NOTATION

F_{c-g}	View factor to the ground
F_{C-S}	View factor to the sky
G_c	Total solar radiation on a horizontal surface$[Watt/m^2]$
G_{cb}	Clear-sky horizontal solar beam radiation$[Watt/m^2]$
G_{cd}	Clear- sky diffuse solar radiation on a horizontal surface$[Watt/m^2]$
G_{cnb}	Clear-sky solar normal beam radiation$[Watt/m^2]$
G_d	Diffuse solar radiation$[Watt/m^2]$
G_o	Extra-terrestrial solar radiation on a horizontal surface$[Watt/m^2]$
G_{on}	Normal incident solar radiation for $[Watt/m^2]$
I_T	Hourly total solar radiation$[Watt/m^2]$
I_b	Horizontal solar beam radiation $[Watt/m^2]$
I_b	Beam solar radiation $[Watt/m^2]$
I_{bn}	Normal solar beam radiation $[Watt/m^2]$
I_{bt}	Titled solar beam radiation $[Watt/m^2]$
I_c	Hourly total solar radiation on a horizontal surface$[Watt/m^2]$
I_{cb}	Hourly clear-sky horizontal solar beam radiation$[Watt/m^2]$
I_{cd}	Hourly clear- sky diffuse solar radiation on a horizontal surface$[Watt/m^2]$
I_d	Diffuse solar radiation $[Watt/m^2]$
K_T	Hourly clearness index
R_b	Geometric factor
θ_z	Zenith angle$[Dgree]$
ρ_g	Diffuse solar radiation reflectance factor
τ_b	Atmospheric transmittance of solar beam radiation

CER	Carbon Emission Reduction$[kg\ C]$
CR	Cost Reduction[£]
FG	Finance Gain[£]
Gsc	Solar constant $(1367\ Watt\ /\ m^2hr)$
kWp	PV maximum power $[kilo\ Watt\ peak]$
TCR	Total Cost Reduction[£]
WHC	Whole house electrical energy consumption cost[£]
$WHCE$	Whole House Carbon Emission $[kg\ C]$
COR	Correlation factor
n	Number of the day
δ	Declination$[Dgree]$
θ	Angle of incidence$[Dgree]$
ω	Hour angle$[Dgree]$
ϕ	Latitude $[Dgree]$

1 Introduction

Six types of gases (carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride) covered by Kyoto Protocol as Greenhouse Gas (GHG) emissions, which are major sources of global warming [1, 2]. Among the GHG basket, CO_2 accounts for the majority of greenhouse gas emissions (82% for both UK and US) [3, 4].

Kyoto Protocol drawn up in 1997 and its amendment in 2012 have agreed on global reduction of GHG emissions by reducing the dependence on conventional energy sources for both developed and developing countries [5]. However, its initial set binding emission reduction targets are assigned to 37 industrialised countries on the basis the current GHG in the atmosphere is largely responsible by them. Since most of the Member States of European Union (EU) are categorised as developed/industrialised countries, the European Parliament and the European Council agreed upon the “Climate and energy Package”, which is a set of binding legislation aiming to ensure EU meets its ambitious climate and energy targets, known as “20-20-20” targets; reduce the GHG emission by 20% on 1990 levels, provide 20% of their total energy from renewable, and increase energy efficiency by 20% from 2007 levels [6].

The UK as a Member State of EU has a legally binding emission reduction commitment under the Kyoto Protocol. The UK government has undertaken actions to tackle the GHG emission reduction such as; a target to reduce GHG emission up to 80% by 2050, legally binding ‘Carbon Budgets’ in its National Adaptation Plan [7].

Among the CO_2 emission, approximately 38.44% and 16.56% are contributed by electricity supply and residential sectors respectively in 2013 at UK [4]. According to these figures, renewable energy sources would be one of the most efficient and effective solutions for the reduction of the GHG emission and environmental friendly energy generation [2].

Renewable energy is one of the promising solutions to tackle the climate change with many advantages such as sustainable energy with large varieties of sources, minimal impact to the environment because they generate little or no GHG or other pollutants and could bring economic benefits to the local region. However, renewable energy sources also have their issues such as intermittent supply which create reliability issue in supply and much larger capital investment when compared with traditional fossil fuel generation.

Due to the huge potential of renewable energy, both the EU and UK government encourage the research in different facets in the area of renewable energy (e.g. technologies, policies, environmental and ethical issues) through the EU and local funded projects (e.g. EU framework programmes and the NER300 funding programme) [8].

1.1 Research motivation

Housing regulations from the UK government mandated zero carbon new homes by 2016 [9] and the Micro-generation Feed-In-Tariff introduced by the UK government in 2010 [10, 11] has encouraged the UK general households to undertake micro-generation as an alternative energy source. These policies aim to ensure that domestic micro-generation of energy is no longer a niche sector promoted only by governments and environmentalists. These distributed micro-generation energy sources are expected not only to generate heat/electricity without depleting the natural resources, but also to reduce domestic energy demand from the grid and improve energy efficiency by reducing transportation loss. However, there is a common and recurrent issue on output intermittency of several most promising renewable energy generations (e.g. solar, wind) which led to temporal energy mismatch between local energy generation and energy consumption.

In order to address the temporal energy mismatch issue without disruption of the current household living style, most popular approach focuses on developing energy storage mechanisms to store “surplus” electricity for later use. Although significant research advancement has been made in both searching for cost-effective and efficient methods of storage (e.g. battery bank, hydrogen, compressed air, flywheel) [12, 13] and design methodologies to determine the proper capacity of storage [14-16], these solutions are neither cost effective nor viable for the domestic environment due to their current associated costs (e.g. capital investment and maintenance costs) and the system operational complexity.

Another approach intends to address the problem by managing the energy consumption to meet the characteristic of energy production. Such a scheme plays a significant and active role [17] to reduce/eliminate the needs (or size) for energy storage (or conventional shadow capacities) and/or the possibilities of energy grid fluctuation [18, 19]. According to the Smart-A project [20] such system can potentially reduce domestic energy consumption from the grid by 10% whilst consuming only 35% of the locally generated renewable energy (the surplus is fed to the grid). Obviously, there is still plenty of room to improve and further research is required.

The author is inspired by these previous research works and motivated by the challenge in tackling the temporal energy mismatch between the local energy generation and consumption. The author believes the success of this research study not only in addressing a research challenge in engineering, but also has a considerable impact in much wider aspects such as environmental and societal benefits.

1.2 Research aim and objectives

The aim of this research study is to tackle the temporal mismatch between energy consumption and local energy generation in the domestic environment.

1.2.1 The main research questions

The research questions for this research study are:

- What are the challenges (or barriers) facing the proposed research?
- What are the roles, limitations and potential of the smart domestic appliances in meeting the challenges?
- Are there any relationships (or patterns) between the local renewable energy generation and consumption in the domestic environment?
- To what degree the proposed challenges could be solved?

1.2.2 Research objective

The objectives of this research study are:

- To investigate the dynamic Supply and Demand relationships between local renewable energy generation and energy consumption in order to establish a system model to facilitate the study of the temporal mismatch between local energy generation and energy consumption.

- To investigate the roles of domestic energy-aware smart appliances in tackling the temporal mismatch between local energy generation and local energy consumption.
- To devise control strategies to tackle temporal mismatch between local energy generation and energy consumption.
- To develop simulation models for supporting the research study.
- To evaluate the proposed control strategies with the aid of the developed simulation models.

1.3 Research approach

The aim of this research is to explore a new approach for solving the temporal energy mismatch problem between the local energy generation and local energy consumption. This research adopts a holistic approach to investigate the dynamic ‘Supply & Demand’ relationships between local energy generation and local energy consumption that contributes to the internal and external dynamic behaviours of domestic energy ecosystem, which will effectively establish a model for supporting the design of domestic energy management systems.

Simulation will be the major vehicle to conduct the research investigation. Research data from other research project (DEMS [21], funded by TSB/EPSRC) and establishment (National Energy Research Centre/Jordan) will be kindly provided by their owners for supporting this research study.

Various modelling approaches will be adopted in this research study. The top-down IDEF$_0$ functional modelling approach is adopted in this research study. It provides the required information of the system component. This modelling approach is flexible; it is easy to manage the complexity of the system model, and the established model components could be re-used for other system models. This modelling approach is adopted to model the chosen domestic appliances (e.g. fridge-freezer), to gain in-depth understanding of the interrelationships between the functional components (e.g. parameters) that may affect the system/components being modelled, and to identify the inputs and the outputs of the identified functional components.

Matlab/Simulink is employed for implementation of the system models and facilitates the simulation-based case studies. All the identified functional components through the

IDEF_0 modelling process will be implemented as ‘Simulink Blocks’. These developed ‘Simulink Blocks’ will subsequently be used to synthesise the system model being modelled.

This research will address the identified research challenges in five stages:

- The first stage is to identify the barriers and obstacles of the research challenges. Literature review is the major vehicle to carry out this task. This stage also lays down the foundation study of the proposed challenges by intensive review of other research papers and documentation. This stage of work is not a one-off task because the author should keep abreast of the other research and development works in this area throughout the project period.
- The second stage is to establish models of a domestic energy ecosystem to facilitate the subsequent planned research studies and is mainly divided into three tasks:
    - Establish models for the chosen home appliances (e.g. fridge-freezer), which would be part of the domestic energy ecosystem to facilitate the studies on the energy consumption behaviours of these appliances.
    - Establish models for the chosen domestic micro-generation systems (i.e. PV system), which would be part of the domestic energy ecosystem to facilitate the studies on the behaviours of the local energy generation.
    - Establish a completed domestic energy ecosystem with the aid of the models developed in the previous tasks.
- The third stage is to study the dynamic ‘Supply & Demand’ relationships between local energy generation and local energy consumption that contributes to the internal and external dynamic behaviours of domestic energy ecosystem and establish various control strategies that would tackle the temporal mismatch between the local energy generation and local energy consumption within domestic environments, with the aid of the developed domestic energy ecosystem model.
- The fourth stage is to carry out the analysis of the proposed temporal energy mismatch control strategies with the aid of the simulation results, which generated by the models developed in stage two.

- The final stage is to document all the research works in a formal document (i.e. PhD thesis), which is ready for submission to Graduate School Office at De Montfort University.

1.4 Thesis Outlines

This thesis has six chapters in total, excluding reference and appendices. The remaining chapters of this thesis are outlined as below.

Chapter 2 presents a comprehensive literature review on previous research works, which are directly or indirectly relating to the proposed research study. This chapter also reviews the current state-of-the-art technologies and/or developed solutions.

Chapter 3 presents the modelling works on the energy generation system of the chosen renewable source (i.e. solar). Component-based modelling approach was adopted for the model development to improve the model reusability, for example, the developed solar radiation component model can be used for supporting other research studies or system design relating to solar energy such as solar-based hot water systems.

Chapter 4 presents various research works on domestic energy consumption with focus on some of the chosen smart domestic appliances (SDA). Modelling works on the chosen SDA will be reported.

Chapter 5 presents the proposed temporal energy mismatch control strategy; reports the analysis of the simulation case studies which are based on the models developed in Chapters three and four; and, reports on the socio-economic impact analysis of the simulation case studies.

Chapter 6 presents a summary of the research findings, contributions of this research study and recommendation for the future works.

2 Literature review

This chapter provides an overview on the current State-Of-the-Art (SOA) systems and technologies in addressing the temporal energy mismatch between renewable energy generation and consumption locally in the domestic environments; it critically appraises these SOA and relevant research works in order to understand the advantages and disadvantages of these approaches and/or solutions.

Simulation is the major vehicle chosen for supporting this research study, hence, review of the relevant modelling works have also been conducted.

2.1 Technologies for domestic energy generation

Technologies which relating to domestic energy generation can be categorised in: Distributed Generation such as photovoltaic panels on the roofs, micro wind turbine and micro Combined Heat and Power (micro-CHP) [22]; Distributed Storage such as rechargeable batteries, super-capacitors and flywheels [23]; Demand Side Management (DSM) such as dynamic pricing, and demand response programs [24].

2.1.1 Distributed generation

A micro-generation system is defined as generation for both electricity and/or heat for individual house in an efficient way to meet the electric and thermal load with low greenhouse gas (GHG) emissions [25, 26]. In addition, producing electricity by using micro-generation systems in dwellings will minimise the power plant transmission losses, increase the energy efficiency, increase the ability of matching demand and supply, and reduce the emission of carbon dioxide as most of the micro-generation systems are using green energy sources [27]. Micro-generation can reduce the peak demand effectively during daytime by disconnecting the house from the grid and switching to the micro-generator as an electrical supply or connecting the micro-generation system to the grid during this period [28]. In addition, the micro-grid can work in parallel with the grid with the ability to work in off-grid mode during the peak periods [29].

Small-scale active distributed generation of electricity and heat, energy storage, and responsive load demand distributed generation in the domestic environment is referred as Distributed Energy Resources (DER) [30]. This means small-scale (ranging from less than one kW to tens of MW) electricity generation unit(s) located within the electricity distribution system at/or near the end-users [31]. Residential DER technologies are sub-systems that utilised different types of renewable resources to generate, store and manage electrical and/or thermal energy in domestic environments [32].

DERs, namely Distributed Generation (Medium Voltage level) and micro generation (Low Voltage level), poses several technical challenges for distribution network voltage control [33]. In addition, a drawback of the DEGs is their variability, which generates fluctuating and unpredictable amounts of electricity over time. Due to these variable energy sources, energy storage will be an apparent solution for overcome the temporal mismatches between load demands and the electrical supply [34]. Distributed storage has considered well matched to these distributed energy generation technologies [35].

2.1.2 Energy storage systems

As renewable energy sources are intermittent in nature, the energy storage systems are playing an important role in improving the utilization of these systems. The essential storage for the application of these systems in the domestic environment is the short term storage (e.g. no more than 24 hours). As an example, the solar energy is available for few hours during the day so the energy collected from these systems could be stored to be used at other times (e.g. evening and night). Energy storage is well suited to respond to the local supply and demand challenge and ensure a continued security of energy supply at any time by storing energy in times of excess supply and releasing power when there is not enough generation.

2.1.2.1 Distributed Electricity Storage

Distributed power generation/storage technologies have claimed as a flexible energy system that can utilise fluctuating renewable energy sources more efficiently, and increase the sharing of renewable energy via the electricity grid [36].

Energy storage device complements the power generated by the distributed generation by compensating the lags in generator response and peak power demands with stored energy [37]. The motivation behind a research done by Ahlert and Dinther [38] was to investigate the possibility of the distributed storage devices to lower the average electricity cost. The authors claimed that a cost reduction from 5% up to 17% on total annual costs has been achieved by using distributed storage devices, and this cost reduction could be further increased by increasing the gap between peak and off-peak prices.

2.1.2.2 Thermal storage

The most commonly method used for thermal energy storage is the sensible heat method [39]. In liquid based systems water is used as heat storage media, while bricks are the media used for storage electrical heaters (night storage electric heaters) [40].

In UK approximately 49% of the primary energy is used for heating and cooling. Thermal energy storage can play a significant role in shaping the energy demand profile. In addition thermal storage does not have any energy conversion losses, and it can be stored in solid, liquid or gaseous media [41]. To reduce the energy consumption there will be a need for reducing energy consumption at peak periods and shift the time for electricity use. The utility providers are seeking for storage ways for the renewable generation. The Thermal Energy Storage (TES) systems have been widely used to store energy for later use. Thermal energy storage technologies can play an important role in reshaping the load profile of electricity use for heating and cooling. Electrical storage heaters and hot water systems within the domestic sector seem to be one way to achieve this target [42].

Pedersen et al. [43] developed a powered refrigerator (SolarChill) which is able to store the electrical energy provided by a PV panel attached to the refrigerator in ice instead of in batteries. The authors used the Phase Change Materials (PCMs) technologies to use the surplus energy of the generating system to convert water into ice in the surrounding area of the refrigerator cabinet. During the time the electrical power is not a viable the ice will melt and provide the cabinet with the cooling load. The authors claimed that this was a funded project by Danish Energy Agency and was conducted by Danish Technological Institute. The developed refrigerator was designed for the specific purpose which is to be used as for vaccine cooler, and every refrigerator needs the necessary PV panel size (the minimum current for starting the compressor should be determined)

Farid et al. [44] reviewed on previous work on latent heat storage and the recent efforts for developing new classes of PCMs to be used in energy storage. Verma and Singal [45] reviewed on modelling of latent heat thermal energy storage. Sharma et al. [46]

reviewed on thermal energy storage materials and applications. Tatsidjodoung et al. [47] reviewed on recent developments on materials for thermal energy storage in building applications. Hsnain [40] reviewed on the cool thermal energy storage technologies for both demand side as electric load management DSM, and for the supply side as the Supply Side Management (SSM) for efficient power production. The author stated that cool storage technology is an effective way of shitting the electrical load out of the peak periods. They stated that using the TES technologies for air condition and refrigerating systems, cooling could be supplied by circulating the cooling medium rather than operating the compressor when the electrical supply is not available.

2.1.2.3 Rechargeable batteries systems

Batteries have been of limited use as an electric power systems storage device due to their limited storage capacity and high cost. However, newer rechargeable batteries technologies have been advanced significantly since the middle of the first decade of the 21st century. Rechargeable batteries also called a storage battery or accumulator store readily convertible chemical energy [48] which can be converted to electrical energy anytime to supplement the main supply when it required [49].

Rechargeable batteries such as lead-acid type for ‘deep cycle’ are commonly used as storage systems for renewable energy systems because this type of rechargeable batteries are much less susceptible to degradation due to cycling, and are required for applications where the batteries are regularly discharged. However, such a ‘deep cycle’ battery requires thicker lead plates which is not only costly but also has significant impact to the environment. It is not recommended to use the ‘car starter (or engine starting)’ batteries, also lead-acid type, on a power system as it will sulphate the plate material in deep discharging cycle which will cause the battery to fail prematurely [50].

Lead-acid batteries have many drawbacks such as limited storage capacity, short cycle life, high maintenance requirements and environmental aspects associated with lead and sulphuric acid [41]. In addition, the datasheet of the batteries provides information about cycle lifetime of the batteries (usually 300–2000 full cycles depending on the technology) is obtained in laboratory tests under standard conditions. However, the real conditions of the cycles when installing these batteries as storage systems in PV systems applications are habitually very different from standard conditions and the real cycle lifetime can be much lower [51].

Lithium-ion rechargeable batteries are expensive when compared to lead-acid, and have its drawbacks such as fragility and requires a protection circuit and battery management system to maintain operation safety such as battery charging. Although its cost dropped significantly in recent years, it is still comparatively expensive as a storage media in domestic applications [52].

The general characteristics of rechargeable batteries are similar to those of conventional car batteries which can hold about 0.5 kWh. These rechargeable batteries will return a proportion of the energy used to charge them with a maximum 80% efficiency. The proportion depends on the charging and discharging rates and the depth of discharge. These rechargeable batteries had a limited number of charge/discharge cycles, which approximately 400 deep discharge cycles [49].

Although this type of energy storage system is one of most popular types adopted in the domestic environment to deal with the intermittency issue of renewable energy sources, it does not seem as socio-economic viable because their high initial cost, regular replacement of the rechargeable batteries in 3 to 4 years are needed, and has significant impacts to the environments when the rechargeable batteries are manufactured and disposed at the end of their life [49].

2.1.3 Demand Side Management

Demand Side Management (DSM) can be defined as “The planning, implementation, and monitoring of utilities activities designed to influence customer use of electricity in ways that will produce desired changes in the utilities load profile” [53].

One of the main planning options for the electric utility industry nowadays is implementing DSM strategy to manage and reduce energy consumption of the end users [54]. The DSM strategy encourages the end users to implement efficient technologies that will consume less energy or shift the loads demand to the off-peak period to reduce the energy bill [55]. Furthermore, the energy suppliers will plan their energy generation according to the needs of the customers; taking into account on how and when the customers will consume the electricity [56]. In addition, DSM can increase the generation efficiency by peak shaving [57]. Utilities can benefit from this strategy as end users reduce or shift their use of energy will reduce their peak power purchases; thereby lowering their cost of operations, minimise the needs of building new power plant(s) and/or burns the dirty fuels such as coals [58].

2.2 Domestic energy management system

Energy management system for domestic sector (DEMS) still in its infancy and not many people are comfort with this new technology. Appling DEMS in the residential sector requires different understanding of the recent technologies, as the knowledge and experience in the commercial and industrial sectors cannot directly applying in the domestic sectors due to their differences such as constraints on costing. These systems are playing a main role in renewable energy systems implementations, and an effective communication technology is needed to gain the benefits of the available energy sources. As an example when a smart grid informs a smart appliance that the grid is operating under peak load conditions, the smart appliance could take an action to reduce its electricity consumption [59]. The domestic EMS generally consists of many elements such as smart energy-aware appliances and systems, communication facilities, and smart meters.

2.2.1 Domestic smart energy-aware appliances

Block et al. [60] stated that about 50% of the households’ electricity consumption is dedicated to refrigerators, freezers, (water) heaters, washing machines and dryers. According to the International Institute of Refrigeration in Paris (IIF/ IIR), approximately 15% of all the electricity produced worldwide is consumed by various kinds of refrigeration and air-conditioning systems [61]. According to the U.S. Department of Energy, air conditioning and refrigeration (AC&R) appliances account one third of the total electricity consumed in the U.S. domestic and commercial buildings [62]. Residential refrigerators are the largest energy consumption appliances in the U.S. houses, approximately 7% consumption of the nation’s electricity [63].

Smart technology can help reducing the energy consumption of most energy consuming appliances used in the house such as refrigerators, freezers, washing machines, clothes dryers and dishwashers. These appliances are designed to work within smart grids with the existence of smart meters and smart devices in the house.

The smart appliances should have the capability to deliver smart services within the home environment in the area of utilities and entertainment [64]. In addition, some of these appliances have optimization potential which give the appliances the ability to shift energy consumption in time without harming the comfort of the householder, smart freezers and fridges can adjust their cooling cycles according to the availability of the energy sources [65].

“Smart Domestic Appliances in Sustainable Energy Systems (Smart-A)” project which is supported by the European Commission under the ‘Intelligent Energy-Europe’ Program, is an important study in terms of determine the degree of which the smart appliances can adapt their operation (without compromising the quality of the service) to the requirements set by the variations in the regional and local energy supply, in other words, this project aims at developing strategies for smart domestic appliances contribution to load management in future energy systems [66].

A proposal to integrated different groups of smart appliances and to provide more added services were introduced by Chun-Yu et al. [67] to eliminate the gap between users habits and the services offered by smart appliances. Due to the authors the applications of smart sensors and smart home networks, the waste energy could be reduced and the resident comfort could be maintained. Although, taking into account the consumer opinion and attitude towards new ways of energy consumption and energy management. Stragier et al. [68] employed a user-centric perspective to map the consumer’s perception of application the demand side management through smart appliances. The authors conducted a quantitative survey among 500 households, and the Technology Acceptance Model (TAM) was used to measure these perceptions. The result of this study shows that there is a challenge in convincing people about the safety of demand side management; in addition, the result showed that there is a positive effect on the intention to use smart appliances at home. Nagesh et al. [59] prepared a framework for utilizing the real time information feedback based on aggregated consumption and supply data regarding peak load conditions (available at the distribution centres), this data can be used to provide information whether the demand is on off-peak, or on mid-peak or on peak. By sending these data to the smart appliances control panels, the smart appliances should take intelligent decisions for automatically adjusting their demand, which can help to manage the “demand and supply” relationship.

Rosin et al. [69] analysed a household electricity consumption of workdays and holidays, taking into account the high and low tariff scheme by shifting some of the house appliances load from the high to the low tariff period, together with the adoption of energy saving devices such as reduce the standby power. According to the authors, the total energy consumption was reduced by 5.6% and 12% saving from total energy consumption costs. The authors recommended for using of appliances with scheduling functionality.

According to the above-mentioned studies, smart appliances have a great potential in energy conservation and contribute to the smart grid concept. Furthermore, energy-aware smart appliances would be a key element in supporting domestic energy management system to optimise the use of energy and leads to carbon reduction.

2.2.2 Information and Communication Technologies

Information and communication technologies (ICT) are playing a key role in transforming the traditional power grid into a smart power grid, and hence, they provide opportunities to develop the interconnections of the home smart appliances and the energy generation systems (smart grid and micro-generation) [70].

With the emerging smart technologies from the ubiquitous computing domain the ability to reduce the growing energy consumption in the residential sectors is now emerging [71]. In addition, with the advancement of Internet and associated technologies, the usefulness of connectivity becomes more pervasive, so the home appliances could be connected to a network within the home [64].

The integration of ICT tools for management of distribution networks and smart meters at the consumer premises would improve the power grid management and facilitate the integration of renewable energy systems to reduce the energy consumption. According to the French regulator, the residential consumption would be decreased by up to 5% when implementing smart meters [72].

The goals of the ICT infrastructure for energy-positive buildings and neighbourhoods project by Energy Saving Information Platform (ENERsip) were to develop and test an

ICT platform which will provide tools for real-time optimal matching between energy generation and consumption in buildings. The project seeks to allow different domestic networks to integrate within the distributor's network [73].

Robust and flexible Home Area Network (HAN) communication is a requirement for smart grid and demand response infrastructure to monitor, control and optimize energy consumption. HAN provides two-way communication among smart meters, home gateways, and appliances within the home environment. It enables the exchanged between the energy data and smart meters inside a home [74].

Dusit et al. [75] investigated the application of Machine-to-Machine (M2M) communications in smart grid. Recently, M2M communications has attracted much attention as the network infrastructures of existing communication systems (e.g. GSM/GPRS) could be adopted in M2M communication. Although, the sensors used to collect information for M2M systems are widespread adopting. The authors stated that the objective of M2M communications is to increase system automation level in which the data is exchange and shared. They address the network design issue (optimal HEMS traffic concentration) of M2M communications for a Home Energy Management System (HEMS) in the smart grid. The authors claimed that the total cost of HEMS could be reduced with the proposed optimal traffic concentration scheme.

2.2.3 Smart Meters

Smart meters are electrical meters usually involve real-time sensors, power quality monitoring, and power outage notification. Each smart meter contains a processor, non-volatile storage, and communication facilities. They can gather energy consumption data, send out alarms in case of problems and record the electrical energy consumption in pre-determined time intervals (e.g. hourly or less). The smart meter can interface with energy-aware appliances to facilitate the implementation of Demand Side Management [76].

The utility sectors would gain benefits of adopting smart meters for the residential sectors as these meters enable the utility offering better customer services, reduced manual meter reading costs, fewer estimated and inaccurate billing, and delivering essential energy savings to meet the regulatory requirements [77].

Smart meter can send price and power information to controllable devices within the household. These devices (e.g. washing machine) will consume the electricity according to the requirements of the customer and the price information. In other words, the device will decide to work within the low price tariff [78].

Owen and Ward reported on the results of ‘Sustainability First’ project. The aims of this project were; to assess the benefits and the cost of smart meters in the UK, taking in consideration the structure and operation of the UK metering market, to compare smart meters deployment in the UK with the international experience on energy saving, and to identify the regulations and policy that should be undertaken for wide deployment of smart meters in the residential sector in the UK. A comprehensive desk research and interviews were involved in this project. The authors state that the smart meters are a gateway to achieve energy saving for both energy suppliers (e.g. finding new ways of tackling energy management to improve market operation), and for households (e.g. improved feedback on energy consumption, develop individual demand-response, and develop new scope for micro-generation) [79].

2.3 Solutions for temporal energy mismatch between domestic energy consumption and local energy generation

In addressing the temporal energy mismatch issue between local generation and demand profile in the domestic environment, Rae and Bradley [80] compared the output from micro wind turbine and the energy demand profile of a small UK house over a 48 hours period. The authors suggested two methods to tackle the temporal energy mismatch problem; one is to employ dedicated energy storage systems (e.g. Fuel cells, Pumped hydro storage, Flywheels, Compressed Air Energy Storage (CAES), and Super capacitors), and the other is to adopt Demand Side Management (DSM) approach to control the demand profiles to better suit of the local renewable energy generation profile. Most of the energy storage technologies mentioned by the authors are mainly designed for larger installation such as national grid or wind farms and not suitable for the domestic environments; mainly because either too costly and/or complex to run.

Born et al. [81] were used a 3 kW wind turbine and a 3 kW PV systems as the local renewable energy generation systems, together with one-week demand profile of a small commercial building in the summer season at UK climate to demonstrate the proposed matching techniques of local energy “supply and demand”. The authors claimed that the energy demand during weekends were lowest, while the power generation of the wind turbine in this period was highest, and the power generation of the PV system exceeded the energy demand over the midday hours. The authors claimed both of the generation systems did not met the energy demand profile all the time and surplus generated energy would be either exported to the grid or wasted. The authors used different types of search methods (e.g. Best Overall Search, and Led Search Method) to optimise the renewable energy options for given energy demand scenarios to achieve a matching of supply and demand. The authors claimed that by comparing search and match evaluation techniques with one another a perfect matching of energy demand and supply can be easily assessed. However, their proposed rating method for assessing the energy profiles matching in the degree of ‘goodness’ is ambiguous and not well defined. The authors claimed that dedicated energy storage system can have a significant effect on matching the local energy “supply and demand” profile. The authors were used rechargeable batteries as energy storage media, and back-up generator (diesel generator) as stand by generator to improve the supply profile. The major problem of this studies not only the proposed solution is expensive to install and maintain, but also not suitable for domestic environments.

Morgan et al. [82] used genetics algorithm as a search technique to assure achieving the best matching between both demand and renewable energy generation profiles, and they included a short term load forecasting module in order to give a good estimation of the load profile one day ahead for supporting the implementation of DSM algorithm (load shifting, and load shedding) to solve the temporal energy mismatch problem in the domestic environments. The proposed DSM algorithm employed full and partial “shifting and shedding” techniques to solve the local temporal energy mismatch problem. The authors claimed their success but admitted the proposed solution did affect the resident comfort in some degree.

Most of the previous research works in solving temporal energy mismatch problem between local energy generation and demand in domestic environments have been concentrated on the improvements the efficiency of the generation systems and domestic appliances, improvements of efficiency and the capacity of various energy storage systems, influencing/managing the energy consumption habits and/or profile of the householders. None of these research works have a holistic view to investigate the potential of utilising domestic networked appliances to solve the problem.

2.4 Modelling approaches and related modelling works

2.4.1 Modelling approaches

Models and modelling approaches can be considered as fundamental methods and essential tools in every science and engineering disciplines. There are large varieties of modelling approaches developed for various purposes: from supporting quantitative analysis such as mathematical modelling to qualitative analysis such as 'what-if' analysis. This review is no attempt to cover all different types of modelling approaches and only focus on the modelling approaches that would related to the proposed project.

2.4.1.1 Functional modelling approach

Functional model is the structured functions representation of the engineering system and emphasis on identify and decompose system functionality [83]. The objects and the functions are used as the basis of this modelling approach. It addresses the system's processes and the flow of information from one process to another. This modelling approach often uses data-flow diagrams which shows the transformation of data as it flows through a system, this diagram consists of processes, data flows, actors, and data stores. It is used to describe the functions, activities, actions, operations, and processes of an engineering system. It is widely adopted and recommended in the cases where functions are more important than data [84].

Modarres [85] used functional modelling approach (Goal Tree-Success Tree (GTST)) and Master Logic Diagram (MLD) as framework for modelling physical systems. Classification based on the conservation laws for the most common elements of the engineering systems was proposed using function-based lexicon. The author claims that the GTST-MLD is a good framework for functional modelling of complex physical systems.

Integration Definition (IDEF) refers to a family of modelling languages in the field of information engineering. IDEF cover a wide range of applications such as functional modelling to data, simulation, and object-oriented analysis/design. The IDEF family contains many methods of modelling such as IDEF0 function modelling, IDEF1 information modelling, IDEF3 process description capture, IDEF4 object oriented design, IDEFS ontology capture, and IDEF1X data modelling [86].

Integration Definition for Function Modelling (IDEF0) is a simple method, easy to understand, and provide better communication between technical developers and industrial end-users [87]. Each single process in the model is represented with a box and directional arrows. These arrows represent the inputs, outputs, controls, and mechanisms of the modelled system. Controls are a form of input, but which are used to direct the activity in the process. The mechanisms are the resources and tools required to complete the process. The inputs are changed in some way to create the outputs, while the controls are seldom changed [88].

IDEF0 is a strictly top-down process using ‘black-box’ view, which starting from a top-level diagram and progressively down to its bottom-levels. This simplistic approach enables the system analysts to investigate the interrelationships between the functional blocks with ease.

2.4.1.2 Object-oriented (OO) modelling approach

It is a hierarchically structured programming oriented modelling techniques that can shorten the development life cycle [87]. Object is the fundamental construct of this approach, as it identifies objects first then operations and functions. The building blocks in this modelling approach are classes, attributes, operations, and relationships. It has the following advantages: modelling complex objects are easier, better extensibility, and compatible with the intended implementation environment [83]. Non-causal modelling approach presents the models as their actual structure (differential, algebraic and discrete equation), rather than the actual algorithm of the simulation (e.g. Modelica programming language) [89].

Modelica is a modern language built on non-causal modelling with mathematical equations and object-oriented constructs [90]. Casas et al. [91] have employed this tool and component oriented modelling approach to evaluate the performance of the desiccant assisted air conditioning process. The authors claimed that this modelling approach offers a high level of flexibility with respect to boundary settings.

2.4.1.3 Signal flow (causal) modelling approach

Signal flow (causal) modelling approach is widely used by control engineers to model the plant for supporting the development of real-time control systems, and it is the dominating modelling paradigm (e.g. Simulink from MathWorks) [92] in control system modelling and design. Causal modelling provides a clear graphical visualization of individual mathematical relationships. The values of individual variables from the output of one block to the inputs of other blocks are transmitted through signals flow connection between individual blocks [89].

Using this modelling approach, the model is described in a form closed to the solution algorithm, and the interaction between the models is formalized in terms of input and output variables. The system model could be divided into sub-systems each sub-system model depends on the selection of input and output variables at the system boundary [93].

2.4.2 Related modelling works

The review of the modelling is focused on the solar photovoltaic (PV) related research works because PV panels has been chosen as local renewable energy generation to facilitate this research study.

A simulation model for predicting the performance of a solar photovoltaic (PV) system was developed by Sukamongkol et al. [94]. The aim of this simulation was to predict the performance of the PV system under specified load requirements (for alternating current (AC) electrical devices), and prevailing meteorological conditions at the site location. The authors claimed this model can be used for analysing the PV system performance and determine the most suitable size of the PV system to meet the load requirement at any location. However, the authors admitted further research to improve the model accuracy is necessary.

Khalil and Shaffie [95] have analysed twenty years (1990-2010) collected data of direct and diffuse solar irradiation incidents on a horizontal and an inclined surfaces in Cairo, to evaluate the validate various numbers of models previously developed by other researchers. The authors reported tests and statistical methods (e.g. t-test, Root Mean Square Error (RMSE), and Mean Percentage Error (MPE)) were employed to facilitate these model validation and assessment. They reported the values of correlation coefficients were higher than 0.95, and claimed a good agreement between measured and calculated values of the total solar radiation. Furthermore, the authors recommended the models of Hottel and Hoyt [96] , Skartveit et al.[97] , and Perez et al. [98] for the south-facing surface, and Hottel and Woertz [99] and Perez et al. [100] models for the west-facing surface to predict the solar radiation values.

C.K.Pandey and A.K.Katiyar [101] have investigated the variation of hourly global solar radiation for inclined surfaces, in order to improve the efficiency of the solar based energy generated systems by aligning these systems to the sun with optimised angle. The authors used collected data for horizontal and different inclined South-facing surfaces at Lucknow, Uttar Pradesh, India for supporting their research investigation.

The authors claimed that the isotropic model developed by Liu and Jordan [102] have provided better results over the models developed by Hay [103], Klucher [104] or circumsolar [105]. The authors also claimed that their analyses revealed the best results obtained from the isotropic model developed by Liu and Jordan model are estimating the solar radiation on a tilted surface. Although this research work has clear contributions to the application aspect of the solar panels, some of the presented results did raise the doubt of accuracy (i.e. figure 6 in the paper showed the global solar radiation on the horizontal surfaces are greater than on tilted surfaces which is odd and without clear explanation).

Khoo et al. [106] adopted three sky models (Liu and Jordan [102] , Klucher [105], and Perez et al. [98]) to estimate the tilted irradiance for different orientations and tilt angles in Singapore. The authors reported the modelled results were compared with measured values via irradiance sensors tilted at different angles. They concluded that model developed by Perez et al. gives the maximum annual tilted irradiation on the East-facing PV panels in Singapore. The authors reported their results as monthly irradiation variation, which is much useful for supporting daily investigation of solar irradiation; a vital requirement in devising strategy to tackle the intermittency supply issue of renewable energy from solar source.

The majority of these models are used to estimate the mean solar radiation values in daily and monthly, which is not suitable for predicting the solar radiation in hourly (or less than one hour) basis throughout the day. These models are developed for estimation of long-term solar radiation, which are useful for supporting the performance assessment of solar energy systems, facilitating the appropriate systems design and supporting capacity sizing and matching. Some of these models are established for specific locations and climatic conditions which limited their applicability or usefulness [107, 108]. Some of the models are established for predicting the solar radiation on a horizontal surface only, which are not suitable for most of the domestic set-up [109, 110]. All these previously established models are various degrees of limitations, which none of them is suitable for assisting the accurate prediction on the output of PV panel systems; installed at different tilted angles, in different locations and climate conditions in hourly basis throughout the day.

2.5 Summary

This chapter reviewed on the current State-Of-the-Art (SOA) systems and technologies in relating and/or addressing the temporal energy mismatch between renewable energy generation and consumption locally in the domestic environments.

Technology review on the domestic energy generation indicates the temporal energy mismatch between renewable energy generation and consumption locally in the domestic environments still largely exist. Due to various reasons, the current practice is selling the local generated surplus to the grid at a meagre price, which is not only unattractive to the householders but also inefficient due to transmission losses.

Technology review also shows that the current research efforts are largely concentrating on the improvements of the efficiency of the renewable energy generation systems and appliances in the domestic environments. Although significant research efforts have been conducted in advanced energy storage systems to tackle the temporal energy mismatch issue, they are focused on large scale installations such as solar and wind farms, and hydroelectric plants. Solving this problem by using storage system technologies (e.g. rechargeable batteries) in the domestic sector does not seem socio-economically viable due to their comparatively higher cost in capital investment, requires regular maintenance (or replacement) throughout the life-time of the renewable energy generation systems and significant impacts on the environments.

