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OPTIMIZATION OF HOUSEHOLD ENERGY MANAGEMENT BASED ON THE SIMPLEX ALGORITHM

Information Technology and Communication Sciences
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ABSTRACT

Ran Zheng: Optimization Of Household Energy Management Based On The Simplex Algorithm
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Small scale intermittent renewable energy consisting of roof-mounted photovoltaic generators and micro wind turbines for the household residential have been widely integrated into the power grid. Meanwhile, more and more home appliances are utilized, including schedulable and non-schedulable home appliances. With the deployment of smart technologies, the control strategies of home energy management system are developed and this provides the possibility to minimize the energy bill and improve the energy efficiency by scheduling the controllable home appliances without sacrificing preference of the customer.

In this thesis, an optimization strategy based on the Simplex algorithm has been proposed. The target is to optimize the energy consumption in households by scheduling the household appliances, considering the day-ahead electricity price from Nord Pool market and the roof-mounted PV production. Firstly, the schedules are generated from the optimization algorithm and then interpreted to control the appliances to achieve energy bill saving.

In order to evaluate the optimization algorithm, the water boiler is used as the controllable load. Two case studies for 24-hour illustrate that the implementation controlled by HEMS using this algorithm can contribute greatly to the energy bill savings. According to the two implementations, around 43% of reduction for the energy bill can be achieved. Considering the PV production integrated into HEMS and support from the distribution network operators, the more benefits can be achieved.

The switch panel in the AC Microgrid laboratory acts a crucial part in the implementations and it has seven 3-phase channels that can be utilized to connect with electrical appliances, home energy storage systems, and distributed generations such as micro wind turbines and roof-mounted PV panels. Each channel is equipped with two connectors to control the operation, the top of which is controlled by HEMS computer using wireless Z-Wave and the other one is controlled by dSpace which can be used to emulate the consumption pattern in the households. The algorithm and Z-wave interface are implemented in Matlab / Simulink environment and Z-wave makes it possible to control the boiler or other loads in real-time.

Keywords: Demand response, Household energy management, Smart home, Simplex algorithm, Optimization

PREFACE

I am greatly indebted to all those who helped me during the process of writing the thesis. First, my thanks would go to my supervisor, Prof. Sami Repo, for his patient guidance and valuable suggestions on the academic research on this project. Thanks to his constant encouragement and inspiring advance, I can overcome all the difficulties and move forward and complete all the stages.

My sincere thanks also should go to Antti Supponen, who provided much help to me in the process of doing the research, especially on understanding the microgrid and the work in the laboratory. And also special thanks should go to my friends who proposed the comments on the draft. Besides, sincere thanks will go to Antti Rautiainen, who gave me a lot of help to modify the thesis.

Last but not least, special thanks will go to my family for their consistent support and encouragement for those years.

Tampere, 29th August 2019

Ran Zheng

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LIST OF SYMBOLS AND ABBREVIATIONS

AC	Alternating current
AMI	Automated meter reading
BESS	Battery Energy Storage System
BMS	Battery Management System
CAES	Compressed air energy storage
CET	Central European Time
DC	Direct current
DG	Distributed generation
DSM	Demand-side management
DSO	Distribution System Operator
EU	European Union
GHG	Greenhouse Gas
HCAs	Heating and cooling appliances
HEMS	Home energy management system
IBR	Inclining block rates
MPP	Maximum power point
PV	Photovoltaics
RES	Renewable energy sources
RTP	Real-Time Pricing
TSO	Transmission System Operator
TWh	Terawatt hours

1 INTRODUCTION

Energy is a key factor in today's society not only for business but also for private households. Sustainable, secure, safe and reliable energy can provide a strong driving force to the development of the industry and economy, as well as the well-being of the people. Nowadays, the energy productions are mainly from fossil fuels including petroleum, solid fuels and gas, which account for 81% of the whole energy production in the world, while renewables and nuclear account for 13.6% and 4.9% [15]. The primary usage of fossil fuels should be responsible for greenhouse gas emissions (GHG) and the rise for carbon emissions has a negative effect on combating global climate change. It has been predicted the temperature would rise one to six degrees Celsius in the next few decades. Moreover, the worst case is that ice melting would lead to around 60 meters rise of sea level when the ice melts in Greenland and Antarctica [8].

The European Union (EU) countries now have decided to transform its economy to reduce GHG emissions. According to the Europe 2020 strategy, the EU has set a target to reduce 20% of GHG emissions compared with that of 1990 by the end of the year 2020 [23]. In 2016, the overall GHG emission in the EU has dropped to 78% of the level of 1990 and it experienced a slight rise by 0.6% from 2016 to 2017. Despite the small rise, the EU will probably meet the projection made in 2007 [16]. The reason for the reduction of GHG emission lies in improving the energy efficiency in the EU and the increasing utilization of renewable energy sources (RES) contributes much to achieve to the target. The existing measures and policies cannot meet the demand to reduce 40% of GHG emission of the level in 1990 [22].

The increasing deployment of renewable energy sources can virtually help mitigate GHG emissions. The EU started to adapt the RES to energy production in the EU wide from the mid-nineties. The proportion of RES took up almost 12.8% of the total energy production in the EU in 2010, and the share rose to 16.7% in 2015 [22]. Instead of improving the share in other energy consumption sector like transportation, the electricity generation is more cost-friendly because of development of RES technologies. Renewable electricity generation will act an important role in the progress to reduce conventional energy consumption. Because of the projection for the reduction of GHG emissions by 2050, the electricity generation from wind power and photovoltaics (PV) would dominate the change. The shares for distributed generation (DG) including wind power and solar power is forecasted to represent 14% and 3% respectively in the energy consumption by 2020 in the EU countries [39].

DG is expected to provide some potential benefits to the power system. From the view of the power system operator, DG can defer the investment to strengthen the grid and enable island mode of operation of the grid. Meanwhile, the need for peak and reserve generation capacity reduces. There are several popular DG technologies like photovoltaic systems, wind turbines. Photovoltaic arrays for the households have been more popular because of reducing the cost of electricity bill of energy end-users. Otherwise, the distribution losses get minimal as the installation point near to the customer's location [14]. The general idea is that Finland is not suitable for solar power generation due to low amount of solar irradiation, but in fact, southern Finland has nearly the same global irradiation with northern Germany [34]. Finland will see a significant increase in the small-scale PV installation. With the wide deployment of intelligence devices like smart meters at the end-user level, customers now pay more focus on their energy use.

The main challenge for the operation of the power system is to keep the balance of the system and this indicates electricity production must keep balance with electricity demand. The electricity generation of the small-scale PV system is intermittent. In Finland, the time for peak generation of PV may not happen at the same time with the peak electricity demand for private residential customers. The peak generation usually takes place on midday in summer but the peak demand for electricity occurs at night in winter due to space heating [3]. Even though it is difficult to maintain the balance for seasonal variation of generation and demand, but the variations within a day could be compensated by applying energy storage systems or demand response. For example, there are pilot houses in Canada, where solar thermal and seasonal heat storage is utilized to balance heating demand and solar thermal production [33]. Finland has been a leading country in the utilization of intelligence devices such as smart meters and automatic meter reading. The application of the intelligence at the customer-level side and the retailer's perspective make home energy optimal management possible.

1.1 Research objective

The objective of this thesis is to design, implement and test a control algorithm to optimize the energy consumption for household customers. The target is to make the optimal schedule of the energy consumption of the electrical appliances (heating boiler) by considering the day-ahead hourly price of electricity, forecasted temperature and the real production of roof-mounted PV arrays. The proposed algorithm aims to minimize the energy bill for the customers and improve the energy efficiency effectively without scarifying the comfortable experience of the end-user.

The research tasks to be implemented in this thesis are listed below:

1. Data acquisition from Nord Pool market for day-ahead prices and from Finnish Meteorological Institute(FMI) for weather forecast
2. Determination of the control algorithm in this research

3. Utilization of the Simplex algorithm to optimize the behavior of the boiler and minimize the electricity cost of the household customer, and make the scheduler based on the results
4. Implementation of the schedule in AC microgrid laboratory environment

1.2 Structure of this thesis

The structure of this thesis is listed as below:

- Chapter 1: Introduction of the background for this topic and the motivation for the thesis. Otherwise, the structure of this thesis is addressed.
- Chapter 2: Overview of the smart home and the components in the smart home have been presented in detail.
- Chapter 3: A review of HEMS strategies and algorithms from literature as well as the components in HEMS have been introduced. Three strategies for different models have been addressed. Moreover, the algorithm for HEMS has been proposed.
- Chapter 4: The strategies used in the optimization of energy management are documented in this part. The strategy for my thesis research is presented in detail.
- Chapter 5: The Microgrid and Microgrid laboratory are presented. The experiment results are presented and discussed.
- Chapter 6: Conclusions and future development

2 SMART HOME IN SMART GRID

Residential energy consumption has been a hot topic within the energy and environmental research in the last few decades. The research on the household energy conversation first came out in the 1970s due to the rising concern on the energy crisis caused by the rapid exhaustion of the non-renewable energy resources especially fossil fuels. Recently, reducing the threats from environmental problems such as global warming and maintaining the biodiversity are the main driving forces to research on optimization of the household energy consumption[19].

Household energy consumption takes up more than 30% in the global energy consumption sectors, optimal scheduling energy supply of households is crucial for energy conservation and environmental protection. Residential energy consumption has been the major factor in GHG emissions, which contributes greatly to global warming. According to Annual Energy Outlook 2005 from the U.S. Department of Energy, in 2003, residential consumption in the United States accounted for more than 20% of global energy-related GHG emissions, increasing by 2.4% annually since 1990. Comparing with the U.S, European Union countries have seen a similar trend. According to the data of energy consumption collected by Eurostat, in 2016, the residential energy sector accounted for almost a quarter of global energy consumption. Residential energy consumption for end users covers various uses such as space heating, air ventilation, cooking, and other electrical appliances. An inside look at the energy use for U.S and EU households suggests the main use is for space heating, followed by water heating, cooking, other electrical appliances and space cooling[2, 19].

According to Figure 2.1 about the different usage of energy products used in residential energy consumption in the European countries, nearly all of the energy resources can be utilized to warm the water and space. The derived heat that is provided by combined heat and power plants and heating plants is used for heating while electricity has been widely used for all usages in households including space and water heating, lighting, cooking and cooling, accounting for 26.3%, 56.6%, 11.0%, and 1.1% respectively [12].

In Finland, the energy consumption for space heating took up 68% of energy consumption in households, while water heating and saunas heating account for 15% and 5% respectively. The other energy consumption such as electrical appliances, cooking and lighting accounted for 13% of the whole household energy consumption. In 2017, nearly 30% of household energy consumption was electricity, about 23 TWh, of which 48% was used for space heating and 36% was supplied to electrical appliances. The remaining was utilized for heating water and saunas [50].