Research in smart domestic appliances proved networked domestic appliances can provide support to demand side management to lower the grid demand during its peak period. Furthermore, some research also showed the potential of using the domestic appliances such as refrigerators to buffer energy storage. Although these research works are not directly addressing the issue of temporal energy mismatch issue in the domestic environment, they did indicate their potential as part of the solution.

The literature review revealed there is lack of research efforts to provide a holistic view to investigate and tackle the temporal energy mismatch problem in the domestic environment.

3 Modelling of solar renewable energy generation system

As the research approach stated in Chapter one (section 1.3), simulation was adopted as the major vehicle to facilitate this research study. Hence, accurate and appropriate models are essential and a pre-requisite for this research study. This chapter reports the research on the development of a photovoltaic (PV) energy generation model.

Research has proved there is a direct proportionality between solar radiation and output of solar panel such as PV panels [111]. Furthermore, installations of PV panel systems in UK are commonly mounted onto a south-facing roof with an angle between 30^o and 50^o in order to receive maximum solar radiation (or sunlight). As the literature review in section 2.4 of chapter 2 has revealed the previous established solar radiation models do have various limitations; none found was suitable for assisting the development of solar based renewable energy generation system models that would apply in various conditions (i.e. PV panels installed at different tilted angles, in different locations and climate conditions in various time intervals throughout the day) and also encapsulate the characteristics of intermittency due to the renewable source (i.e. solar radiation). As a result, an advanced solar radiation model was developed for supporting this research study.

The PV power generation system model (PV-GSM) for this research study has adopted a component based approach, in which the PV-GSM is comprised of two major components (or sub-models); they are “Solar radiation prediction model” and “PV power output prediction model”.

The overview of the structure of this PV power generation system model is illustrated in figure 3.1.

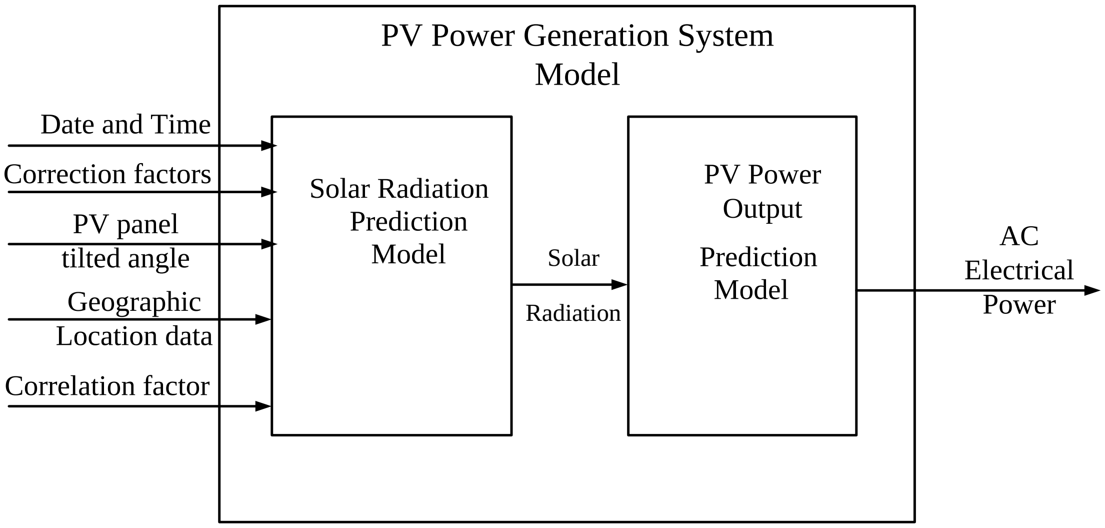

Figure 3.1 Overview of the structure of PV power generation system model

An experimental dataset was provided by the National Energy Research Centre Amman/Jordan to facilitate the modelling work of this research study. Half of this dataset was used to establish the PV output prediction model with the aid of the system identification tool box in the Matlab/Simulink environment. Another half of the dataset was used for supporting the validation of established solar radiation prediction and PV power generation system models.

3.1 Modelling and implementation of an advanced solar radiation model

This section describes the mathematical principles behind the model development. The solar radiation model was developed in Matlab/Simulink environment with the support of various toolboxes. Simulink is a graphical extension to Matlab environment for supporting modelling, simulating, and analysing dynamic systems, including controls, signal processing, communications and other complex systems. Matlab/Simulink has a comprehensive support of various customisable toolboxes, which providing natural support to realise the component-based modelling paradigm; a modelling approach which has been adopted in this research project.

The simulated results were compared with the measured results to validate the developed models.

3.1.1 Determination of the clear-sky solar radiation on a horizontal surface

It is well known the Earth goes around the sun in an elliptical orbit on the ecliptic plane annually. The Earth also spins once a day on its own central axis, the polar axis. This axis orbits around the sun, maintaining a constant angle of 23.45^{o} along the ecliptic plane [112].

The following section presents the mathematical model that would facilitate the determination of both hourly and daily solar radiation on a horizontal surface.

The normal incident solar radiation for any day of the year, ($\mathrm{G_{on}}$), is determined with the following equation [104, 113]:

$$G_{on} = G_{sc} * \left(1 + 0.033 * cos\left(\frac{2*\pi*n}{365}\right)\right) [W/m^2] \qquad 3.1$$

Where,

Gsc is a solar constant (1367 W / m^{2}hr) represents the amount of energy from the sun per unit time received on a unit area of surface perpendicular to the direction of propagation of the solar radiation at mean earth-sun distance outside the atmosphere [114] .

n represents the number of the day $(1 < n < 365)$, and is determined with the following formula

$n = M + i$ where i is the number of the day within the month and M represents the number of total days before the start of the month of the ith day, and it is given in table 3.1 [114].

Table 3.1 Number of total days before the starting month of the ith day

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
M	0	31	59	90	120	151	181	212	243	273	304	334

The extra-terrestrial solar radiation on a horizontal surface for the nth day of the year at any hour between sunrise and sunset (G_o) is determined with the following equation [114]:

$$G_o = G_{sc}\left(1 + 0.033\ cos\left(\frac{2\pi\ n}{365}\right)\right)(cos\phi\ cos\delta\ cos\omega + sin\phi\ sin\delta)\ [W/m^2] \qquad 3.2$$

Where,

ϕ represents latitude ($-90° \leq \phi \leq 90°$) which is the angular location north or south of the equator (north positive, and south negative).

δ represents declination ($-23.45° \leq \delta \leq 23.45°$), an angular position of the sun at solar noon with respect to the plane of the earth's equator (north positive, and south negative).

It is determined with the following equation [115]:

$$\delta = 23.45^{\circ} \, sin\left[\frac{2*\pi(n+284)}{365}\right] [degree] \qquad 3.3$$

ω represents the hour angle which is the angular displacement of the sun east or west of the local meridian due to rotation of the earth on its axis at $15°$ per hour (morning negative, afternoon positive). It is determined with the following equation [114]:

$$\omega = -(noon\ hour\ - solar\ hour) * 15°\ \ [degree] \qquad 3.4$$

The extra-terrestrial solar radiation on a horizontal surface **(** G_o **)** is determined with the following equation [114]:

$$G_o = G_{sc}\left(1 + 0.033\, cos\left(\frac{360\, n}{365}\right)\right) cos\theta_z\ \ [W/m^2] \qquad 3.5$$

Where,

θ_z is the zenith angle which is the angle between the vertical and the line to the sun (the angle of incidence of solar beam radiation on horizontal surface). For horizontal surfaces the zenith angle is determined with the following equation [96, 114]:

$$cos\theta_z = cos\phi\, cos\delta\, cos\omega + sin\phi\, sin\delta \qquad 3.6$$

The atmospheric transmittance of solar beam radiation τ_b is determined with the following equation [96]:

$$\tau_b = a_0 + a_1 exp\left(\frac{-k}{cos\theta_z}\right) \qquad 3.7$$

Where,

> a_0, a_1, and k are constants for standard atmosphere with 23 km visibility. They are found for altitudes less than 2.5 km [96] by:
>
> $a_0^* = 0.4237 - 0.00821(6 - A)^2$
>
> $a_1^* = 0.5055 + 0.00595(6.5 - A)^2$
>
> $k^* = 0.2711 + 0.01858(2.5 - A)^2$
>
> Where, A is the altitude in km.

To allow the changes in climate types, correction factors are applied to a_0^*, a_1^* and k^*. These correction factors are given in table 3.2[96].

Table 3.2 Correction factors for climate types

Climate Type	$r_0 = a_0/a_0^*$	$r_1 = a_1/a_1^*$	$r_k = k/k^*$
Tropical	0.95	0.98	1.02
Mid-latitude summer	0.97	0.99	1.02
Subarctic summer	0.99	0.99	1.01
Mid-latitude winter	1.03	1.01	1.00

The occurrence frequency of clear-sky and cloudy hours, and their distribution within a day are not easy to predict and forecasting details are required to be applicable. Furthermore, such details are varying from day to day throughout the year and still remain as a major research challenge to be addressed. For this reason the author did not take into account the cloudiness effect in this research study.

The clear-sky solar normal beam radiation is determined with the following equation [96]:

$$G_{cnb} = G_{on}\tau_b \, [W/m^2] \qquad 3.8$$

Where,

$$G_{on} = G_{sc}\left(1 + 0.033\cos\left(\frac{2*\pi*n}{365}\right)\right) \quad [W/m^2] \qquad 3.9$$

The clear-sky horizontal solar beam radiation is determined with the following equation:

$$G_{cb} = G_{on}\,\tau_b\,cos\theta_z\,\tau_b\ \ [W/m^2] \qquad 3.10$$

The hourly clear-sky horizontal solar beam radiation is determined with the following equation:

$$I_{cb} = I_{on}\,cos\theta_z\ [W/m^2] \qquad 3.11$$

The relationship between the transmission coefficients of solar beam and diffuse radiation for clear-sky horizontal solar radiation is determined with the following equation [116]:

$$\tau_d = \frac{G_d}{G_o} = 0.271 - 0.294\,\tau_b \qquad 3.12$$

Where,

G_d represents the diffuse solar radiation.

This relationship could be used to estimate the standard clear-day solar radiation on horizontal surface.

The clear- sky diffuse solar radiation on a horizontal surface is determined with the following equation [116]:

$$G_{cd} = G_o\,\tau_d = G_{on}\,cos\theta_z\,\tau_d\ [W/m^2] \qquad 3.13$$

The total solar radiation on a horizontal surface is the sum of the solar beam and diffuses solar radiations and is determined with the following equation [116]:

$$G_c = G_{cb} + G_{cd}\ \ [W/m^2] \qquad 3.14$$

The total solar radiation on a horizontal surface is determined with the following equation [116]:

$$I_c = I_{cb} + I_{cd}\ \ [W/m^2] \qquad 3.15$$

3.1.2 Determination of the total solar radiation on a tilted surface

The total solar radiation on a tilted surface can be obtained by two methods. The first method is to determine the total solar radiation on the tilted surface with measured data for the total solar radiation on the horizontal surface. The second method is based on mathematical modelling stated in Section 3.1.1.

3.1.2.1 Determination of the total solar radiation on a tilted surface with measured solar radiation on a horizontal surface

The total solar radiation on a tilted surface at slope β from the horizontal include three radiation components; solar beam, isotropic diffuse, and reflecting from the ground solar radiations [117].

- The solar beam radiation component is given by $I_b * R_b$

  R_b represents a geometric factor which representing as the ratio of solar beam radiation on a tilted surface and on a horizontal surface, this factor is determined with the following equation [118]:

$$R_b = \frac{I_{bt}}{I_b} = \frac{I_{bn} * cos\theta}{I_{bn} * cos\theta_z} = \frac{cos\theta}{cos\theta_z} \qquad 3.16$$

Where,

I_{bt} represents titled solar beam radiation $[W/m^2]$

I_b represents horizontal solar beam radiation $[W/m^2]$

I_{bn} represents normal solar beam radiation $[W/m^2]$

θ represents an angle of incidence which is the angle between the solar beam radiation on a surface and normal to that surface, and it is determined with the following equation[118]:

$$cos\,\theta = sin\,\delta\,sin\,\phi\,cos\,\beta - sin\,\delta\,cos\,\phi\,sin\,\beta\,cos\,\gamma + cos\,\delta\,cos\,\phi\,cos\,\beta\,cos\,\omega + cos\,\delta\,sin\,\phi\,sin\,\beta\,cos\,\gamma\,cos\,\omega + cos\,\delta\,sin\,\beta\,sin\,\gamma\,sin\,\omega \qquad 3.17$$

Figure 3.2 illustrates the Zenith, slope, surface azimuth, and incidence angles for a tilted surface.

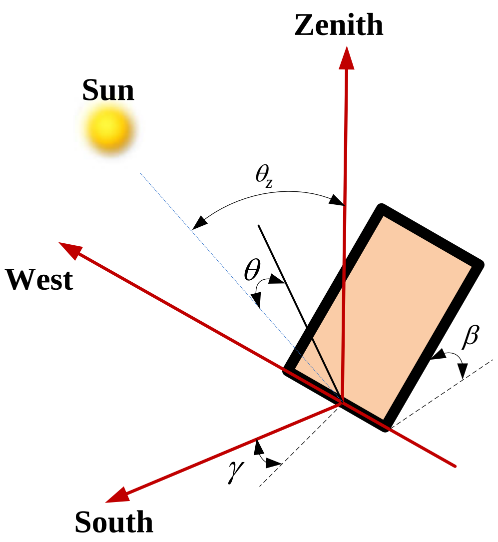

Figure 3.2 Zenith, slope, surface azimuth, and incidence angles for tilted surface

Notes:

The equation is only valid when the sun is not behind the surface (the hour angle $[\omega]$ is between sunrise and sunset).

- When angle $\theta > 90°$, the sun is situated behind the surface.

β represents the slope (tilted angle), $(0° \leq \beta \leq 180°)$, which is the angle between the plane of the surface in question and the horizontal surface [118].

γ is the surface azimuth angle**,** $(-180° \leq \gamma \leq 180°)$ which is the deviation of the projection on horizontal plane of the normal to the surface from the local meridian, east negative, and west positive.

If $(\beta > 90°)$, the surface has a downward-facing component (i.e. solar irradiance that is reflected off the earth's surface [118]).

The surfaces with slope β to the north or south have the same angular relationship to solar beam radiation as a horizontal surface at an artificial latitude of $(\phi - \beta)$.

- In the northern hemisphere the incidence angle is determined with the following equation [118]:

$$cos\theta = cos(\phi - \beta)\ cos\delta\ cos\omega + sin(\phi - \beta)\ sin\delta$$

$$R_b = \frac{cos(\phi-\beta)\ cos\delta\ cos\omega+sin(\phi-\beta)\ sin\delta}{cos\phi\ cos\delta\ cos\omega+sin\ \phi\ sin\delta} \quad 3.18$$

For the southern hemisphere the incidence angle is determined with the following equation [118]:

$$cos\theta = cos(\phi + \beta)\ cos\delta\ cos\omega + sin(\phi + \beta)\ sin\delta \quad 3.19$$

$$R_b = \frac{cos(\phi+\beta)\ cos\delta\ cos\omega+sin(\phi+\beta)\ sin\delta}{cos\phi\ cos\delta\ cos\omega+sin\ \phi\ sin\delta} \quad 3.20$$

Note

Determine the ratio R_b with the equations above might obtain some extraneous results in some conditions (e.g. Negative, less than 1, or high values). Such obtained results should be discarded [118].

- The isotropic diffuse solar radiation component is determined with the following equation: $I_d * F_{c-s} = I_d * \left(\frac{1+cos(\beta)}{2}\right)\ [W/m^2]$

Where F_{C-S} represents the view factor to the sky which equal to $\left(\frac{1+cos(\beta)}{2}\right)$

I_d is the diffuse solar radiation component of the total solar radiation on the horizontal surface and is determine with the following equation:

$$I_d = I * COR\ [W/m^2] \quad 3.21$$

The solar beam radiation I_b is determined with the following equation:

$$I_b = I * (1 - COR) \quad 3.22$$

The total solar radiation on a horizontal surface consists of two components; diffuse solar radiation and beam solar radiation. COR is the correlation factor represents the fraction of total solar radiation on a horizontal surface. In other words COR is used to determine the values of each components of the total solar radiation on a horizontal surface (diffuse and beam solar radiation components). This correlation factor depends on the hourly clearness index K_T [99].

The hourly clearness index K_T represents the ratio of solar radiation in a particular hour on a horizontal surface and the total horizontal solar radiation in the same hour.

It is determined with the following expression [118]:

$$k_T = \frac{I}{I_o} \tag{3.23}$$

The value of I_o is determined with the following equation for the period between two hourly angles ω_1 and ω_2 ($\omega_2 > \omega_1$) [118]:

$$I_o = \frac{12*3600*G_{SC}}{\pi} * \left(1 + 0.033 * cos\left(\frac{2*\pi*n}{365}\right)\right) * \left(\cos(\phi) * \cos(\delta) * \sin(\omega_2 - \omega_1) + \frac{\pi*(\omega_2-\omega_1)}{180} * \sin(\phi) * \sin(\delta)\right) \; [W/m^2] \tag{3.24}$$

The values of cleanness index are divided in ranges, and the correlation factor is determined according to these ranges as below [119]:

$$COR = \begin{cases} 1 - 0.09\, k_T & \text{for } k_T \leq 0.22 \\ 0.9511 - 0.1604\, k_T + 4.388\, k_T^2 - 16.638\, k_T^3 + 12.336\, k_T^4 & \text{for } 0.22 < k_T \leq 0.8 \\ 0.165 & \text{for } k_T > 0.8 \end{cases}$$

- The solar radiation reflecting from the ground component is determined with the following equation

$$I * \rho_g * F_{C-g} = I * \rho_g \left(\frac{1-cos(\beta)}{2}\right) \; [W/m^2] \tag{3.25}$$

Where,

F_{c-g} represents the view factor to the ground which equal is $\left(\frac{1-cos(\beta)}{2}\right)$

ρ_g represents the diffuse reflectance.

The total solar radiation is equal to the solar beam radiation component plus the isotropic diffuse solar radiation component plus the solar radiation component reflecting from the ground.

It is determined with the following equation [117]:

$$I_T = I_b * R_b + I_d * \left(\frac{1+cos(\beta)}{2}\right) + I * \rho_g \left(\frac{1-cos(\beta)}{2}\right)\ [W/m^2] \qquad 3.26$$

3.1.2.2 Determination of the total solar radiation on a tilted surface with the theoretical value of the total solar radiation on a horizontal surface

The theoretical value of the total solar radiation on a horizontal surface is determined as explained in Section 3.1.1, and then applied in the established equation 3.26 described in Section 3.1.2.1 to determine the theoretical value of the total solar radiation on a tilted surface.

3.1.3 An advanced solar radiation model

Armed with the understanding of the mathematical principles stated in sections 3.1.1 and 3.12, an advanced solar radiation model has been implemented within the Matlab/Simulink environment, which can simulate and determine the solar radiation in a wide variety of conditions (i.e. the received solar radiation plane in different tilted angles, different locations and climate conditions in various time intervals throughout the day).

The implemented model is illustrated in figure 3.3 and details are shown in appendix A.

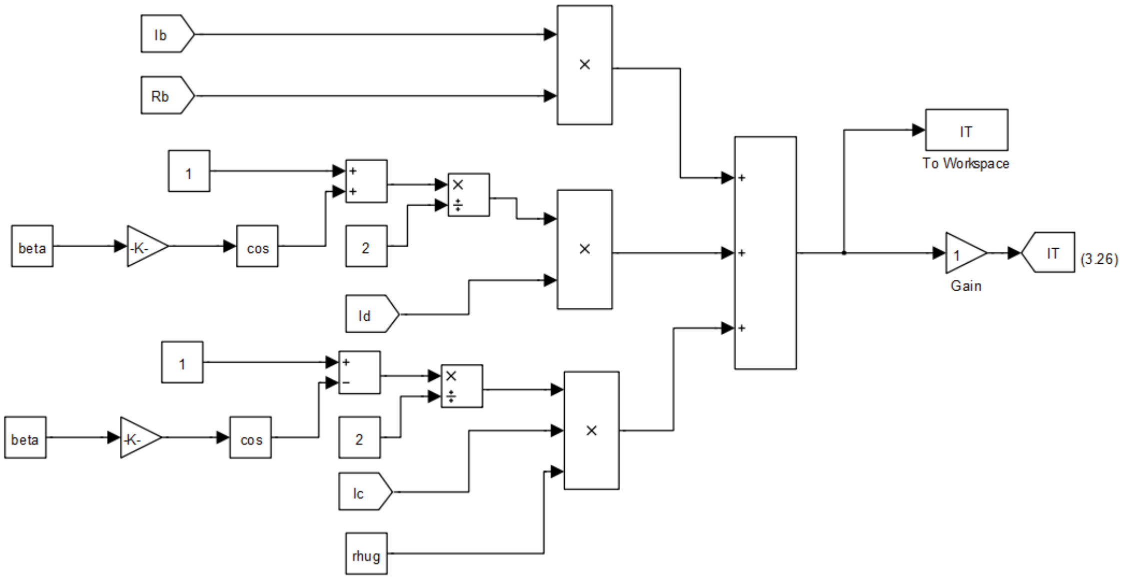

Figure 3.3 Solar radiation prediction model structure

The implemented solar radiation model is tested and validated with the measured data kindly provided by National Energy Research Centre/Jordan (NERC/J). This dataset represent the real data collected in a PV power station located in Amman/Jordan (32^o latitude, 35^o longitude, and 800m Altitude). The provided measured dataset was recorded in 10 minutes interval throughout 2010.

Some results of the developed model are illustrated in figure 3.4

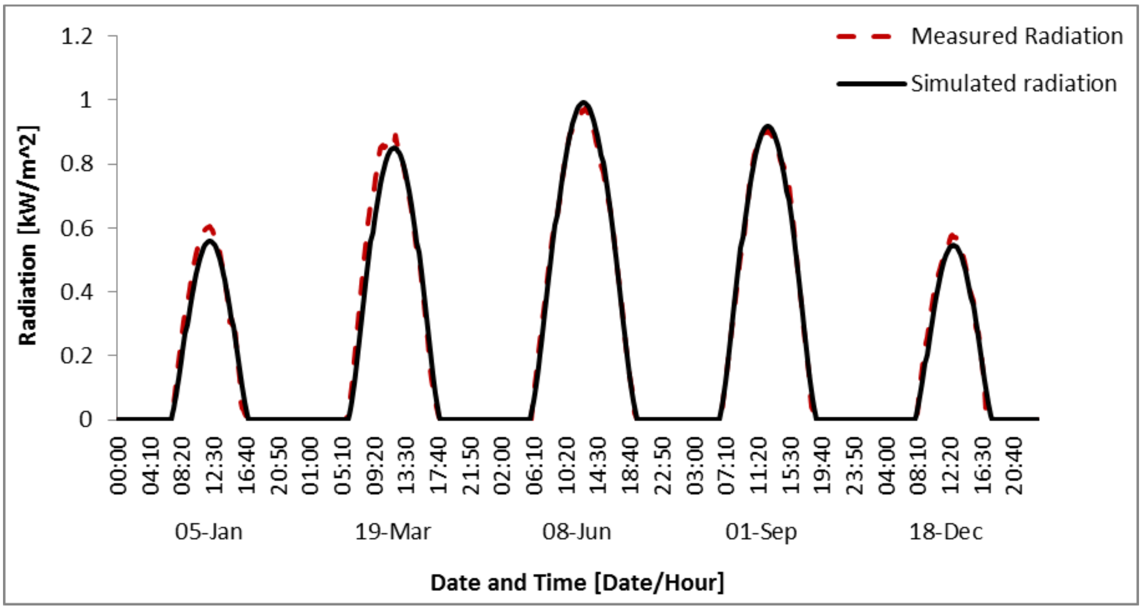

Figure 3.4 Measured and simulated solar radiation

The correlation analysis was adopted to verify the solar radiation prediction model by correlating the simulated outputs with corresponding measured values. The measured and the simulated value have further evaluated with the correlation data analysis and the results are illustrated in table 3.4.

Table 3.4 Correlation results of the measured and simulated solar radiation

	Measured solar radiation	*Theoretical solar radiation*
Measured solar radiation	1	0.99
Theoretical solar radiation	0.99	1

The correlation value in the table indicates the developed solar radiation prediction model has a high degree of accuracy because the correlation coefficient has the value of 0.99.

System identification modelling technique, a black box approach, was adopted in this research study to develop the PV power output prediction model. The required input-output dataset is kindly provided by National Energy Research Centre/Jordan (NERC/J). This dataset represent the real data collected in a PV power station located in Amman/Jordan (32^{o} latitude, 35^{o} longitude, and 800m Altitude), which has installed 1600 PV panels (NU-S0E3E, Sharp [120]). Each of these panels has a nominal peak power at 180 Wp . The developed model models one of these installed PV panels.

The PV output power prediction model is developed within the Matlab/Simulink environment with the aid of System Identification toolbox. Nonlinear Hammerstein-Wiener (nlhw) model with input-output nonlinearities such as saturation and dead zone was chosen for supporting the model development. The basic model structure of nlhw is illustrated in figure 3.5.

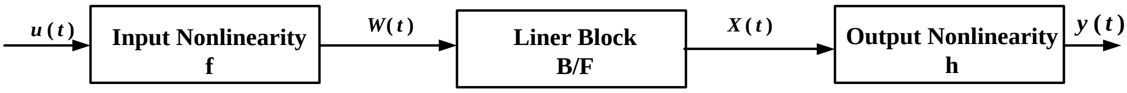

Figure 3.5 Nonlinear Hammerstein-Wiener model structure

Nonlinear Hammerstein-Wiener model computes the output value of the PV panel output power ($y(t)$) with solar radiation input data ($u(t)$) in three steps:

- Compute the value of $W(t)$ which is a static function, where the value of the output at a given time (t) depends only on the input value at time (t).
- Computes the output of the linear block using $W(t)$ and initial set conditions: $X(t) = (B/F)W(t)$.
  Where $B/$F is a linear transfer function, for ny outputs and nu inputs, the linear block is a transfer function matrix containing entries:
  $$\frac{B_{ji}(q)}{F_{ji}(q)}$$
  Where $j = 1,2,\ldots,ny \; and \; i = 1,2,\ldots,nu$
- Compute the model output by transforming the output of the linear block $X(t)$ using the nonlinear function h: $y(t) = h(X(t))$.

The linear block structure could be configured by specifying different input and output non linearity estimators, and a different number of units (break-points).

The identification model structure is illustrated in figure 3.6.

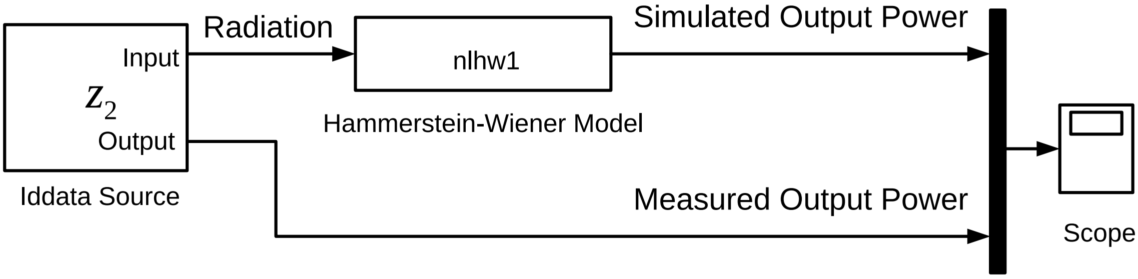

Figure 3.6 Identification model structure

The model was established with 1000 samples from the dataset provided by NERC/J, and other 1662 samples were employed as validation data. Sigmoid network function with 10 units was used as an input and output nonlinearity estimator. The linear transfer function corresponding were to the order of nb =1, nf =1, nk =1. The developed model delivered 70.72% fit to estimated dataset, and 73.78% fit to the validation dataset. Although the model fitness is not high due to issue of the available dataset[1], it does give a good approximation of the trends.

---

[1] There are data gaps existed in the dataset due to the way of the PV system was operated in NERC/J. The PV system was shut down when there was no demand on energy consumption even there were plenty of sunlights (i.e. high in solar radiation). Data gaps (or deadzone) were existed because there are no corresponding power output to the measured solar radiation under those situations.

Some results of the developed PV power output prediction model are illustrated in figure 3.7.

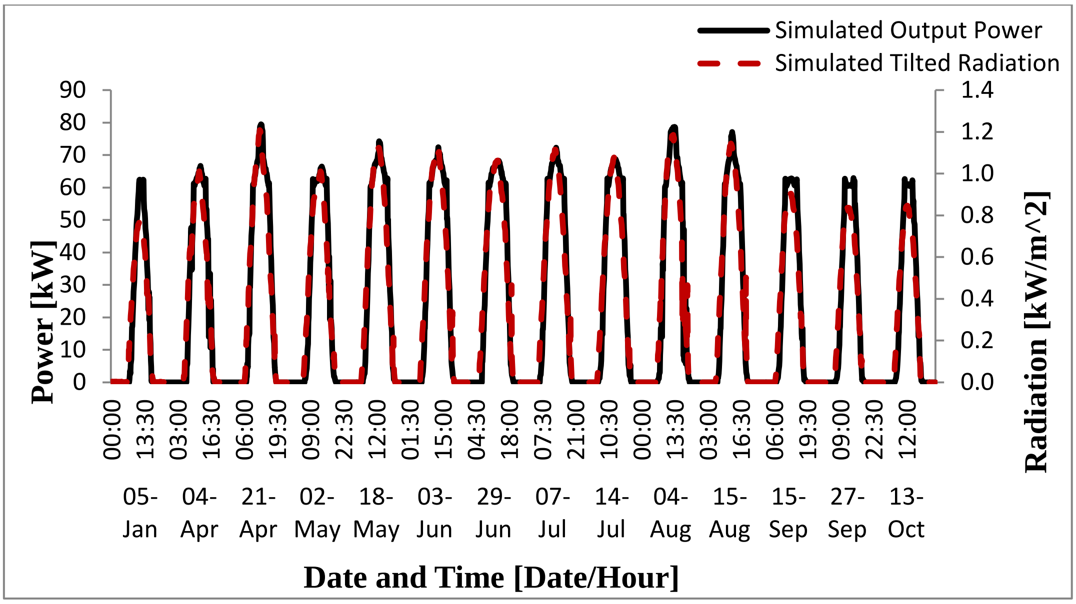

Figure 3.7 Simulated solar radiation and the simulated PV power output for different days

3.2 PV power generation system model

The PV power generation system model is constructed with the models developed in Sections 3.1.3 and 3.2. This top level of the developed Simulink model is illustrated in figure 3.8. For details of the developed Simulink model please refer to appendix A.

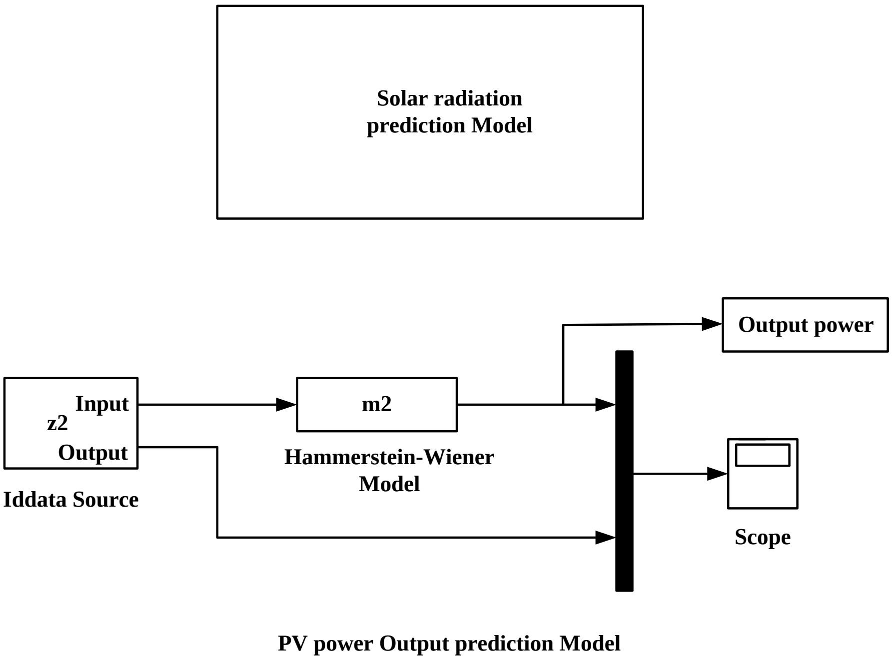

Figure 3.8 PV power generation system model

The measured and simulated output power of PV power generation system model is illustrated in figure 3.9

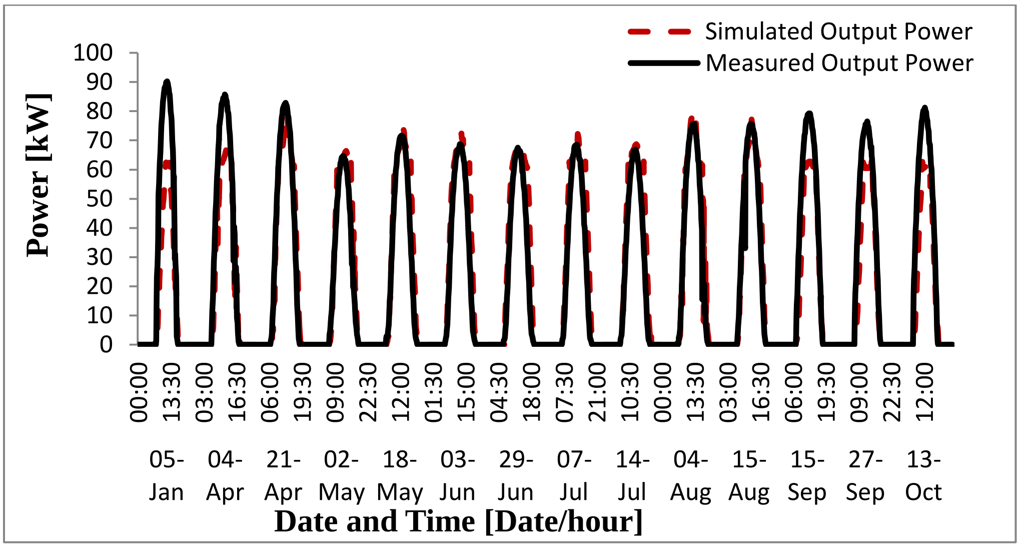

Figure 3.9 Comparison between Measured and simulated Power Output

In figure 3.9 the measured output power of the PV panels exceeded the simulated output power (e.g. 05-Jan) which is due to the hourly clearness index K_T value as the cloudy conditions have not been taken into account in the model.

The measured and simulated output power of PV power generation system model is further evaluated with the correlation data analysis and the results are illustrated in table 3.5.

Table 3.5 Correlation results of the measured and simulated output power of PV power generation system model

	Simulated output power	Measured output power
Simulated output power	1	0.96
Measured output power	0.96	1

The correlation evaluation results of the model shows a very good correlation between the measured and the simulated data (The correlation coefficient$X_C = 0.96$).

3.3 Summary

This chapter reports the research works on the development of PV a power generation system model, which comprised both a solar radiation prediction model and a PV power output model. These models are implemented as Simulink models, which run in a Matlab/Simulink environment. These models have been tested and evaluated against the measured data, which was provided by the National Energy Research Centre Amman/Jordan. The established PV power generation system model has the ability to predict the output power of a PV panels installed at any place with different orientations (solar radiation facing, and tilted angle) at any period of time throughout the whole year. This developed Simulink model in conjunction with domestic energy consumption Simulink model will be used to form a Domestic Energy Ecosystem Model for supporting these research studies.

4 Investigation of the potentials for supporting temporal energy consumption matching to the local renewable energy generation

Collecting detailed domestic energy consumption data is an essential process for any throughout investigation of domestic energy consumption profile, however, such data collection is complex to organise and expensive to carry out; not mentioning such research study demands large dataset (i.e. hundreds of homes if not thousands) to iron out the potential data anomaly/discrepancy and/or variable factors such as household types, numbers of householders and seasonal effects etc. Due to the time and resources constraints, detailed study on the domestic energy consumption profile is not part of the scope of this research study.

As this research studies is addressing the temporal energy mismatch issue between renewable energy generation and consumption locally in the domestic environments, taking into account the carbon emission reduction targets, the role of natural gas as an energy source for space and water heating will not be considered although it is a popular source of energy in the UK domestic environment.

Although this research study is not focusing on the understanding of the detailed energy consumption profile for the domestic environments in the UK, the understanding of the general electricity consumption daily profile in the domestic environment is a pre-requisite for this research study. The author not only gained his understanding through the literature review, but also fortunately gained the access of a collected domestic energy consumption dataset from the research project named, “Holistic framework & tools for sustainable energy efficiency in networked home appliances (DEMS)” [21] funded by TSB/EPSRC. Unlike other research publications only reporting their findings with the support of the secondary data, this collected raw dataset provides an opportunity for the author to conduct his own assessment on the potentials for supporting temporal energy consumption matching to the local renewable energy generation in the domestic environment.

This chapter presents the investigation results of the potentials for supporting temporal energy consumption matching to the local renewable energy generation in the domestic environment. Modelling works on the identified potentials (i.e. domestic appliances and systems) also reported.

The models established in this chapter will be aggregated with the developed models in chapter three to form a domestic electricity energy ecosystem model, which will be used to facilitate the subsequent research investigation and studies in devising control strategies to tackle the temporal energy mismatch between the local renewable energy generation and local energy consumption in the domestic environment.

4.1 Investigation of electricity consumption profile in domestic environment

Other than plotting graphs after graphs which based on the DEMS dataset, the author only presented few graphs relating to the concepts ("shift time of use" and "energy buffering"), which have the potential to create solutions to overcome the temporal energy mismatch between local renewable energy generation and local energy consumption in the domestic environment.

Two daily electricity consumption profiles (one in summer and one in winter) of a three-bedroom semi-detached house, with two adults are illustrated in Figures 4.1 and 4.2. This house has installed and run with an economy 7 tariff scheme. The consumption data was extracted from the DEMS dataset.

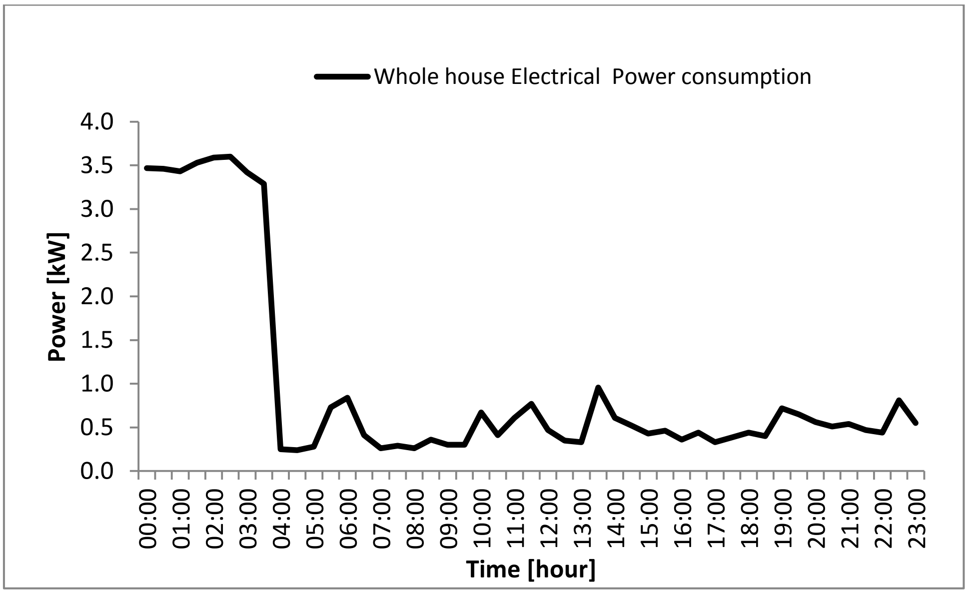

Figure 4.1Whole house electrical power consumption in summer time (data source: DEMS)

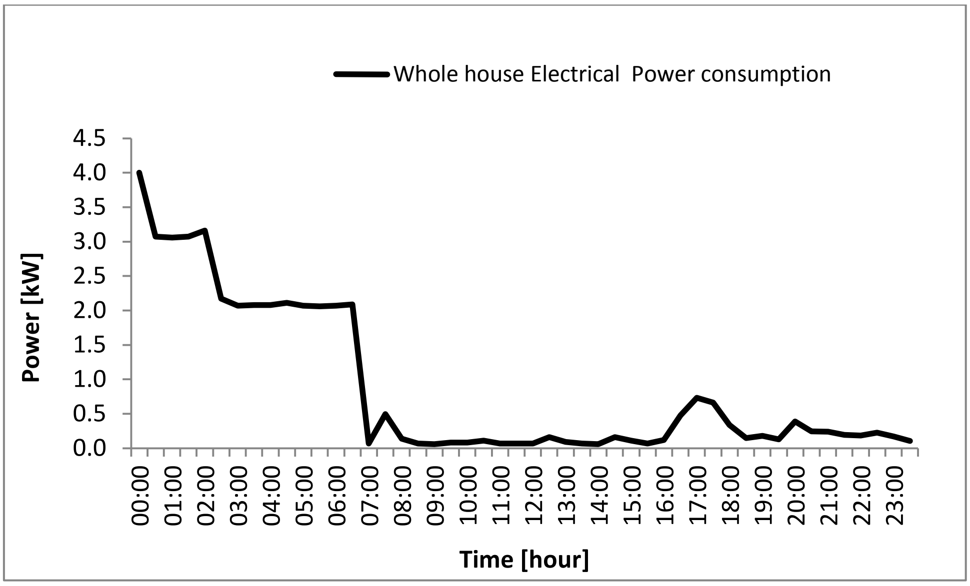

Figure 4.2 Whole house electrical power consumption in winter time (data source: DEMS)

The consumption profiles indicated significant amount of electricity is consumed during the low tariff (i.e. between midnight to 7:00 am) period. According to the data, it was consumed by storage heating system and hot water tank. Although these two consumption profiles do not reveal too much detailed information on the domestic energy consumption, it reveals the energy consumption of the systems/appliances could be scheduled; albeit the scheduling strategy is fairly simple because the economy 7 tariff scheme is fairly static.

Unlike economy 7 tariff scheme, the time and amount of energy supply from the local renewable sources are comparatively dynamic, the energy consumption scheduling scheme demands better support from the domestic electrical appliances to realise the implementation of the adopted concepts.

The domestic appliances which are able to provide support of dynamic scheduling of energy consumption must possess one or both of the characteristics presented in sections 4.1.1 and 4.1.2.

4.1.1 Potential domestic appliances for shift time of use

The domestic electrical appliances, which allow shifting their time of use, must be time insensitive in providing their services to the householders. Most importantly, no impact on the quality of living to the householders is paramount to gain their acceptance.

Through the literature review and looking into the DEMS dataset, the domestic appliances which are able to support the "shift time of use" are described in the following sub-sections.

4.1.1.1 Washing machine

This domestic appliance can be operated at any time during the day without affecting the resident comfort. The nominal power of this appliance used in DEMS project is 2.5 kW, the average running time for each washing cycle is between 110 and 125 minutes depending on the chosen wash programme; its average energy consumption for each cycle is between 0.3 and 0.4 kWh depending on both wash programme and hot water setting temperature. The energy consumed for this domestic appliance could be shifted to the period of time when the renewable generated power is available.

Figure 4.3 illustrates the energy demand profile of one washing cycle of a washing machine installed in the DEMS project.

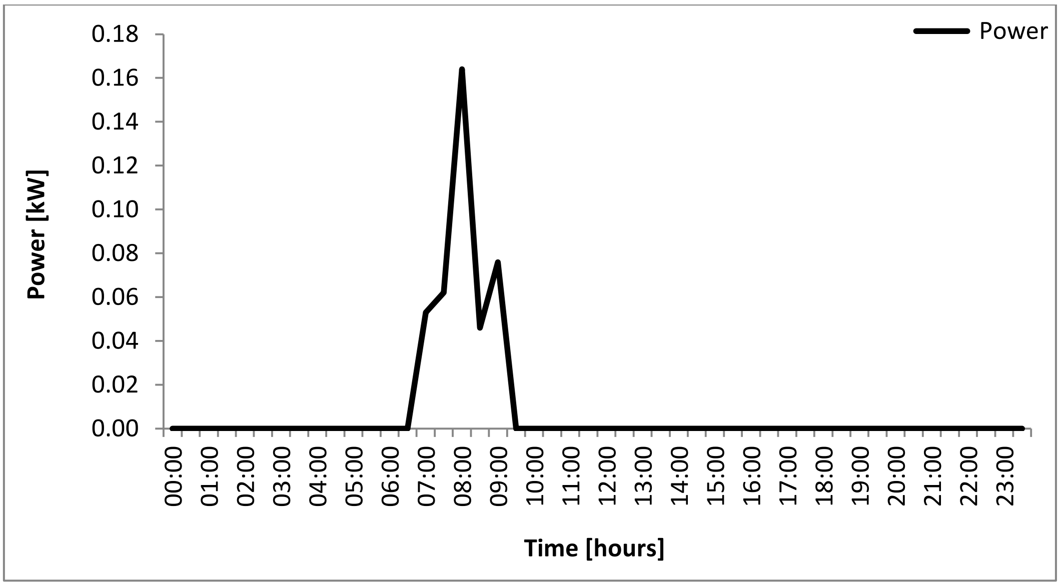

Figure 4.3Energy demand profile of one washing cycle of a washing machine (data source: DEMS)

4.1.1.2 Dishwasher

This domestic appliance can be operated at any time during the day without affecting the resident comfort. The nominal power of this appliance used in DEMS project is 2.5 kW, the average running time for this appliance is between 110 and 150 minutes depending on the chosen wash programme; its average energy consumption for each wash is between 0.26 and 0.32 kWh depending both wash programme and hot water setting temperature. The energy consumed for this domestic appliance could be shifted to the period of time when the renewable generated power is available.

Figure 4.4 illustrates the energy demand profile of one washing cycle of a dish washer installed in the DEMS project.

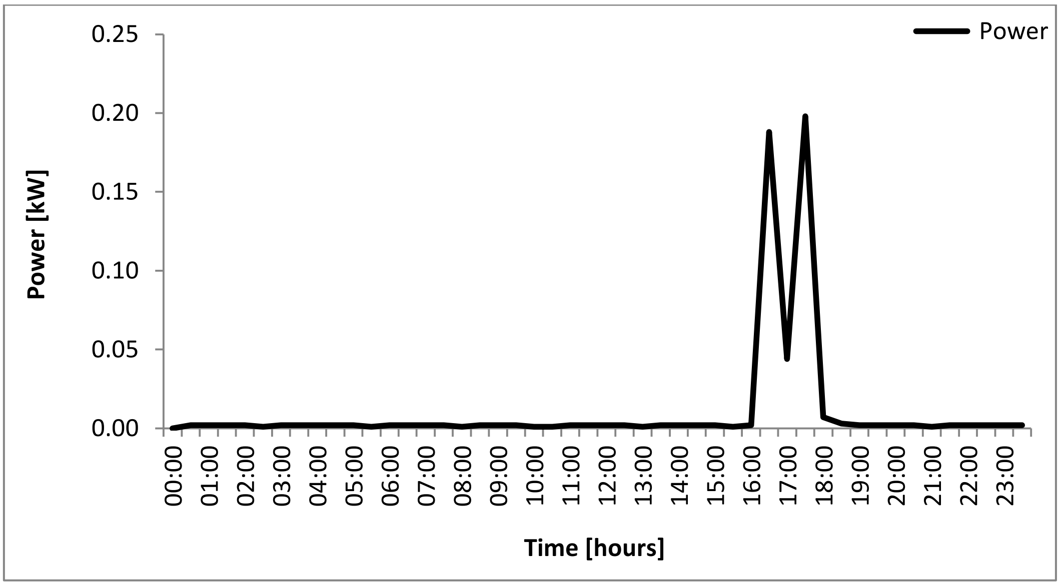

Figure 4.4 Energy demand profile of one washing cycle of dish washer (data source: DEMS)

4.1.1.3 Fridge-freezer or standalone refrigerator and freezer

This domestic appliance is running 24/7 throughout the year. Although the energy consumed for its normal service (keep cool and cold) cannot be interrupted, one of its vital auxiliary function (i.e. defrost cycle) can be shifted, without impairing its performance and efficiency. The defrost cycle for the fridge-freezer used in DEMS with average duration between 158 and 190 minutes depends on various conditions such as the ambient temperature and the food content. The average energy consumption for the defrost cycle is between 0.19 to 0.25 kWh.

Figures 4.5 and 4.6 illustrate the energy consumption profile of the fridge/freezer in winter and summer times respectively. These figures have clearly shown the energy consumption in the summer season is much higher than the winter season.

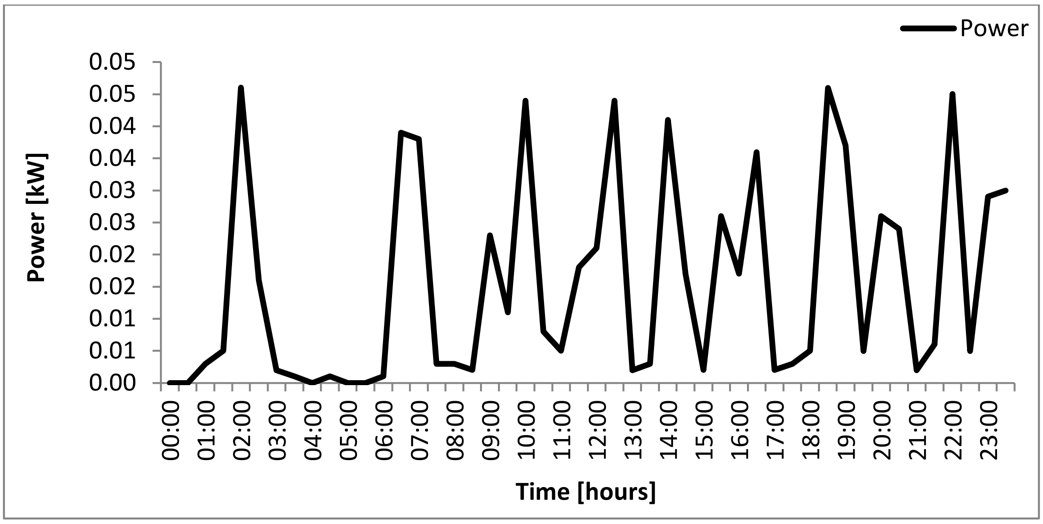

Figure 4.5 Daily energy consumption profile in winter time (data source: DEMS)

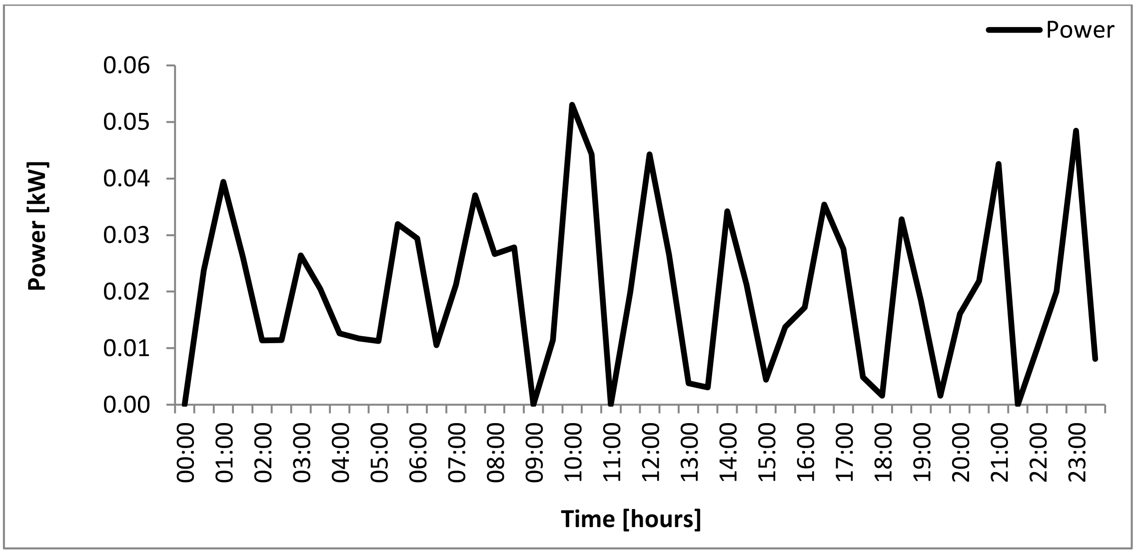

Figure 4.6 Daily energy consumption profile in summer time (data source: DEMS)

4.1.2 Potential appliances for energy buffering

The domestic electrical appliances, which are able to buffer energy anytime for another period of use without impairing their quality of services to the householders are in the following sub-sections:

4.1.2.1 Electrical hot water systems with integrated hot water tank

The electrical hot water systems with an integrated hot water tank can buffer energy and its working principle is same as operating under economy 7 tariff scheme (only operate in low tariff period), except the time of energy supply from the local renewable energy system is dynamic rather than fixed. The storing capacity depends on the size of hot water tank, the temperature state at the time (i.e. temperature before the electrical heater is turned on) and the temperature set point (common temperature set point is 60℃).

Figure 4.7 illustrates the daily energy consumption profile of an electrical water system with integrated hot water tank, under an economy 7 tariff scheme.

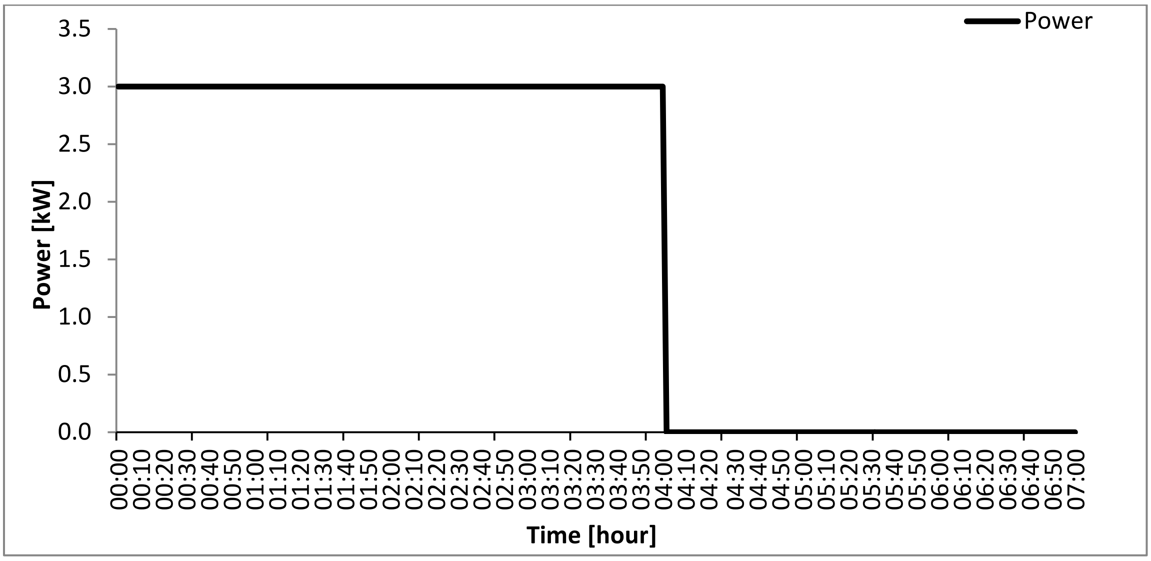

Figure 4.7 Daily energy consumption profile of an electrical water system with integrated hot water tank (data source: DEMS)

4.1.2.2 Electrical storage heating systems

The electrical storage heating system can buffer energy and its working principle is same as operating under economy 7 tariff scheme (only operate in low tariff period), except the time of energy supply from local renewable energy system is dynamic rather than fixed. The electrical storage heating system installed in one of the DEMS trail homes (i.e. 3 bedrooms semi-detached with 2 adults and 3 teenagers) has 17 kWh in total capacity.

The relationship between the power of the smart storage electrical heater and charging time is illustrated in figure 4.8.

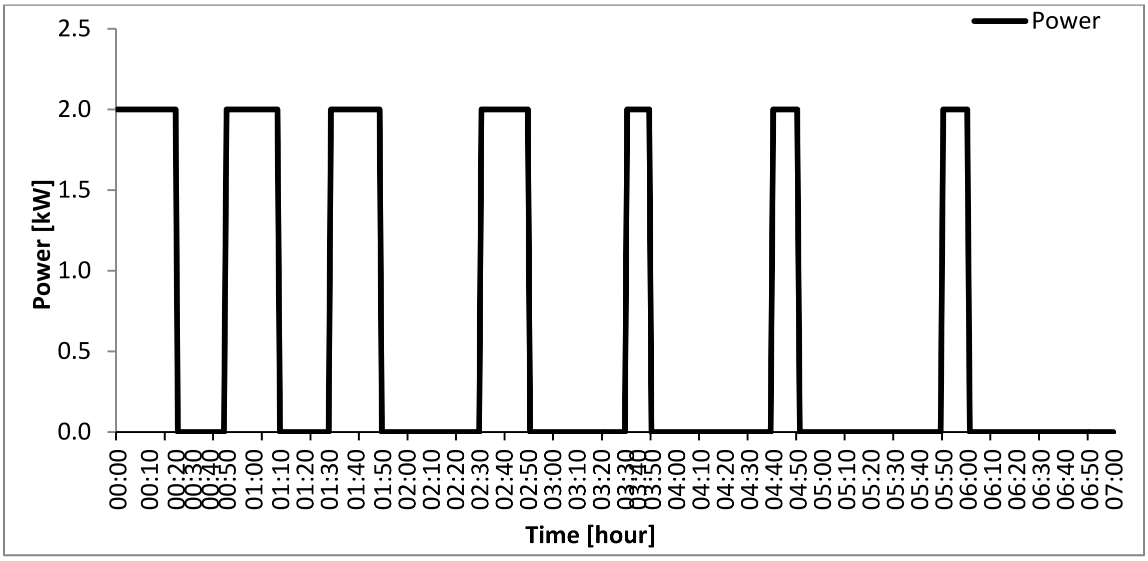

Figure 4.8 Daily energy consumption profile of an electrical storage heating system with integrated hot water tank (data source: DEMS)

4.1.2.3 Fridge-freezer or standalone refrigerator and freezer

Although this appliance is not designed for energy buffering, it could buffer energy by changing its set parameters. The nominal power of this smart appliance depends on its size and the fridge-freezer used in DEMS is approximately 0.1 kW when the compressor is on and approximately 3W when the compressor is off. The average compressor running cycle is between 69 and 82 minutes and its average energy consumption per compressor cycle between 0.115 and 0.137 kWh depending on the various conditions such as ambient temperature (e.g. energy consumption in summer is higher than winter).

Phase change material heat storage technologies could be applied for the design of next generation of smart fridge freezer. Such next generation smart fridge-freezers could be attached (or built-in) with compartment contains phase change material such as water. The water in the compartment could be transformed to ice when the surplus PV generated power is available; the ice will maintain the temperature of the normal compartments of fridge-freezer for a period of time without consuming energy from the grid through its ‘melting’ process (i.e. transforming back to liquid through heat absorbed in the normal compartments of fridge-freezer).

4.1.3 Essential requirements of smart domestic appliances

In principle, the identified electrical domestic appliances in sections 4.1.1 and 4.1.2 can provide the required support (i.e. "shift time of use" and "energy buffering") to realise the proposed control strategy in tackling the temporal energy mismatch between the local renewable energy generation and local energy consumption in the domestic environment. However, the current generation of these identified domestic appliances are lacking some of the vital functions which are required for supporting the realisation of proposed temporal energy mismatch control strategy. The essential 'smart' requirements which enable the domestic appliances to partake of the proposed temporal energy mismatch control strategy are listed below:

- Digital communication is a 'MUST' to enable the domestic appliances to partake of the local domestic appliances control network.
- The time of operation of the smart domestic appliances should allow setting, modifying and controlling in 'real-time' via the local domestic appliances control network.
- Depending on the types of appliances, relevant operational parameters should allow setting and modifying in 'real-time' via the local domestic appliances control network.

4.2 Modelling of smart domestic appliances

Among all the identified domestic appliances, only the fridge-freezer provids the support of energy buffering via this innovative operating scheme, unlike other appliances such as electrical storage heating system. Due to this reason, the author has developed a sophisticated fridge-freezer model to facilitate further investigation on the energy consumption behaviours under different operating schemes. Other identified appliances models are well established and their energy consumption behaviours also well understood. Due to this reason, the author will adopt the models developed by other researchers for these identified domestic appliances that would support "shift time of use" and "energy buffering" to further develop the domestic electricity energy ecosystem model, which is the major tool to facilitate the simulation studies reported in chapter five.

4.2.1 Smart refrigeration (fridge-freezer) system

The fridge-freezer is one of the 24/7 working domestic appliances and contributes to the base load of domestic energy consumption. This appliance has the ability to buffer the electrical energy for some time by changing the fridge and/or freezer temperature set-points by one or two degrees without affecting its performance or the food content within the cool/cold compartments of the fridge-freezer. In addition, the defrost process of these smart appliances could be controlled to operate in anytime during the day (i.e. shift time of use). This type of appliance is unique in the domestic environment because it is the only appliance could support both “shift time of use” and “energy buffering”.

The parameters that would affect the electrical energy consumption and the time of operation of the smart fridge-freezer was investigated to gain better understanding of the performance of these appliances. A model for this purpose is established with the aid of Matllab/Simulink and thermolib toolbox (Appendix B).

The established fridge-freezer model has served two purposes

- To facilitate the investigation of relationships between various operating parameters such as temperature set-point(s) and the energy consumption. This is vital for the understanding of its capability in energy buffering. It was also employed to study the effect on the energy consumption with dynamic scheduling of defrost process.
- Be part of the domestic energy ecosystem to facilitate the test and validation of the proposed temporal energy mismatch control strategies.

4.2.1.1 Model structure

IDEF$_0$ modelling methodology was adopted to conduct the system analysis process (i.e. break the system into various sub-components). During this analysis process, the main functional components of the refrigeration system will be identified, and their interrelationships will be modelled. Modelling details of the refrigeration system using IDEF0 technique is given in appendix C.

Figure 4.9 illustrates the 2nd level of refrigeration system model using the IDEF$_0$ modelling methodology.

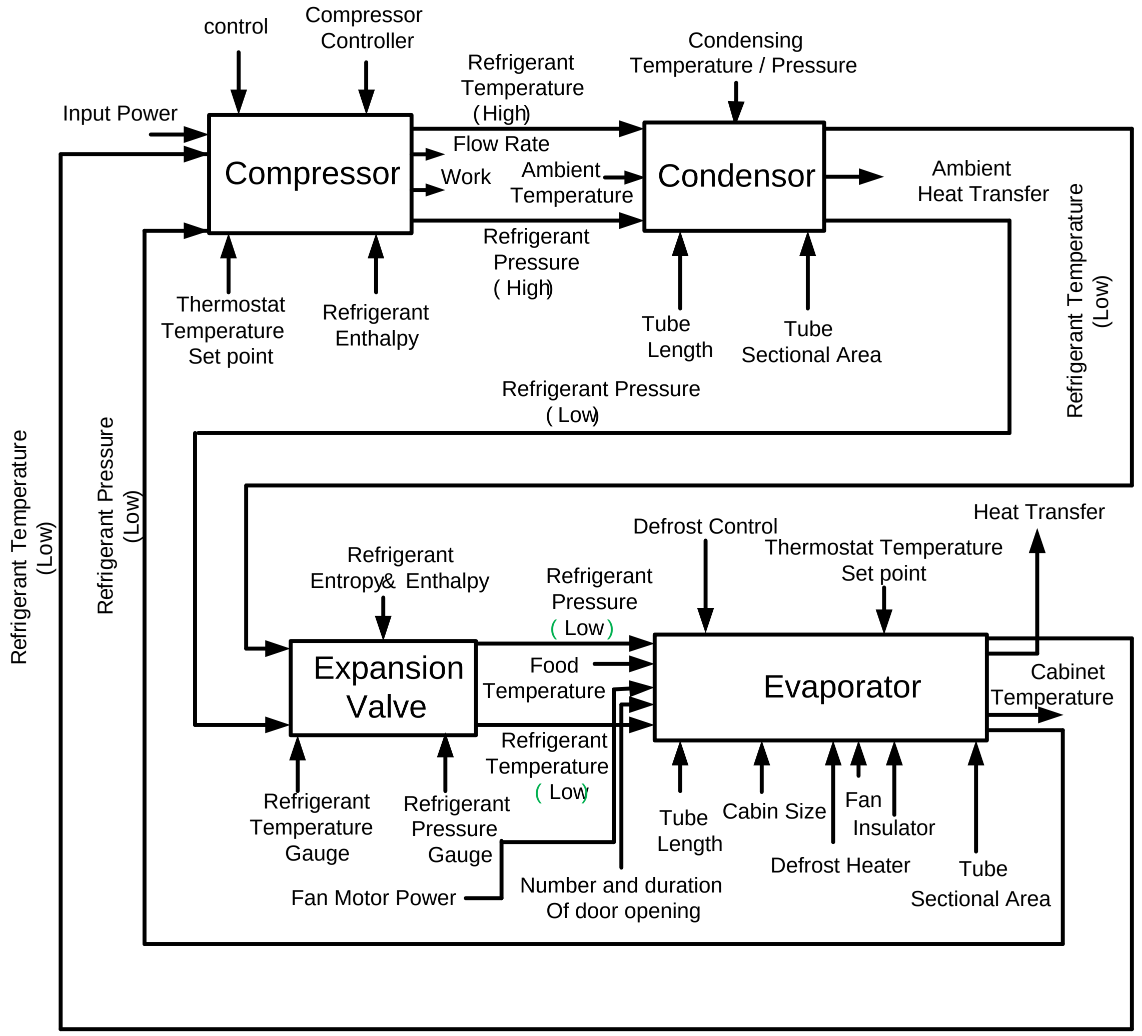

Figure 4.9 2nd level IDEF$_0$ model of the refrigeration system

The IDEF functional modelling approach was adopted to identify the key components of the refrigeration system (e.g. compressor, condenser, expansion valve, and evaporator) through functional decomposition. This approach also helps to model the interrelationships between the identified components, the control parameters of the identified components and their required mechanisms for supporting the realisation of the individual component. Details of applying this modelling approach in the refrigeration system can be found in appendix C.

Figure 4.10 illustrates the top level of implemented model in the Matlab/Simulink environment and the details can be found in appendix B.

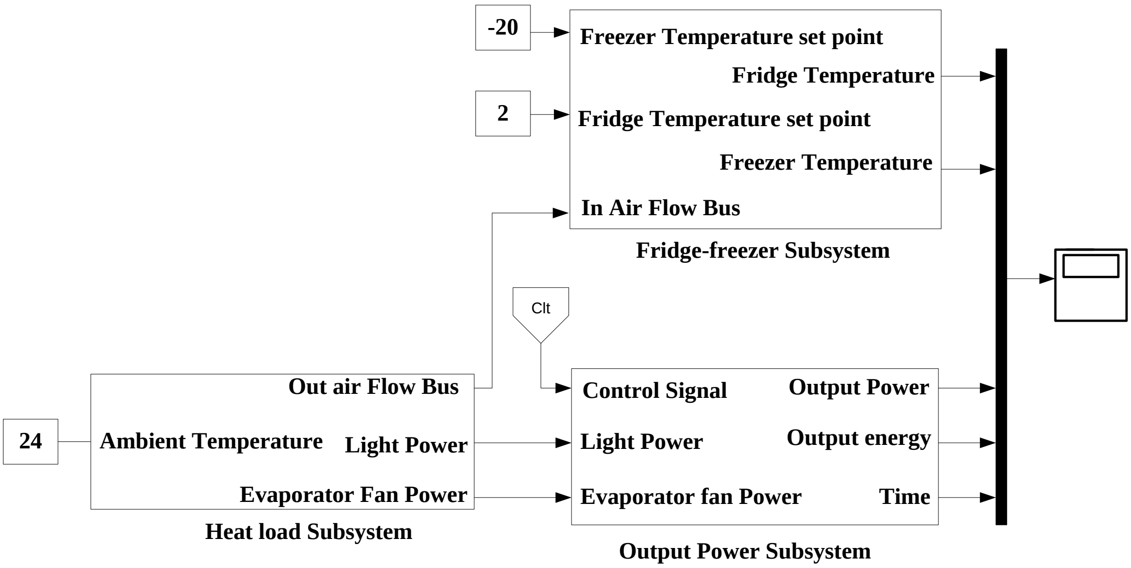

Figure 4.10 Simulation model of a smart fridge-freezer

This Simulink model enables the study of the behaviours (e.g. power consumption and compressor run-time) of a fridge-freezer in different configurations (e.g. power rating of the compressor and size of the compartments) and under different operating conditions (e.g. compartment temperature set-points and ambient temperature).

4.2.1.2 Simulation results

The fridge and freezer temperature set points of the fridge-freezer are in the range of:

- The fridge temperature set point ranging between 2℃ and 8℃.
- The freezer temperature set point ranging between -18 ℃ and -26 ℃.

The simulation results were obtained by changing both the freezer and fridge temperature set points for three environment temperature change of operation (24℃, 19 ℃ and 14 ℃), and for three sizes of smart fridge-freezer compressor rated power (60 W, 80 W, and 100 W). These selected values were based on the collected dataset provided by DEMS.

The results were obtained for a Hotpoint Free standing Frost free fridge-freezer (model FF200TP) with the detailed specifications in appendix B.

Figures 4.11 and 4.12 illustrate the relationship between daily fridge-freezer energy consumption and various temperature set-points for a fridge-freezer with a compressor rated in 80 watt and operating in 24 ℃ environment temperature.

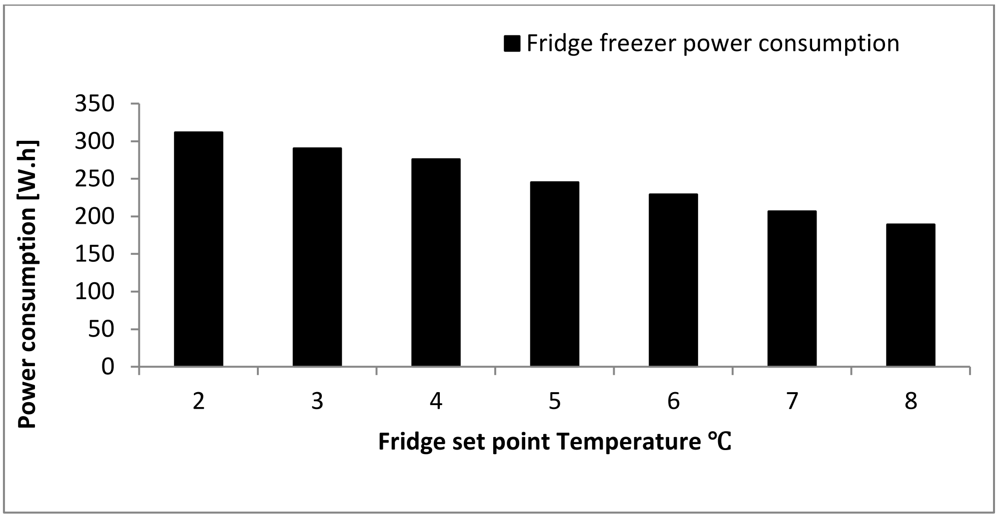

Figure 4.11 Daily energy consumption for various temperature set-points of the fridge compartment

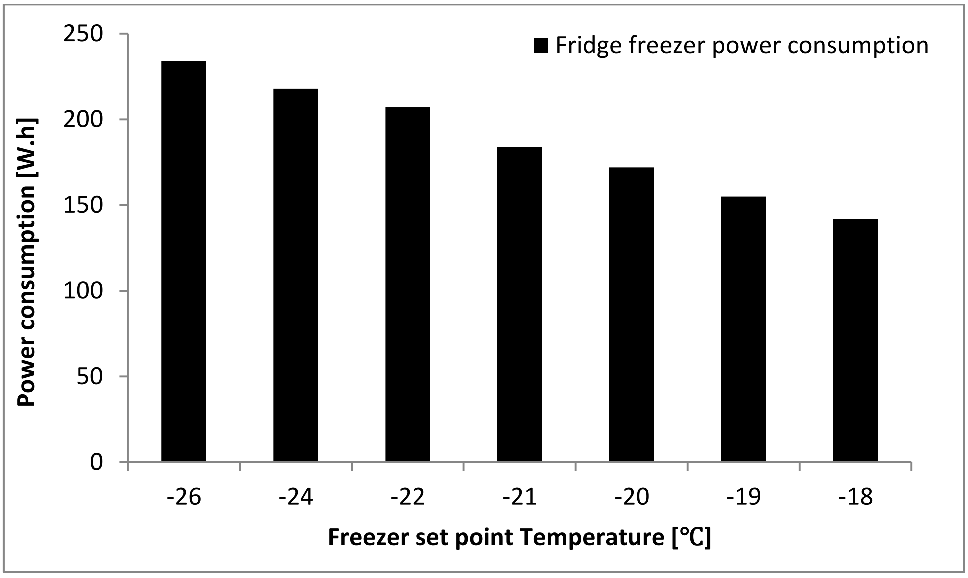

Figure 4.12 Daily energy consumption for various temperature set-points of the freezer compartment

Simulation results indicated both fridge and freezer compartment will increase the energy consumption when their temperature set-point is decreased.

The compressor running time is also increased by decreasing the fridge and the freezer temperature set-points as shown in figures 4.13 and 4.14.

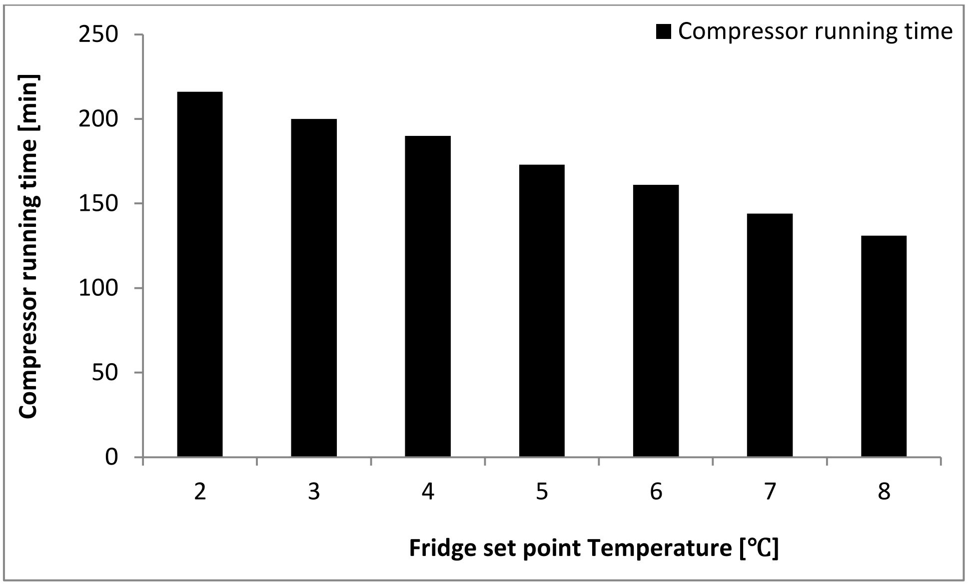

Figure 4.13 Daily total run-time of the compressor for various temperature set-points of the fridge compartment.

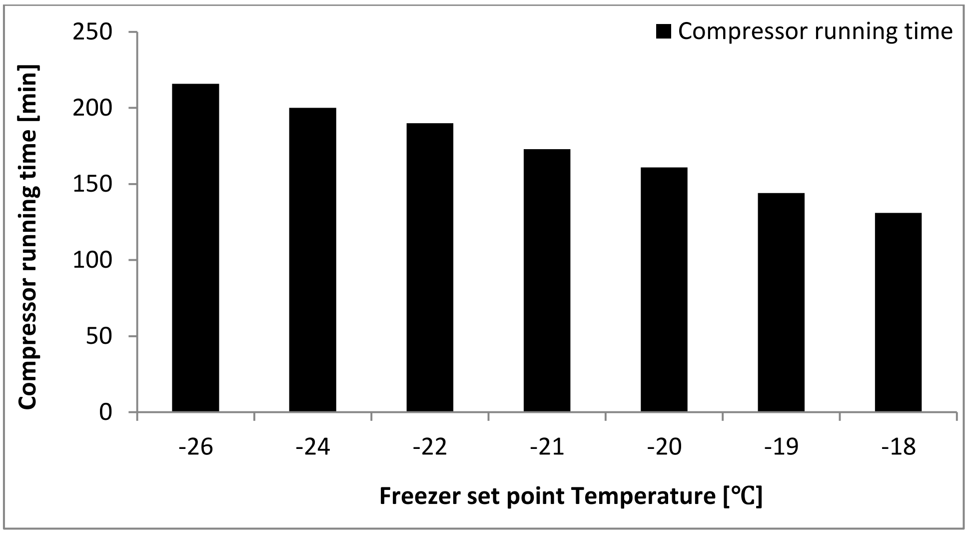

Figure 4.14 Daily total run-time of the compressor for various temperature set-points of the freezer compartment.