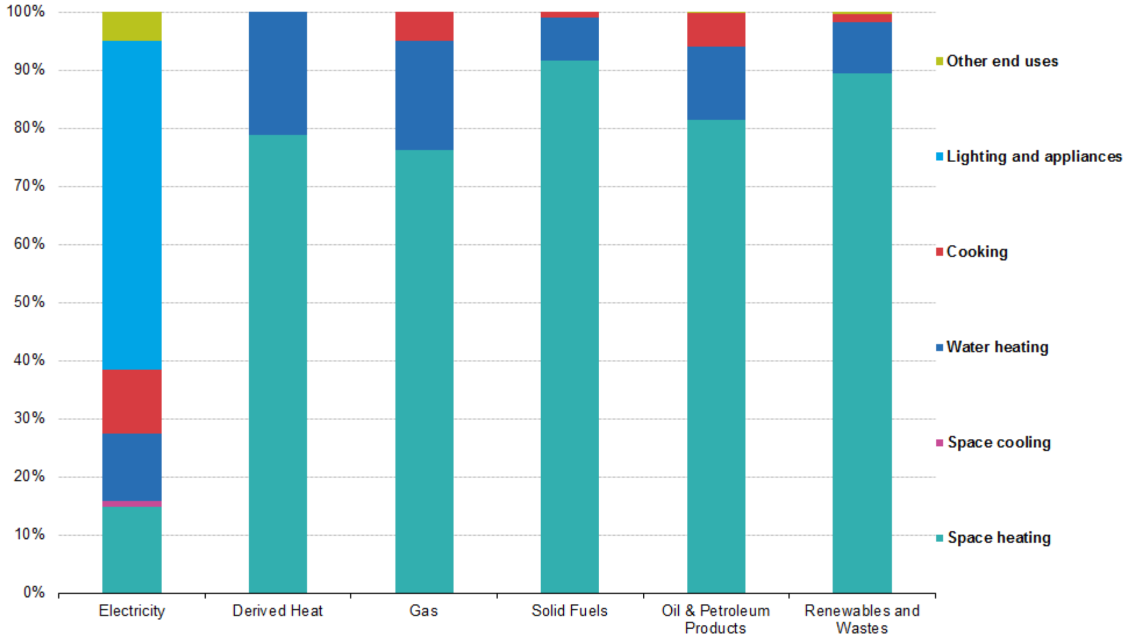


Figure 2.1. *The different usage of energy products used in residential energy consumption in the EU, 2016*

Most household energy consumption tasks can be operated flexibly rather than at the fixed time. Economical energy consumption and reduction of GHG emissions can be achieved if the flexible household loads can be rescheduled coordinately by home energy management system (HEMS) in smart homes. This chapter will present the smart home within the microgrid, where the coordinated schedule is determined for the energy consumption of household appliances and the generation of the distributed energy resources (DERs).

Currently, centralized energy production generated by a few large fossil fuel power plants dominates the power supply system and operates in the central areas. Over two-thirds of energy is lost in the process of generation, transmission and distribution [17]. As another option to the power supply system, microgrid as a growing trend can provide the energy to the local customers by application of DERs, which consist of distributed generation, energy storage system, options for load management [31]. With the improvement of information and sensing technologies, the smart home integrated with intelligent devices such as automated meter reading (AMI), smart home appliances enable the end-users to arrange the optimal schedule for energy conservation and environmental protection [21].

Bi-directional information exchange in microgrid between end-users and electricity markets makes it possible that household electrical appliances data can be sent to customers by application of HEMS and the customers can act more active for the reduction of energy consumption [41]. Energy consumption of households relies on the physical properties of

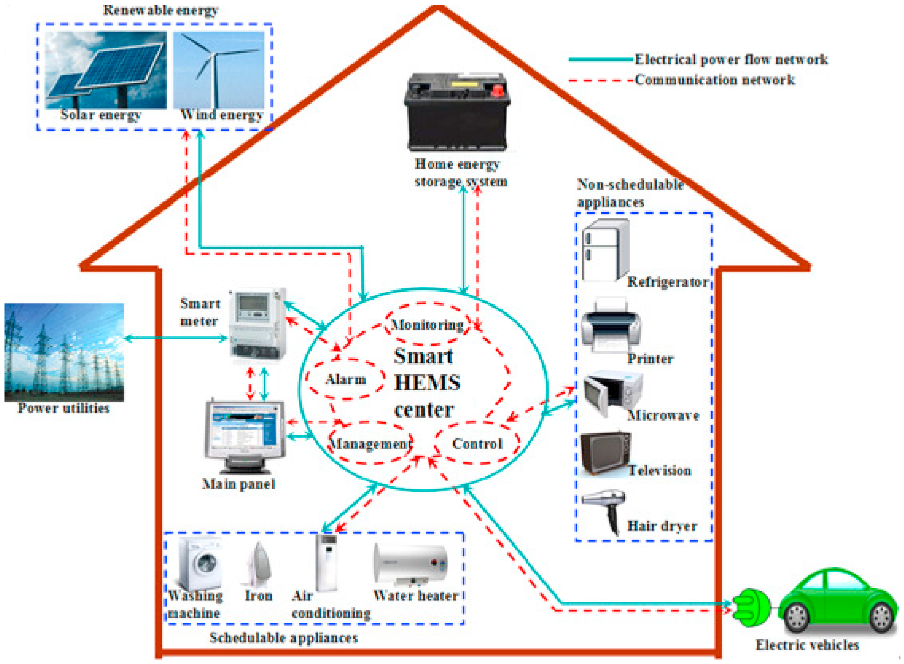


Figure 2.2. *Example of Smart Home for the physical layer*

dwellings, efficiencies of electrical appliances and the behaviors of the end-users. 10% to 30% reduction of energy consumption could be achieved by utilizing demand-side management (DSM), which can coordinate the distributed generation and the consumption demand of the end-users by changing the customers' behaviors such as scheduling the household appliances [48]. DSM in households is the optimal operation of household appliances, such as water boiler, electric heaters, and dishwasher [35]. One representative example of a smart home for the physical layer is presented in Figure 2.2. A smart home is a well-structured utility for information exchange between home appliances and end-users rather than acts as the aggregator for power supply to electric appliances from power grid [55]. Smart HEMS center can provide the functionalities including monitoring, alarm, management and control by home area network (HAN) [25].

2.1 Home Energy Management System (HEMS)

HEMS is a crucial part of smart homes, which is utilized to supervise and control household appliances in real-time according to preferences of customers to achieve energy efficiency improvement and reduction of the energy bills by the implementation of optimal dispatch of energy consumption in smart homes. The increasing attraction on energy crisis and global warming leads to the growing deployment of distributed renewables generation like small scale solar photovoltaic (PV) panels, wind turbines integrated with the distribution system. HEMS holds the potential to improve the in-home energy conservation by coordinating the distributed generation (DG) and home energy storage systems [27]. Therefore, this would be an intensive driving force to improve energy management in households or residential buildings.

To conserve energy and save the electricity cost, HEMS will be more active in the flexible management of household electric appliances, distributed generations and storage systems. The intelligent devices including advanced metering infrastructure (AMI) can provide real-time information such as the quantity of consumed energy in households to HEMS. The end-users could select the HEMS strategy to operate and manage the schedule of smart household appliances to optimize the energy cost and energy efficiency without sacrificing their comfortable experience [46]. Figure 2.3 presents the functionalities of a HEMS and the details are addressed as followed:

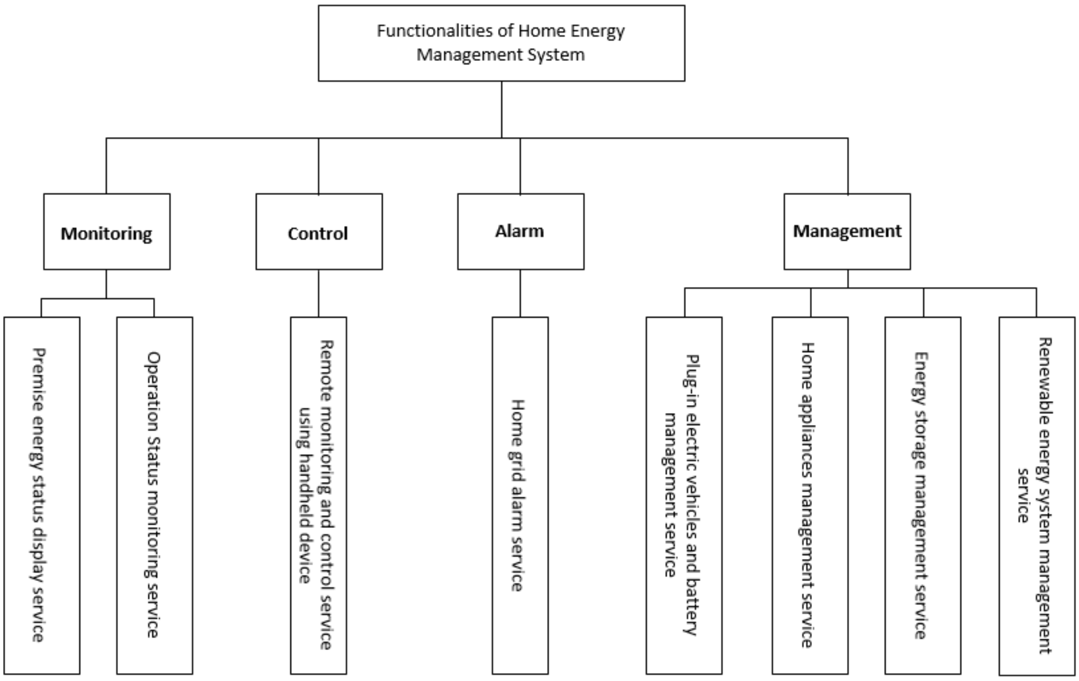


Figure 2.3. *Example of Functionalities of a HEMS [52]*

- Monitoring: Monitoring is one of the most important functions for HEMS, which can enable HEMS to collect real-time data about quantities of the used energy or generation from DG including micro wind turbines and PV panels. The amount of electricity charged or discharged by the home energy storage systems. And the smart human-machine interface can present the operation state of home appliances. Moreover, the task of demand response to real-time or day-ahead pricing of the electricity market will be finished in this process.
- Control: In this process, the smart devices including home appliances, distributed generation and HEMS can be controlled locally or remotely by application in a computer or mobile phone using the internet or manually by users.
- Alarm: When some fault or abnormality happens, the information about the location will be processed and sent to HEMS.
- Management: This process is the most important part of HEMS. In this process,

the strategy will be selected to optimize the operation of distributed renewable generation, home electric appliances and the home energy storage systems including battery systems and Plug-in electric vehicles. The optimization of smart devices makes it possible to reduce the energy cost and improve energy efficiency.

2.2 Distributed Renewable Energy Sources in Smart households

2.2.1 The development of renewable energy sources

Currently, renewable energy sources (RES) have been widely utilized in all energy-consuming sectors, consisting of public sectors, residential, industrial and commercial. As presented in Figure 2.4, in 2012, the utilization in residential, commercial and public sectors accounted for 50.4% of the whole renewable consumption while electricity and heating usage accounted for 31.1% [1]. This means the research on renewable energy used in the smart home has great importance and promising prospect. From a technical and economic point of view, it is possible to utilize the renewable energy for home electricity to substitute traditional energy resources.

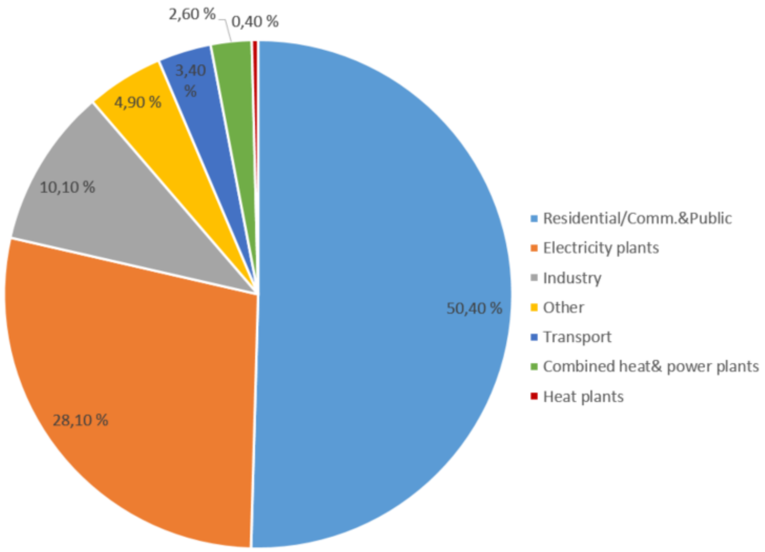


Figure 2.4. *Renewable Consumption in 2012 [1]*

European countries are always the leading countries in applying renewable electricity in households. Germany planned to gain 300 MW solar power from the roof-mounted PV on the residential buildings by implementation the plan of "100,000 Roofs Plan" in 1998. And now the solar power production has accounted for 0.9% of the energy use in German households [52]. After the installation of PV arrays for households, the end-users would also act as energy producers. It is feasible to utilize solar power production in smart homes because of easy installation. By 2016, the installed capacity of PV for the residential households in the EU has reached almost 17GW, accounting for 17% of total solar PV capacity. The projected residential PV in the EU will be double by the year 2030, reaching 32GW [43]. Besides, the solar heater system is another way to utilize solar power in households. According to the report from European Solar Thermal Industry Federation Federation (ESTIF) based on the EU-funded project RESTMAC, in Europe, the solar heater has been widely used and the installed capacity was 14.17GW by the end of the year 2006. It is projected to have a significant increase by the year of 2030 with the installed capacity of 340GW, where around 485,000,000m^2 of solar collectors will be installed.