4.2.1.3 Defrost process

The electric heater resistance of the defrost process is equal to 387.2 Ω[121], and the nominal operated voltage of this fridge-freezer is$220/240\ V$. In this case the power of the defrost heater is calculated as follows:

$$Defrost\ power(minimum) = (220)^2/387.2 = 125\ [W]$$

$$Defrost\ power(maximum) = (240)^2/387.2 = 148.76\ [W]$$

In this fridge- freezer the defrost process is taking place every 600 minutes of the compressor running time (Approximately once every day), and last for 30 minutes, the energy consumption of the defrost process could be calculated as follows:

$$Defrost\ process\ energy\ consumption = \frac{30}{60} * 125 = 62.5\ [watt.hour]$$

The time of this defrost process could be shifted to take place when the local renewable energy is available, resulting in less consumption from the grid.

4.3 Summary

The concepts of local DSM or ‘Load shifting’ (e.g. Fridge-freezer, washing machine, and dishwasher), and the energy buffering of the smart domestic appliances (e.g. fridge-freezer, electrical storage system and electrical hot water system) were presented in this chapter. With the aid of the dataset from the DEMS project, the potentials of various identified domestic appliances were examined and they did show promising results in realisation of the adopted concepts in tackling the temporal energy mismatch between energy consumption and local renewable energy generation in the domestic environment.

A flexible Simulink model of a fridge-freezer has been developed to facilitate the study of its behaviour in realising the concepts of ‘Load shifting’ and ‘Energy buffering’. Energy consumption Simulink models of other identified domestic appliances have also been developed with the aid of the DEMS dataset for supporting further research studies of this project.

The Simulink models established in this chapter will be aggregated with the developed Simulink models in chapter three to form a domestic electricity energy ecosystem model, which will be used to facilitate the subsequent research investigation and studies in devising control strategies to tackle the temporal energy mismatch between the local renewable energy generation and local energy consumption in the domestic environment.

5 A novel control strategy for solving local temporal energy mismatch

5.1 Introduction

The household electricity survey report [122] stated that the peak electricity consumption during the evening is three times higher than the base load; for which the cooking, lighting, and audio-visual appliances take the largest share with 20%, 14%, and 14% respectively. The report further stated that washing machines, electric showers, electric heaters, and cold appliances also have a significant share of this electrical peak load and suggest changing the time of use of these domestic appliances would reduce the home energy consumption during the evening period. These controllable appliances account for 19% of the whole consumed electrical energy for the monitored houses. Shifting the energy consumption from high tariff period to low tariff period not only reduces the energy bill, but also reduces the carbon emission. A trial conducted by PowerCentsDc program between 2008 and 2009, which monitored 850 customers in Washington over 15 months had reported the peak load pricing helped to reduce peak load consumption between 4% to 34% in summer and 2% to 13% in winter [123]. In addition, a US based modelling report suggested that smart appliances such as dishwashers, cold appliances, washing appliances and tumble driers could reduce peak load consumption between 3% to 6% via load shifting strategy [124].

These findings have inspired the author to establish a hypothesis which proposed changing the time of use of the domestic appliances and/or changing their operational parameters of the domestic appliances could provide a solution to solve the local temporal energy mismatch between the energy consumption and local energy generation for the domestic homes.

5.2 A novel temporal energy mismatch control strategy

In this research, a novel control strategy which built upon the hypothesis stated in previous section 5.1 was proposed. This proposed control strategy is to exploit and integrate ICT with smart domestic appliances in creating a local energy prosumption[2] way to tackle the local temporal energy mismatch between the energy consumption and

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[2] ***Prosumption*** involves both production and consumption rather than focusing on either one (production) or the other (consumption).

local energy generation for the domestic homes. Obviously, the proposed control strategy must not compromise or affect quality of the services offered by the involved smart domestic appliances and residents' comfort.

The chosen smart domestic appliances are divided into two major categories according to their operational characteristics, which are 'Shifting time of use' and 'Energy buffering'.

5.2.1 Shifting time of use

This group contains the smart domestic appliances which can be operated anytime during the day without affecting the comfort of the residents (e.g. washing machines and dishwasher). The proposed control strategy will exploit this characteristic to minimise local temporal energy mismatch by schedule the use of this group of appliances in 'real-time' (i.e. when surplus local generated energy is available).

5.2.2 Energy Buffering

This group contains the smart domestic appliances that can be used to buffer electrical energy in other form (e.g. thermal) anytime for supporting their routine services (e.g. cold/cool storage, heating, hot-water and air-conditioning). The proposed control strategy will exploit this characteristic to minimise local temporal energy mismatch by schedule and/or change of settings of their operational parameters in 'real-time' (i.e. when surplus local generated energy is available).

5.2.3 Control rules and structure

The proposed control strategy has adopted a rule-based approach to realise the implementation of the proposed temporal energy mismatch control strategy, where surplus local generated energy triggers the appropriate control procedure(s), which meet the desired performance (i.e. to minimise the temporal energy mismatch between local generation and local consumption).

A set of rules have been established to facilitate the implementation of the proposed control strategy and are listed as follow:

Rule_1: If local generated power exists, always supply the base load first.

Rule_2: If local generated power is higher than the needs of base load, apply "time shifting" control strategy in the selected smart domestic appliances until the local generated power is equal to or less than the needs of base load.

Rule_3: If local generated power is higher than the needs of base load and the time-shifted smart domestic appliances, turn on the smart hot water system until the local generated power equals or is less than the needs of base load and the time-shifted smart domestic appliances.

Rule_4: If local generated power is higher than the needs of base load, and time-shifted smart domestic appliances and hot water system, turn on the smart storage heating system; until the local generated power equals or is less than the needs of base load, time-shifted smart domestic appliances and smart hot water system.

Rule_5: If local generated power is higher than the needs of the house (assume both time-shift and energy buffer strategies have activated), surplus generated power will be sold to the Grid.

An overview of a control structure of the proposed temporal energy mismatch control strategy is illustrated in figure 5.1.

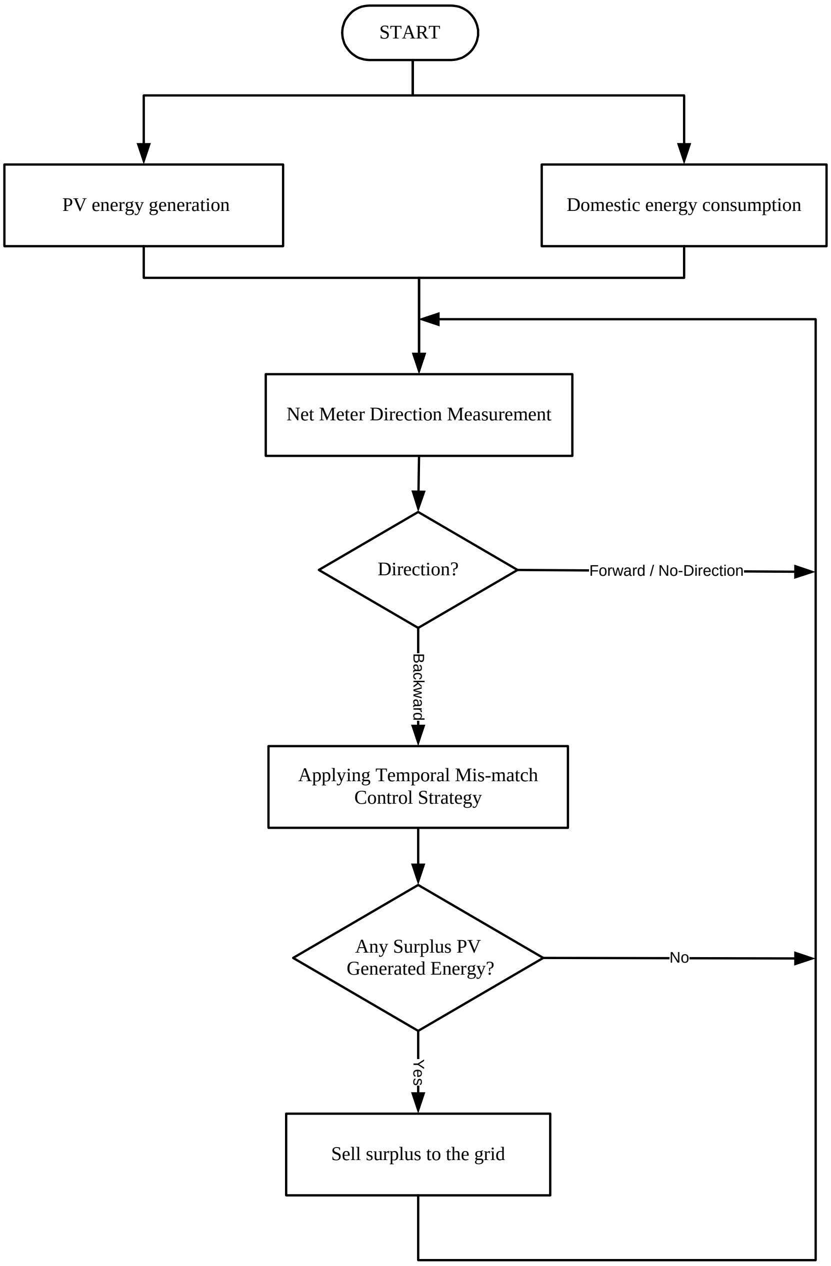

Figure 5.1 Overview of the control structure

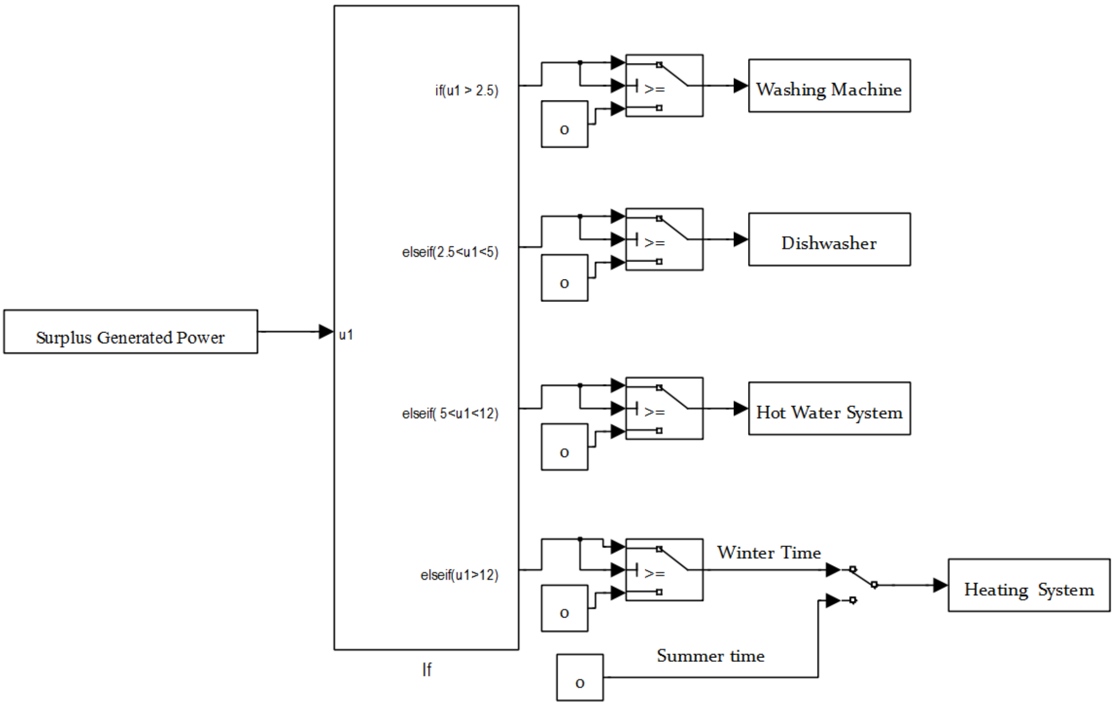

Figure 5.2 Simulink model of the controller (top level)

The control rules and proposed control strategy formed the basis to design a controller and has been implemented as Simulink model. This Simulink model is illustrated in figure 5.2.

Controller configuration will be as followed:

- The initial conditions of the controller will be set to a positive value of the error signal (the difference between the PV generated power and the domestic energy consumption).
- Follow the requirements of energy consumption and operational cycle-time of the individual chosen domestic appliance.

The controller will have one input, which represents the difference between the PV generated power and the house energy consumption (e.g. The surplus generated power). A set of pre-defined rules have been implemented as described in section 5.2.3 to trigger an appropriate action when surplus generated PV energy is available. The decision of these rules is based on the amount of surplus PV generated energy, and the energy consumption and cycle-time of individual domestic appliances. As an example, the controller will switch on the washing machine if the surplus PV generated power is large enough to complete the operation cycle of this appliance because this kind of appliances cannot be stopped before it completes its operational cycle. If the surplus PV generated power is not large enough to complete the operation cycle, the controller will decide to switch on another appliance (e.g. Hot water system). The same principle will be applied for other appliances which have the load shifting ability (e.g. Dishwasher, and defrost process of the fridge-freezer).

5.3 Domestic energy ecosystem model

A Domestic Energy Ecosystem Model (DEEM) was developed for supporting the investigation of temporal energy mismatch between local energy generation and its consumption. The developed DEEM model mainly comprised of a PV power generation model and domestic energy consumption model (details of the models please refers to chapter 3 and chapter 4).

DEEM is not only employed for supporting the investigation of relationships between the PV power generation system and the domestic energy consumption, but also for facilitating the development of domestic temporal energy mismatch control strategy. The DEEM model is established with the aid of Matlab/Simulink and relevant toolboxes such as commonly used control and signal blocks. The overview of a DEEM model is illustrated in figure 5.3 and its details can be found in Appendix D.

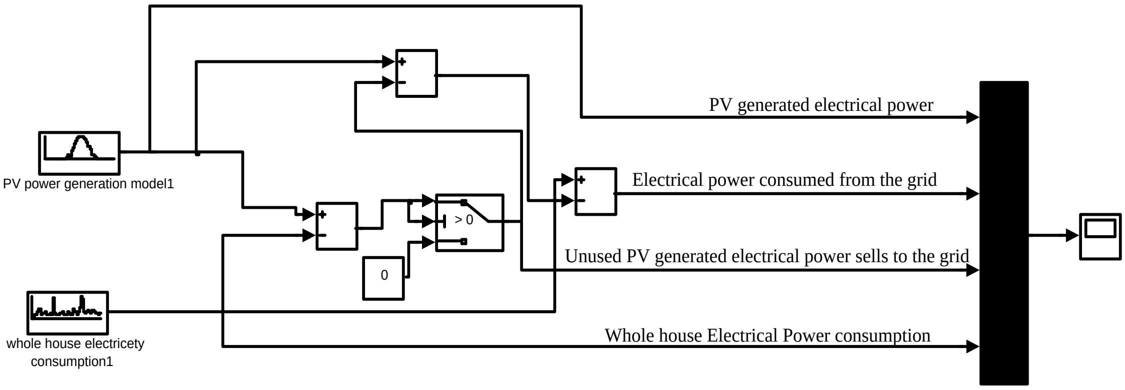

Figure 5.3 Overview of DEEM model

The investigation has adopted the ‘What-if’ analysis approach with the aid of the developed DEEM model.

5.4 Simulation results

The DEEM model is configured with different parameters (e.g. PV generation capacity, seasonal conditions and appliance types) to represent different setups of domestic energy ecosystem for supporting the investigation.

Most of PV panels installed in UK houses have the power generation capacity ranging from 1 to 4 kWp, mainly because of various considerations (e.g. available roof space and its facing direction, renewable incentive scheme from the government). Due to this reason, three different configurations on PV power generation model (i.e. 1, 2.5 and 4 kWp) were chosen for supporting the research investigation. Furthermore, winter and summer seasons were chosen to setup the DEEN model because of their distinct seasonal contrasts in both energy consumption and PV power generation.

Throughout these studies, each year only considered two seasons (i.e. Summer occupying 185 days and Winter occupying 180 days) rather than four seasons to minimise the efforts of investigation; mainly because the average daylight hours in autumn and winter seasons are fairly close (equally applied for spring and summer seasons) [125, 126].

5.4.1 Simulation results for 1 kWp PV power generation in winter season

The simulation results of the DEEM model configured with 1 kWp PV power generation in winter, together with different setups are presented in following sub-sections.

5.4.1.1 Simulation results without applying any control strategy

Under this setup, generated power through the PV panels will be immediately consumed to meet the demand of the house. Any unused (or surplus) local generation will be sold to the grid.

The whole house electrical power consumption, PV generated electrical power, unused PV generated electrical power sold to the grid, and electrical power consumed from the grid are illustrated and summarised in figure 5.4 and table 5.1 respectively.

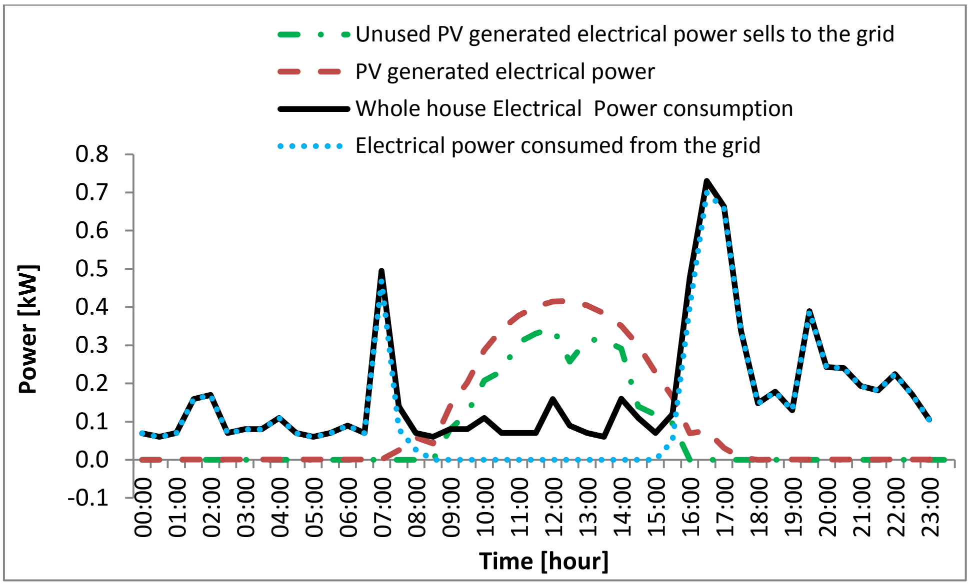

Figure 5.4 Simulation results without applying any control strategy

Table 5.1 Simulation results without using any control strategy

Season	PV maximum output power kWp	Whole house Electrical energy consumption kWh	PV generated electrical energy kWh	Unused PV generated electrical energy sells to the grid kWh	Energy consumed from the grid kWh
Winter	1	7.72	4.74	3.15	6.14

For this setup, the house consumed 6 kWh (80 % of its total consumption) is supplied by the grid and the rest of demand is consumed from the local PV panels. It means most of the local generated energy (67% of the total local generated energy) is not consumed locally and will be sold to the grid.

5.4.1.2 Simulation results with load shifting control strategy

Under this setup, generated power through the PV panels will be immediately consumed to meet the demand of the house. Load shifting control strategy was adopted to consume any unused (or surplus) local generation with chosen smart domestic appliances (e.g. electrical water heater, dishwasher, and washing machine) to minimise the overall demand from the grid and reducing (if not completely avoid) the local PV generated energy sold to the grid.

The whole house electrical power consumption, PV generated electrical power, unused generated electrical power sells to the grid, and electrical power consumed from the grid are illustrated and summarised in figure 5.5 and table 5.2 respectively.

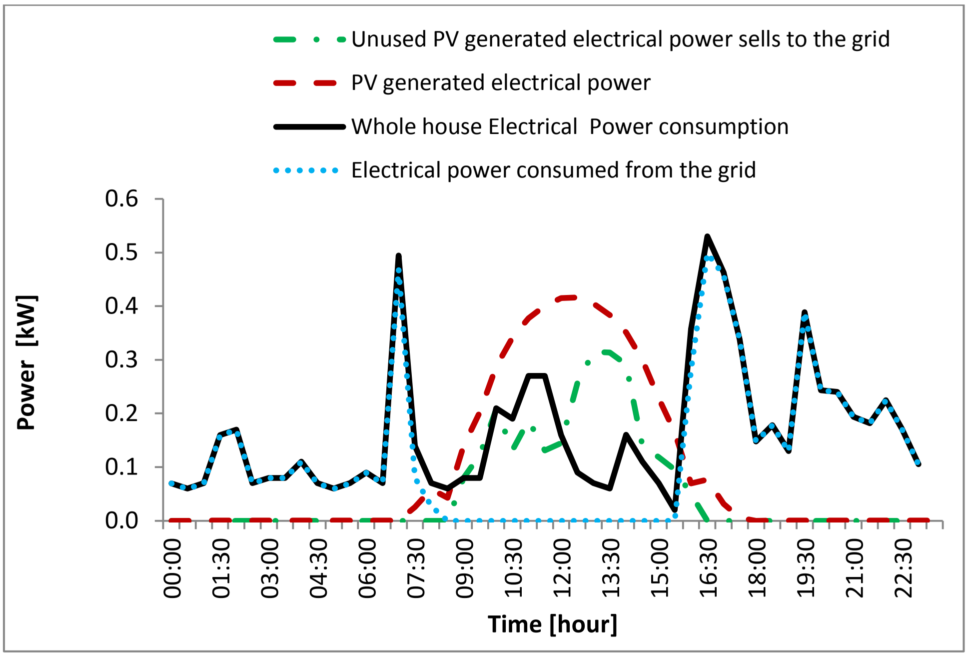

Figure 5.5 Simulation results with load shifting control strategy

Table 5.2 Simulation results with shifting control strategy which exploits smart electrical water heater, dishwasher, and washing machine.

Season	PV maximum output power kWp	Whole house Electrical energy consumption kWh	PV generated electrical energy kWh	Unused PV generated electrical energy sells to the grid kWh	Energy consumed from the grid kWh
Winter	1	7.72	4.74	2.58	5.57

For this setup, the house consumed 5.6 kWh (72% of its total consumption) is supplied by the grid and consumed 0.6 kWh (6% of its total consumption) less from the grid when compared without any control strategy applied. However, there is still a substantial amount of local generated energy (2.6 kWh, 55% of the total local energy generation) is not consumed locally and will be sold to the grid.

5.4.1.3 Simulation results with load shifting and energy buffering control strategy

Under this setup, the author assumed that heating of the house will be supported with smart electrical storage heaters. These smart heaters are able to store 17kWh energy in total and are usually expected to operate in a low tariff period (e.g. economy 7 scheme in UK) to buffer the required energy, if the energy supply is solely from the grid. The proposed control strategy will further use the surplus local generated energy (i.e. after applying the load shifting strategy) to charge these smart storage heaters. Once the surplus is no longer available, the charging process will stop immediately to avoid the use of energy from the grid in its peak period (or high tariff period).

The whole house electrical power consumption, PV generated electrical power, unused generated electrical power sold to the grid, and electrical power consumed from the grid are illustrated and summarised in figure 5.6 and table 5.3 respectively.

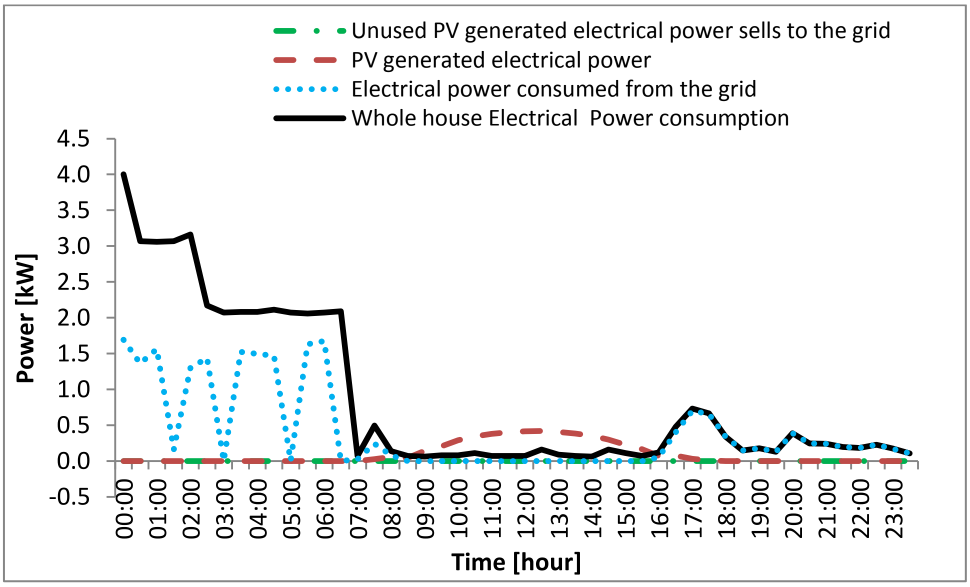

Figure 5.6 Simulation results with load shifting and energy buffering control strategy

Table 5.3 Simulation results with load shifting and energy buffering control strategy which exploit smart electrical water heater, dishwasher, washing machine and smart storage heater

Season	PV maximum output power kWp	Whole house Electrical energy consumption kWh	PV generated electrical energy kWh	Unused PV generated electrical energy sells to the grid kWh	Energy consumed from the grid kWh
Winter	1	24.72	4.73	0.000	19.99

For this setup, the house consumed 20 kWh (81% of its total consumption) is supplied by the grid and the rest is from the local PV panels (4.7 kWh, 19% of total energy consumption). It means all the local generated energy is consumed locally.

5.4.2 Simulation results for 2.5 kWp PV power generation in winter season

The simulation results of the DEEM model configured with 2.5kWp PV power generation in winter, together with different setups are presented in following sub-sections.

5.4.2.1 Simulation results without applying any control strategy

Under this setup, generated power through the PV panels will be immediately consumed to meet the demand of the house. Any unused (or surplus) local generation will be sold to the grid.

The whole house electrical power consumption, PV generated electrical power, unused PV generated electrical power sold to the grid, and electrical power consumed from the grid are illustrated and summarised in figure 5.7 and table 5.4 respectively.

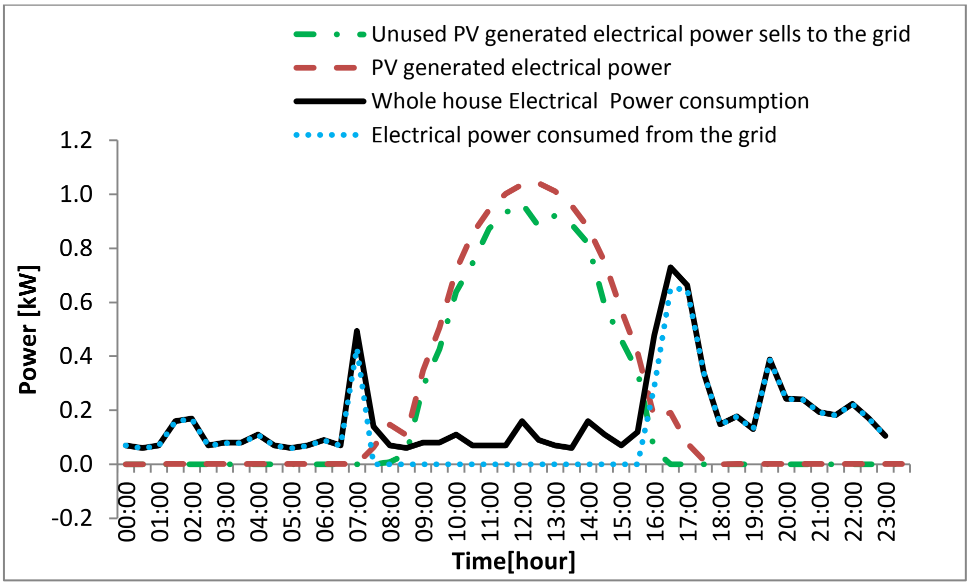

Figure 5.7 Simulation results without applying any control strategy

Table 5.4 Simulation results without using any control strategy

Season	PV maximum output power kWp	Whole house Electrical energy consumption kWh	PV generated electrical energy kWh	Unused PV generated electrical energy sells to the grid kWh	Energy consumed from the grid kWh
Winter	2.5	7.72	11.84	9.87	5.76

For this setup, the house consumed 5.8 kWh (75% of its total consumption) is supplied by the grid and the rest is from the local PV panels. It means most of the local generated energy (9.9 kWh, 83 % of the total local generated energy) is not consumed locally and will be sold to the grid.

5.4.2.2 Simulation results with load shifting control strategy

Under this setup, generated power through the PV panels will be immediately consumed to meet the demand of the house. Load shifting control strategy was adopted to consume any unused (or surplus) local generation with smart appliances (e.g. electrical water heater, dishwasher, and washing machine) to minimise the overall demand from the grid and reduced (if not completely avoided) the local PV generated energy sold to the grid.

The whole house electrical power consumption, PV generated electrical power, unused generated electrical power sold to the grid, and electrical power consumed from the grid are illustrated and summarised in figure 5.8 and table 5.5 respectively.

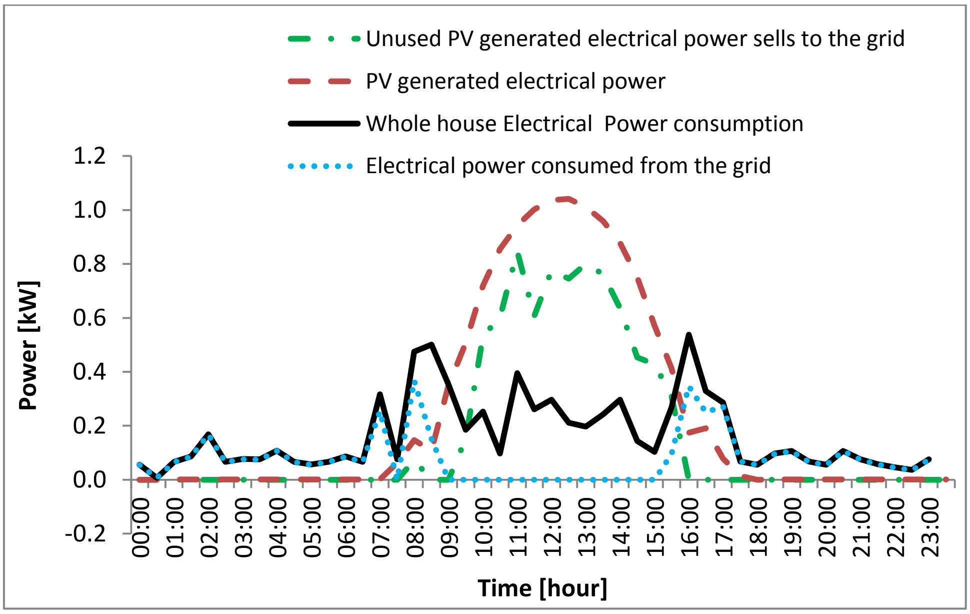

Figure 5.8 Simulation results with load shifting control strategy

Table 5.5 Simulation results with shifting control strategy which exploits smart electrical water heater, dishwasher, and washing machine

Season	PV maximum output power kWp	Whole house Electrical energy consumption kWh	PV generated electrical energy kWh	Unused PV generated electrical energy sells to the grid kWh	Energy consumed from the grid kWh
Winter	2.5	7.72	11.84	7.72	3.60

For this setup, the house consumed 3.6 kWh (47 % of its total consumption) is supplied by the grid and the rest of demand is consumed from the local PV panels. However, large amount of local generated energy (7.7 kWh, 65% of the total local generated energy) still not consumed locally and will be sold to the grid.

5.4.2.3 Simulation results with load shifting and energy buffering control strategy

Under this setup, the author assumed that heating of the house will be supported with smart electrical storage heaters. These smart heaters are able to store 17kWh energy in total and are usually expected to operate in a low tariff period (e.g. economy 7 scheme in UK) to buffer the required energy, if the energy supply is solely from the grid. The proposed control strategy will further use the surplus local generated energy (i.e. after applying the load shifting strategy) to charge these smart storage heaters. Once the surplus is no longer available, the charging process will stop immediately to avoid the use of energy from the grid in its peak period (or high tariff period).

The whole house electrical power consumption, PV generated electrical power, unused generated electrical power sold to the grid, and electrical power consumed from the grid are illustrated and summarised in figure 5.9 and table 5.6 respectively.

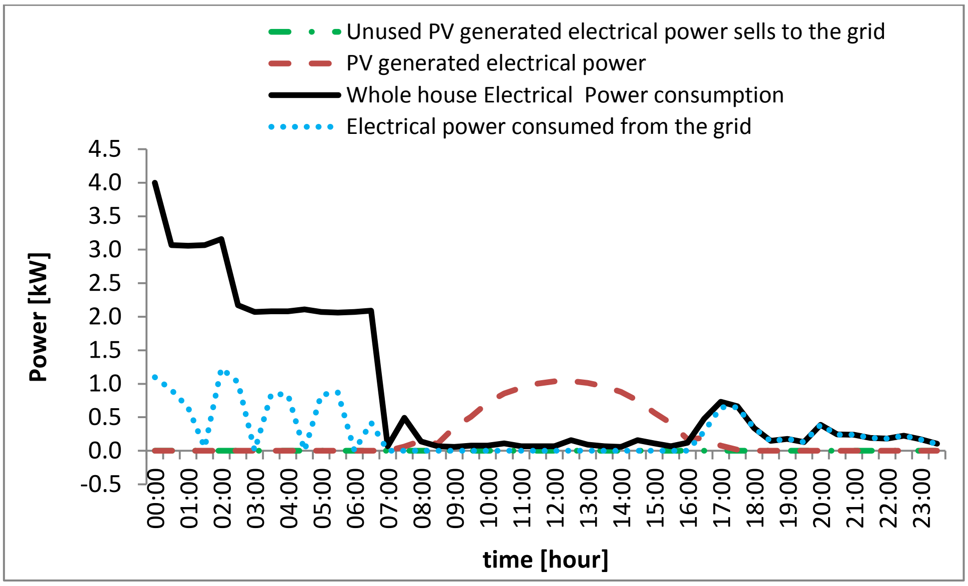

Figure 5.9 Simulation results with load shifting and energy buffering control strategy

Table 5.6 Simulation results with load shifting and energy buffering control strategy which exploit smart electrical water heater, dishwasher, washing machine and smart storage heater

Season	PV maximum output power kWp	Whole house Electrical energy consumption kWh	PV generated electrical energy kWh	Unused PV generated electrical energy sells to the grid kWh	Energy consumed from the grid kWh
Winter	2.5	24.72	11.84	0.00	12.88

For this setup, the house consumed 13 kWh (52% of its total consumption) is supplied by the grid and the rest of demand is supplied from the local PV panels (12 kWh, 48 % of total energy consumption). It means all the local generated energy is consumed locally.

5.4.3 Simulation results for 4 kWp PV power generation in winter season

The simulation results of the DEEM model configured with 4 kWp PV power generation in winter, together with different setups are presented in following sub-sections.

5.4.3.1 Simulation results without applying any control strategy

Under this setup, generated power through the PV panels will be immediately consumed by the demand of the house. Any unused (or surplus) local generation will be sold to the grid.

The whole house electrical power consumption, PV generated electrical power, unused PV generated electrical power sold to the grid, and electrical power consumed from the grid are illustrated and summarised in figure 5.10 and table 5.7 respectively.

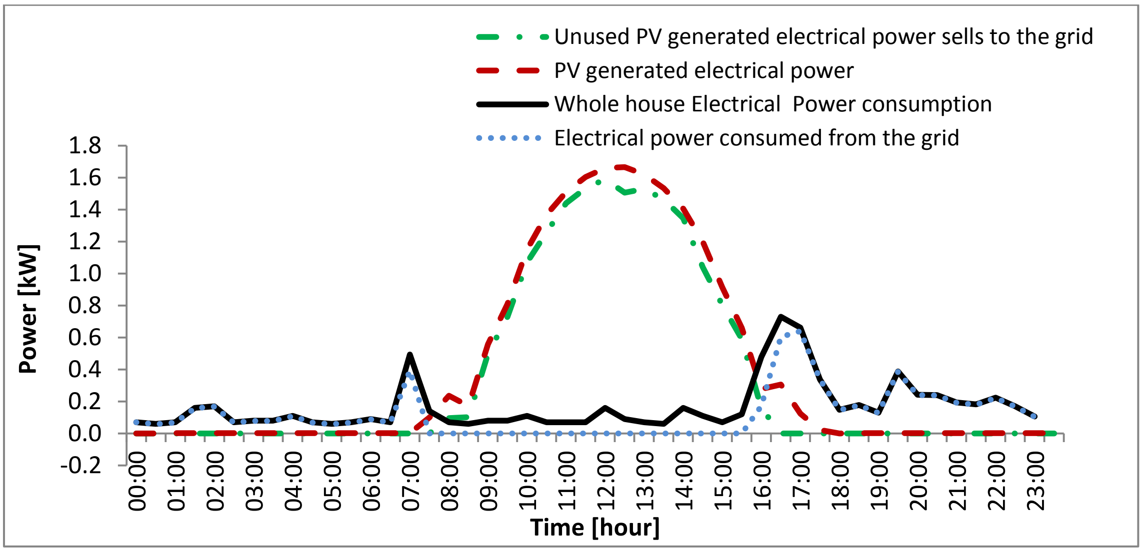

Figure 5.10 Simulation results without applying any control strategy

Table 5.7 Simulation results without using any control strategy

Season	PV maximum output power kWp	Whole house Electrical energy consumption kWh	PV generated electrical energy kWh	Unused PV generated electrical energy sells to the grid kWh	Energy consumed from the grid kWh
Winter	4	7.72	18.94	16.75	5.53

For this setup, the house consumed 5.5kWh (72% of its total consumption) is supplied by the grid and the rest of demand is consumed from the local PV panels. It means most of the local generated energy (16.8 kWh, 88% of the total local generated energy) is not consumed locally and will be sold to the grid.

5.4.3.2 Simulation results with load shifting control strategy

Under this setup, generated power through the PV panels will be immediately consumed by the demand of the house. Load shifting control strategy was adopted to consume any unused (or surplus) local generation with smart appliances (e.g. electrical water heater, dishwasher, and washing machine) to minimise the overall demand from the grid and reduced (if not completely avoid) the local PV generated energy sold to the grid.

The whole house electrical power consumption, PV generated electrical power, unused generated electrical power sold to the grid, and electrical power consumed from the grid are illustrated and summarised in figure 5.11 and table 5.8 respectively.

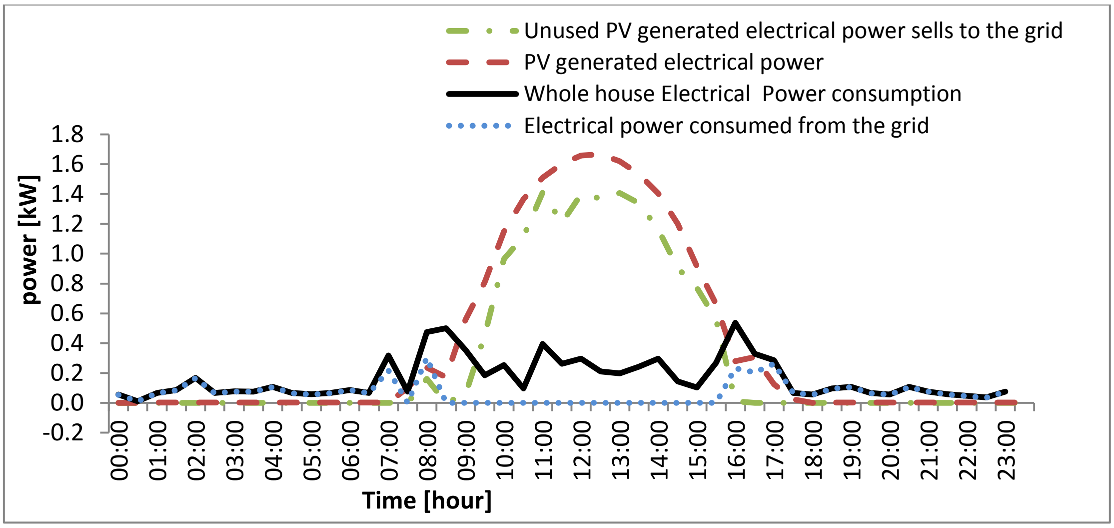

Figure 5.11 Simulation results with load shifting control strategy

Table 5.8 Simulation results with shifting control strategy which exploits smart electrical water heater, dishwasher, and washing machine.

Season	PV maximum output power kWp	Whole house Electrical energy consumption kWh	PV generated electrical energy kWh	Unused PV generated electrical energy sells to the grid kWh	Energy consumed from the grid kWh
Winter	4	7.72	18.94	14.29	3.07

For this setup, the house consumed 3kWh (40% of its total consumption) is supplied by the grid and consumed 2.5 kWh (32% of its total consumption) less from the grid when compared without any control strategy applied. However, large amount of local generated energy (14kWh, 75 % of the total local generated energy) still not consumed locally and will be sold to the grid.

5.4.3.3 Simulation results with load shifting and energy buffering control strategy

Under this setup, the author assumed that heating of the house will be supported with smart electrical storage heaters. These smart heaters are able to store 17kWh energy in total and usually expecting to operate in low tariff period (e.g. economy 7 scheme in UK) to buffer the required energy, if the energy supply is solely from the grid. The proposed control strategy will further use the surplus local generated energy (i.e. after applying the load shifting strategy) to charge these smart storage heaters. Once the surplus is no longer available, the charging process will stop immediately to avoid the use of energy from the grid in its peak period (or high tariff period).

The whole house electrical power consumption, PV generated electrical power, unused generated electrical power will be sold to the grid, and electrical power consumed from the grid are illustrated and summarised in figure 5.12 and table 5.9 respectively.

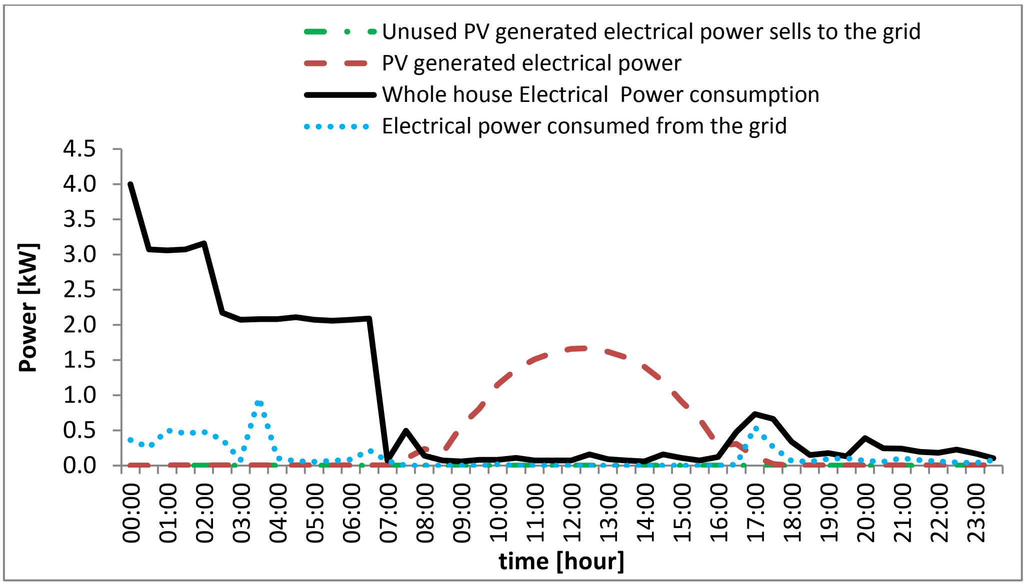

Figure 5.12 Simulation results with load shifting and energy buffering control strategy

Table 5.9 Simulation results with load shifting and energy buffering control strategy which exploit smart electrical water heater, dishwasher, washing machine and smart storage heater

Season	PV maximum output power kWp	Whole house Electrical energy consumption kWh	PV generated electrical energy kWh	Unused PV generated electrical energy sells to the grid kWh	Energy consumed from the grid kWh
Winter	4	24.72	18.94	0.00	5.79

For this setup, the house consumed 5.8 kWh (23% of its total consumption) is supplied by the grid and the rest of the demand is consumed from the local PV panels (19 kWh, 77% of total energy consumption). It means all the local generated energy is consumed locally.

5.4.4 Simulation results for 1 kWp PV power generation in summer season

The simulation results of the DEEM model configured with 1 kWp PV power generation in summer, together with different setups are presented in following sub-sections.

5.4.4.1 Simulation results without applying any control strategy

Under this setup, generated power through the PV panels will be immediately consumed to meet the demand of the house. Any unused (or surplus) local generation will be sold to the grid.

The whole house electrical power consumption, PV generated electrical power, unused PV generated electrical power sold to the grid, and electrical power consumed from the grid are illustrated and summarised in figure 5.13 and table 5.10 respectively.

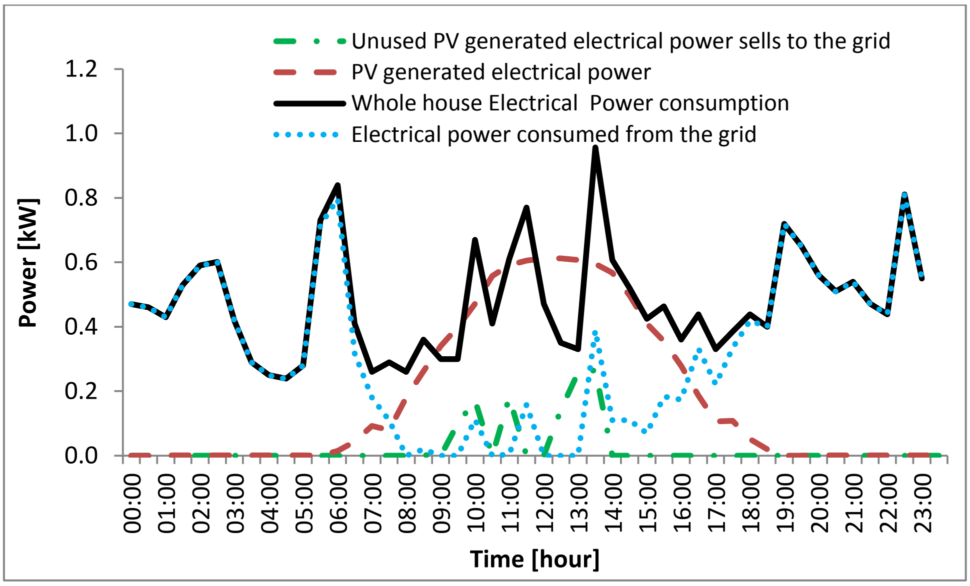

Figure 5.13 Simulation results without applying any control strategy

Table 5.10 Simulation results without using any control strategy

Season	PV maximum output power kWp	Whole house Electrical energy consumption kWh	PV generated electrical energy kWh	Unused PV generated electrical energy sells to the grid kWh	Energy consumed from the grid kWh
Summer	1	22.50	8.65	1.12	14.96

For this setup, the house consumed 15 kWh (66% of its total consumption) is supplied by the grid and the rest of demand is consumed from the local PV panels. It means most of the local generated energy (1kWh, 13% of the total local generated energy) is not consumed locally and will be sold to the grid.

5.4.4.2 Simulation results with load shifting control strategy

Under this setup, generated power through the PV panels will be immediately consumed to meet the demand of the house. Load shifting control strategy was adopted to consume any unused (or surplus) local generation with smart appliances (e.g. electrical water heater, dishwasher, and washing machine) to minimise the overall demand from the grid and reducing (if not completely avoid) the local PV generated energy selling to the grid.

The whole house electrical power consumption, PV generated electrical power, unused generated electrical power sold to the grid, and electrical power consumed from the grid are illustrated and summarised in figure 5.14 and table 5.11 respectively.

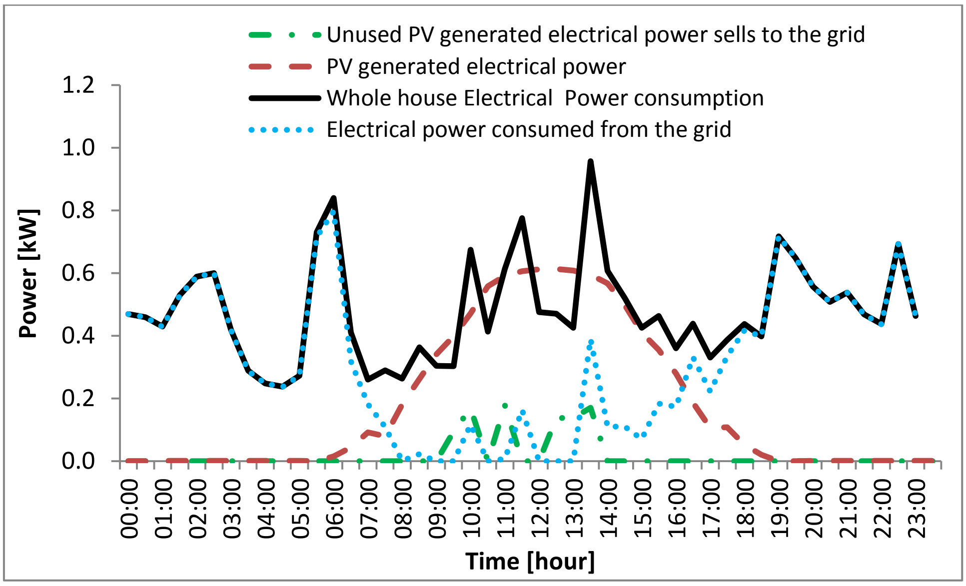

Figure 5.14 Simulation results with load shifting control strategy

Table 5.11 Simulation results with shifting control strategy which exploits smart electrical water heater, dishwasher, and washing machine.

Season	PV maximum output power kWp	Whole house Electrical energy consumption kWh	PV generated electrical energy kWh	Unused PV generated electrical energy sells to the grid kWh	Energy consumed from the grid kWh
Summer	1	22.50	8.65	0.89	14.72

For this setup, the house consumed 14.7 kWh (65% of its total consumption) is supplied by the grid and consumed 0.2 kWh (1% of its total consumption) less from the grid when compared without any control strategy applied. However, there is still small amount of local generated energy (0.9 kWh, 10% of the total local energy generation) is not consumed locally and will be sold to the grid.

5.4.4.3 Simulation results with load shifting and energy buffering control strategy

Under this setup, the author assumed that the hot water in the house will be supported with smart electrical water heaters. The hot water will be stored in a tank (e.g. 200 litres), the smart electrical heaters will consume 12kWh to raise the water temperature in the tank from 10℃ up to 60℃. The water in the tank is stored to be used at a later time. Usually these smart heaters are expected to operate in low tariff period (e.g. economy 7 scheme in UK) to buffer the required energy, if the energy supply is solely from the grid. The proposed control strategy will further use the surplus local generated energy (i.e. after applying the load shifting strategy) to use these smart electrical heaters to heat the water in the tank. Once the surplus is no longer available, the heating process will stop immediately to avoid the use of energy from the grid in its peak period (or high tariff period).

The whole house electrical power consumption, PV generated electrical power, unused generated electrical power sold to the grid, and electrical power consumed from the grid are illustrated and summarised in figure 5.15 and table 5.12 respectively.

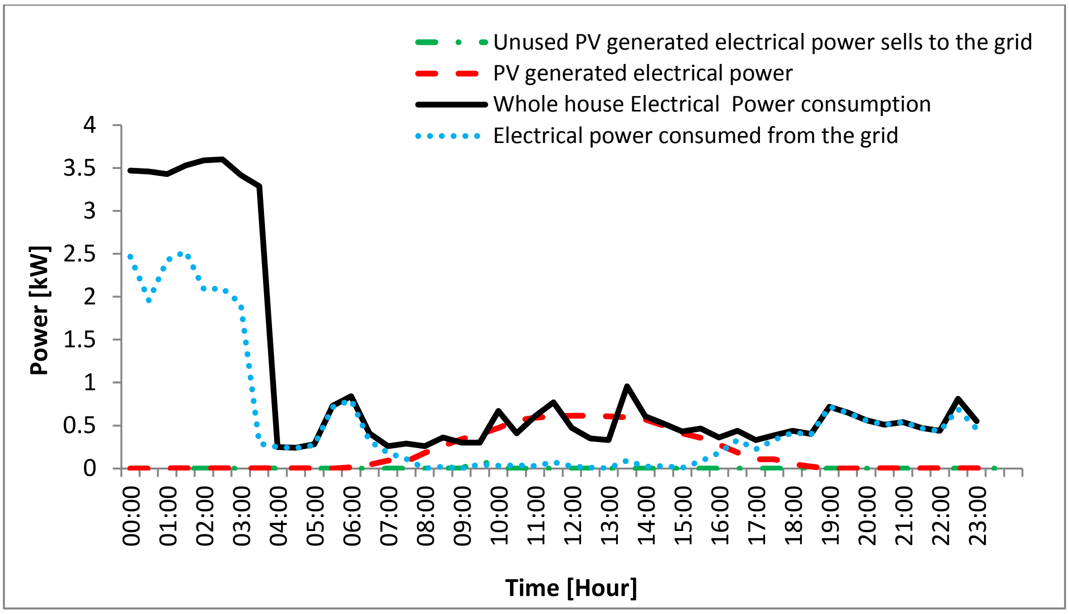

Figure 5.15 Simulation results with load shifting and energy buffering control strategy

Table 5.12 Simulation results with load shifting and energy buffering control strategy which exploit smart electrical water heater, dishwasher, and washing machine

Season	PV maximum output power kWp	Whole house Electrical energy consumption kWh	PV generated electrical energy kWh	Unused PV generated electrical energy sells to the grid kWh	Energy consumed from the grid kWh
Summer	1	34.62	8.65	0.10	26.07

For this setup, the house consumed 26kWh (75% of its total consumption) is supplied by the grid and the rest is from the local PV panels. It means some of the local generated energy (0.1 kWh, 1% of the total local generated energy) is not consumed locally but sold to the grid.

5.4.5 Simulation results for 2.5 kWp PV power generation in summer season

The simulation results of the DEEM model configured with 2.5 kWp PV power generation in summer, together with different setups are presented in following sub-sections.

5.4.5.1 Simulation results without applying any control strategy

Under this setup, generated power through the PV panels will be immediately consumed to meet the demand of the house. Any unused (or surplus) local generation will sell to the grid.

The whole house electrical power consumption, PV generated electrical power, unused PV generated electrical power sold to the grid, and electrical power consumed from the grid are illustrated and summarised in figure 5.16 and table 5.13 respectively.

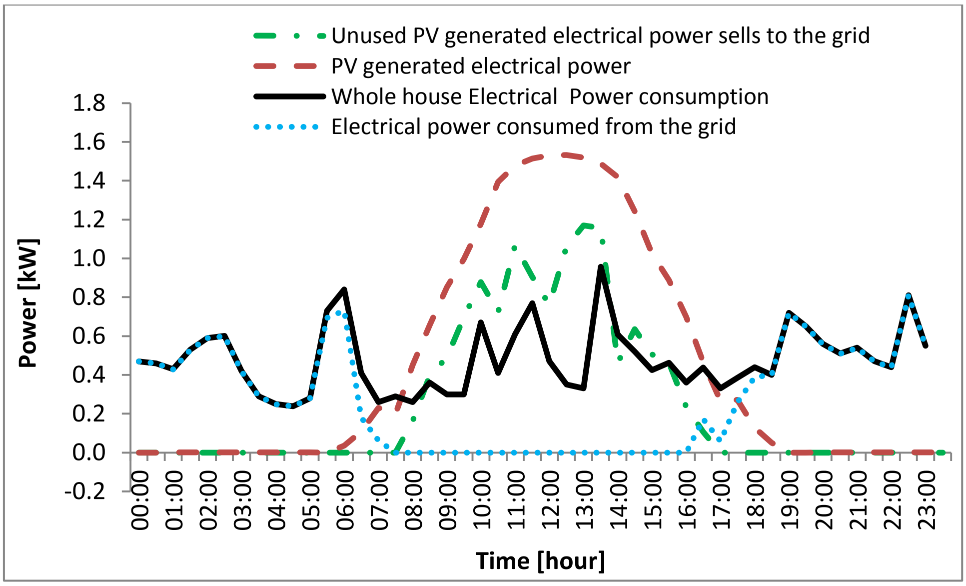

Figure 5.16 Simulation results without applying any control strategy

Table 5.13 Simulation results without using any control strategy

Season	PV maximum output power kWp	Whole house Electrical energy consumption kWh	PV generated electrical energy kWh	Unused PV generated electrical energy sells to the grid kWh	Energy consumed from the grid kWh
Summer	2.5	22.50	21.64	11.88	12.74

For this setup, the house consumed 13 kWh (57% of its total consumption) is supplied by the grid and the rest of demand is consumed from the local PV panels. It means most of the local generated energy (12 kWh, 55% of the total local generated energy) is not consumed locally will be sold to the grid.

5.4.5.2 Simulation results with load shifting control strategy

Under this setup, generated power through the PV panels will be immediately consumed to meet the demand of the house. Load shifting control strategy was adopted to consume any unused (or surplus) local generation with smart appliances (e.g. electrical water heater, dishwasher, and washing machine) to minimise the overall demand from the grid and reducing (if not completely avoid) the local PV generated energy selling to the grid.

The whole house electrical power consumption, PV generated electrical power, unused generated electrical power sold to the grid, and electrical power consumed from the grid are illustrated and summarised in figure 5.17 and table 5.14 respectively.

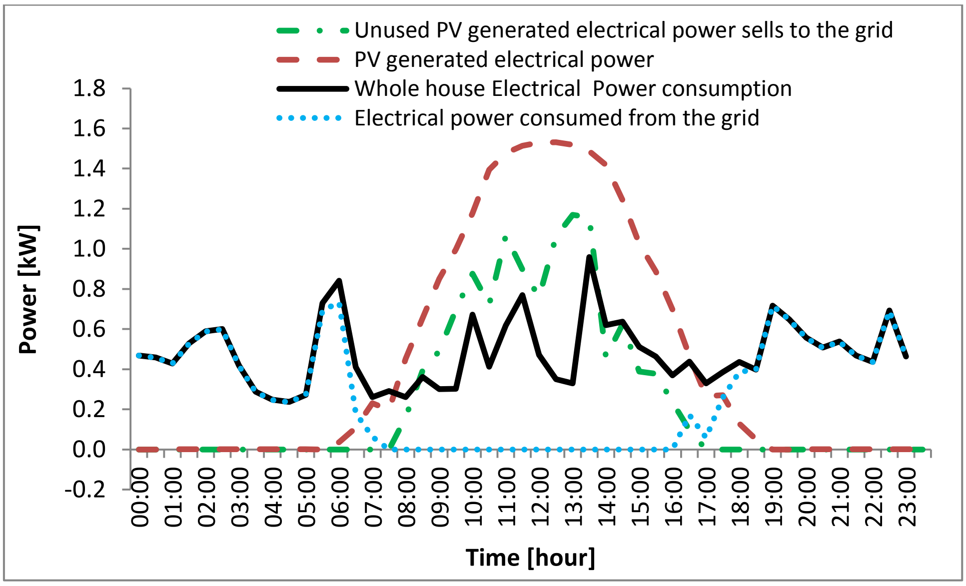

Figure 5.17 Simulation results with load shifting control strategy

Table 5.14 Simulation results with shifting control strategy which exploits smart electrical water heater, dishwasher, and washing machine.

Season	PV maximum output power kWp	Whole house Electrical energy consumption kWh	PV generated electrical energy kWh	Unused PV generated electrical energy sells to the grid kWh	Energy consumed from the grid kWh
Summer	2.5	22.50	21.64	11.63	12.49

For this setup, the house consumed 12.5 kWh (56 % of its total consumption) is supplied by the grid and consumed 0.3 kWh (1% of its total consumption) less from the grid when compared without any control strategy applied. However, there is still substantial amount of local generated energy (12 kWh, 54 % of the total local energy generation) is not consumed locally and will be sold to the grid.

5.4.5.3 Simulation results with load shifting and energy buffering control strategy

Under this setup, the author assumed that the hot water in the house will be supported with smart electrical water heaters. The hot water will be stored in a tank (e.g. 200 litre), the smart electrical heaters will consume 12kWh to raise the water temperature in the tank from 10℃ up to 60℃. The water in the tank is stored to be used at a later time. Usually these smart heaters are expected to operate in low tariff period (e.g. economy 7 scheme in UK) to buffer the required energy, if the energy supply is solely from the grid. The proposed control strategy will further use the surplus local generated energy (i.e. after applying the load shifting strategy) to use these smart electrical heaters to heat the water in the tank. Once the surplus is no longer available, the heating process will stop immediately to avoid the use of energy from the grid in its peak period (or high tariff period).

The whole house electrical power consumption, PV generated electrical power, unused generated electrical power sold to the grid, and electrical power consumed from the grid are illustrated and summarised in figure 5.18 and table 5.15 respectively.

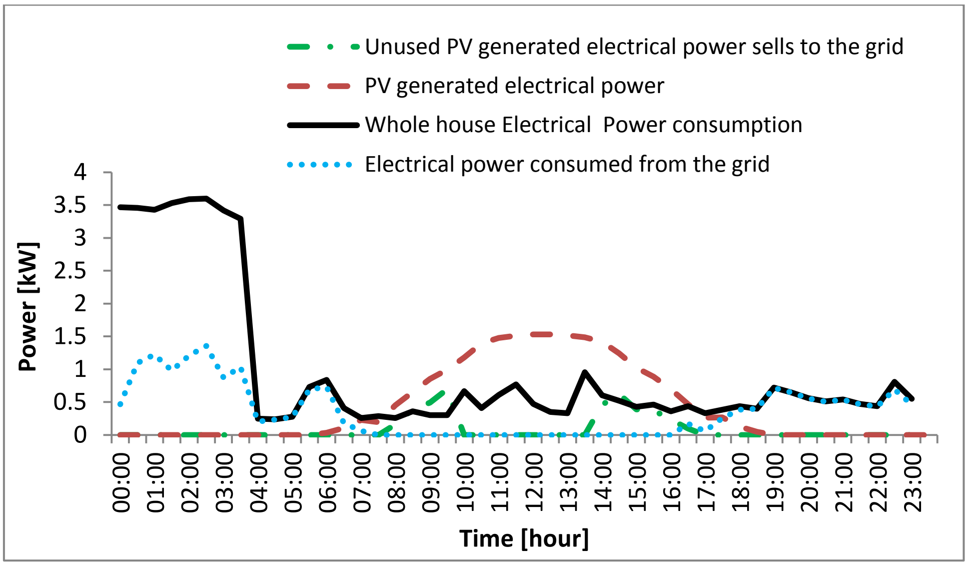

Figure 5.18 Simulation results with load shifting and energy buffering control strategy

Table 5.15 Simulation results with load shifting and energy buffering control strategy which exploit smart electrical water heater, dishwasher, and washing machine

Season	PV maximum output power kWp	Whole house Electrical energy consumption kWh	PV generated electrical energy kWh	Unused PV generated electrical energy sells to the grid kWh	Energy consumed from the grid kWh
Summer	2.5	34.62	21.64	3.92	16.91

For this setup, the house consumed 17 kWh (49% of its total consumption) is supplied by the grid and the rest of demand is consumed from the local PV panels. It means small amount of the local generated energy (4 kWh, 18% of the total local generated energy) is not consumed locally and will be sold to the grid.

5.4.6 Simulation results for 4kWp PV power generation in summer season

The simulation results of the DEEM model configured with 4 kWp PV power generation in summer, together with different setups are presented in following sub-sections.

5.4.6.1 *Simulation results without applying any control strategy*

Under this setup, generated power through the PV panels will be immediately consumed to meet the demand of the house. Any unused (or surplus) local generation will be sold to the grid.

The whole house electrical power consumption, PV generated electrical power, unused PV generated electrical power sold to the grid, and electrical power consumed from the grid are illustrated and summarised in figure 5.19 and table 5.16 respectively.

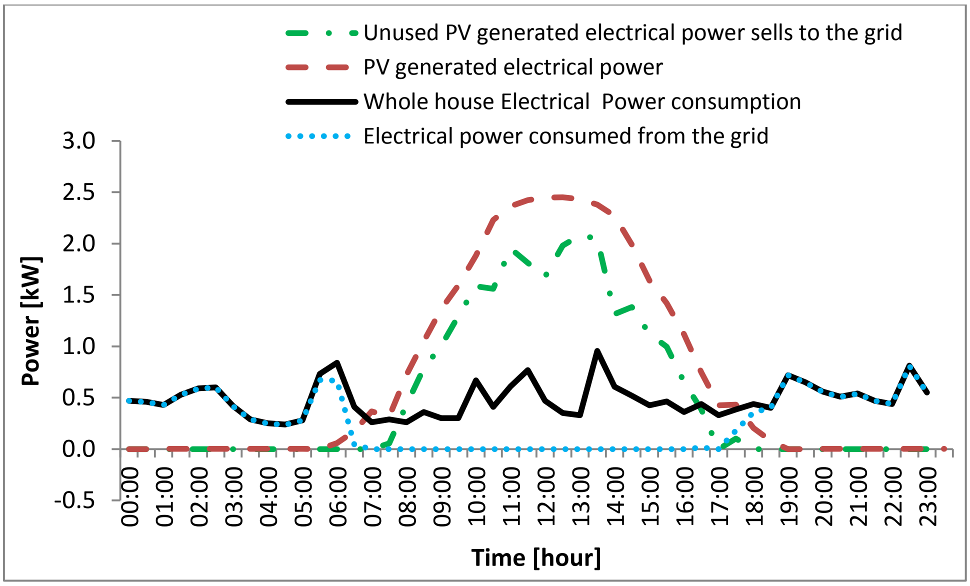

Figure 5.19 Simulation results without applying any control strategy

Table 5.16 Simulation results without using any control strategy

Season	PV maximum output power kWp	Whole house Electrical energy consumption kWh	PV generated electrical energy kWh	Unused PV generated electrical energy sells to the grid kWh	Energy consumed from the grid kWh
Summer	4	22.50	34.62	24.23	12.11

For this setup, the house consumed 12kWh (54% of its total consumption) is supplied by the grid and the rest is from the local PV panels. It means most of the local generated energy (24kWh, 70% of the total local generated energy) is not consumed locally but sold it to the grid.

5.4.6.2 Simulation results with load shifting control strategy

Under this setup, generated power through the PV panels will be immediately consumed by the demand of the house. Load shifting control strategy was adopted to consume any unused (or surplus) local generation with smart appliances (e.g. electrical water heater, dishwasher, and washing machine) to minimise the overall demand from the grid and reducing (if not completely avoid) the local PV generated energy sold to the grid.

The whole house electrical power consumption, PV generated electrical power, unused generated electrical power sold to the grid, and electrical power consumed from the grid are illustrated and summarised in figure 5.20 and table 5.17 respectively.

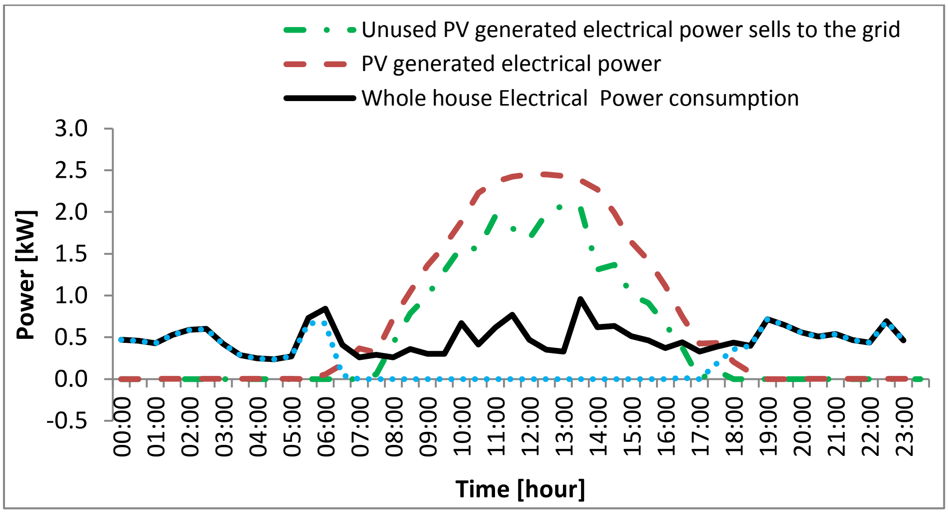

Figure 5.20 Simulation results with load shifting control strategy

Table 5.17 Simulation results with shifting control strategy which exploits smart electrical water heater, dishwasher, and washing machine.

Season	PV maximum output power kWp	Whole house Electrical energy consumption kWh	PV generated electrical energy kWh	Unused PV generated electrical energy sells to the grid kWh	Energy consumed from the grid kWh
Winter	4	22.50	34.62	23.98	11.86

For this setup, the house consumed 12 kWh (53% of its total consumption) is supplied by the grid and consumed 0.3 kWh (1. % of its total consumption) less from the grid when compared without any control strategy applied. However, there is still a substantial amount of local generated energy (24 kWh, 70% of the total local generated energy) is not consumed locally and will be sold to the grid.

5.4.6.3 Simulation results with load shifting and energy buffering control strategy

Under this setup, the author assumed that the hot water in the house will be supported with smart electrical water heaters. The hot water will be stored in a tank (e.g. 200 litres), the smart electrical heaters will consume 12kWh to raise the water temperature in the tank from 10℃ up to 60℃. The water in the tank is stored to be used at a later time. Usually these smart heaters are expected to operate in low tariff period (e.g. economy 7 scheme in UK) to buffer the required energy, if the energy supply is solely from the grid. The proposed control strategy will further use the surplus local generated energy (i.e. after applying the load shifting strategy) to use these smart electrical heater to heat the water in the tank. Once the surplus is no longer available, the heating process will stop immediately to avoid the use of energy from the grid in its peak period (or high tariff period).

The whole house electrical power consumption, PV generated electrical power, unused generated electrical power sold to the grid, and electrical power consumed from the grid are illustrated and summarised in figure 5.21 and table 5.18 respectively.

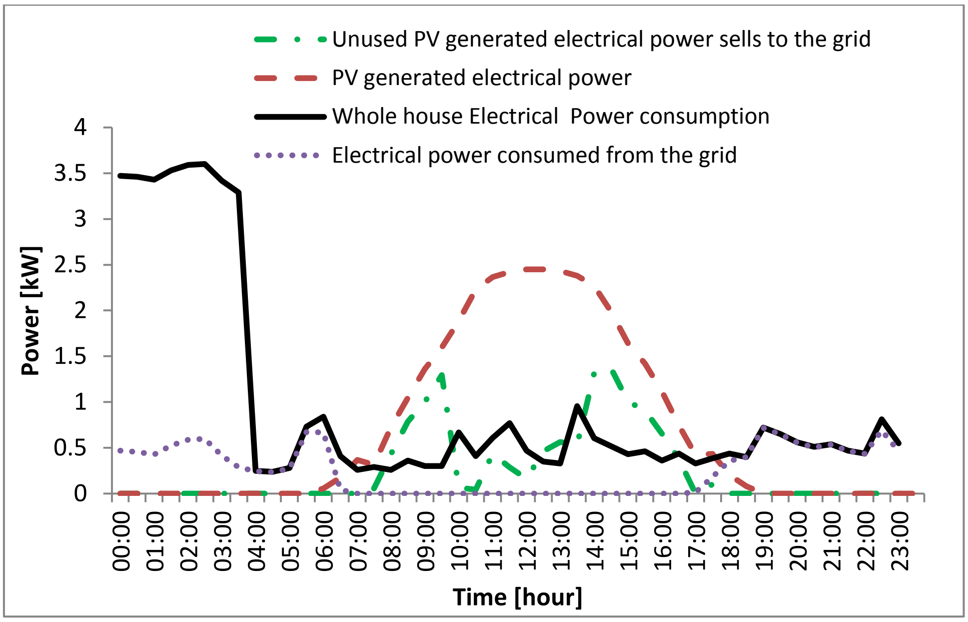

Figure 5.21 Simulation results with load shifting and energy buffering control strategy

Table 5.18 Simulation results with load shifting and energy buffering control strategy which exploits smart electrical water heater, dishwasher, and washing machine.

Season	PV maximum output power kWp	Whole house Electrical energy consumption kWh	PV generated electrical energy kWh	Unused PV generated electrical energy sells to the grid kWh	Energy consumed from the grid kWh
Summer	4	34.62	34.62	11.86	11.86

For this setup, the house consumed 12 kWh (34% of its total consumption) is supplied by the grid and the rest is from the local PV panels. However, there is still approximately one-third of local generated energy (12 kWh, 34% of the total local energy generation) is not consumed locally and will be sold to the grid.

5.4.7 Summary of simulation results

The investigating results are summarized in table 5.19.

Table 5.19 Investigated results

Max. PV Power output (kWp)	**Season**	**Local energy generation period (kWh)**				
		Total local generated energy	**Whole house base energy consumption**	**Unused energy**		
				without control strategy	**With load shifting strategy**	**With load shifting and buffering strategy**
1	**Summer**	**8.65**	**22.5**	**1.12**	**0.89**	**0.10**
	Winter	**4.74**	**7.73**	**3.15**	**2.58**	**0.00**
2.5	**Summer**	**21.64**	**22.50**	**11.88**	**11.63**	**3.92**
	Winter	**11.84**	**7.725**	**9.87**	**7.72**	**0.00**
4	**Summer**	**34.62**	**22.50**	**24.23**	**23.98**	**11.86**
	Winter	**19.94**	**7.73**	**16.75**	**14.29**	**0.00**

The investigated results from table 5.19 have further transformed to provide an annual view of the impact; a more common view in presenting long term data. The transformed results are summarised in table 5.20.

Table 5.20 Summary of investigated results in annual basis:

Max. PV Power output (kWp)	**Local energy generation period (kWh)**				
	Total local generated energy	**Whole house base energy consumption**	**Unused energy**		
			Without control strategy	**With load shifting strategy**	**With load shifting and buffering strategy**
1	**2,453**	**5,553**	**774**	**629**	**18**
2.5	**6,135**	**5,553**	**3,974**	**3,542**	**726**
4	**9,993**	**5,553**	**7,498**	**7,009**	**2,194**

The annual view of the impact results is illustrated in figure 5.22.

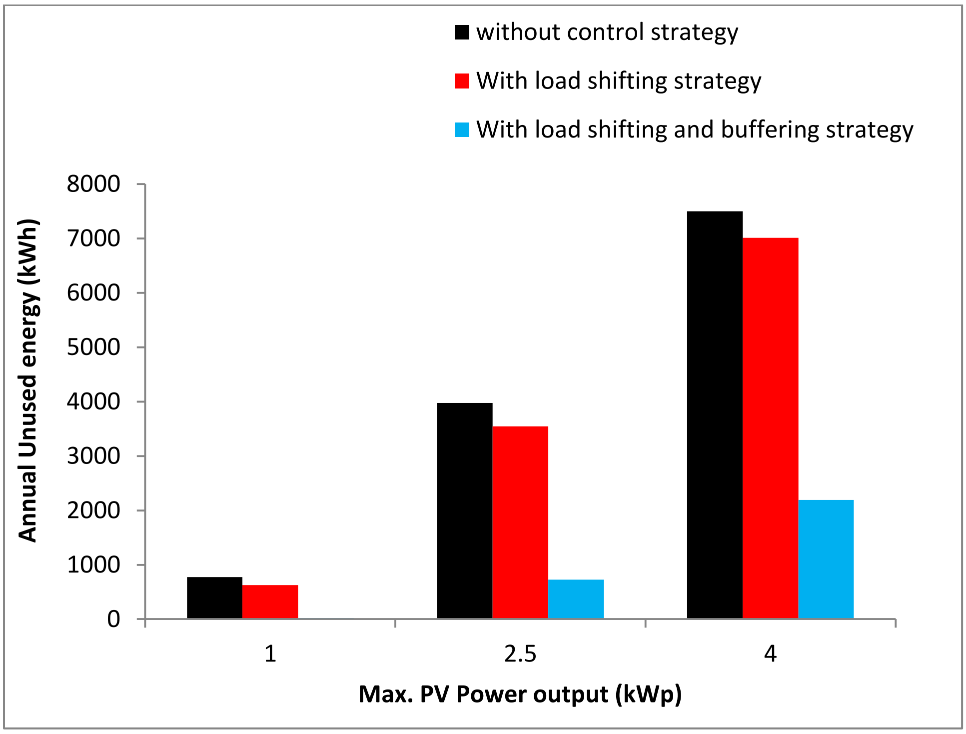

Figure 5.22 Annual view of the impact results

Figure 5.22 shows the most effective control strategy is combining the concepts of load shifting and energy buffering. Although the control strategy with load shifting concept alone still shows some effect in tackling the temporal energy mismatch problem, its effect is comparatively minimal when compared with combined concepts.