2.2.2 The utilization of renewable energy sources

Solar energy is generally used in smart houses and it is easy to convert solar power to electricity by the application of PV technology. Solar energy production could be utilized as the primary energy when the sunshine is enough for the whole year. Otherwise, because of easy installation as well as economical cost, PV panels are regarded as a good way to provide the energy for the residential. PV module acts a crucial role in the solar system while two angles of the PV module can be adjusted to collect more solar irradiation. DC/AC inverters which can modify square wave generated by PV panels will be used in the conversion system to provide AC electricity for the residential [30].

2.3 Battery Energy Storage System (BESS)

The BESS is important for smart home energy management and contributes significantly to the improvement of smart grid technologies. To minimize the energy bill and improve energy efficiency, an optimal schedule would be provided by HEMS for the BESS to store or supply the energy based on the real-time electricity pricing [54]. The growing deployment of renewable energy including PV production in an intelligent home would lead to concerns about the intermittency of the power production caused by the inconstant weather. Energy storage systems hold the potential to act as the backup and make the renewable energy production supply match the demand [47].

Energy storage technologies include four types, namely electromechanical, electromagnetic, electrochemical and thermal storage according to the forms of stored energy. As presented in Figure 2.5 in detail, these storage technologies consist of batteries, compressed air energy storage (CAES), flow batteries, flywheel, supercapacitors, power-to-gas, and so on. Considering the size and the installation cost of the storage system, pumped hydro and CAES are not feasible for the small scale renewable energy production. Nowadays, battery technologies are widely used in home energy storage systems due to mature technology [36]. The electricity produced by the renewables including PV production and micro wind power production is intermittent, and the production could be balanced with the consumption at the same time. Therefore, the battery energy system with a well-designed schedule can be used to eliminate the fluctuation of renewable energy production and supply the electricity continuously. Most importantly, the electricity generated by renewable energy sources can reduce the AC peak demand and the production can also be a backup power when the outage happens in the power grid [26].

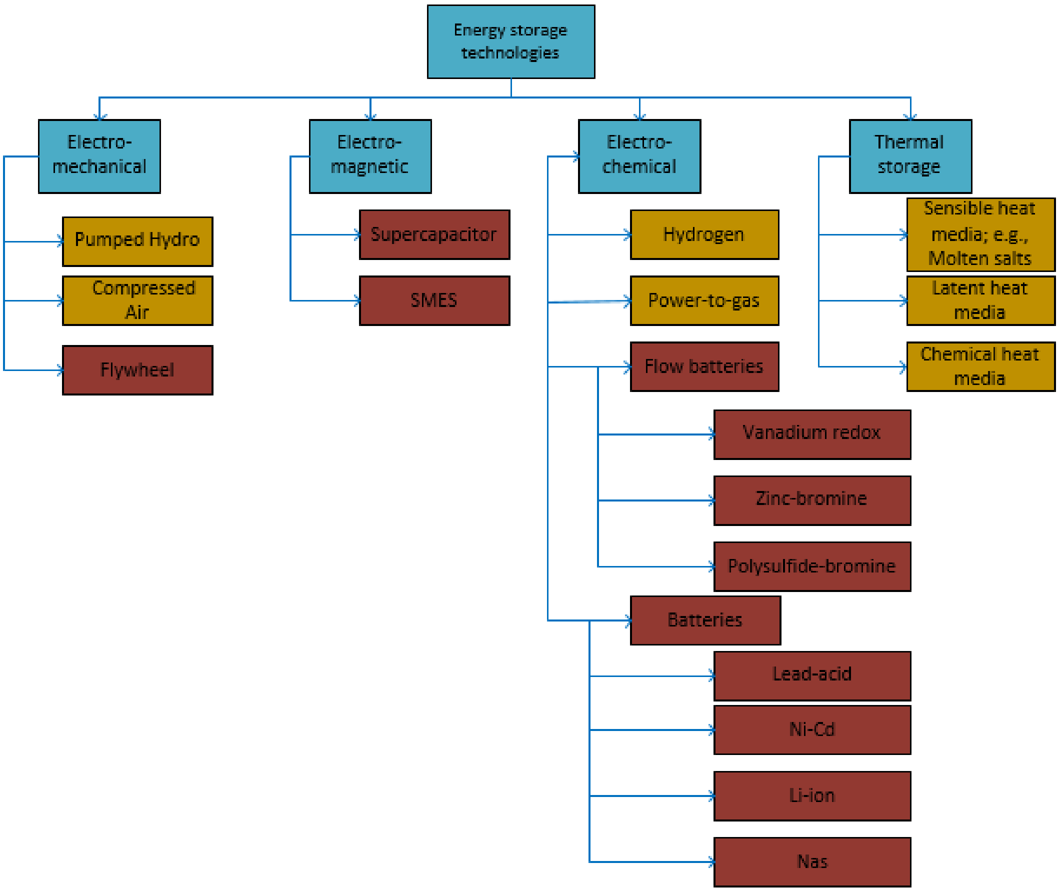


Figure 2.5. *Categories of Storage Technologies*

Due to the application of stored energy and renewable energy, energy conversion technologies would take an important part in energy efficiency improvement. With the growing penetration of RES in the power grid, power electronics technologies are widely applied in the energy conversion system [30]. In smart households, DC power supplied by the PV system will be converted into AC power or the AC power with variable frequencies generated by wind microturbines will be converted into rated frequency AC power by utilizing power converters.

2.4 Home Appliances

Electric appliances are used in each household. In the analysis of optimization of the energy cost of residential consumers, home appliances are generally classified into two categories based on the preference of consumers, namely non-schedulable and schedulable appliances. Non-schedulable home appliances mean the schedule of these appliances cannot be shifted such as oven, microwave, and printer, While the schedule of schedulable home appliances can be shifted for optimization including water boiler, heater, air conditioner and washing machine [51]. These schedulable appliances can be rescheduled in an energy home management system to minimize energy bills and improve energy efficiency [6].

Schedulable home appliances also consist of two groups, namely ‘non-interruptible’ appliances and ‘interruptible’ appliances which can be operated in another time interval without sacrificing their preferences [6]. For non-interruptible appliances, the operation can be postponed but once it starts, these appliances cannot be stopped until they complete the task [42]. Non-interruptible home appliances include cloth dryer and washing machine while interruptible appliances include air conditioner, iron, water boiler, dishwasher, water pump, vacuum, cleaner, and refrigerator.

3 HOME ENERGY MANAGEMENT SYSTEM

The growing energy demand and the deployment of smart grid technologies have been the driving force for the application of HEMS to optimize energy consumption. HEMS is the energy management tool that schedules the controllable home appliances to minimize the energy bill and improve energy efficiency in smart houses. With the deployment of smart technologies including sensor technologies, AMI and bidirectional communication technology, the real-time information and operation state of electric appliance can be collected and delivered to the optimization algorithm in HEMS. Moreover, HEMS can coordinate the operation of the energy storage system and small scale renewable energy sources with home appliances [26]. In this chapter, HEMS has been introduced in details including the components and the functionalities, which help understand how HEMS works. Moreover, three models with different focus and contributions have been proposed, which gives the idea of how to develop a strategy or algorithm for HEMS. Based on these, a model and optimization algorithm has been developed in the thesis.

3.1 The Components of HEMS

Generally, HEMS consists of three parts:

- information and communication system
- smart sensor
- HEMS center

Smart meters are generally used to provide data for HEMS, so this kind of component will be also presented in this chapter. With these components, HEMS can supervise and control the operation of the electric appliance, collect information and deliver to the smart interface, and optimize the operation of the controllable appliances and DERs including home energy storage systems (HESS).

3.1.1 Smart meter

Smart meters are the core part of HEMS and act as an important role in the energy management system. By using the bidirectional communication technologies, the smart meters have opportunities to collect real-time data including energy consumption and other information between power suppliers and end-users [10]. The total energy consumption or production of home appliances or DERs are easily monitored and tracked by using smart meters. And the customers will be able to optimize their energy usage and save the energy bill. Therefore, the customers hold the potential to make an optimal schedule of home appliances, home energy storage systems, and small scale distributed energy resources [4]. Integrated with communication technologies and measurement technologies, smart meters as one of the state-of-art technologies, enable end-users to read real-time values locally from the meter. Otherwise, HEMS may also utilize billing data collected by DSO from the customer information system (CIS), but this data is typically collected once a day, and in future, billing data will be available in Data Hub [7].

3.1.2 Information and Communication system

Information and communication system is used to transmit information between HEMS and smart meters, controllable home devices, and sensors. With the development of information and communication technologies, there have been some communication schemes used in HEMS until now such as power line communication, BACnet, Bluetooth, MiWi, ZigBee, WiFi, HomePlug, and Z-wave. The researches on the improvement of communication technologies have been done to integrate various household devices in HEMS. The communication framework in HEMS is usually termed home area network(HAN), which is utilized for information collection from the home appliances, HESS and DERs. Comparing these communication technologies, Z-Wave and Home-plug are more suitable for usage in HAN because of easy installation and low-cost [28]. Z-Wave is a wireless protocol that can handle 232 devices while power line communication is usually used for high-speed communication [32].

3.1.3 HEMS center

HEMS center, as the brain of HEMS, plays a crucial role in home energy optimization. It is a home appliance integrated with energy management strategies, which will schedule the controllable household appliances. But until now there is not a fit-for-all energy management system which can be suitable for customers due to the different focus of different manufactures. Generally, the energy management center has some functionalities as followed:

- collect information measured by smart meters and send the command to controllable appliances
- display the real-time data to the customers by the human-machine interface and provide some other services such as real-time monitoring, data browsing and strategies resetting
- can be used to optimize and schedule the operation of home appliances, HESS and

DERs

3.2 Models for home energy management

Recently, there have been significant changes in electricity networks with the growing integration of distributed energy generations. Along with smart grid technologies, HEMS with a modern communication system has been widely deployed in smart homes [5]. HEMS can use a set of available measured data to improve energy conservation and minimize the energy cost by changing the operation time of home appliances. To analyze the energy optimization, the operation of the home appliances should be modeled. During the last decades, several kinds of models with different energy management strategies have been created to achieve the improvement of energy efficiency. In this chapter, three home energy management models namely, optimization based on real-time pricing, a model with DGs and real-time pricing integrated and optimization considering social welfare have been presented in detail.

3.2.1 Optimization of energy cost based on real-time pricing

Heating and cooling appliances (HCAs) usually take up the majority part of energy consumption in households. For traditional control, Heating service will start to operate when the temperature reaches the lower limit, and it will turn off when the temperature reaches the upper limit. While for cooling service, it is the opposite. But this will lead to high energy costs when taking real-time pricing into account [53].