5.5 Impact analyses of the proposed temporal energy mismatch control strategy

The impact analysis is mainly through the finance and carbon emission perspectives.

5.5.1 Analysis of 1 kWp PV power generation in winter season

5.5.1.1 Scenario without applying any control strategy

In this scenario the electrical energy consumed from the grid is reduced from 7.72 to 6.14 kWh and 3.2 kWh of the PV generated energy (66% of total local generated energy) sold to the grid.

Cost reduction[3] (CR) due to local generated renewable energy:

$$CR = (7.725 - 6.14)(13.8705/100) = £\ 0.22$$

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[3] The cost of the electricity unit price for the high tariff period $= 13.21 + 5\%\ VAT = 13.8705\ p/kWh$

The financial gain (FG) through selling the unused renewable surplus energy to the grid[4]:

$FG = 3.15\ \times\ (4.77/100) = £\,0.15$

Total cost reduction (TCR) due to local generated renewable energy and gain through selling the unused renewable surplus energy to the grid:

$TCR = 0.22 + 0.15 = £\,0.37$

Carbon emission[5] reduction (CER) due to local generated renewable energy:

$CER = (7.725 - 6.14)(0.44548) = 0.7\ kg\ C$

5.5.1.2 *Scenario with applying load shifting control strategy*

In this scenario the electrical energy consumed from the grid is reduced from 7.72 to 5.57 kWh and 2.58 kWh of the PV generated energy (54.56 % of total local generated energy) will sell to the grid.

Cost reduction due to local generated renewable energy:

$CR = (7.725 - 5.573)(13.8705/100) = £\,0.30$

The finance gain through selling the unused renewable surplus energy to the grid:

$FG = 2.584\ \times\ (4.77/100) = £\,0.12$

Total cost reduction due to local generated renewable energy and gain through selling the unused renewable surplus energy to the grid:

$TCR = 0.30 + 0.12 = £\,0.42$

Carbon emission reduction due to local generated renewable energy:

$CER = (7.725 - 5.573)(0.44548) = 0.96\ kg\ C$

5.5.1.3 *Scenario with applying load shifting and energy buffering control strategies*

In this scenario, the house will be equipped with smart electrical storage heating system which will consume 17 kWh in low tariff period (e.g. economy 7 scheme in UK). The whole house energy consumption is equal to 25 kWh, of which 18kWh is consumed in the low tariff period, and 7 kWh is consumed in the high tariff period.

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[4] Selling the unused renewable generated energy to the grid unit price = 4.77 p/kWh

[5] Carbon emission factor for electricity=$0.44548\ kg\ C/kWh$

With applying the load shifting and energy buffering control strategy, the energy consumed from the grid is reduced from 25 to 20 kWh, of which 15kWh is consumed in the low tariff period and 5 kWh is consumed in the high tariff period. In this scenario, there is no unused PV generated energy sold to the grid.

Cost reduction[6] due to local generated renewable energy:

$$CR = [(6.495 \times 13.8705 + 18.23 \times 8.694)/100] - [(4.69 \times 13.8705 + 15.301 \times 8.694)/100] = £\,0.51$$

The financial gain through selling the unused renewable surplus energy to the grid:

$$FG = 0 \times 4.77/100 = £0$$

Total cost reduction due to local generated renewable energy and gain through selling the unused renewable surplus energy to the grid:

$$TCR = 0.51 + 0 = £\ 0.51$$

Carbon emission reduction due to local generated renewable:

$$CER = (24.725 - 19.991)(0.44548) = 2.11\ kg\ C$$

5.5.2 Analysis of 2.5 kWp PV power generation in winter season

5.5.2.1 Scenario without applying any control strategy

In this scenario the electrical energy consumed from the grid is reduced from 7.7 to 5.8 kWh and 10 kWh of the PV generated energy (83% of total local generated energy) sold to the grid.

Cost reduction due to local generated renewable energy:

$$CR = (7.725 - 5.76)(13.8705/100) = £\,0.27$$

The financial gain through selling the unused renewable surplus energy to the grid

$$FG = 9.87 \times (4.77/100) = £\,0.47$$

Total cost reduction due to local generated renewable energy and gain through selling the unused renewable surplus energy to the grid:

$$TCR = 0.27 + 0.47 = £\ 0.74$$

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[6] The cost of the electricity unit price for the low tariff period (economy 7 scheme in UK)$= 8.28 + 5\%\ VAT = 8.694\ \ p/kWh$

Carbon emission reduction due to local generated renewable energy:

$$CER = (7.725 - 5.76)(0.44548) = 0.88\ kg\ C$$

5.5.2.2 Scenario with applying load shifting control strategy

In this scenario the electrical energy consumed from the grid is reduced from 7.7 to 3.6 kWh and 7.7 kWh of the PV generated energy (65% of total local generated energy) will sell to the grid.

Cost reduction due to local generated renewable energy:

$$CR = (7.725 - 3.608)(13.8705/100) = £\,0.57$$

The finance gain through selling the unused renewable surplus energy to the grid:

$$FG = 7.723\ \times\ 4.77/100 = £\,0.37$$

Total cost reduction due to local generated renewable energy and gain through selling the unused renewable surplus energy to the grid:

$$TCR = 0.57 + 0.37 = £\ \ 0.94$$

Carbon emission reduction due to local generated renewable energy:

$$CER = (7.725 - 3.608)(0.44548) = 1.83\ kg\ C$$

5.5.2.3 Scenario with applying load shifting and energy buffering control strategies

In this scenario, the house will be equipped with smart electrical storage heating system which will consume 17 kWh in low tariff period (e.g. economy 7 scheme in UK). The whole house energy consumption is equal to 25 kWh, of which 18kWh is consumed in the low tariff period, and 7 kWh is consumed in the high tariff period.

With applying the load shifting and energy buffering control strategy, the energy consumed from the grid is reduced from 24.7 to 13 kWh, of which 8.8 kWh is consumed in the low tariff period and 4kWh is consumed in the high tariff period. In this scenario, there is no unused PV generated energy will be sold to the grid.

The whole house electrical energy consumption cost (WHC):

$$WHC = (4.115 \times\ 13.8705 + 8.771 \times 8.694)/100 = £\,1.33$$

Cost reduction due to local generated renewable energy:

$$CR = [(6.495 \times 13.8705 + 18.23\ \times\ 8.694)/100] - \ [(4.115 \times\ 13.8705 + 8.771 \times 8.694)/100] = £\ \ 1.16$$

The financial gain through selling the unused renewable surplus energy to the grid:

$FG = 0 \times 4.77 = £0$

Total cost reduction due to local generated renewable energy and gain through selling the unused renewable surplus energy to the grid:

$TCR = 0 + 1.16 = £\ 1.16$

Carbon emission reduction due to local generated renewable energy:

$CER = (24.725 - 12.886\ )(0.44548) = 5.27\ kg\ C$

5.5.3 Analysis of 4 kWp PV power generation in winter season

5.5.3.1 Scenario without applying any control strategy

In this scenario the electrical energy consumed from the grid is reduced from 7.7 to 5.5 kWh, and 16.8 kWh of the PV generated energy (88% of total local generated energy) will sell to the grid.

Cost reduction due to local generated renewable energy:

$CR = (7.725 - 5.534)(13.8705/100) = £\ 0.34$

The finance gain through selling the unused renewable surplus energy to the grid:

$FG = 16.75\ \times\ 4.77/100 = £\ 0.80$

Total cost reduction due to local generated renewable energy and gain through selling the unused renewable surplus energy to the grid:

$TCR = 0.34 + 0.80 = £\ 1.14$

Carbon emission reduction due to local generated renewable energy:

$CER = (0.44548) = 0.98\ kg\ C$

5.5.3.2 Scenario with applying load shifting control strategy

In this scenario the electrical energy consumed from the grid is reduced from 7.7 to 3kWh and 14kWh of the PV generated energy (75% of total local generated energy) sold to the grid.

Cost reduction due to local generated renewable energy:

$CR = (7.725 - 3.072)(13.8705/100) = £\ 0.64$

The finance gain through selling the unused renewable surplus energy to the grid:

$FG = 14.291\ \times\ 4.77/100 = £\ 0.68$

Total cost reduction due to local generated renewable energy and gain through selling the unused renewable surplus energy to the grid:

$TCR = 0.64 + 0.68 = £\ 1.32$

Carbon emission reduction due to local generated renewable energy:

$CER = (7.725 - 3.072)(0.44548) = 2.07\ kg\ C$

5.5.3.3 *Scenario with applying load shifting and energy buffering control strategies*

In this scenario, the house will be equipped with smart electrical storage heating system which will consume 17 kWh in low tariff period (e.g. economy 7 scheme in UK). The whole house energy consumption is equal to 25 kWh, of which 18kWh is consumed in the low tariff period, and 7 kWh is consumed in the high tariff period.

The whole house electrical energy consumption cost:

$WHC = (6.495 \times 13.8705 + 18.23\ \times\ 8.694)/100 = £2.49$

The whole house carbon emission due to electrical energy consumption($WHCE$):

$WHCE = 0.44548\ \times 24.725 = 11.01\ kg\ C$

With applying the load shifting and energy buffering control strategy, the energy consumed from the grid is reduced from 24.7 to 5.8 kWh, of which 1kWh is consumed in the low tariff period and 4.8 kWh is consumed in the high tariff period. In this scenario, there is no unused PV generated energy will be sold to the grid.

Cost reduction due to local generated renewable energy:

$$\begin{aligned} CR = {} & [(6.495 \times 13.8705 + 18.23\ \times\ 8.694)/100] \\ & - [(4.757\ \times\ 13.8705 + 1.03 \times 8.694)/100] = £\ 1.74 \end{aligned}$$

The financial gain through selling the unused renewable surplus energy to the grid:

$FG = 0\ \times\ 4.77/100 = £0$

Total cost reduction due to local generated renewable energy and gain through selling the unused renewable surplus energy to the grid:

$TCR = 1.74 + 0.0 = £\ 1.74$

Carbon emission reduction due to local generated renewable:

$CER = (24.75 - 5.787)(0.44548) = 8.44\ kg\ C$

5.5.4 Analysis of 1 kWp PV power generation in summer season

5.5.4.1 Scenario without applying any control strategy

In this scenario the electrical energy consumed from the grid is reduced from 22.5 to 15 kWh, and 1kWh of the PV generated energy (13% of total local generated energy) sold to the grid.

Cost reduction due to local generated renewable energy:

$$CR = (22.5 - 14.96)(13.8705/100) = \text{£}\ 1.05$$

The finance gain through selling the unused renewable surplus energy to the grid:

$$FG = 1.12\ \times\ 4.77/100 = \text{£}\ 0.05$$

Total cost reduction due to local generated renewable energy and gain through selling the unused renewable surplus energy to the grid:

$$TCR = 1.05 + 0.05 = \text{£}\ 1.10$$

Carbon emission reduction due to local generated renewable energy:

$$CER = (22.5 - 14.96)(0.44548) = 3.36\ \text{kg C}$$

5.5.4.2 Scenario with applying load shifting control strategy

In this scenario the electrical energy consumed from the grid is reduced from 22.5 to 14.7 kWh and 0.9 kWh of the PV generated energy (10% of total local generated energy) sold to the grid.

Cost reduction due to local generated renewable energy:

$$CR = (22.5 - 14.729)(13.8705\ /\ 100) = \text{£}\ 1.08$$

The finance gain through selling the unused renewable surplus energy to the grid:

$$FG = (0.887\ \times\ 4.77)/100 = \text{£}\ 0.04$$

Total cost reduction due to local generated renewable energy and gain through selling the unused renewable surplus energy to the grid:

$$TCR = 1.08 + 0.04 = \text{£}\ 1.12$$

Carbon emission reduction due to local generated renewable energy:

$$CER = (22.5 - 14.729)(0.44548) = 3.46\ \text{kg C}$$

5.5.4.3 Scenario with applying load shifting and energy buffering control strategies

In this scenario, the house will be equipped with smart electrical water heating system. The smart electrical water heaters will consume 12kWh in low tariff period (e.g. economy 7 scheme in UK) to raise the water temperature of a 200 litre tank from 10℃ up to 60℃. The whole house energy consumption is equal to 34.6 kWh, of which 18.5 kWh is consumed in the low tariff period, and 16.1 kWh is consumed in the high tariff period.

With applying the load shifting and energy buffering control strategy, the energy consumed from the grid is reduced from 34.6 to 26kWh, of which 18kWh is consumed in the low tariff period and 7.7 kWh is consumed in the high tariff period, and 0.1 kWh of the PV generated energy (1% of total local generated energy) sold to the grid.

Cost reduction due to local generated renewable energy:

$$CR = [(16.104 \times 13.8705 + 18.521 \times 8.694)/100] \\ - [(7.702 \times 13.8705 + 18.367 \times 8.694)/100] = £\,1.18$$

The financial gain through selling the unused renewable surplus energy to the grid:

$$FG = 0.098 \times 4.77/100 = £\,0.005$$

Total cost reduction due to local generated renewable energy and gain through selling the unused renewable surplus energy to the grid:

$$TCR = 1.18 + 0.005 = £\,1.185$$

Carbon emission reduction due to local generated renewable:

$$CER = (34.625 - 26.069)(0.44548) = 3.81\ \text{kg C}$$

5.5.5 Analysis of 2.5 kWp PV power generation in summer season

5.5.5.1 Scenario without applying any control strategy

In this scenario the electrical energy consumed from the grid is reduced from 22.5 to 12.7 kWh and 11.9 kWh of the PV generated energy (50 % of total local generated energy) sold to the grid.

Cost reduction due to local generated renewable energy:

$$CR = (22.5 - 12.74)(13.8705\ /\ 100) = £\,1.35$$

The finance gain through selling the unused renewable surplus energy to the grid:

$FG = (11.88 \times 4.77)/100 = £\,0.57$

Total cost reduction due to local generated renewable energy and gain through selling the unused renewable surplus energy to the grid:

$TCR = 1.35 + 0.57 = £\,1.92$

Carbon emission reduction due to local generated renewable energy:

$CER = (22.5 - 12.74)(0.44548) = 4.35\ kg\ C$

5.5.5.2 *Scenario with applying load shifting control strategy*

In this scenario the electrical energy consumed from the grid is reduced from 22.5 to 12.5 kWh and 11.6 kWh of the PV generated energy (54 % of total local generated energy) sold to the grid.

Cost reduction due to local generated renewable energy:

$CR = (22.5 - 12.491)(13.8705\ /\ 100) = £\,1.39$

The finance gain through selling the unused renewable surplus energy to the grid:

$FG = (11.631 \times 4.77)/100 = £\,0.56$

Total cost reduction due to local generated renewable energy and gain through selling the unused renewable surplus energy to the grid:

$TCR = 1.39 + 0.56 = £\,1.95$

Carbon emission reduction due to local generated renewable energy:

$CER = (22.5 - 12.491)(0.44548) = 4.46\ kg\ C$

5.5.5.3 *Scenario with applying load shifting and energy buffering control strategies*

In this scenario, the house will be equipped with smart electrical water heating system. The smart electrical water heaters will consume 12kWh in low tariff period (e.g. economy 7 scheme in UK) to raise the water temperature of a 200 litre tank from 10℃ up to 60℃. The whole house energy consumption is equal to 34.6 kWh, of which 18.5 kWh is consumed in the low tariff period, and 16.1 kWh is consumed in the high tariff period.

With applying the load shifting and energy buffering control strategy, the energy consumed from the grid is reduced from 34.6 to 16.9 kWh, of which 10.6 kWh is consumed in the low tariff period and 6.4 kWh is consumed in the high tariff period, and 4 kWh of the PV generated energy (18% of total local generated energy) is sold to the grid.

Cost reduction due to local generated renewable energy:

$$CR = [(16.104 \times 13.8705 + 18.521 \times 8.694)/100] - [(6.36 \times 13.8705 + 10.55 \times 8.694)/100] = £\,2.04$$

The financial gain through selling the unused renewable surplus energy to the grid:

$$FG = 3.923 \times 4.77/100 = £\,0.19$$

Total cost reduction due to local generated renewable energy and gain through selling the unused renewable surplus energy to the grid:

$$TCR = 2.04 + 0.19 = £\,2.23$$

Carbon emission reduction due to local generated renewable:

$$CER = (34.625 - 16.91)(0.44548) = 7.89\ kg\ C$$

5.5.6 Analysis of 4 kWp PV power generation in summer season

5.5.6.1 Scenario without applying any control strategy

In this scenario the electrical energy consumed from the grid is reduced from 22.5 to 12.1 kWh and 24kWh of the PV generated energy (70 % of total local generated energy) sold to the grid.

Cost reduction due to local generated renewable energy:

$$CR = (22.5 - 12.109)(13.8705\ /\ 100) = £\,1.44$$

The finance gain through selling the unused renewable surplus energy to the grid:

$$FG = (24.232 \times 4.77)/100 = £\,1.16$$

Total cost reduction due to local generated renewable energy and gain through selling the unused renewable surplus energy to the grid:

$$TCR = 1.44 + 1.16 = £\,2.6$$

Carbon emission reduction due to local generated renewable energy:

$$CER = (22.5 - 12.109)(0.44548) = 4.63\ kg\ C$$

5.5.6.2 Scenario with applying load shifting control strategy

In this scenario the electrical energy consumed from the grid is reduced from 22.5 to 12 kWh and 24 kWh of the PV generated energy (70% of total local generated energy) sold to the grid.

Cost reduction due to local generated renewable energy:

$$CR = (22.5 - 11.862)(13.8705\ /\ 100) = £\ 1.48$$

The finance gain through selling the unused renewable surplus energy to the grid:

$$FG = (23.984\ \times\ 4.77)/100 = £\ 1.14$$

Total cost reduction due to local generated renewable energy and gain through selling the unused renewable surplus energy to the grid:

$$TCR = 1.48 + 1.14 = £\ 2.62$$

Carbon emission reduction due to local generated renewable energy:

$$CER = (22.5 - 11.862)(0.44548) = 4.74\ kg\ C$$

5.5.6.3 Scenario with applying load shifting and energy buffering control strategies

In this scenario, the house will be equipped with smart electrical water heating system. The smart electrical water heaters will consume 12kWh in low tariff period (e.g. economy 7 scheme in UK) to raise the water temperature of a 200 litre tank from 10℃ up to 60℃. The whole house energy consumption is equal to 34.6 kWh, of which 18.5 kWh is consumed in the low tariff period, and 16.1 kWh is consumed in the high tariff period.

With applying the load shifting and energy buffering control strategy, the energy consumed from the grid is reduced from 34.62 to 11.86 kWh, of which 5.90 kWh is consumed in the low tariff period and 5.96 kWh is consumed in the high tariff period, and 11.86 kWh of the PV generated energy (34.25% of total local generated energy) sold to the grid.

Cost reduction due to local generated renewable energy:

$$\begin{aligned} CR = {} & [(16.104 \times 13.8705 + 18.521\ \times\ 8.694)/100] \\ & - [(5.961\ \times\ 13.8705 + 5.903 \times 8.694)/100] = £\ 2.5 \end{aligned}$$

The financial gain through selling the unused renewable surplus energy to the grid:

$FG = 11.858 \times 4.77/100 = £\,0.57$

Total cost reduction due to local generated renewable energy and gain through selling the unused renewable surplus energy to the grid:

$TCR = 2.5 + 0.57 = £\,3.07$

Carbon emission reduction due to local generated renewable:

$CER = (34.625 - 11.864)(0.44548) = 10.14\ kg\ C$

5.5.7 Summary of the impact analyses

The analysed results are summarized in table 5.21.

Table 5.21 Summary of cost and carbon emission reduction in daily basis:

Max. PV Power output kWp	**Season**	**Cost reduction £**			**Carbon emission reduction kg C**		
		Without control strategy	**With load shifting strategy**	**With load shifting and buffering strategy**	**Without control strategy**	**With load shifting strategy**	**With load shifting and buffering strategy**
1	**Summer**	**1.10**	**1.12**	**1.19**	**3.36**	**3.46**	**3.81**
	Winter	**0.37**	**0.42**	**0.51**	**0.70**	**0.96**	**2.11**
2.5	**Summer**	**1.92**	**1.95**	**2.23**	**4.35**	**4.46**	**7.89**
	Winter	**0.74**	**0.94**	**1.16**	**0.88**	**1.83**	**5.27**
4	**Summer**	**2.6**	**2.62**	**3.07**	**4.63**	**4.74**	**10.14**
	Winter	**1.14**	**1.32**	**1.74**	**0.98**	**2.07**	**8.44**

The data from table 5.21 have further transformed to provide an annual view of the impact; a more common view in presenting long term benefits. The transformed results are summarised in table 5.22.

Table 5.22 Summary of annual cost and carbon emission reduction:

Max. PV Power output kWp	**Cost reduction £**			**Carbon emission reduction kg C**		
	Without control strategy	**With load shifting strategy**	**With load shifting and buffering strategy**	**Without control strategy**	**With load shifting strategy**	**With load shifting and buffering strategy**
1	**270**	**299**	**311**	**747**	**813**	**1,085**
2.5	**488**	**528**	**621**	**963**	**1,155**	**2,405**
4	**686**	**722**	**881**	**1,033**	**1,250**	**3,395**

The summary of annual cost and carbon emission reduction are illustrated in the figures 5.23 and 5.24 respectively.

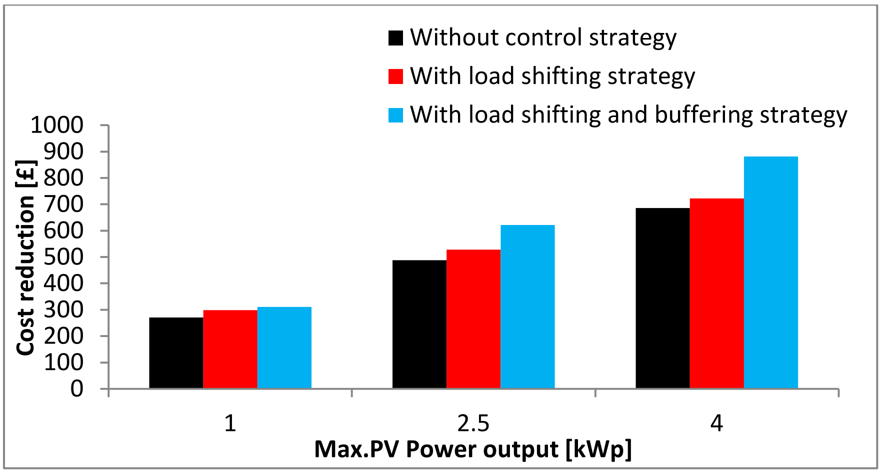

Figure 5.23 Annual cost reduction

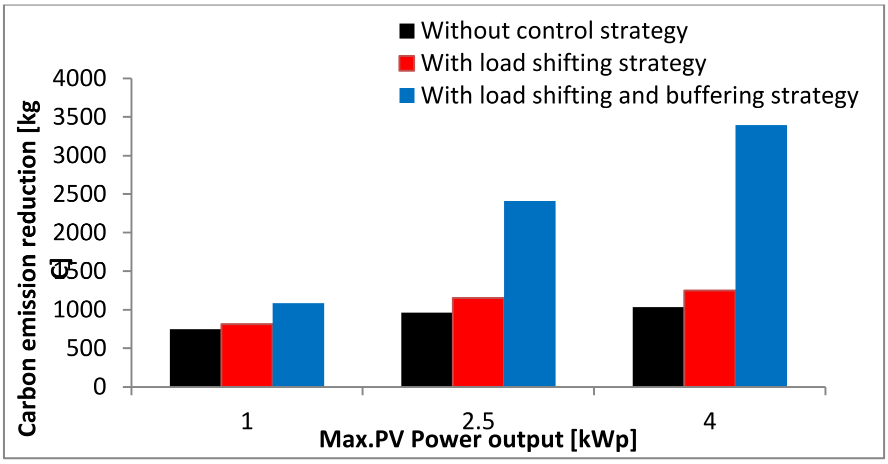

Figure 5.24 Annual carbon emission reduction

The summarised results from table 5.20 has proved the viability of the proposed temporal energy mismatch control strategy, which maximising the use of local generated energy (99%, 99% and 78% for 1kWp, 2.5kWp and 4kWp installed PV panels respectively) and reducing the energy demand from the grid (22%, 50% and 70% for 1kWp, 2.5kWp and 4kWp installed PV panels respectively). Through the results, it also clearly indicated the most effective control strategy is through energy buffering although load shifting also has its contribution to the overall results

Further analyses in section 5.5 have shown significant impact in socio-economic aspect of the society if the proposed temporal energy mismatch control strategy has adopted.

From economic perspective, the household who installed the local renewable energy generation system without extra energy storage device no longer required to sell the surplus energy to the grid in a much lower price (4.77 per kWh) due to temporal energy mismatch issue. The proposed temporal energy mismatch control strategy will maximise the use of the local generated energy and demand less from the grid. As a result, the energy bill for the household will be reduced, depending on the capacity of the installed system. Installing PV panels from 1 KWp to 4 kWp might be expected to annually save £40 to £195 energy costs.

From the environmental perspective, significant carbon emissions will be reduced because of the demand reduction in the high tariff period. Figure 5.24 and table 5.22 show 340 kg C, 1450 kg C and 2360 kg C can be less produced annually for a 3 bedrooms semi-detached house with the installation of 1kWp, 2.5kWp and 4kWp PV panels respectively. According to these figures, the amount of carbon emission reduction achieved with a 4kWp PV panel can be equated to the total carbon emission produced by 26 fridge-freezers (206 kWh per year) annually or equated to 46 washing machines (0.63 kWh per run) running for 187 times annually [127].

If 5% (1.32 million house) of the UK houses (26.4 million homes) [128] installed with 4kWp PV panels and adopt the proposed temporal energy mismatch control strategy, 3.12 million tonnes C (or 2% carbon emission reduction in the UK residential sector [129, 130]) will be reduced annually. This simple analysis indicates significant contribution to Climate Change Act 2008 to help the UK reduce greenhouse gas emissions by at least 80% by 2050 [131] can be obtained, if the proposed temporal energy mismatch control strategy could be widely adopted by the houses which installed with local renewable energy generation system such as PV panel system.

6 Conclusions and Future work

6.1 Research summary

This research study has been undertaken to try and address the temporal energy mismatch problem between local PV generated energy and domestic energy consumption without using dedicated energy storage systems such as rechargeable battery systems. Most importantly, the solution proposed should not affect comfort and/or impose operational burdens on householders.

The literature review in chapter 2 revealed that current state-of-the-art technologies/solutions for tackling the temporal energy mismatch problem relating to renewable energy sources rely on various types of energy storage technologies, of which most are not suitable for the domestic environment. This is in the main because they are designed for industrial scale application (e.g. hydroelectric power plant and solar/wind farms). The most popular energy storage option for the domestic environment today are rechargeable batteries systems, however, such systems are costly to install and maintain but additionally they are not so environmental friendly because of the need for rechargeable batteries to be replaced every few years. The literature review also reveals that Demand Side Management (DSM) has the potential to be part of the solution, although it was originally designed for reducing the peak electricity consumption by load shifting and not explicitly targeting the temporal energy mismatch problem in the domestic environment.

The author has proposed a novel temporal energy mismatch control strategy to address the problem by combining the concepts of DSM (i.e. load shifting) and energy buffering, with the support of appropriate smart domestic appliances. One of the key benefits of the proposed temporal energy mismatch control strategy is addressing the problem without the need for dedicated energy storage systems.

A Simulink model for the fridge freezer has been established in order to investigate the potential of using a smart fridge-freeze to buffer energy. Due to resources constraints, simulation has been chosen as the major vehicle to facilitate the research investigation, although data collected from other research projects (two year data set of domestic energy consumption from DEMS, project funded by EPSRC/TSB and a one year data set of measured PV from the National Energy Research Centre Amman, Jordan) have also been used to support and validate the research investigation.

A set of Simulink models have been developed to establish a Domestic Energy Ecosystem Simulink Model (DEEM). These models have been used to facilitate the study of 'local supply and demand' relationships between local renewable energy source generation (PV panels) and local domestic energy consumption. These models have been employed to facilitate the evaluation and validation of the proposed temporal energy mismatch control strategy. A 'what-if' analysis approach has been adopted to study 'cause-effect' under different scenarios with the proposed temporal energy mismatch control strategy.

The analysis not only considers the effectiveness of the proposed temporal energy mismatch control strategy, but also its potential socio-economic impacts. The economic analysis is limited to the potential impact on the householders only; it does not include business considerations or national level factors.

The socio-economic impacts of the proposed temporal energy control strategy can be summarised as follows:

- Adopting the proposed temporal energy mismatch control strategy, when compared with no control strategy, the reduction of the energy consumed from the grid could potentially be reduced from 54% to 34% in the summer time and from 71% to 23 % in the winter time if a 4kWp PV panel is installed in a three bedroom semi-detached house.
- Adopting the proposed temporal energy mismatch control strategy, when compared with no control strategy, the use of the locally generated energy has the potential to approach up to 70%, 40% and 32% with 1, 2.5 and 4kWp PV panels respectively installed.
- Adopting the proposed temporal energy mismatch control strategy, when compared with no control strategy, the annual energy spend has the potential to be reduced by up to 13%, 21% and 22% with 1, 2.5 and 4kWp PV panels installed respectively.
- Adopting the proposed temporal energy mismatch control strategy, when compared with no control strategy, the annual carbon emission has the potential

to be reduced by up to 31%, 60% and 70% with 1, 2.5 and 4kWp PV panels installed respectively.

6.2 Research findings

The following research findings can be concluded based on the research investigation undertaken. Although the research produced some promising quantifiable results from the proposed temporal energy mismatch control strategy, it can only be used as being indicative because the actual energy consumption of an individual house depends on a range of variables (no home is alike) such as size and type of the house, numbers of householders resident etc., and most importantly the living patterns and behaviours of the householders.

1. When dedicated energy storage system is installed and no temporal energy mismatch control strategy is applied, potentially significant amounts (31%, 65% and 75% with 1, 2.5 and 4kWp PV panels installed respectively) of the locally generated renewable energy are not consumed locally as a result of temporal energy mismatch issues. As such, in UK, the locally generated surplus energy is sold to the grid via export tariffs with significantly lower prices (4.77p/kWh) when compared with the purchase of energy from the grid (8.694p/kWh and 13.8705p/kWh in low and high tariff periods respectively).
2. The proposed temporal energy mismatch control strategy will not reduce the energy consumption of the house, but it will reduce the demand from the grid by potentially increasing the use of local generated renewable energy. As a result, the annual carbon footprint (e.g. approximately 340, 1450 and 2360 kg C with 1, 2.5 and 4kWp PV panels installed respectively) of the house could potentially be significantly reduced and also the annual energy spend (e.g. approximately £41, £133 and £195 with 1, 2.5 and 4kWp PV panels installed respectively) of the house could potential reduced.
3. The daily peak demand of the house can potentially be reduced (e.g. indications suggest up to approximately 70%, 38% and 20% in summer time, and approximately 42%, 31% and 24% in winter time with 1, 2.5 and 4kWp PV panels installed respectively) because there could be less demand from the grid due to increased use of locally generated renewable energy. If this strategy was

used widely a significant carbon emission reduction would result in the upstream of the energy supply chain (i.e. less fossil fuel based generation could be required) when large numbers of domestic homes have PV panels installed and adopt the proposed temporal energy mismatch control strategy.

4. Due to the intermittent nature of the solar energy, the proposed temporal energy mismatch strategy would have to be implemented as an automated controller because manual intervention could not be relied upon. As a result, further research and development work on the design of next generation of smart domestic appliances would be required, because most current smart domestic appliances could not readily support the temporal energy mismatch control strategy (neither in terms of the concept of DSM or energy buffering).
5. Research investigations into fridge-freezers have shown promising capabilities in terms of energy buffering. With some innovative design possibilities in next generation of smart fridge-freezers (e.g. a new compartment for energy storage) it could be a promising avenue to pursue. The simulation results show that if the set-points of the fridge and the freezer are decreased by one degree below the common set points (i.e. 5 ^{o}C and -18 ^{o}C respectively), the compressor will run 21 minutes longer, which means 28Wh will be buffered if the nominal power rating of the compressor is 80 W.

6.3 Research contributions

Most of the renewable energy sources are intermittent in nature which causes a temporal energy mismatch problem between energy supply and demand. To address this issue, dedicated energy storage technologies and systems have been developed such as rechargeable batteries, pumped hydrogen, compressed air, flywheel, fuel cells, and super capacitors. However, the majority of these technologies and systems, except rechargeable batteries systems, are designed for industrial scale, and not suitable for the domestic sector because of their cost and the systems operational complexity. Although rechargeable batteries systems are accepted as an energy storage option for the domestic environment, they have not been widely taken up because of their cost, size and significant impact to the environment. This research study has opened new research avenues in tackling temporal energy mismatch problems in a domestic environment without using dedicated energy storage systems.

1. This research study has contributed to knowledge in establishing a unique solar radiation prediction model in Simulink, which is able to predict the solar radiation on horizontal and tilted surfaces at any place at any time of the day during the year with potentially high degrees of accuracy (a correlation factor of 0.99 based the measured data); albeit the solar radiation Simulink model does not cover all weather conditions and the author recognises this is an important limitation. However, this solar radiation Simulink model can act as a basis for further research to cover various weather conditions. Unlike other previous solar radiation models established, which have lower resolutions in time (i.e. majority of them have a daily or monthly basis; some are hourly but use mean values) and were not sufficient to support this research investigation; the solar radiation Simulink model devised in this research study is capable of higher resolution in time (i.e. minute level resolution). This solar radiation Simulink model is not only beneficial to this research study, but also has potential in supporting future research in developing model-based temporal energy mismatch controllers for PV panels based in domestic environments.
2. This research study has contributed to knowledge in establishing a novel control strategy to help address the temporal energy mismatch problem between the PV energy generation and domestic energy consumption. The adoption of the temporal energy mismatch control strategy could lead to the following benefits:
    - It could reduce the energy demand of the house from the grid by increasing the use of the locally PV generated energy. The impact analysis in Chapter five, Section 5.5 has shown potentially useful socio-economic benefits could be gained without using dedicated energy storage systems. Furthermore, the adoption of the temporal energy mismatch control strategy has a potential to assist the UK government to meet its GHG emissions target set in “The Climate Change Act 2008”, which requires an 80% cut in emissions by 2050 where a significant part of such a cut is expected in terms of the domestic buildings sector.
    - The application of the proposed temporal energy mismatch control strategy would require the support from smart domestic appliance manufacturers. The results of this research study might inspire a future

direction of research and development in next generation of smart domestic appliances. How to provide new capabilities (e.g. developing the digital communications, allow setting, modifying, and controlling the time of operation, and allow setting and modifying the operational parameters of these smart appliances) for supporting domestic appliances to operate effectively and efficiently to maximise the use of local renewable energy sources in a domestic environment could be a direction for consideration.

3. This research study has contributed to knowledge in provoking new thinking related to small installations of renewable energy generation systems in domestic environments. Current research directions and efforts on local renewable energy generation are largely directed into the process of generation and energy generation technologies. There is a lack of incentive and research in smart consumption of local generated energy. The results of this research study proves significant socio-economic gain can be obtained through innovative approach in consuming the locally generated energy from renewable energy sources, even if the energy consumption level has not been reduced.

6.4 Recommendations for the future work

Although this research study has broadly met its defined project aim and objectives, there are still many questions, issues and enhancements that remain, which are beyond the scope of this study, in order to realise the potential socio-economic impacts to society. The author has identified the following:

- Further research study on solar radiation prediction models is required which can account for most weather conditions to further improve the application scope of the model. Such improvement not only enhances the roles of the model in this research area (e.g. supporting the research in advanced controller design), but also becomes a useful tool for other research areas which relates to solar radiation (e.g. agriculture).
- Further research into the next generation of smart domestic appliances, which will provide effective and efficient support of the proposed temporal energy

mismatch control strategy (i.e. supporting local DSM and energy buffering) to maximise the use of local renewable energy sources in a domestic environment.

- Further studies and research on the potential of local micro-grids, which enable direct trading of surplus renewable energy in the neighbourhood.

Further verification and validation of the proposed concepts within a large-scale demonstration field trial is required. Such a field trial would not only facilitate further research in other aspects of the proposed concepts such as interactions between householders and the systems, householder acceptability, but also provide evidence to support to various stakeholders such as the general public, smart appliances manufacturers and policy holders to promote the acceptance of the proposed concepts of this research study.

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Appendix A

A.1 Solar radiation model

A.1.1 Solar radiation prediction Matlab/Simulink structure

The solar radiation prediction Simulink model is composed with a number of subsystems. The structure of the solar radiation prediction model is illustrated in figure A.1.1.