The strategy for HCAs is presented with the purpose to reduce the energy bill without scarifying the preference of customers. In this algorithm, the dynamic electricity price and real-time temperature have been considered.

The operation of HCAs consist of two periods: pre-working period refers to the periods that HCAs do not work, and stable working period means that HCAs are working to heat or cool the space according to the requirements of the end-users. Now the control for the stable working period is mature, and with the improvement of technologies in the wireless communication and indoor insulation, it is feasible to control HCAS in pre-working periods.

Figure 3.1 presents the scheme of energy management in a one-room apartment. Two electric heaters can be controlled by measuring the indoor temperature with the sensors at the indoor nodes, and the other sensor can detect the outdoor temperature. The indoor temperature in this model is related to the temperature difference between indoor and outdoor, indoor insulation significantly and the power of HCAs. Ideally, the indoor temperature changes in linear, when without considering the thermal losses.

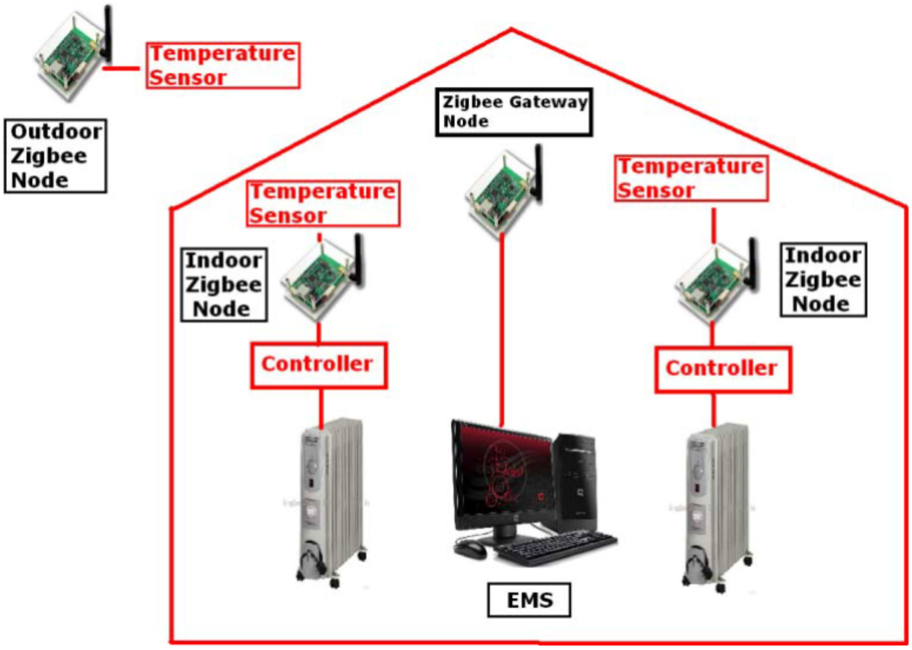


Figure 3.1. *The scheme of an HCA model*

Equation 3.1 presents the increment of the temperature ΔT in a time interval Δt:

$$\frac{\Delta T}{\Delta t} = \frac{P_{Heater}}{S_A H_A \rho_A C_A + V_w \rho_w C_w + V_f \rho_f C_f} \tag{3.1}$$

Where:

ΔT represents the temperature increment in the unit time

Δ t represents the unit time

P_{Heater} represents the power of electric heaters

S_A represents the area of the singe room apartment

H_A represents the height of the singe room apartment

ρ_A represents the air density

C_A represents specific heat capacity of air

C_w represents specific heat capacity of the wall

ρ_w represents the density of the wall

V_w represents the volume of the wall

C_f represents specific heat capacity of the floor

ρ_f represents the density of the floor

V_f represents the volume of the floor

Actually, the building material is not ideal, so thermal losses cannot be ignored. To simply the model, not all the factors related to temperature change are considered. The In this model, the thermal losses from the window and wall will be implemented. Equation 3.2

presents the changes of indoor temperature:

$$\frac{\Delta T_{change}}{\Delta t} = \frac{\varepsilon_{wa}S_{wa} + \varepsilon_{wi}S_{wi}}{S_A H_A \rho_A C_A + V_w \rho_w C_w + V_f \rho_f C_f} T_d \tag{3.2}$$

Where:
ΔT_{change} represents the change of the indoor temperature
ε_{wa} represents the thermal exchange parameter of wall
S_{wa} represents the area of wall
ε_{wi} represents the thermal exchange parameter of window
S_{wi} represents the area of window
T_d represents temperature difference between indoor and outdoor

According to equation 3.2, the temperature difference T_d varies with the variation of indoor temperature. The relation between the temperature difference and the indoor temperature is addressed via equation 3.3, which is relevant to the indoor temperature in the previous time interval:

$$T_d(t) = T_{in}(t-1) + \Delta T(t) - T_{out}(t) \tag{3.3}$$

Where:
$T_{in}(t-1)$ represents the indoor temperature of previous time interval
T_{out} represents the outdoor temperature

Based on equations 3.1 and 3.2, the indoor temperature changes without the operation of EMS can be described:

$$\begin{aligned}
T_1 &= T_0 + \Delta t(-\frac{\Delta T_{change(1)}}{\Delta t} + \frac{\Delta T}{\Delta t}) \\
T_2 &= T_1 + \Delta t(-\frac{\Delta T_{change(2)}}{\Delta t} + \frac{\Delta T}{\Delta t}) \\
T_3 &= T_2 + \Delta t(-\frac{\Delta T_{change(3)}}{\Delta t} + \frac{\Delta T}{\Delta t}) \\
&\cdots\cdots \\
T_k &= T_{k-1} + \Delta t(-\frac{\Delta T_{change(k)}}{\Delta t} + \frac{\Delta T}{\Delta t})
\end{aligned} \tag{3.4}$$

The equations presented above address the relation between indoor temperature and the operation time of the heaters. To make the heaters work more efficiency, the operation time for heaters can be rescheduled based on real-time pricing. The end-users can reduce the energy cost by presetting the operation time before arriving at home by remote communication. According to the varying price, the periods for pre-working and stable working will be assigned to different time intervals. The control signals marked as "M", is a matrix, of which, "0" means "OFF" and 1 means "ON". Based on equations 3.4, the new equations related to M are addressed as 3.5:

$$
\begin{aligned}
&T_1 = T_0 + \Delta t(-\frac{\Delta T_{change(1)}}{\Delta t} + \frac{\Delta T}{\Delta t}M(1)) \\
&T_2 = T_1 + \Delta t(-\frac{\Delta T_{change(2)}}{\Delta t} + \frac{\Delta T}{\Delta t}M(2)) \\
&T_3 = T_2 + \Delta t(-\frac{\Delta T_{change(3)}}{\Delta t} + \frac{\Delta T}{\Delta t}M(3)) \\
&\cdots\cdots \\
&T_k = T_{k-1} + \Delta t(-\frac{\Delta T_{change(k)}}{\Delta t} + \frac{\Delta T}{\Delta t}M(k))
\end{aligned}
\tag{3.5}
$$

This strategy is to control the operation of heaters at the pre-working periods on the basis of real-time pricing. The objective function is given as follow:

$$Min(Cost) = \Sigma_{t=0}^{k} M(k)C(k)\Delta t \tag{3.6}$$

Where,
M represents the matrix of control commands
C represents the price of the electricity

Because the time interval k is the time when the customer will arrive at home, the time interval 0 is the one when the customer leaves the home and the temperature of this period is related to the preference of user so the temperature T_k should follow the constraint, and the constraint can be presented:

$$T_k = T_e(1 \pm 5\%) \tag{3.7}$$

Where,
T_e represents the expected indoor temperature

3.2.2 Model with DGs and real-time pricing (RTP) information integrated

According to [38], this section addresses a model to optimize the energy consumption for a household considering DGs and real-time pricing information. Figure 3.2 shows the home energy system which consists of small scale solar and wind power, and a set of home appliances such as a TV and washing machine. The appliances can be controlled by HEMS through the home area communication network.

For this work, the following assumption is made that all the household appliances work

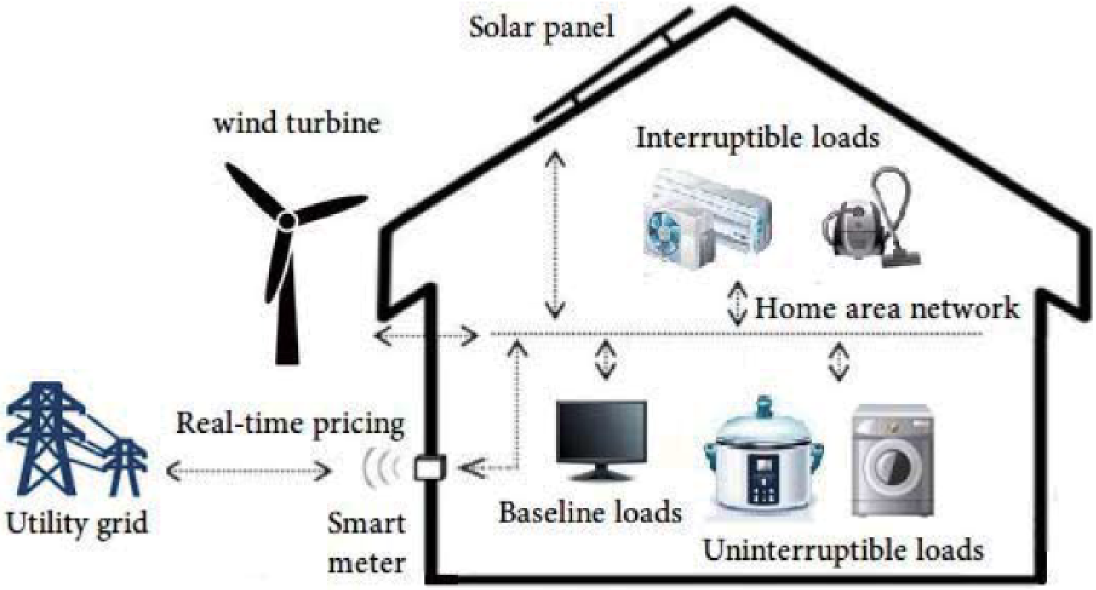


Figure 3.2. *The model of household energy system*

at the rated power during the working periods and according to the characteristics of the appliances, the model should meet the constrains in the load management as followed:

$$\begin{cases} \alpha_a \leq t_a^{start} \leq h_a \leq t_a^{end} \leq \beta_a, \\ x_a^h = \{0,1\}, h \in \forall h_a \\ \beta_a - \alpha_a \geq d_a, \\ E_a = P_a \times d_a = \Sigma_{h=\alpha_a}^{\beta_a} x_a^h \times P_a \end{cases} \tag{3.8}$$

Where,
t_a^{start} represents the operation stating time;
t_a^{end} represents the operation ending time;
h_a represents time h that appliance ’a’ may work;
(β_a-α_a) represents the allowable time range for operation;
x_a^h represents the operation state (ON or OFF) at time h;
d_a represents operation time;
P_a represents the rated power of appliance ’a’;
E_a represents the energy consumption of appliance ’a’;

The target is to achieve the reduction of the electricity bill by full utilization of the production of DG. The main consideration for load control is to allocate the controllable appliances into the time slots (The 24-hour is divided into 48 slots) which the production from DG is sufficient. This can be implemented to minimize the difference between load demand and the power production of DG by optimizing the schedule of the operation of the household appliances. The mathematical formulation can be presented as 3.9:

$$f = min\Sigma_{h=1}^{48} \mid P_{DG}^{h} - P_{must}^{h} - \Sigma_{1}^{m+n} x_{a}^{h} P_{a} \mid \tag{3.9}$$

Where,
P_{DG}^{h} represents the power production of DG at time h;
P_{must}^{h} represents power consumption for the baseline loads at time h;
m represents the number of uninterruptible appliances;
n represents the number of interruptible appliances;

Moreover, the optimization of household energy consumption can be designed based on two ways: DG-based load scheduling and real-time pricing based scheduling. For DG-based scheduling, the usage of DG generation can be optimized and for real-time pricing based scheduling, the flexible loads will be operated in the time slots at low prices. This model is different from the model presented in the last section and the model to be presented in the next section because the combination of DG and price is considered.

3.2.3 Model of optimization based on social welfare

Reference [40], addressed an approach to optimize the energy consumption based on the end-users' social welfare level which remains unchanged while changing the pricing policy from a flat one to a real-time one. In this model, the 24-hour also can be divided into three time slots based on the inclining block rates (IBR) levels with a 3-level peak-load pricing structure. The assumptions related to the pricing structure have been made for the summer daily usage of the electricity as followed:

1. Peak load happens at night because of lighting
2. low demand happens in the morning
3. day-time demand is the average

Based on the assumptions addressed, a three-level price structure and a three-level coefficient of time have been designed. The designed structure creates a 33% difference between the high and the average level, otherwise, the same difference has assigned between the average level and the low level. The price in peak time should be twice of that in low demand time. Based on this, the three-level IBR structure according to time slot has been created as presented in (3.10):

$$\begin{cases} J_a = 1, & (1am - 9am); \\ J_a = 1.33, & (9am - 5pm); \\ J_a = 2, & (5pm - 1am); \end{cases} \tag{3.10}$$

Where:
J_a represents the coefficient of IBR levels

C_i^t is the electricity price for the customer i in the time slot t, it can be represented in the equation followed:

$$C_i^t = J_a \alpha B \tag{3.11}$$

Where,
B is the basic price of energy set by the retailer, and it is considered as constant for simulations and calculations, but in reality, it will be affected by many parameters such as international oil and gas price
α is the coefficient of time

For each customer, some appliances always consume energy, even though these appliances do not work at their full power. So the constraint for energy consumption at each time slot is presented as 3.12:

$$Q_{i_{\min}} < Q_i^t < Q_{i_{\max}},\ Q_{i_{\min}} \neq 0 \tag{3.12}$$

The energy usages for 24-hour and the corresponding prices are presented in vector 3.13 and 3.14,

$$Q_i = \{Q_i^1, Q_i^2, \ldots, Q_i^{24}\} \tag{3.13}$$

$$C_i = \{C_i^1, C_i^2, \ldots, C_i^{24}\} \tag{3.14}$$

The electricity cost can be calculated according to equation 3.15:

$$f = \sum_{t=t_0}^{t_f} C_i^t Q_i^t \tag{3.15}$$

The total electricity consumption can be represented as followed:

$$Q_{wi} = \sum_{t=1}^{24} Q_i^t \tag{3.16}$$

According to [40], "X" is defined as the vector in which x_k^t represents the power consumption for the device k,

$$X^t = \{x_1^t, x_2^t, \dots, x_n^t\} \tag{3.17}$$

$$\min(x_k) < x_k^t < \max(x_k) \tag{3.18}$$

$$Q_i^t = \sum_{k=1}^{n} x_k^t \tag{3.19}$$

Where,
n represents the total number of the schedulable appliances in household
Q_i^t represents the power consumption in time slot "t" for all the appliances

According to the extent of the importance of the home appliances, a parameter is assigned to each device.

$$S = \{s_1, s_2, \dots, s_n\} \tag{3.20}$$

In reference [40], the minimum value of this parameter is 1, and five values including 1, 1.25, 1.5, 1.75 and 2 are assigned to the electric appliances according to the extent of importance.

1. The usage for appliances is based on normal preference of customer.
2. The users can control the schedulable devices freely.
3. The level of welfare declines as the waiting time for using a certain device (heater, air conditioner) increases.
4. With the waiting time passing by, the slope of decrease in welfare reduces.
5. The more important of the delayed electrical device, the more effect on the welfare cost.
6. The maximum time for postponing is 16 hours (the time needed from high price to low price)
7. The number of delayed appliances has a direct effect on the welfare cost.
8. It is easier to delay an appliance with short time usage.
9. The customer is sensible to the electricity price.
10. The importance changes based on time but in general, an average value is assigned to the device.

W represents the welfare cost function, T represents the delayed time of the electrical device and u represents the usage time of the device. To realize cases presented in assumptions (3), (4)and (6), equation 3.21 has been proposed:

$$W \propto \frac{T}{T+16} \tag{3.21}$$

In addition, in order to realize cases (4) and (8), equation 3.22 has been proposed:

$$W \propto \frac{T+u}{u} \tag{3.22}$$

According to all the cases presented, equation 3.20, 3.21 and 3.22, the welfare cost function could be addressed as:

$$W = \frac{1}{Q_{wi}} \sum_{n=1}^{N_v} \left(\sum_{t=T}^{T+u} s^{\frac{T^2+2Tu+16(T+u)}{nTu+16u}} Q_i^t \right) \tag{3.23}$$

Where,
N_v is the number of the delayed appliances

When all the importance of all appliances is the same, the equation can be expressed:

$$\text{Minimize} : W = \frac{N_v}{Q_{wi}} \sum_{t=T}^{T+u} s^{\frac{T^2+2Tu+16(T+u)}{1Tu+16u}} Q_i^t \tag{3.24}$$

3.2.4 Summary of these models

The model presented in section 3.2.1 introduces an algorithm of HEMS to minimize the energy bill for HCAs in the household, considering the real-time pricing and monitoring. Besides, the pre-working periods for HCAs have been considered, which is not usually utilized in Finland. The model presented in section 3.2.2 presents an approach for optimizing the schedule of operation of household appliances by allocating the controllable loads to the time slots with low electricity prices considering the power production of DG and RTP information. For the model introduced in section 3.2.3, the optimization algorithm is implemented based on the customers' social welfare.

3.3 Optimization model based on the Simplex algorithm used in this thesis

In this section, a new approach based on the Simplex algorithm has been proposed. The target is to optimize the energy consumption in households, considering the day-ahead hourly electricity price of Nord Pool market and the forecasting production of the roof-mounted PV power system. The model can be utilized for energy saving without scarifying the customers' preferences.

3.3.1 Household energy management model

In this section, the model for optimization according to day-ahead pricing and local PV production will be presented. As shown in Fig 3.3, the model of house we will use in this thesis consists of a roof-mounting solar PV system and a water boiler. For this model, we will optimize energy consumption with full usage of PV production. It is assumed that there is a water boiler as controllable devices in the smart house when we optimize energy consumption to reduce the electricity bill. Meanwhile, the day-ahead dynamic price and the forecast PV production based on the weather forecast can be provided to the customer and used for the demand-side management program.

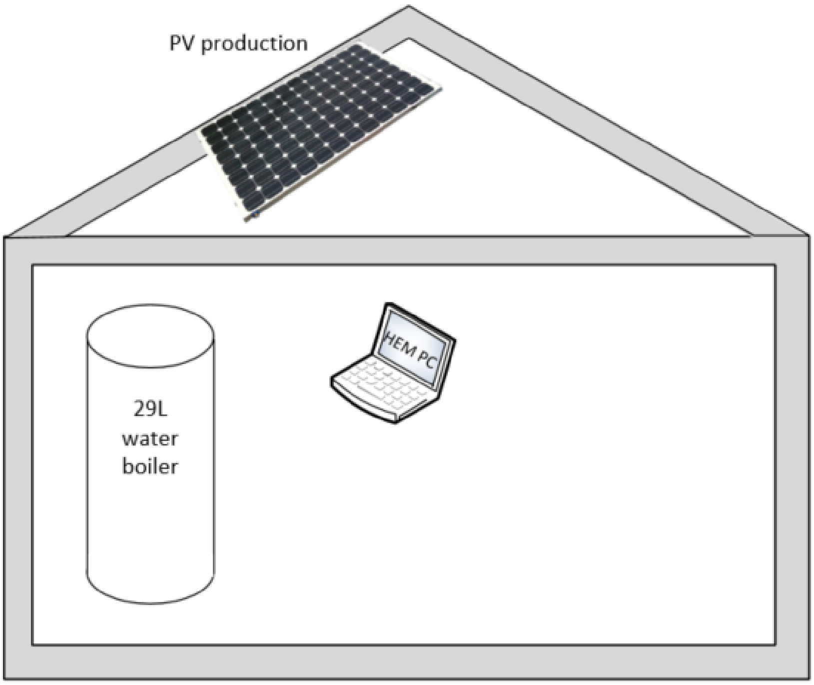


Figure 3.3. *The house model used in this case*

3.3.2 Mathematical formulation

The purpose of this model is to minimize the energy bill by optimizing the schedule of the operation states (ON / OFF) of home appliances while the day-ahead prices and the forecast PV production is considered. It is assumed that HEMS will make the schedule for the next 24 hours (24 slots). In this model, the boiler is modeled as the controllable appliance, and the dissipated power that can be modeled by the cooling system including the radiator with propeller is used to emulate the heated water demand for the customers. The energy bill refers to the injected energy from the distribution grid and it is assumed that the maximum power of PV production is less than the rated power of the boiler. If the maximum power of PV production is more than the rated power of the boiler, the microgrid will power the utility grid, and the contracts and tariffs between DSOs and customers will be considered. To simplify the analysis of the optimization, in this thesis, the tariffs and contracts between DSOs and customers will not be taken into account.

The energy bill for the next day can be modeled based on the day-ahead pricing. The boiler is controlled by HEMS and it may not operate constantly in one time slot due to low demand for heated water, hence, the mean power of heater in one-hour time slot is used in the model. In addition, the PV may not supply the power constantly because of cloudy or other weather conditions, so the mean power of the specific hour based on weather prediction for the PV is also used in the model. The electricity bill is presented as bellow:

$$f^T = \Sigma_{k=1}^{k}(P_{b,k} - P_{pv,k})\tau C(k),\ k \leq 24; \tag{3.25}$$

Where:
$P_{b,k}$ is the mean power of the boiler in time slot k
$P_{pv,k}$ is the mean power of the PV production in time slot k
τ is the time slot, and in this model, we use 24 resolutions based on day-ahead price, so the value of τ is 1
C_k is the day-ahead electricity price in time slot k

The target is to minimize the electricity bill for the next day, so the objective function and the constraints can be addressed as followed:

$$f^T = min\Sigma_{k=1}^{k}(P_{b,k} - P_{pv,k})\tau C(k),\ k \leq 24; \tag{3.26}$$

$$Q_k = (P_{b,k} - P_{d,k})\tau + Q_{k-1} \tag{3.27}$$

Subject to:

$$Q_{min} < Q_k < Q_{max} \tag{3.28}$$

Where:
$P_{d,k}$ is mean power of heat water demand
Q_k is the heat energy stored in the boiler in time slot k
Q_{min} is the minimum energy stored in the water
Q_{max} is the maximum energy stored in the water

The equation 3.27 illustrates the relation between Q_k and Q_{k-1}, which will be applied in the constraints. According to constraint 3.28, the Simplex algorithm will be utilized for the minimization. The variable $P_{b,k}$ can be determined in optimization in Matlab so that the schedule for the operation time of the boiler can be made and it can be emulated by using dissipate power by using cooling system including radiator with the fan. $P_{pv,k}$, C_k are given values, otherwise, Q_k is also a given value at the beginning and it relies on the initial temperature of water in the boiler. Generally, there is also a constraint for Q_k at the end of the optimization period. Otherwise, storage will be empty or in minimum value in the end.

The algorithm for optimization will be addressed in detail in the next chapter.