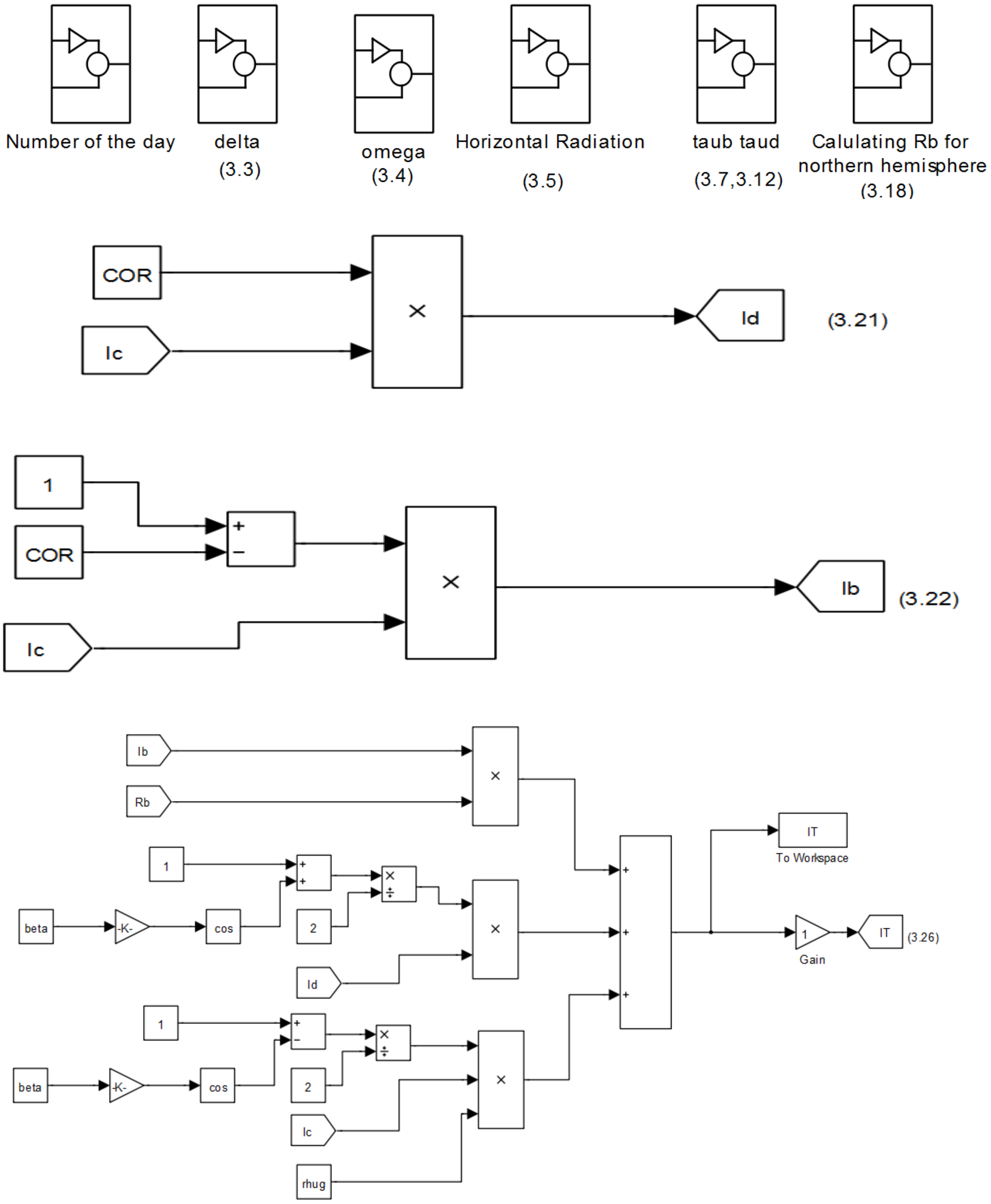

Figure A.1.1 Solar radiation prediction model structure

A.1.2 Number of the day model

Number of the day subsystem structure is illustrated in figure A.1.2.

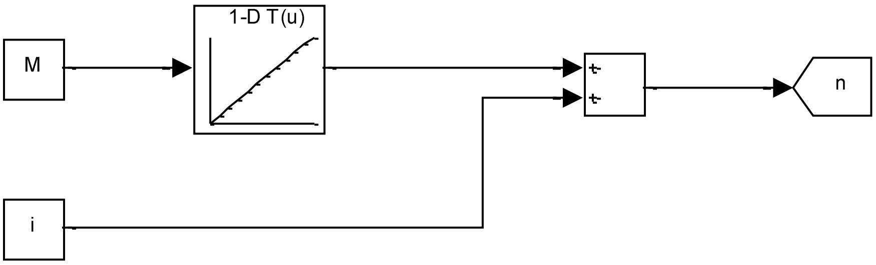

Figure A.1.2 Number of the day subsystem structure

The lockup table block represents the following table:

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
M	0	31	59	90	120	151	181	212	243	273	304	334

A.1.3 Declination angle subsystem structure

Declination angle (equation 3.3) subsystem structure is illustrated in figure A.1.3.

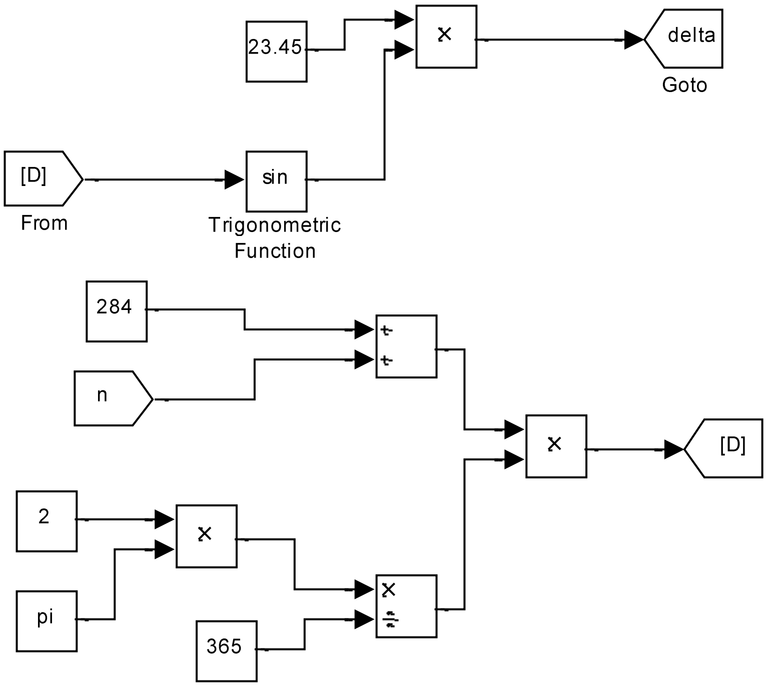

Figure A.1.3 Declination angle prediction subsystem structure

A.1.4 Solar radiation on Horizontal surface prediction model

Solar radiation on Horizontal surface (equation3.18) prediction model structure is illustrated in figure A.1.4.

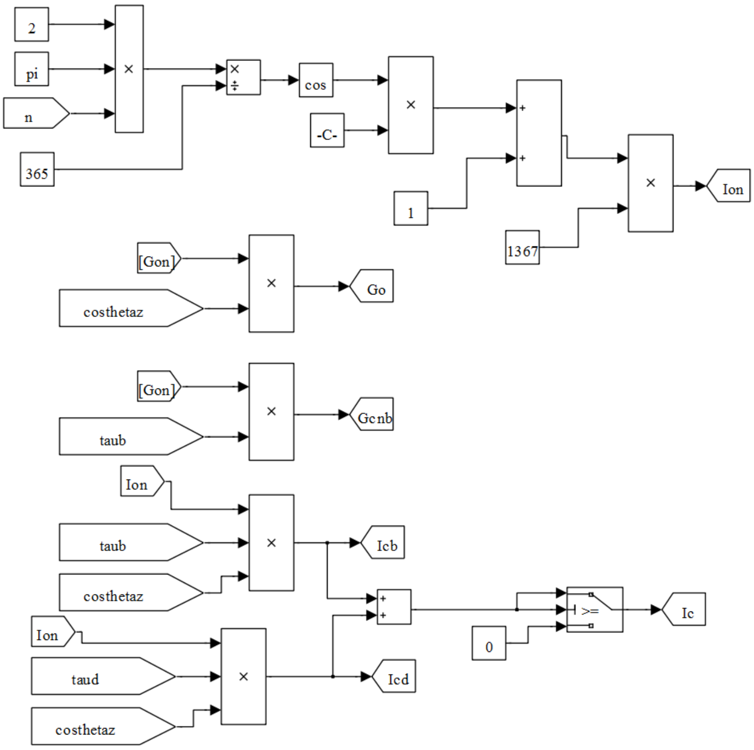

Figure A.1.4 Solar radiation on Horizontal surface prediction model structure

A.1.5 Zenith Angle subsystem structure

Zenith Angle (equation 3.6) subsystem structure is illustrated in figure A.1.5.

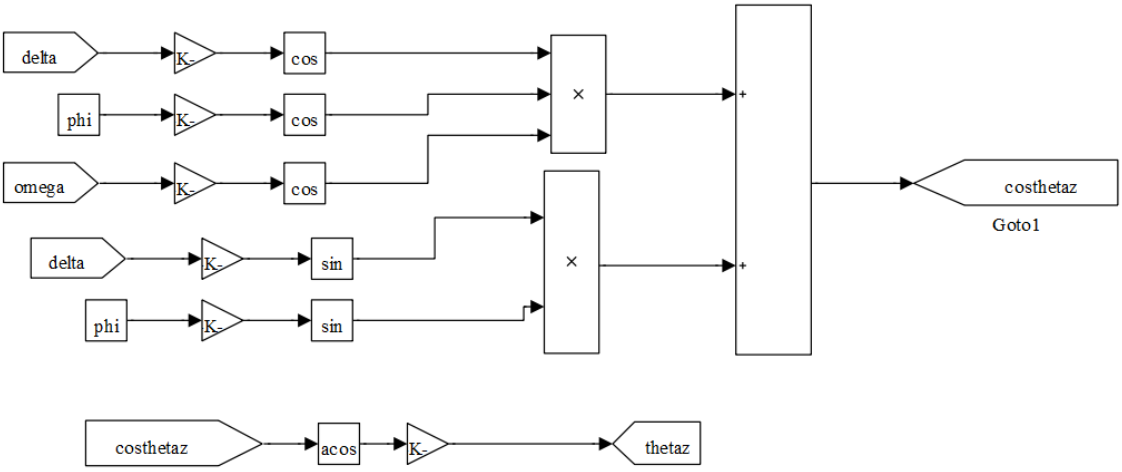

Figure A.1.5 Zenith Angle prediction subsystem structure

A.1.6 Angle of incidence subsystem structure

Angle of incidence (Equation 3.17) subsystem structure is illustrated in figure A.1.6.

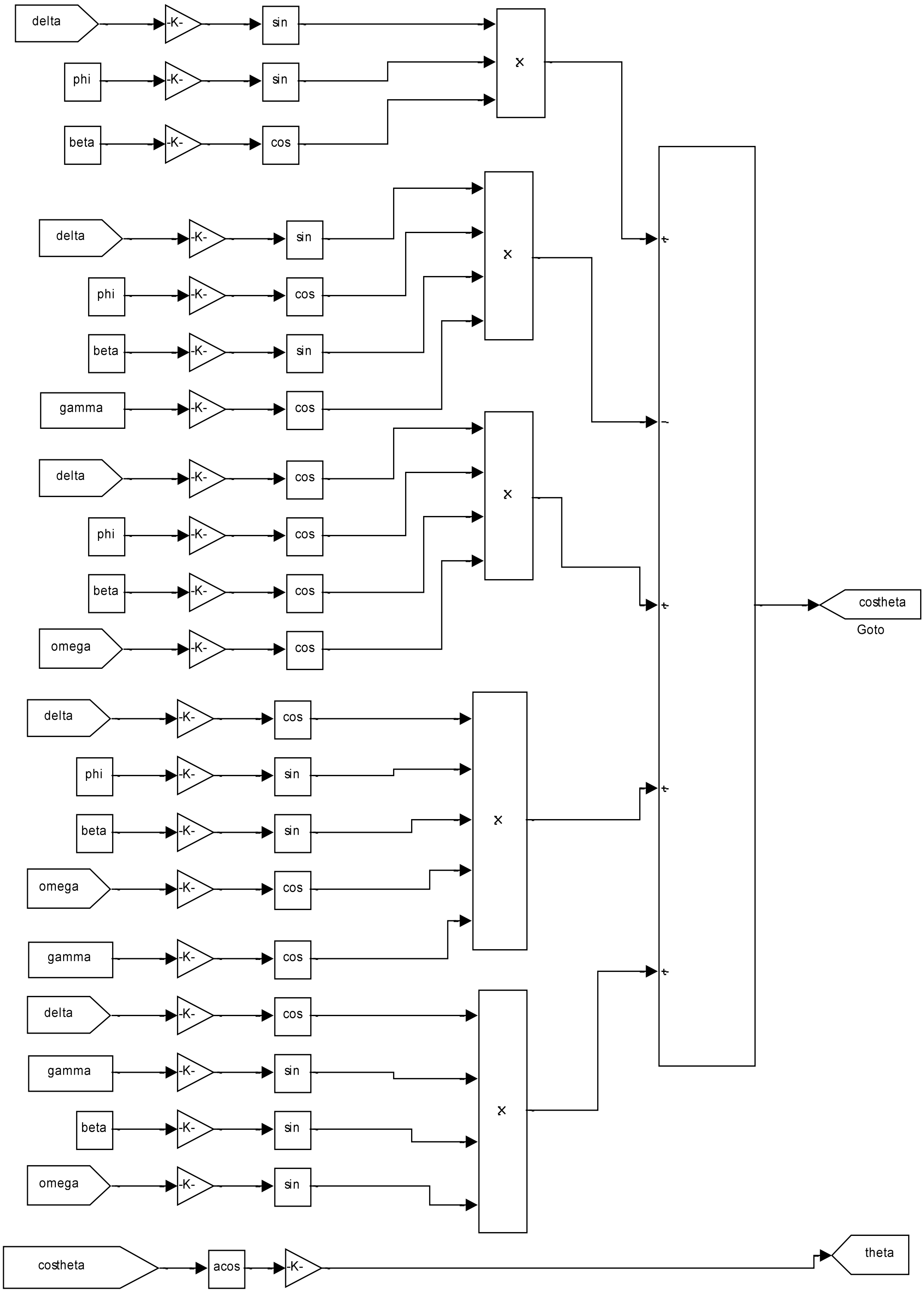

Figure A.1.6 Angle of incidence prediction subsystem structure

A.1.7 Atmospheric transmittance subsystem structure

The atmospheric transmittance (Equation 3.7) subsystem structure is illustrated in figure A.1.7.

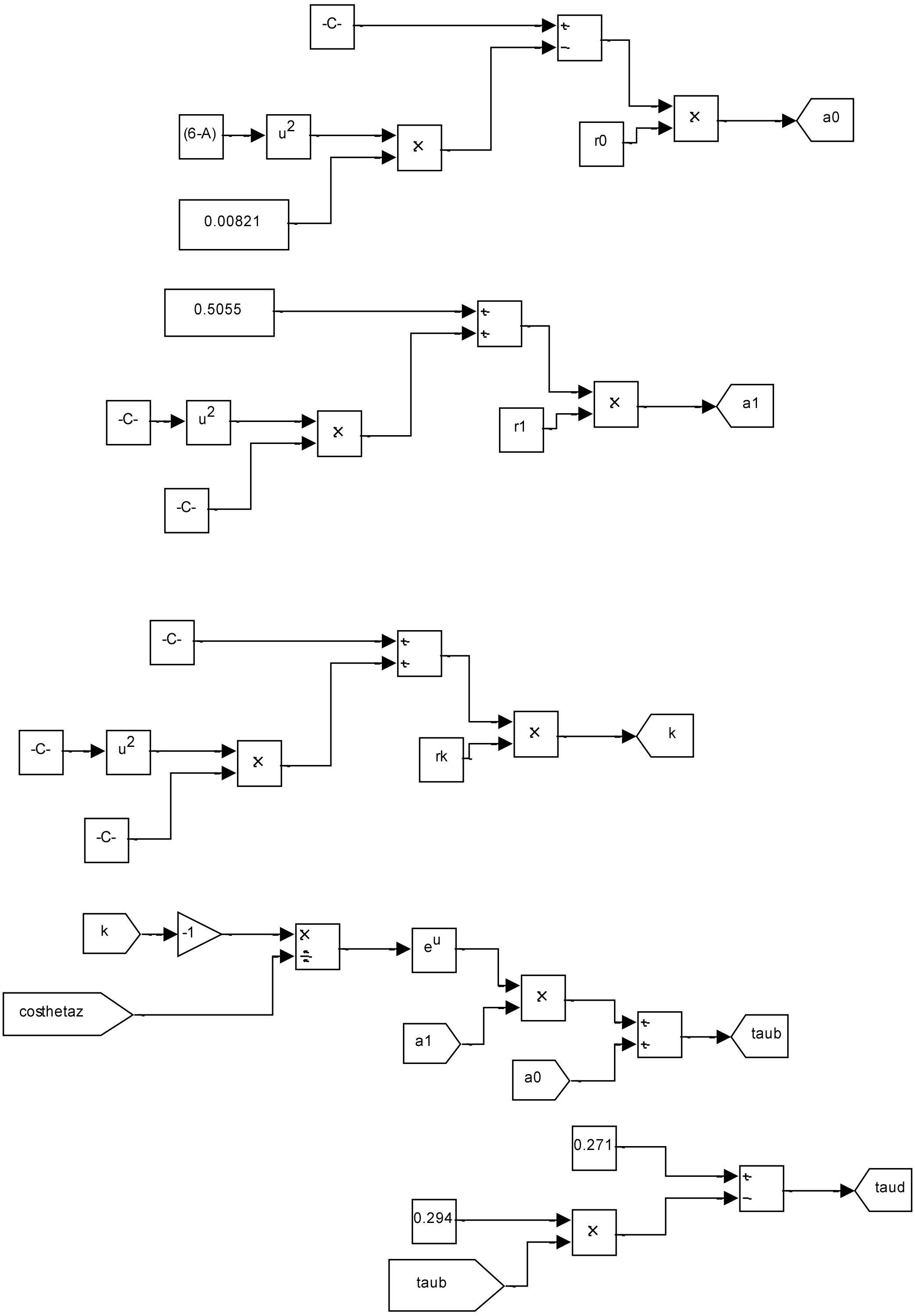

Figure A.1.7 The atmospheric transmittance prediction subsystem structure

A.1.8 Hour angle subsystem structure

Hour angle (Equation 3.4) subsystem structure is illustrated in figure A.1.8.

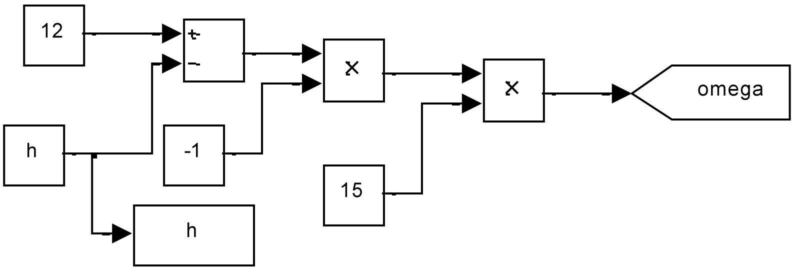

Figure A.1.8 Hour angle prediction subsystem structure

A.1.9 The ratio of beam radiation to that on a horizontal surface subsystem structure

The ratio of beam radiation to that on a horizontal surface (Equation 3.19) subsystem structure is illustrated in figure A.1.9.

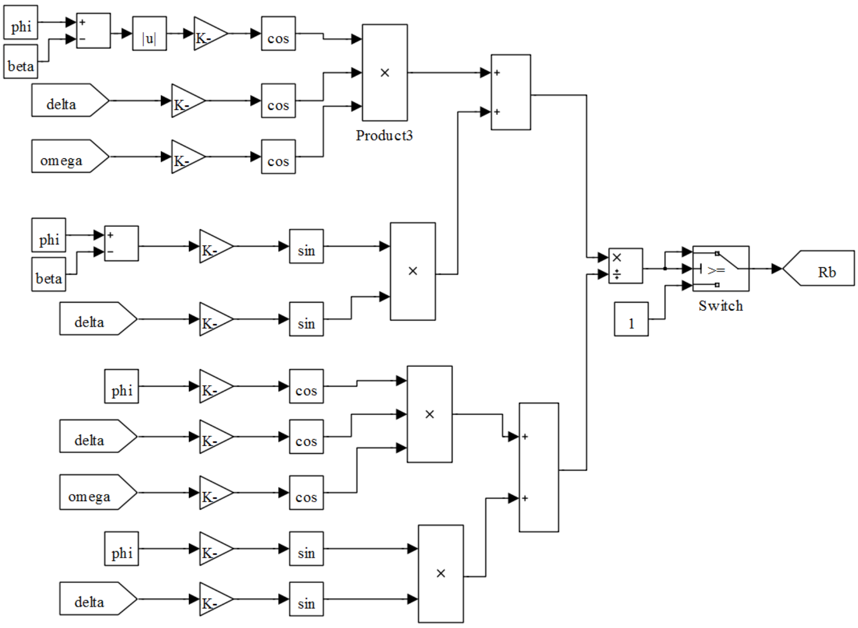

Figure A.1.9 The ratio of beam radiation to that on a horizontal surface prediction subsystem structure

A.2 PV power station specifications

The PV power station has a 1600 PV panel’s model NU-S0E3E Manufacturer by Sharp [120].

Nominal Peak Power for each panel is 180 Wp, with a total of nominal peak power of 288 kWp. The PV power station is divided into three sub-arrays with the following configurations:

- PV Sub-array one:
    - No. of modules = 576 modules (36x16)
    - No. of modules per string (modules connected in series) = 16 modules
    - No. of parallel strings = 36 strings
    - Nominal Peak Power: 103.68 kWp (576x180 Wp)

- PV Sub-array two:
    - No. of modules = 576 (36x16)
    - No. of modules per string (modules connected in series) = 16
    - No. of parallel strings = 36
    - Nominal Peak Power: 103.68 kWp (576x180 Wp)

- PV Sub-array three:
    - No. of modules = 448 (28x16)
    - No. of Strings (modules connected in series) = 16
    - No. of parallel strings = 28
    - Nominal Peak Power = 80.64 kWp (448x180 Wp)

Appendix B

B.1 Modelling the refrigeration system using the Themolib tool box

The ‘Thermolib toolbox’ which developed by EUtech Scientific Engineering GmbH is used in conjunction with the Matlab/Simulink to ease the implementation complexity of the developed models. The ‘Thermolib toolbox’ uses ‘flow bus’ to describe the medium flow between the blocks. The ‘flow bus’ contains the primary information on the flowing media (e.g. molar flow, chemical composition, and thermodynamic properties such as temperature, pressure and vapour fraction). The Thermolib flow bus structure as illustrated in table B.1.

Table B. 1 Thermolib flow bus structure.[7]

Signal Name	Name	Symbol	Unit
ndot	Total molar flow	$\dot{n}$	mol/s
T	Temperature	T	$°K$
P	Pressure	p	Pa
Hdot	Enthalpy flow	$\dot{H}$	W
Sdot	Entropy flow	$\dot{S}$	$W/°K$
Gdot	Gibbs energy rate	$\dot{G}$	W
Cpdot	Heat capacity rate	$\dot{C}_p$	$W/°K$
x	Vapour fraction of all compounds	x	mol/mol
psi	Molar fractions of all compounds	ψ	mol/mol

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[7] Thermolib – User Manual”, Eutech Scientific Engineering, 2008.

Some of the refrigeration sub-systems are modelled in conjunction with the 'Thermolib toolbox'. The components which modelled with this toolbox are:

B.1.1 Compressor

The compressor of the refrigeration system is modelled with the 'compressor' block. The compressor (Isentropic) subsystem model is shown in Figure B.1.1.

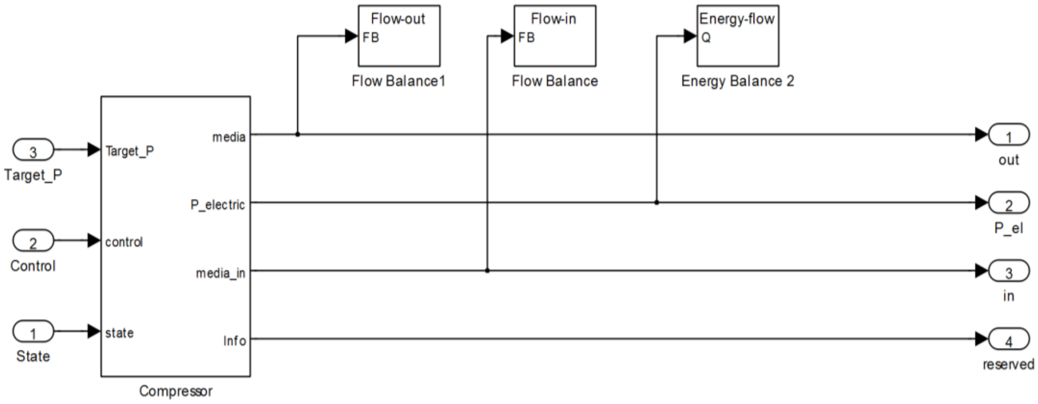

Figure B.1.1 The compressor subsystem model developed with the Thermolib toolbox

The inputs of the compressor subsystem are:

- State: incoming flow bus.
- Ctrl: fraction of maximum mass flow.
- Outlet press: target pressure at the output.

The outputs of the subsystem are:

- Out: outgoing flow bus.
- P_mch : mechanical power consumption .
- in : estimated input flow bus.
- Reserved: terminate.

B.1.2 Condenser

The condenser is modelled with the ‘heat exchange’ block. The subsystem model of the condenser is shown in Figure B.1.2.

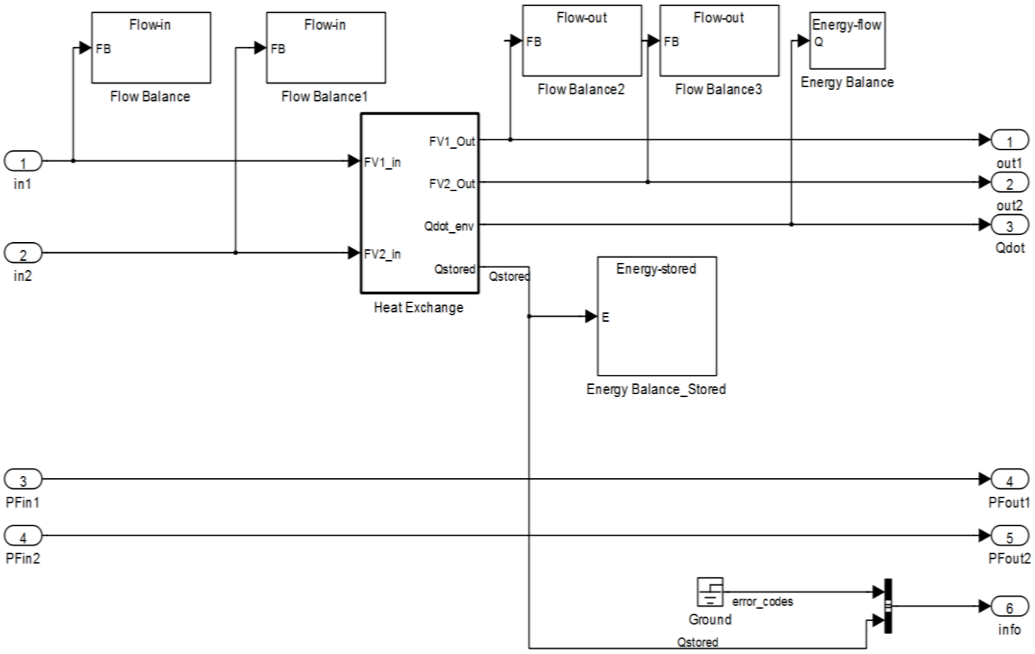

Figure B.1.2 The condenser subsystem developed with the Thermolib toolbox

The inputs of the condenser subsystem are:

- in1 : input flow bus 1.
- in2 : input flow bus 2.
- PFin1 : pressure feedback for output 1.
- PFin2 : pressure feedback for output 2 .

The outputs of the condenser subsystem are:

- out1 : output flow bus 1 .
- out2 : output flow bus 2.
- Qdot : heat exchange with environment .
- PFout1 : pressure feedback for input 1.
- PFout2 : Pressure feedback for input 2.
- info : bus with stored energy in thermal mass.

B.1.3 Expansion valve

The expansion valve is modelled as a flow bus connected to a ‘state heat exchange’ block. The subsystem model of the expansion valve is illustrated in Figure B.1.3.

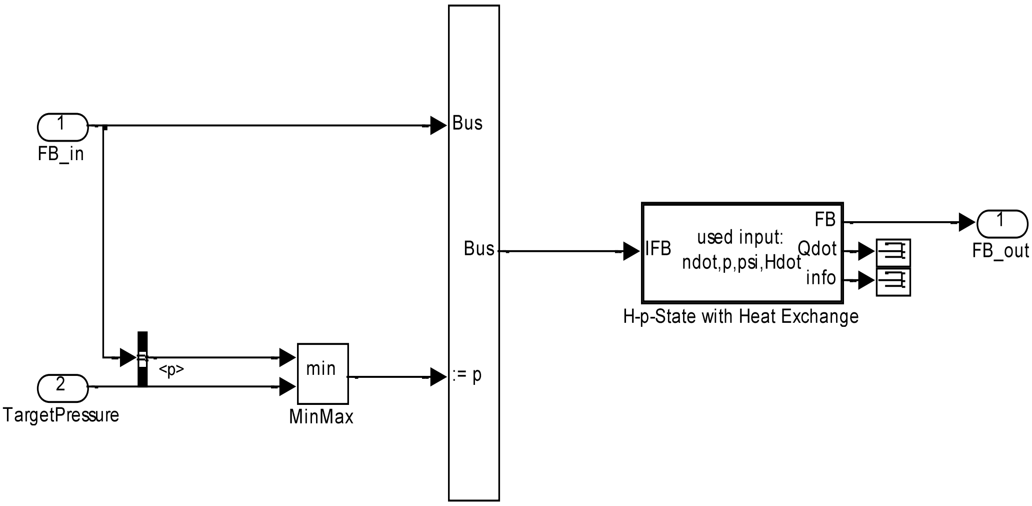

Figure B.1.3 The expansion valve subsystem model developed with the Thermolib toolbox

The inputs of the expansion valve subsystem are:

- FB_in: the input flow bus.
- TargetPressure: target pressure value.

The output of the expansion valve is:

- FB_out: the output flow bus.

B.1.4 Evaporator

The evaporator is modelled with the ‘heat exchanger’ block. The subsystem model of the evaporator is illustrated in Figure B.1.4.

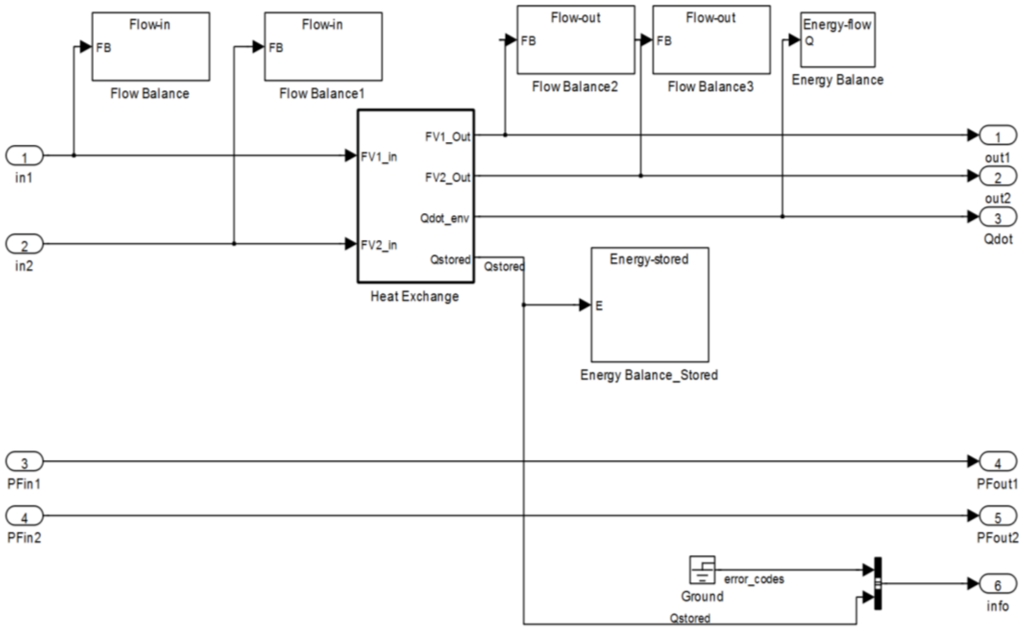

Figure B.1.4 The evaporator subsystem developed with the Thermolib tool box.

The inputs of the evaporator subsystem are:

- in1 : input flow bus1.
- in2 : input flow bus 2 .
- PFin1 : pressure feedback for output 1 .
- PFin2 : pressure feedback for output 2 .

The outputs of the evaporator subsystem are:

- out1 : output flow bus 1.
- out2 : output flow bus 2 .
- Qdot : heat exchange with environment .
- PFout1 : pressure feedback for input 1.
- PFout2 : pressure feedback for input 2 .
- info : bus with stored energy in thermal mass.

B.1.5 Initial conditions

Works like a Simulink memory block for the flow bus with the initial states parameters. It provides a one integration step delay. Usually this block is used to break up algebraic loops in the model.

B.1.6 Bus selector

The bus selector block outputs a specified subset of the elements of the bus at its input.

B.1.7 Flow display

The flow display displays state properties according to the given parameters.

The Matlab/Simulink model for the refrigeration system using the Themolib toolbox is illustrated in Figure B.1.5.

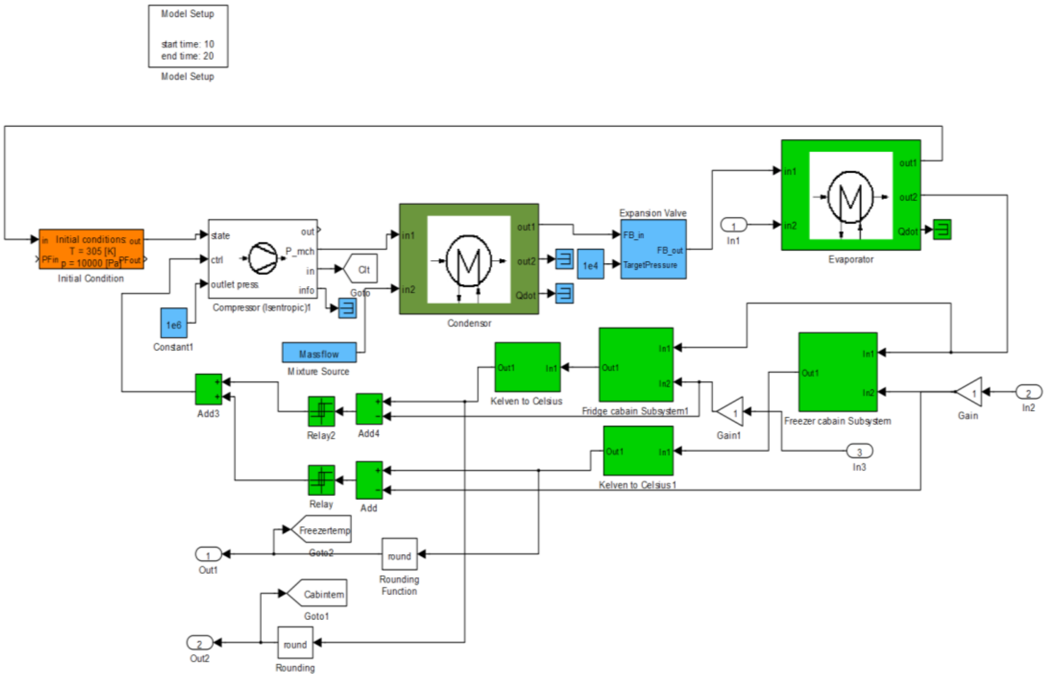

Figure B.1.5 The refrigeration system model developed with the Thermolib toolbox

B.2 Hotpoint fridge-freezer specifications

Hotpoint Free standing Frost free fridge-freezer model FF200TP specifications as follows:

- The fridge-freezer was operated within the recommended ambient temperature range (e.g. +10℃ to + 38 ℃)
- The fridge-freezer has 4 star rating.
- The fridge-freezer energy consumption is 347 kWh/Year or 0.95 kWh/day.
- The fridge-freezer energy band is A.
- The fridge-freezer evaporator defrost heater is 387.2 Ω.
- The fridge-freezer operation voltage is 220/240, 50 Hz.

Appendix C

C.1 Modelling the refrigeration system and components using the IDEF techniques

A refrigeration system is a system that in which heat is transfer from the refrigerated space to the outside through coils. The householder refrigerator consists of two separately insulated sections, the main refrigerator section and the freezer section. These sections are cooled by a refrigerant cycling through the basic parts of a refrigeration system: the compressor, condenser, expansion valve, and the evaporator. In order to model a refrigeration system we have to define the inputs and the outputs of the system first, and then we have to find the mathematical relationship between these inputs and outputs, predict the variables that make the changes in the inputs and how they affect the outputs.

For the householder refrigeration system a subsystem model should be made, as it is known that the refrigeration system has the following basic subsystems the first is consist of refrigerator or cycle system which consists of a compressor , a condenser , throttling device and an evaporator. The second subsystem is the temperature setup point which is the isolated cabin, the doors, and the material (food) to be cooled inside the cabin. So to get a better idea about the system a model using IDEF will be implemented.

C.1.1 Compressor

The compressor in the refrigeration system is the heart of the system, it convert the electrical power to a mechanical power and compressed the low-pressure low temperature refrigerant to high-pressure high temperature refrigerant.

Using the IDEF_0 technique for modelling the compressor is illustrates in figure C.1.1.

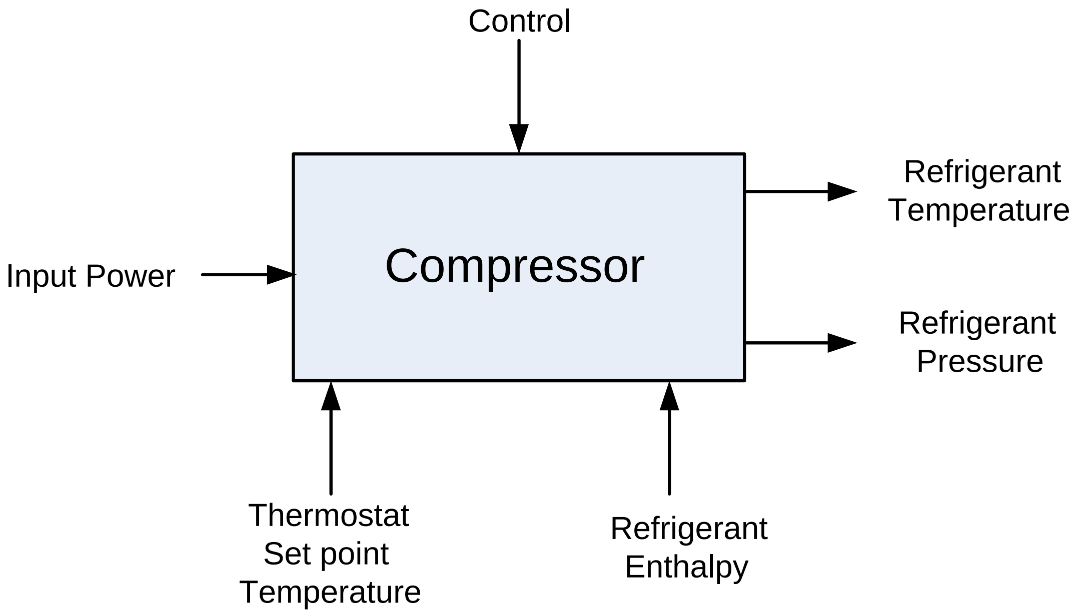

Figure C.1. 1 The inputs, outputs, controls, and mechanisms of the compressor using IDEF0

C.1.2 Condenser

The refrigerant is waiting in the condenser while the compressor is off, and it will pass to the condenser by a signal from the space thermostat which indicates that the temperature of the space is higher than the set temperature. The heat will transfer to the surrounding through the condenser coils.