4 MODEL FRAMEWORK DESCRIPTION AND OPTIMIZATION

The proposed algorithm used in this thesis will utilize simplex for the optimization to minimize the electricity bill and to reduce the energy consumption in the household. The Simplex algorithm, which usually is applied in Linear Programming, enables the calculation for the power usage and the optimization of control for the boiler. The process for the optimization research in this thesis has been presented in Figure 4.1. The process for optimization consists of two steps: data processing and problem formulation. In the first step, the data about weather, PV generation, load, and the market are collected and processed. Weather information including temperature and global irradiance can be used to estimate the PV production and the load here is the mean power of dissipation of heated water, which is utilized to model the heated water demand. The data from the market is the day-ahead price from Nord Pool market. When all the data is collected and processed, the optimization can be achieved by using the simplex algorithm.

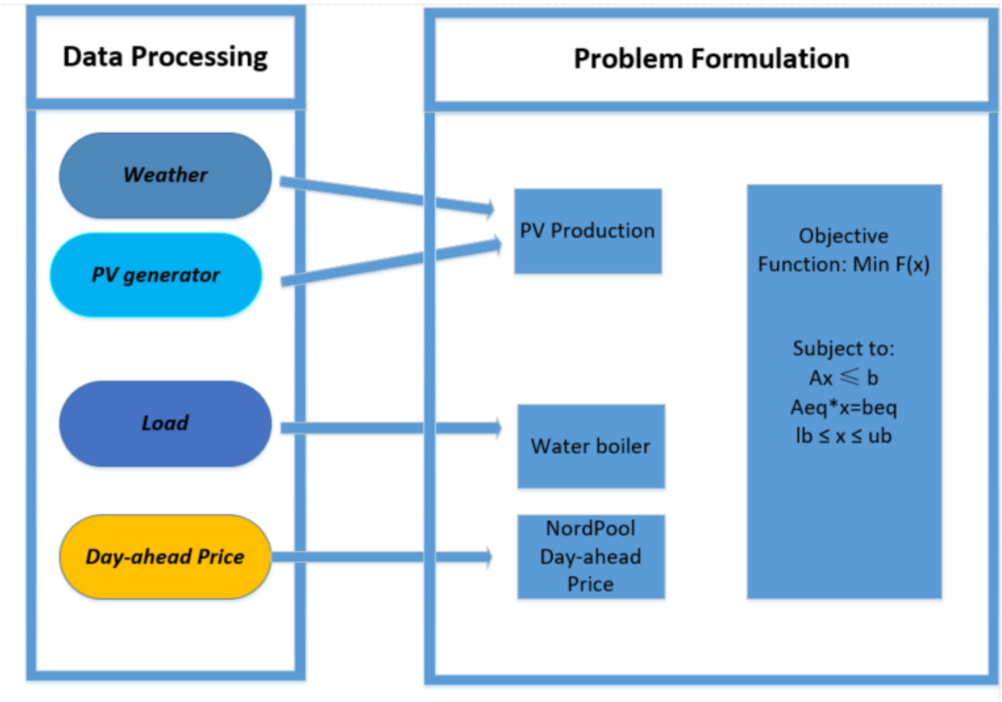


Figure 4.1. *The flow chart of optimization*

4.1 Forecasting weather and global irradiance

The forecasted weather data can be collected from Finnish Meteorological Institute (FMI), which will provide the accurate atmosphere information including temperature, global irradiance, humidity, wind direction, wind speed and so on in open data [49]. The open data is freely available for public use, moreover, open data is machine-readable so that the forecasting data can be used in the research easily. In this research, global irradiance and temperature will be used for forecasting PV production.

The sun produces huge energy by nuclear fusion converting hydrogen atoms into helium. The electromagnetic energy generated from the loss of mass emits into space and the solar power received per unit area is termed solar irradiance, which will be affected by some factors including the tilt of measured surface, weather conditions and the position of the sun above the horizon. The sun's position is the key factor for global irradiance that has a tremendous impact on PV production. Global irradiance on the horizontal plane includes two components, namely, diffuse irradiance and direct irradiance. But for inclined surfaces such as PV arrays, the global irradiance has an additional component named reflected irradiance, and it can be presented in Figure 4.2.

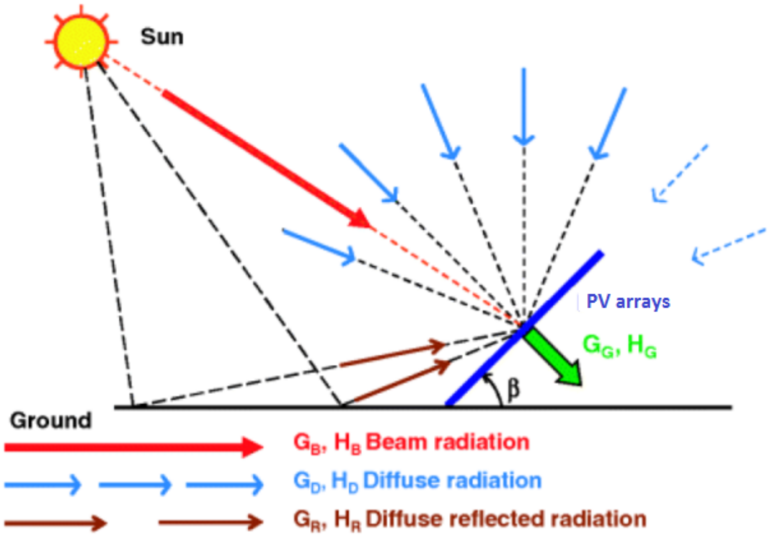


Figure 4.2. *The global irradiance to PV arrays*

PV systems have a long lifespan of 25 years without little maintenance, especially for the PV modules. Shading will result in a tremendous reduction for the output, in case of small shadow on a single cell [24]. At the maximum power point, the electrical characteristics can be stated by the parameters including voltage, current, open-circuit voltage, output power, and short circuit current. Generally, converters and inverters are needed to feed the energy produced by PV arrays to the grid-connected system. Converters are utilized for conversion of the variable output voltage into a constant voltage, especially for battery charging. While by application of the inverter, direct current (DC) voltage can be converted into alternating current (AC) voltage with controlled frequency and magnitude[13, 24].

4.2 Nord Pool electricity price

The day-ahead electricity price used in this thesis is from the Baltic and Nordic power market, Nord Pool. It provides two kinds of service for power trade, namely the intraday market and day-ahead market which is the primary market for power auction of the following day. It takes an important part in maintaining the balance of power demand and supply. The suppliers and purchasers make the contracts and the price for each hour is determined in this market. Power buyers including the utilities or companies and the big end-users should provide the estimated volume of energy they need and the price they plan to bid for the product in each hour. The power suppliers such as the owners of the nuclear power plants or fossil fuel power plants should offer the volume of energy and the price for each hour. The determined price for each hour is the intersection of the supply and demand offer curves (as can be seen in Figure 4.3), where the power supply and demand achieve the balance. The bids for power the next day should be submitted before 12:00 Central European Time (CET), and the final price will be calculated by the specialist computer system. Once the price determined, the power will be supplied to the customers based on the contracts hour by hour. When the price is published, it will be provided to HEMS for optimization, otherwise, the data can be used for research use for free [9].

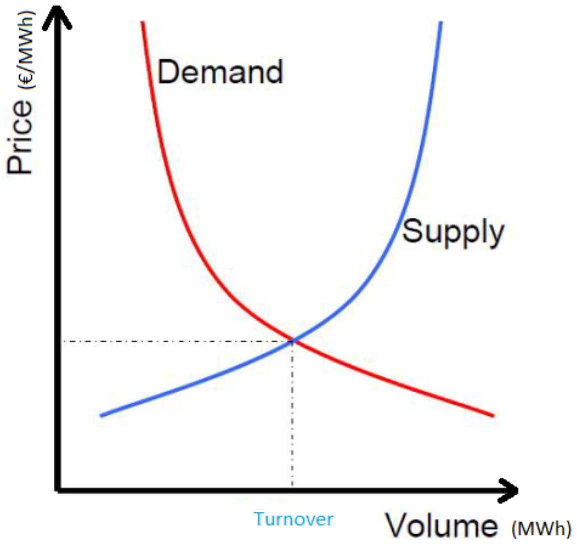


Figure 4.3. *The curve for demand and supply in day-ahead market*

4.3 Simplex algorithm

Simplex is a general optimization method and it is used for energy cost optimization without changing the customer's preferences. When the day-ahead prices and data about the weather are collected, and then they can be used in HEMS for optimization. The mean power of the boiler is the only variable in the problem formulation. When it is determined, the schedule for operation of the boiler will be made.

The optimization programming is utilized in Matlab and the liner optimization has to form the objective function $Minf^T$ as well as the constraints formed as below:

$$\begin{cases} A \times x < b, \\ A_{eq} \times x = b_{eq}, \\ lb \leq x \leq ub \end{cases} \tag{4.1}$$

Where, f is the coefficient vector of the objective function, x, b, b_{eq}, lb, and ub are vectors, A and A_{eq} are matrices.

By using Simplex algorithm in Matlab, the optimization result and x can be defined. For the objective function presented in previous chapter $f^T = min\Sigma_1^k(P_{b,k} - P_{pv,k})\tau C_k$, the formulation can be transformed as below:

$$f^T = min\Sigma_1^k(P_{b,k}\tau C_k - P_{pv,k}\tau c_k) \tag{4.2}$$

Because PV production can be estimated from the forecasting irradiance, this means $P_{pv,k}\tau C_k$ is known and it will not impact the optimization When PV capacity is less than the capacity of the boiler. While the capacity of PV is more than the capacity of the boiler, the microgrid is possible to supply the power to the utility grid, in this case, the tariffs and contracts that with utilities like DSOs and end-users will be taken into account. However, if there are high prices for a long time, consideration of PV in the optimization may help to keep hot water warm during those hours and it has an impact on the optimization. In this thesis, it is assumed that PV capacity is less than the capacity of the boiler. Hence, the new objective function can be made for optimization.

$$f^T = min\Sigma_1^k P_{b,k}\tau C_k \tag{4.3}$$

In this chapter, the constraints will be illustrated in detail because the objective function has been presented in the previous chapter. With the help of Hydro software, we can get the water temperature that is measured by the thermostat installed in the boiler. The heating energy needed for the temperature change of the water can be calculated based on the equation followed:

$$Q = c \times m \times \Delta T \tag{4.4}$$

Where,
Q represents the heating energy needed for the water when temperature change
c represents the specific heat capacity of water
m represents mass of water

ΔT represents temperature change of the water

Considering the initial temperature is T_0, the stored energy in the the water at the maximum temperature or minimum temperature can be calculated using the equation above.

$$Q_{max} = c \times m \times (T_{max} - T_0) \tag{4.5}$$

$$Q_{min} = c \times m \times (T_{min} - T_0) \tag{4.6}$$

Where,
T_{max} and T_{min} are the temperature limits of the water in the boiler

When T_0 is T_{min}, the energy stored in the water is 0 taking T_0 as the basis. Then, the stored energy at maximum temperature and minimum temperature can can be determined by using equation 4.5 and 4.6.

Assuming at the starting temperature T_0, the stored energy in the water is Q_0, τ is the time interval. Moreover, the energy loss from the boiler is nonlinear, hence it is difficult to simulate. In ideal conditions, the energy loss from the insulation layer can be omitted When analyzing the energy consumption for one day. According to the formulation 3.25, the relation between Q_k and Q_{k-1} can be presented as the equation below:

$$Q_k = Q_{k-1} + \tau \times (P_{b,k} - P_{d,k}) \tag{4.7}$$

Where, $P_{b,k}$ is the mean power of the boiler in the time interval k, $P_{d,k}$ is the dissipation power transformed from the customer's hot water requirements. Based on equation 4.7, the formulation of the stored energy characteristic can be deduced as follows:

$$\begin{aligned}
&Q_1 = Q_0 + \tau \times (P_{b,1} - P_{d,1}) \\
&Q_2 = Q_1 + \tau \times (P_{b,2} - P_{d,2}) = Q_0 + \tau \times (P_{b,1} + P_{b,2}) - \tau \times (P_{d,1} + P_{d,2}) \\
&Q_3 = Q_0 + \tau \times (P_{b,1} + P_{b,2} + P_{b,3}) - \tau \times (P_{d,1} + P_{d,2} + P_{d,3}) \\
&Q_4 = Q_0 + \tau \times (P_{b,1} + P_{b,2} + P_{b,3} + P_{b,4}) - \tau \times (P_{d,1} + P_{d,2} + P_{d,3} + P_{d,4}) \\
&\ldots\ldots \\
&Q_{k-1} = Q_0 + \tau \times (P_{b,1} + P_{b,2} + \ldots + P_{b,k-1}) - \tau \times (P_{d,1} + P_{d,2} + \ldots + P_{d,k-1}) \\
&Q_k = Q_0 + \tau \times (P_{b,1} + P_{b,2} + \ldots + P_{b,k}) - \tau \times (P_{d,1} + P_{d,2} + \ldots + P_{d,k})
\end{aligned} \tag{4.8}$$

In the thesis, the boiler is used as energy storage, so the capacity of the energy storage determines the limits for the discharged energy in each hour. Hence, the constraint here used is $Q_k < Q_{max}$ other than $T_k < T_{max}$. Based on the constraint for Q_k in the inequality $Q_k < Q_{max}$ presented in chapter 3 and equation 4.8, the formulations can be addressed as follows:

$$\begin{aligned}
&Q_0 + \tau \times (P_{b,1} - P_{d,1}) < Q_{max} \\
&Q_1 + \tau \times (P_{b,2} - P_{d,2}) = Q_0 + \tau \times (P_{b,1} + P_{b,2}) - \tau \times (P_{d,1} + P_{d,2}) < Q_{max} \\
&Q_0 + \tau \times (P_{b,1} + P_{b,2} + P_{b,3}) - \tau \times (P_{d,1} + P_{d,2} + P_{d,3}) < Q_{max} \\
&Q_0 + \tau \times (P_{b,1} + P_{b,2} + P_{b,3} + P_{b,4}) - \tau \times (P_{d,1} + P_{d,2} + P_{d,3} + P_{d,4}) < Q_{max} \\
&\ldots\ldots \\
&Q_0 + \tau \times (P_{b,1} + P_{b,2} + P_{b,3} + P_{b,4} + \ldots + P_{b,k-2} + P_{b,k-1}) \\
&- \tau \times (P_{d,1} + P_{d,2} + P_{d,3} + P_{d,4} + \ldots + P_{d,k-2} + P_{d,k-1}) < Q_{max} \\
&Q_0 + \tau \times (P_{b,1} + P_{b,2} + P_{b,3} + P_{b,4} + \ldots + P_{b,k-2} + P_{b,k-1} + P_{b,k}) \\
&- \tau \times (P_{d,1} + P_{d,2} + P_{d,3} + P_{d,4} + \ldots + P_{d,k-2} + P_{d,k-1} + P_{d,k}) < Q_{max}
\end{aligned} \tag{4.9}$$

The transformation of inequalities can be seen in 4.10,

$$\begin{aligned}
&\tau \times P_{b,1} < Q_{max} - Q_0 + \tau \times P_{d,1} \\
&\tau \times (P_{b,1} + P_{b,2}) < Q_{max} - Q_0 + \tau \times (P_{d,1} + P_{d,2}) \\
&\tau \times (P_{b,1} + P_{b,2} + P_{b,3}) < Q_{max} - Q_0 + \tau \times (P_{d,1} + P_{d,2} + P_{d,3}) \\
&\tau \times (P_{b,1} + P_{b,2} + P_{b,3} + P_{b,4}) < Q_{max} - Q_0 + \tau \times (P_{d,1} + P_{d,2} + P_{d,3} + P_{d,4}) \\
&\ldots\ldots \\
&\tau \times (P_{b,1} + P_{b,2} + P_{b,3} + P_{b,4} + \ldots + P_{b,k-2} + P_{b,k-1}) < Q_{max} - Q_0 \\
&+ \tau \times (P_{d,1} + P_{d,2} + P_{d,3} + P_{d,4} + \ldots + P_{d,k-2} + P_{d,k-1}) \\
&\tau \times (P_{b,1} + P_{b,2} + P_{b,3} + P_{b,4} + \ldots + P_{b,k-2} + P_{b,k-1} + P_{b,k}) < Q_{max} - Q_0 \\
&+ \tau \times (P_{d,1} + P_{d,2} + P_{d,3} + P_{d,4} + \ldots + P_{d,k-2} + P_{d,k-1} + P_{d,k})
\end{aligned} \tag{4.10}$$

The formulations 4.10 can be expressed in the matrix in the new transformation 4.11,

$$\begin{bmatrix} 1 & & & & & \\ 1 & 1 & & & & \\ 1 & 1 & 1 & & & \\ 1 & 1 & 1\ 1 & & & \\ & \cdots\cdots & & & & \\ 1 & 1 & 1\ 1 & & \ldots 1 & \\ 1 & 1 & 1\ 1 & & \ldots 1 & 1 \end{bmatrix}_{k\times k} \times \begin{bmatrix} P_{b,1} \\ P_{b,2} \\ P_{b,3} \\ P_{b,4} \\ \cdots \\ P_{b,k-1} \\ P_{b,k} \end{bmatrix}_{k\times 1} < \frac{1}{\tau} \begin{bmatrix} Q_{max}-Q_0 \\ Q_{max}-Q_0 \\ Q_{max}-Q_0 \\ Q_{max}-Q_0 \\ \cdots \\ Q_{max}-Q_0 \\ Q_{max}-Q_0 \end{bmatrix}_{k\times 1}$$

$$+ \begin{bmatrix} 1 & & & & & \\ 1 & 1 & & & & \\ 1 & 1 & 1 & & & \\ 1 & 1 & 1\ 1 & & & \\ & \cdots\cdots & & & & \\ 1 & 1 & 1\ 1 & & \ldots 1 & \\ 1 & 1 & 1\ 1 & & \ldots 1 & 1 \end{bmatrix}_{k\times k} \times \begin{bmatrix} P_{d,1} \\ P_{d,2} \\ P_{d,3} \\ P_{d,4} \\ \cdots \\ P_{d,k-1} \\ P_{d,k} \end{bmatrix}_{k\times 1} \tag{4.11}$$

According to $A \times x < b$, the lower triangular matrix A_1 and the vectors x and b_1 can be expressed as follows:

$$A_1 = \begin{bmatrix} 1 & & & & & \\ 1 & 1 & & & & \\ 1 & 1 & 1 & & & \\ 1 & 1 & 1\ 1 & & & \\ & \cdots\cdots & & & & \\ 1 & 1 & 1\ 1 & & \ldots 1 & \\ 1 & 1 & 1\ 1 & & \ldots 1 & 1 \end{bmatrix}_{k\times k} \tag{4.12}$$

$$x = \begin{bmatrix} P_{b,1} \\ P_{b,2} \\ P_{b,3} \\ P_{b,4} \\ \dots \\ P_{b,k-1} \\ P_{b,k} \end{bmatrix}_{k\times 1} \tag{4.13}$$

$$b_1 = \frac{1}{\tau} \begin{bmatrix} Q_{max} - Q_0 \\ Q_{max} - Q_0 \\ Q_{max} - Q_0 \\ Q_{max} - Q_0 \\ \dots \\ Q_{max} - Q_0 \\ Q_{max} - Q_0 \end{bmatrix}_{k\times 1} + \begin{bmatrix} 1 & & & & & \\ 1 & 1 & & & & \\ 1 & 1 & 1 & & & \\ 1 & 1 & 1 & 1 & & \\ & \dots\dots & & & & \\ 1 & 1 & 1 & 1 & \dots 1 & \\ 1 & 1 & 1 & 1 & \dots 1 & 1 \end{bmatrix}_{k\times k} \times \begin{bmatrix} P_{d,1} \\ P_{d,2} \\ P_{d,3} \\ P_{d,4} \\ \dots \\ P_{d,k-1} \\ P_{d,k} \end{bmatrix}_{k\times 1} \tag{4.14}$$

The constraint should be changed into the form $A \times x < b$, so that all the constraints can be used to form one matrix which would be used in the Matlab for optimization. Hence, the inequality Q_{min} <Q_k should be transformed into $-Q_k$ < $-Q_{min}$. Based on the group of equations 4.8 and the inequality $-Q_k$ < $-Q_{min}$, the inequality can be presented as 4.15:

$$\begin{aligned} & - Q_0 - \tau \times (P_{b,1} - P_{d,1}) < -Q_{min} \\ & - Q_1 - \tau \times (P_{b,2} - P_{d,2}) = -Q_0 - \tau \times (P_{b,1} + P_{b,2}) + \tau \times (P_{d,1} + P_{d,2}) < -Q_{min} \\ & - Q_0 - \tau \times (P_{b,1} + P_{b,2} + P_{b,3}) + \tau \times (P_{d,1} + P_{d,2} + P_{d,3}) < -Q_{min} \\ & - Q_0 - \tau \times (P_{b,1} + P_{b,2} + P_{b,3} + P_{b,4}) + \tau \times (P_{d,1} + P_{d,2} + P_{d,3} + P_{d,4}) < -Q_{min} \\ & \dots\dots \\ & - Q_0 - \tau \times (P_{b,1} + P_{b,2} + P_{b,3} + P_{b,4} + \dots + P_{b,k-2} + P_{b,k-1}) \\ & + \tau \times (P_{d,1} + P_{d,2} + P_{d,3} + P_{d,4} + \dots + P_{d,k-2} + P_{d,k-1}) < -Q_{min} \\ & - Q_0 - \tau \times (P_{b,1} + P_{b,2} + P_{b,3} + P_{b,4} + \dots + P_{b,k-2} + P_{b,k-1} + P_{b,k}) \\ & + \tau \times (P_{d,1} + P_{d,2} + P_{d,3} + P_{d,4} + \dots + P_{d,k-2} + P_{d,k-1} + P_{d,k}) < -Q_{min} \end{aligned} \tag{4.15}$$

The transformation of the inequalities can be seen in 4.16,

$$
\begin{aligned}
&-\tau_{b,1} < -Q_{min} + Q_0 - \tau_{d,1} \\
&-\tau \times (P_{b,1} + P_{b,2}) < -Q_{min} + Q_0 - \tau \times (P_{d,1} + P_{d,2}) \\
&-\tau \times (P_{b,1} + P_{b,2} + P_{b,3}) < -Q_{min} + Q_0 - \tau \times (P_{d,1} + P_{d,2} + P_{d,3}) \\
&-\tau \times (P_{b,1} + P_{b,2} + P_{b,3} + P_{b,4}) < -Q_{min} + Q_0 - \tau \times (P_{d,1} + P_{d,2} + P_{d,3} + P_{d,4}) \\
&\cdots\cdots \\
&-\tau \times (P_{b,1} + P_{b,2} + P_{b,3} + P_{b,4} + \ldots + P_{b,k-2} + P_{b,k-1}) < -Q_{min} + Q_0 \\
&-\tau \times (P_{d,1} + P_{d,2} + P_{d,3} + P_{d,4} + \ldots + P_{d,k-2} + P_{d,k-1}) \\
&-\tau \times (P_{b,1} + P_{b,2} + P_{b,3} + P_{b,4} + \ldots + P_{b,k-2} + P_{b,k-1} + P_{b,k}) < -Q_{min} + Q_0 \\
&-\tau \times (P_{d,1} + P_{d,2} + P_{d,3} + P_{d,4} + \ldots + P_{d,k-2} + P_{d,k-1} + P_{d,k})
\end{aligned}
\tag{4.16}
$$