Using the IDEF0 technique for modelling the condenser is illustrates in Figure C.1.2.

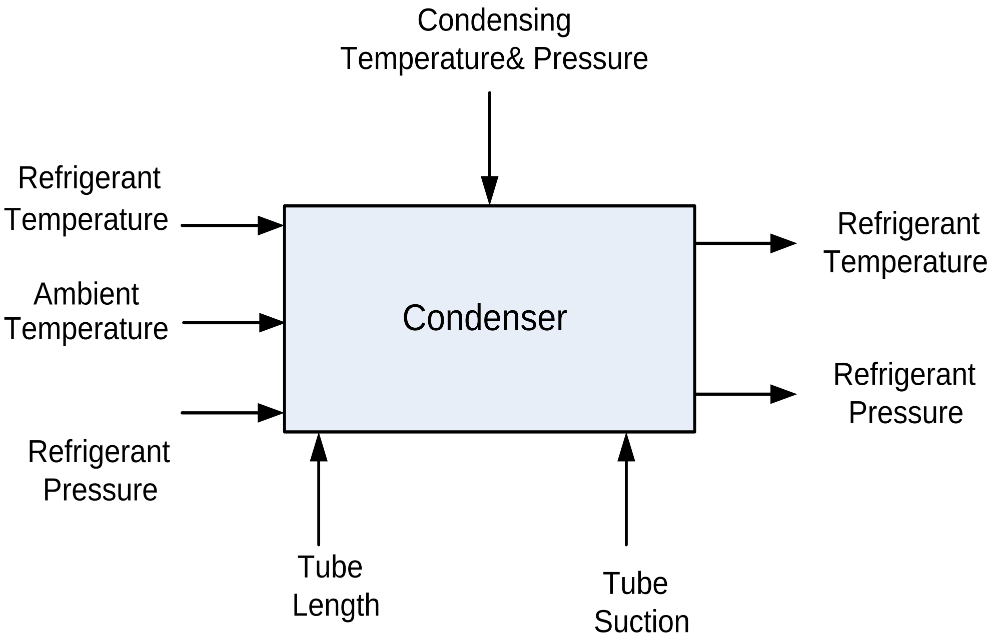

Figure C.1. 2 The inputs, outputs, controls, and mechanisms of the condenser using IDEF0

C.1.3 Evaporator

The refrigerant is passing to the evaporator in the liquid state, and heat is transfer outside the cooled space through the evaporator coils. Using the IDEF$_0$ technique for modelling the evaporator is illustrates in figure C.1.3.

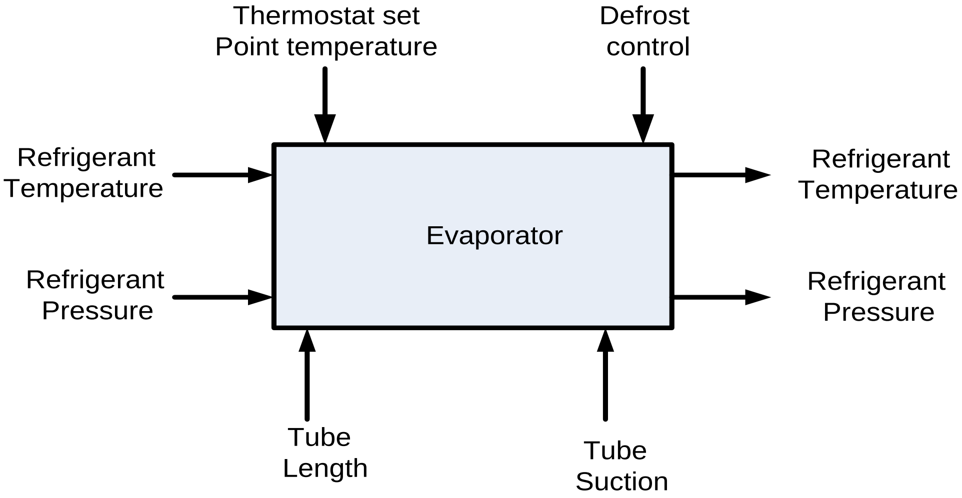

Figure C.1. 3 The inputs, outputs, controls, and mechanisms of the evaporator using IDEF0

C.1.4 Expansion Valve

The expansion valve is a flow control valve which controlled the flow of the refrigerant enters the evaporator depending on the evaporation rate. And it will reduce the refrigerant pressure. Using the IDEF0 technique for modelling the expansion valve is illustrates in figure C.1.4.

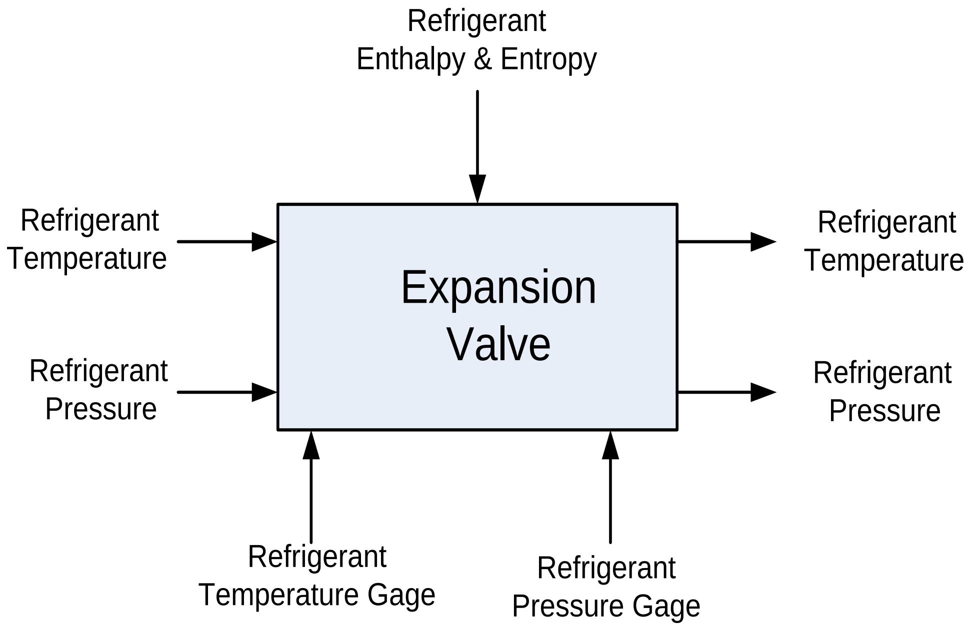

Figure C.1. 4 The inputs, outputs, controls, and mechanisms of the expansion using IDEF0

C.1.5 Cooled Space (Cabin)

The cooled space/or the cabin is the part of the refrigeration system that should be cooled to the thermostat set temperature and maintained at this temperature. Using the IDEF0 technique for modelling the cooled space is illustrates in figure A.1.5.

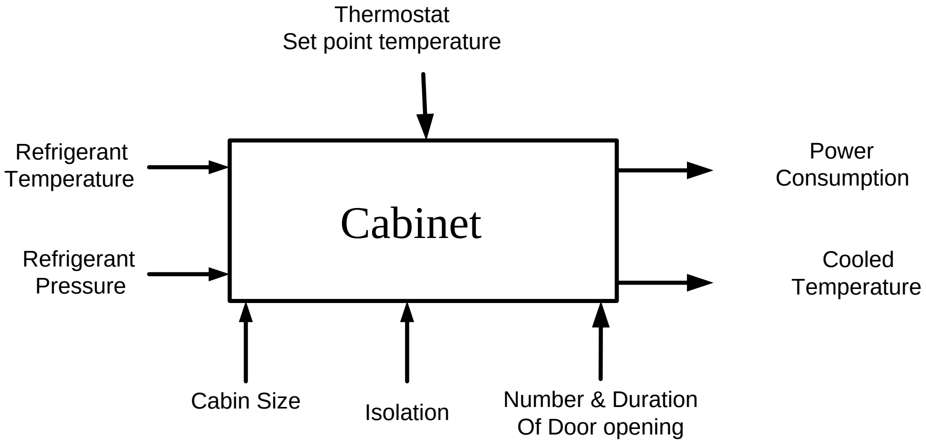

Figure C.1. 5 The inputs, outputs, controls, and mechanisms of the cooled space using IDEF0

Using IDEF0 technique for modelling the refrigeration system as complete system is shown in Figure C.1.6.

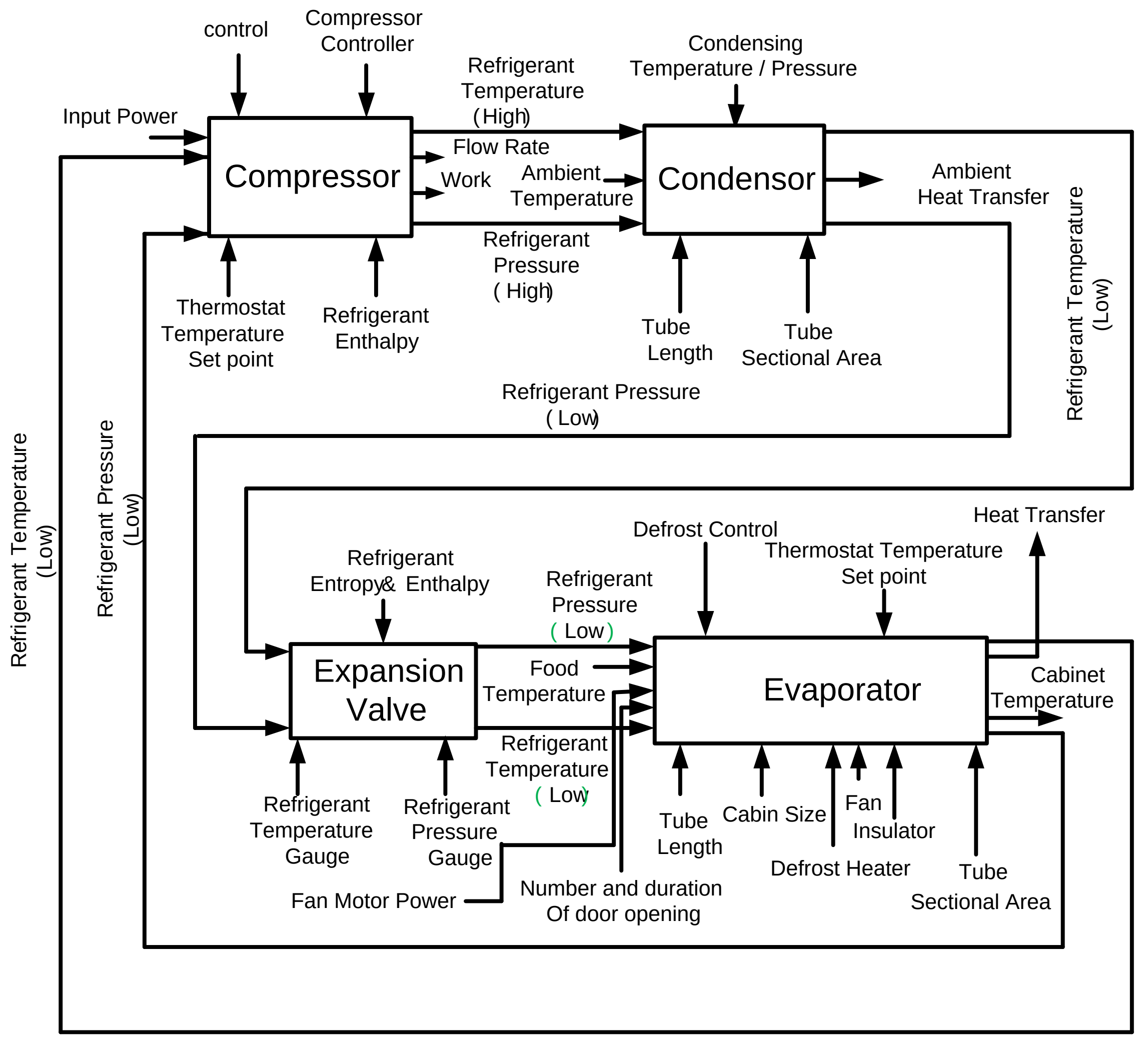

Figure C.1. 6 IDEF0 modelling for the refrigeration system using IDEF0

C.2 Modelling the refrigeration system and components using the IDEF0 and IDEF2 techniques

Analysing the refrigeration system using the IDEF technique the combination of complementary modelling methods such as IDEF1, IDEF2, and IDEF3 should be used. The refrigeration system is a dynamic system so for this reason the complementary modelling IDEF2 will be used.

The model of the components of the refrigeration system using IDEF0 and IDEF2 is illustrated in the following figures.

C.2.1 Compressor

Figure C.2.1 illustrates the model for the compressor.

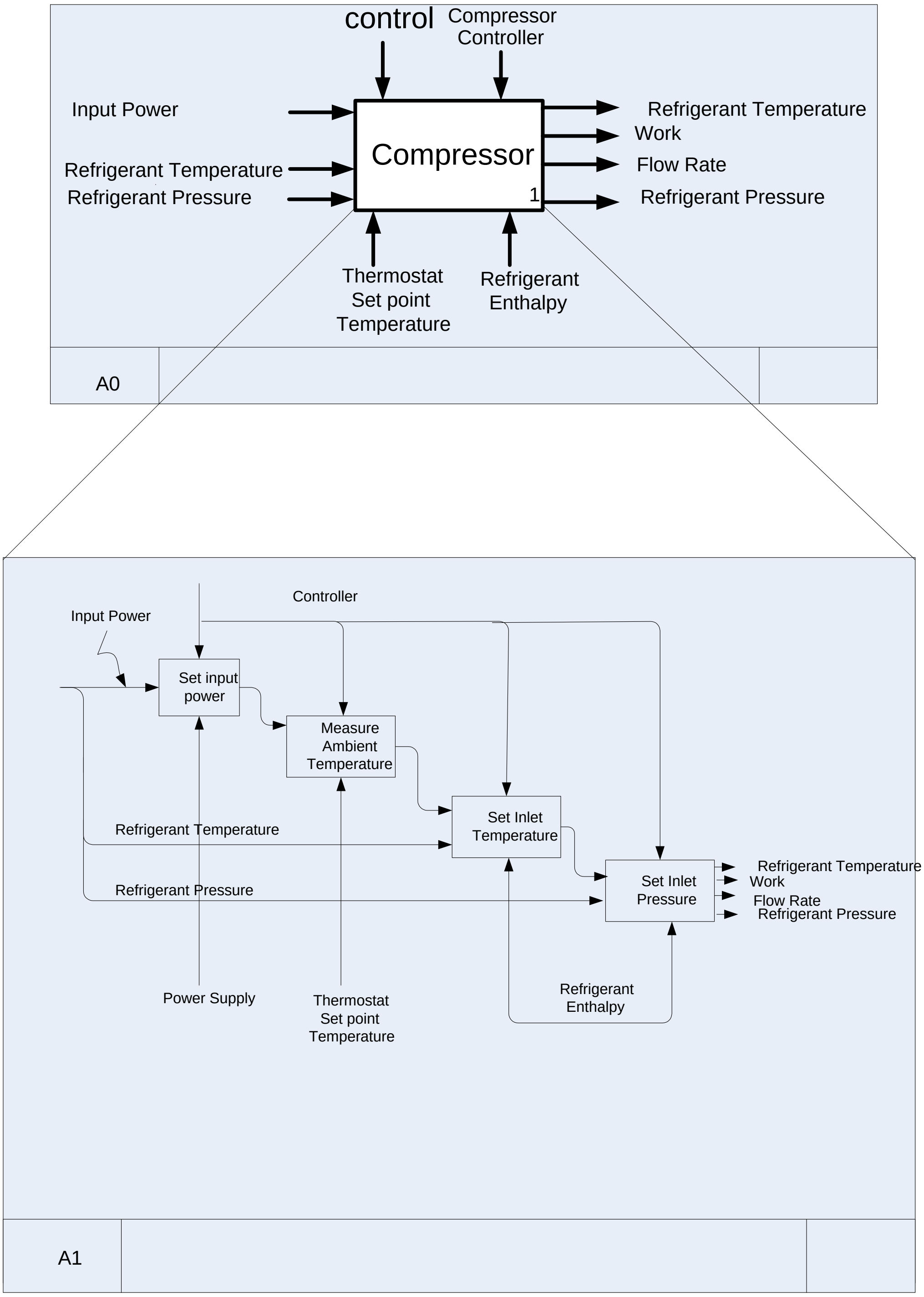

Figure C.2. 1 The IDEF0 and IDEF2 model for the compressor

C.2.2 Condenser

Figure C.2.2 illustrates the IDEF0 and IDEF2 model for the condenser.

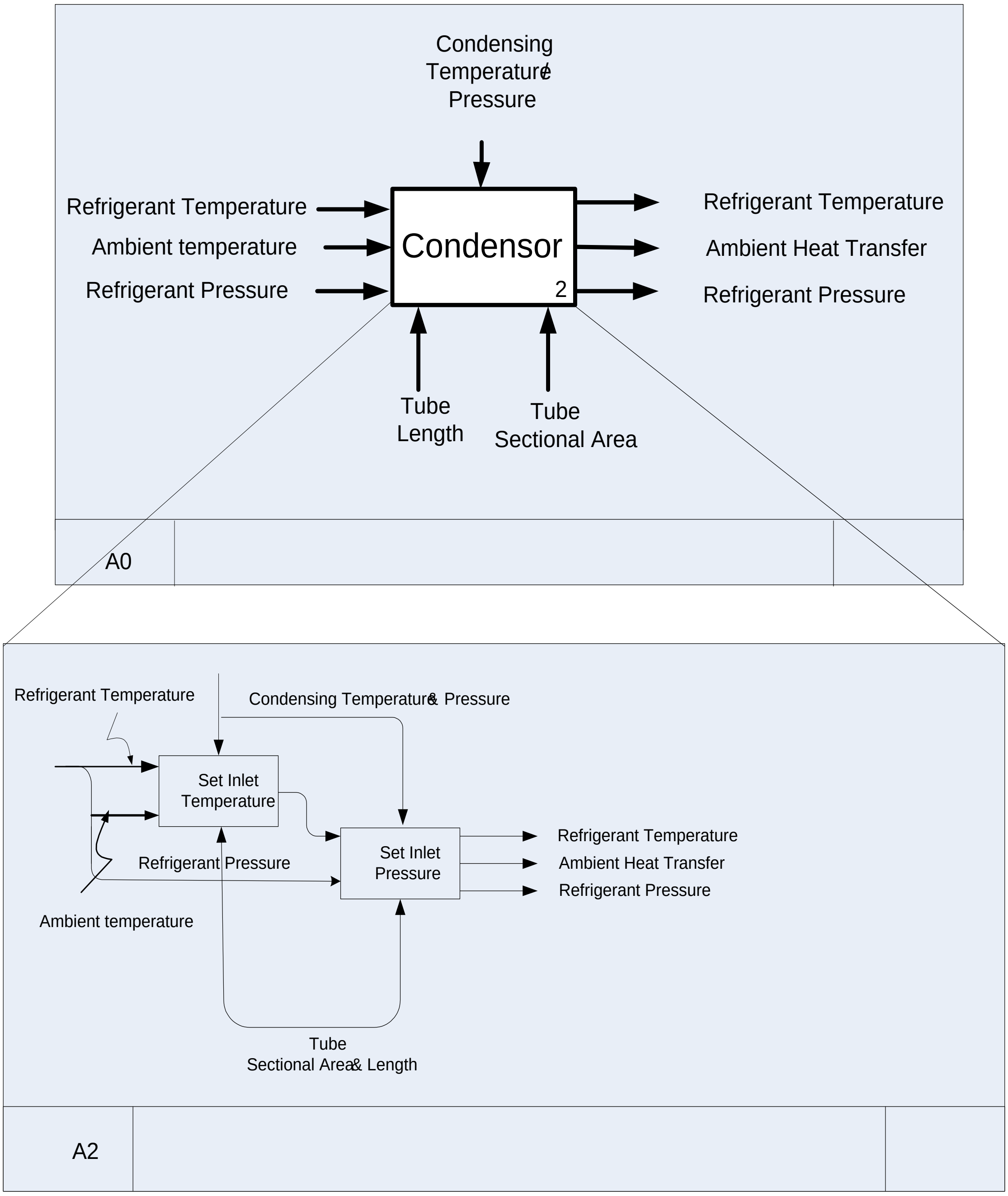

Figure C.2. 2 the IDEF0, IDEF2 model for the condenser

C.2.3 Expansion valve

Figure C.2.3 illustrates the IDEF0 and IDEF2 model for the expansion valve.

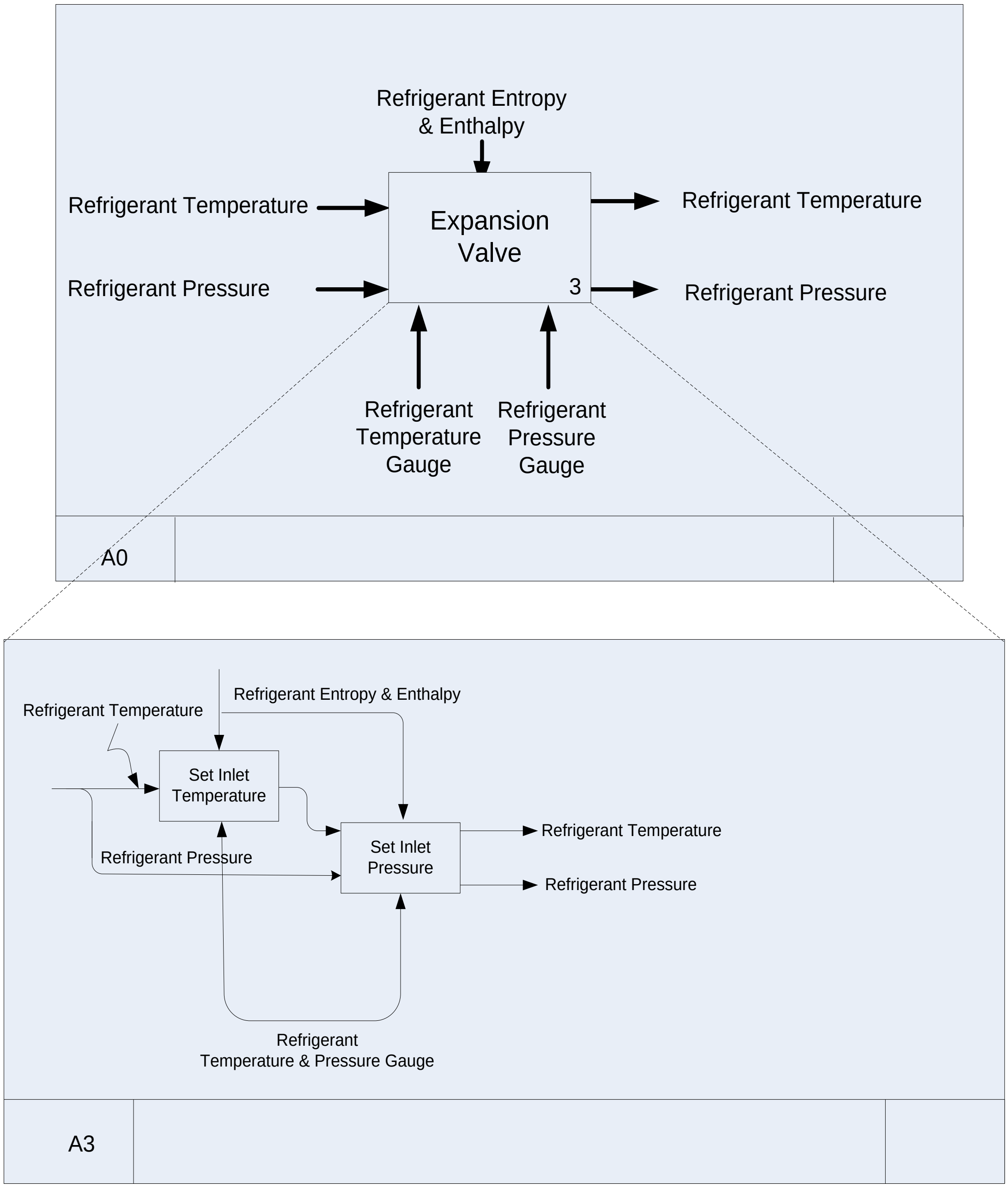

Figure C.2. 3 The IDEF0 and IDEF2 model for the expansion valve

C.2.4 Evaporator

Figure C.2.4 illustrates the IDEF0 and IDEF2 model for the evaporator.

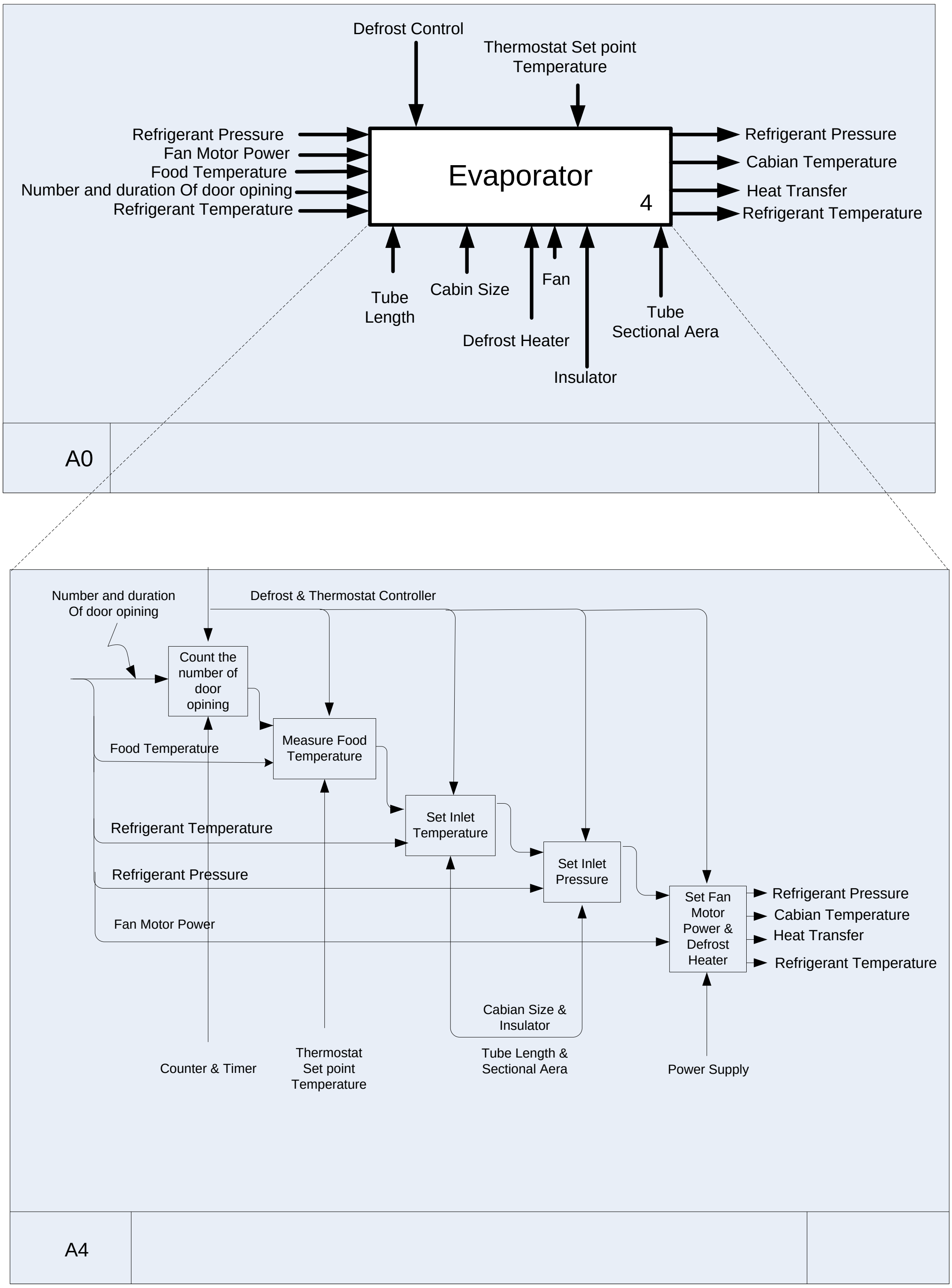

Figure C.2. 4 The IDEF0 and IDEF2 model for the evaporator.

Appendix D

D.1 Domestic energy ecosystem model (DEEM)

This model comprise of a PV power generation model which predicts the output generated power of the PV for the specific day, and the domestic energy consumption model for the same day.

The outputs of this model are the electrical power consumed from the grid, and the unused PV generated electrical power sells to the grid. This model was established for different scenarios.

D.2 Domestic energy ecosystem model (DEEM) structures

D.2.1 DEEM without applying any control strategy in winter time

The model structure is illustrated in figure D.2.1

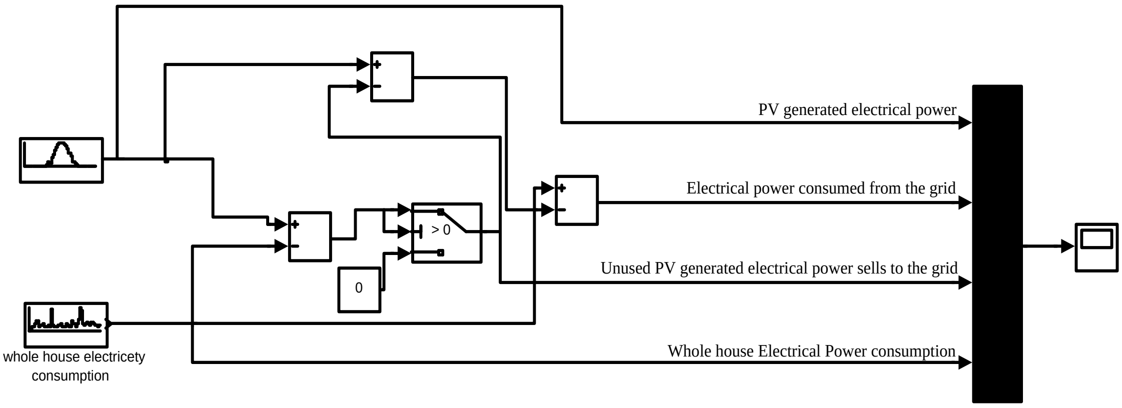

Figure D.2.1 DEEM without applying any control strategy in winter time

D.2.2 DEEM with load shifting control strategy in winter time

The model structure is illustrated in figure D.2.2

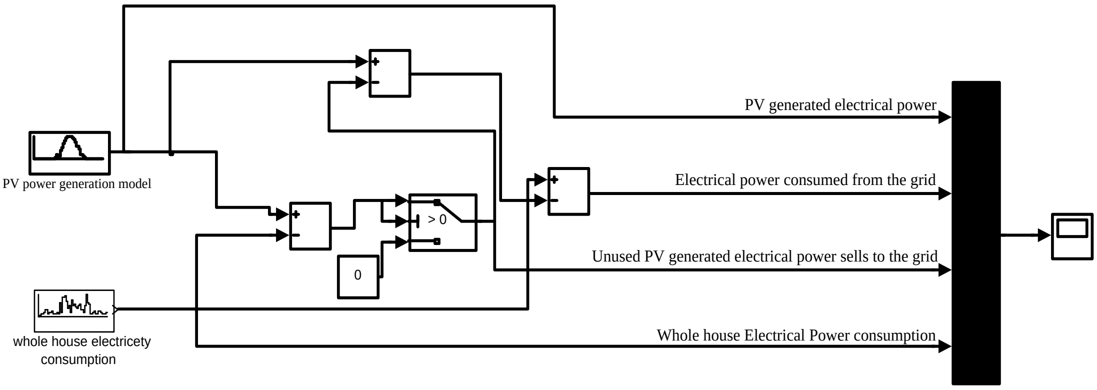

Figure D.2.2 DEEM with load shifting control strategy in winter time

D.2.3 DEEM with load shifting and energy buffering control strategy in winter time

The model structure is illustrated in figure D.2.3

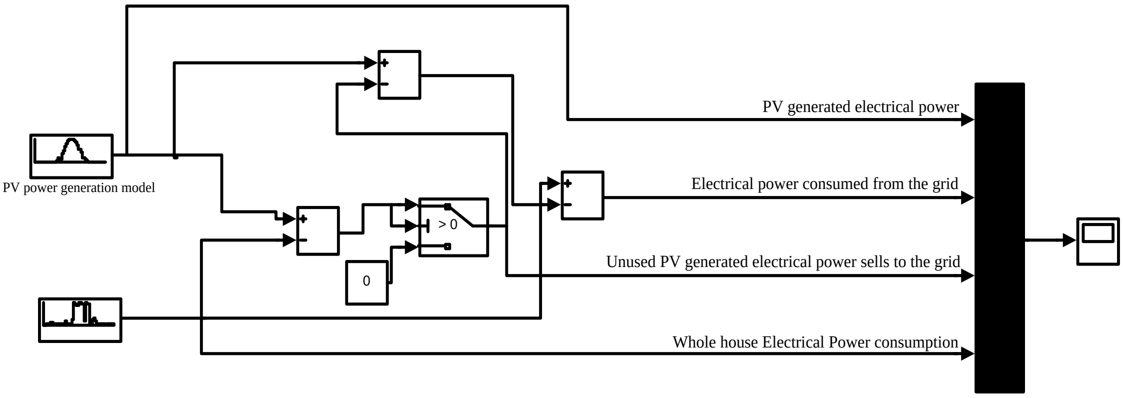

Figure D.2. 3 DEEM with load shifting and energy buffering control strategy in winter time

D.2.4 DEEM without applying any control strategy in summer time

The model structure is illustrated in figure D.2.4

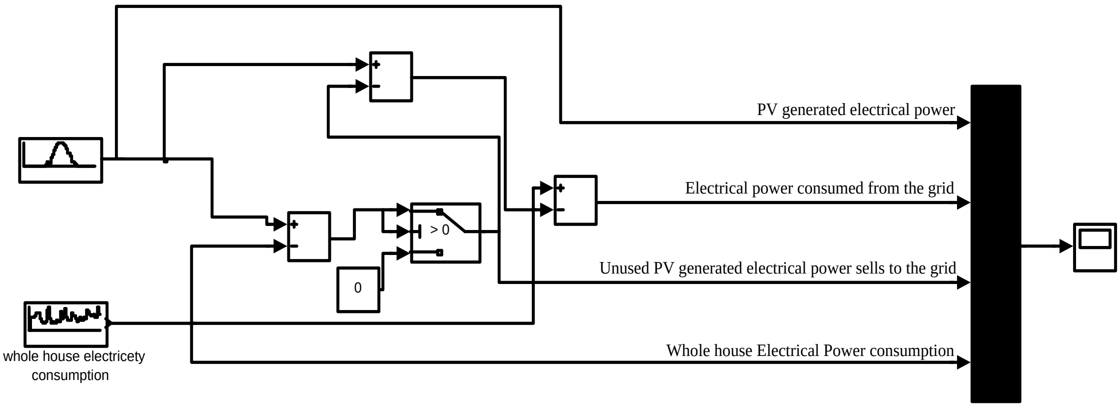

Figure D.2.4 DEEM without applying any control strategy in summer time

D.2.5 DEEM with load shifting control strategy in summer time

The model structure is illustrated in figure D.2.5

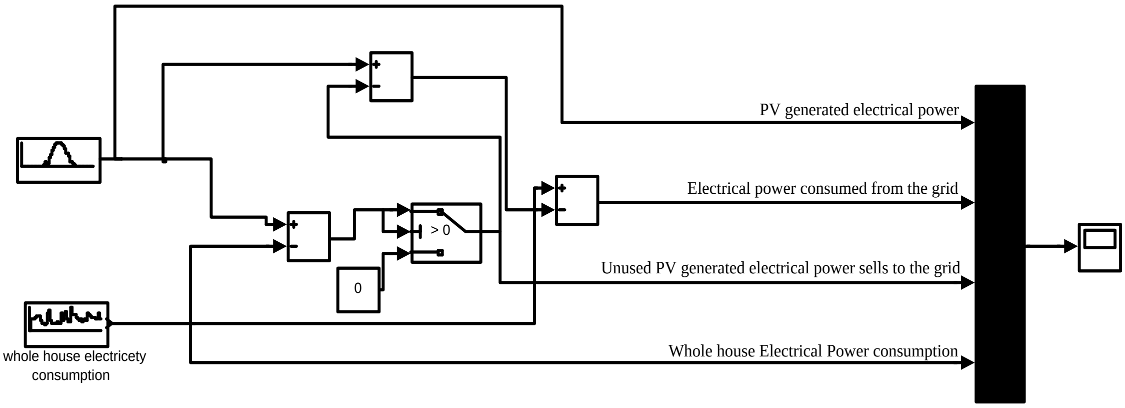

Figure D.2.5 DEEM with load shifting control strategy in summer time

D.2.6 DEEM with load shifting and energy buffering control strategy in summer time

The model structure is illustrated in figure D.2.6

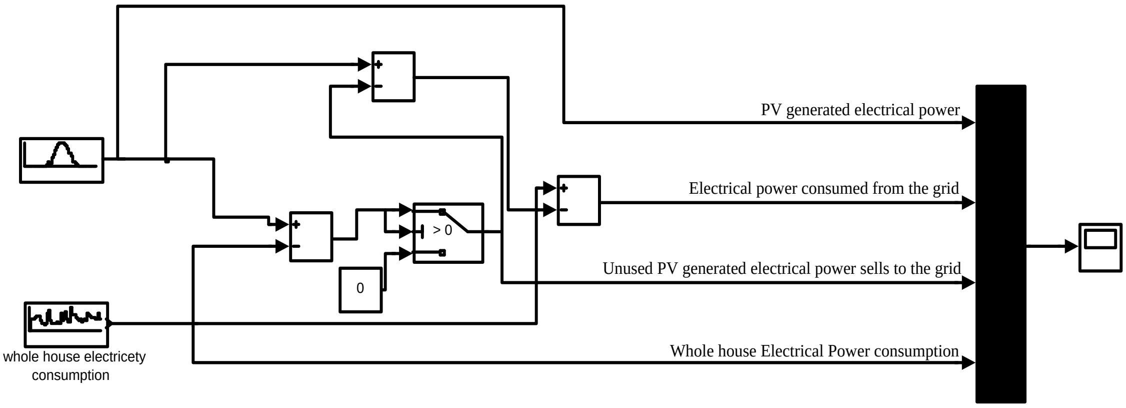

Figure D.2.6 DEEM with load shifting and energy buffering control strategy in summer time