The inequalities in the group 4.16 can be transformed into equation with matrix,

$$
\begin{aligned}
&\begin{bmatrix}
-1 & & & & & \\
-1 & -1 & & & & \\
-1 & -1 & -1 & & & \\
-1 & -1 & -1 & -1 & & \\
& \cdots\cdots & & & & \\
-1 & -1 & -1 & -1 & \ldots -1 & \\
-1 & -1 & -1 & -1 & \ldots -1 & -1
\end{bmatrix}_{k \times k}
\times
\begin{bmatrix}
P_{b,1} \\ P_{b,2} \\ P_{b,3} \\ P_{b,4} \\ \cdots \\ P_{b,k-1} \\ P_{b,k}
\end{bmatrix}_{k \times 1}
< \frac{1}{\tau}
\begin{bmatrix}
-Q_{min} + Q_0 \\ -Q_{min} + Q_0 \\ -Q_{min} + Q_0 \\ -Q_{min} + Q_0 \\ \cdots \\ -Q_{min} + Q_0 \\ -Q_{min} + Q_0
\end{bmatrix}_{k \times 1} \\
&+
\begin{bmatrix}
-1 & & & & & \\
-1 & -1 & & & & \\
-1 & -1 & -1 & & & \\
-1 & -1 & -1 & -1 & & \\
& \cdots\cdots & & & & \\
-1 & -1 & -1 & -1 & \ldots -1 & \\
-1 & -1 & -1 & -1 & \ldots -1 & -1
\end{bmatrix}_{k \times k}
\times
\begin{bmatrix}
P_{d,1} \\ P_{d,2} \\ P_{d,3} \\ P_{d,4} \\ \cdots \\ P_{d,k-1} \\ P_{d,k}
\end{bmatrix}_{k \times 1}
\end{aligned}
\tag{4.17}
$$

Based on $A \times x < b$, A_2 and b_2 can be presented in the same way with A_1 and b_1,

$$A_2 = \begin{bmatrix} -1 & & & & & \\ -1 & -1 & & & & \\ -1 & -1 & -1 & & & \\ -1 & -1 & -1 & -1 & & \\ & \ldots\ldots & & & & \\ -1 & -1 & -1 & -1 & \ldots -1 & \\ -1 & -1 & -1 & -1 & \ldots -1 & -1 \end{bmatrix}_{k \times k} \tag{4.18}$$

$$b_2 = \frac{1}{\tau} \begin{bmatrix} -Q_{min} + Q_0 \\ -Q_{min} + Q_0 \\ -Q_{min} + Q_0 \\ -Q_{min} + Q_0 \\ \ldots \\ -Q_{min} + Q_0 \\ -Q_{min} + Q_0 \end{bmatrix}_{k \times 1} + \begin{bmatrix} -1 & & & & & \\ -1 & -1 & & & & \\ -1 & -1 & -1 & & & \\ -1 & -1 & -1 & -1 & & \\ & \ldots\ldots & & & & \\ -1 & -1 & -1 & -1 & \ldots -1 & \\ -1 & -1 & -1 & -1 & \ldots -1 & -1 \end{bmatrix}_{k \times k} \times \begin{bmatrix} P_{d,1} \\ P_{d,2} \\ P_{d,3} \\ P_{d,4} \\ \ldots \\ P_{d,k-1} \\ P_{d,k} \end{bmatrix}_{k \times 1} \tag{4.19}$$

To optimize the energy cost, the constraints should be formed in one matrix.

$$A = \begin{bmatrix} A_1 \\ A_2 \end{bmatrix} = \begin{bmatrix} 1 & & & & & \\ 1 & 1 & & & & \\ 1 & 1 & 1 & & & \\ 1 & 1 & 1 & 1 & & \\ & \ldots\ldots & & & & \\ 1 & 1 & 1 & 1 & \ldots 1 & \\ 1 & 1 & 1 & 1 & \ldots 1 & 1 \\ -1 & & & & & \\ -1 & -1 & & & & \\ -1 & -1 & -1 & & & \\ -1 & -1 & -1 & -1 & & \\ & \ldots\ldots & & & & \\ -1 & -1 & -1 & -1 & \ldots -1 & \\ -1 & -1 & -1 & -1 & \ldots -1 & -1 \end{bmatrix}_{2k \times k} \tag{4.20}$$

$$
b = \begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \frac{1}{\tau} \begin{bmatrix} Q_{max} - Q_0 \\ Q_{max} - Q_0 \\ Q_{max} - Q_0 \\ Q_{max} - Q_0 \\ \cdots \\ Q_{max} - Q_0 \\ Q_{max} - Q_0 \\ -Q_{min} + Q_0 \\ -Q_{min} + Q_0 \\ -Q_{min} + Q_0 \\ -Q_{min} + Q_0 \\ \cdots \\ -Q_{min} + Q_0 \\ -Q_{min} + Q_0 \end{bmatrix}_{2k\times 1} + \begin{bmatrix} 1 & & & & & \\ 1 & 1 & & & & \\ 1 & 1 & 1 & & & \\ 1 & 1 & 1 & 1 & & \\ & \cdots\cdots & & & & \\ 1 & 1 & 1 & 1 & \ldots 1 & \\ 1 & 1 & 1 & 1 & \ldots 1 & 1 \\ -1 & & & & & \\ -1 & -1 & & & & \\ -1 & -1 & -1 & & & \\ -1 & -1 & -1 & -1 & & \\ & \cdots\cdots & & & & \\ -1 & -1 & -1 & -1 & \ldots -1 & \\ -1 & -1 & -1 & -1 & \ldots -1 & -1 \end{bmatrix}_{2k\times k} \times \begin{bmatrix} P_{d,1} \\ P_{d,2} \\ P_{d,3} \\ P_{d,4} \\ \cdots \\ P_{d,k-1} \\ P_{d,k} \end{bmatrix}_{k\times 1} \tag{4.21}
$$

$A_{eq} \times x = b_{eq}$ represents the equality constraint, but no equality constraint is used for this case, set A_{eq} = [ ] and b_{eq} = [ ]. ub and lb represent the upper and lower bound for the variable because the upper limit for the mean power of the boiler is the rated power of 1.8 kW and the lower limit is 0. Hence, lb and ub can be determined as 0 and 1.8. Now, all the parameters are ready and can be applied to the equation below for optimization in Matlab.

$$
[x, fval] = linprog(f, A, b, [\,], [\,], lb, ub) \tag{4.22}
$$

The variable x is P_d, which means the mean power of the boiler in each hour, and $fval$ means the optimal energy cost.

$$
t = \frac{P_d}{P_{rated}} \tag{4.23}
$$

According to equation 4.23, the operation time in each hour can be obtained, and this means the schedule has been made. The algorithm presented in chapter 3.3 is used for optimization in this thesis while the other algorithms presented are only examples of existing algorithms. The next task for implementation in the AC microgrid laboratory will be presented in the next chapter. The algorithm and the real-time controller will be developed and implemented in Matlab/Simulink, otherwise, the real-time controller utilized to control the boiler is developed based on the real-time controller which is created in reference [14] by Jakub Esner.

5 IMPLEMENTATION IN MICROGRID LABORATORY

5.1 Microgrid

According to [18], microgrid is defined as a local power grid that interconnects the distributed generation resources, loads, and energy storage systems based on the electrical boundaries. As presented in [29], there are several kinds of microgrids consisting of virtual and physical.

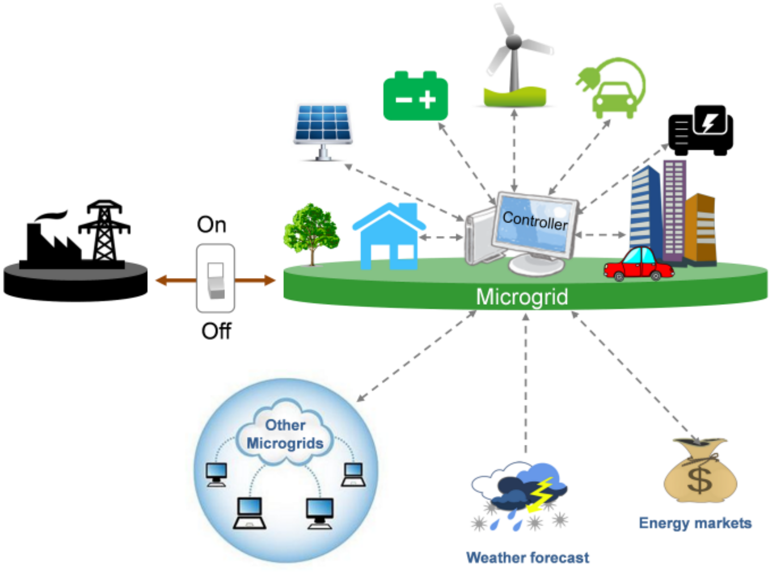


Figure 5.1. *One example of microgrid*

One example of physical microgrids is illustrated in Figure 5.1. It operates autonomously as a controllable entity that can disconnect from the power grid and maintain the operation as an island model. Distributed energy resources include solar PV panels and micro wind turbines. The energy production from renewable energy sources is non-controllable because of dependence on the weather conditions. The controllable energy production used in the utility grid is usually produced by fossil fuels and it takes up a big proportion globally, even though the proportion for fossil fuels is low in Nordic countries. Moreover, the backup power production produced by diesel is powered the microgrid in case of electrical faults in the utility grid. As one of the controllable appliances, the energy storage system that can store the excess power production generated from renewable energy sources or when the electricity price is low. To minimize the electricity cost, the balance of demand and production can be fulfilled by the utilization of the stored energy. In addition to on/off control, flexibility services may be provided by microgrid to distribution system operator (DSO) /transmission system operator (TSO) or other market stakeholders.

Due to the improvement of the communication and networking technologies, the controller can collect the information from energy storage systems, distributed generations, and appliances. By scheduling the operation of the controllable appliances, it can achieve the optimization of energy consumption. Generally, the microgrid is connected to the utility power grid through distribution lines at the point of common coupling (PCC), at which the microgrid can disconnect from the centralized power grid by operating the switch remotely or manually. And then microgrid operates as islanded mode, but before islanding operating, the demand should be balanced with the power production. The benefits for operation the microgrid are listed as follows:

- improve energy efficiencybecause the distributed energy resources located to the customer can reduce transmission and distribution losses
- minimization of energy cost by optimizing the schedule of the appliances, energy storage, and distributed generation
- improve supply reliability such as reduce the power outages
- environment friendly based on photovoltaic/wind/hydro/diesel/battery system
- reduce congestion in distribution network if controlled properly

The controls in microgrid can be divided into three layers, namely, local control or primary control, secondary control and tertiary control. And the details for the control system have been presented in [20, 37]. The control complexity significantly increases from the local control to tertiary control. The hierarchy for microgrid control system is addressed in Figure 5.2.

In the bottom layer of the hierarchy, there is local control or primary control, of which the responsibility is monitoring and controlling the devices in microgrid [44]. The operation of the electrical devices can be monitored and controlled by the locally distributed physical assets such as Intelligent Electronic Devices (IEDs). For example, the relay can supervise the current or voltage constantly at the switch and controls the switch in case of a fault. To prevent the devices from fault, local control should response very fast.

Secondary control is located in the middle of the hierarchy and enables the microgrid operates in the reliable, economical and secure state whether in grid-connected mode or island mode [37]. Comparing with the local control, this process needs remotely measurements and control. In secondary control, both microgrid energy management system (MEMS) and Supervisory Control and Data Acquisition (SCADA) system are needed. SCADA system is utilized in this process for analysis and execution of specific objectives based on the measurements and control remotely.

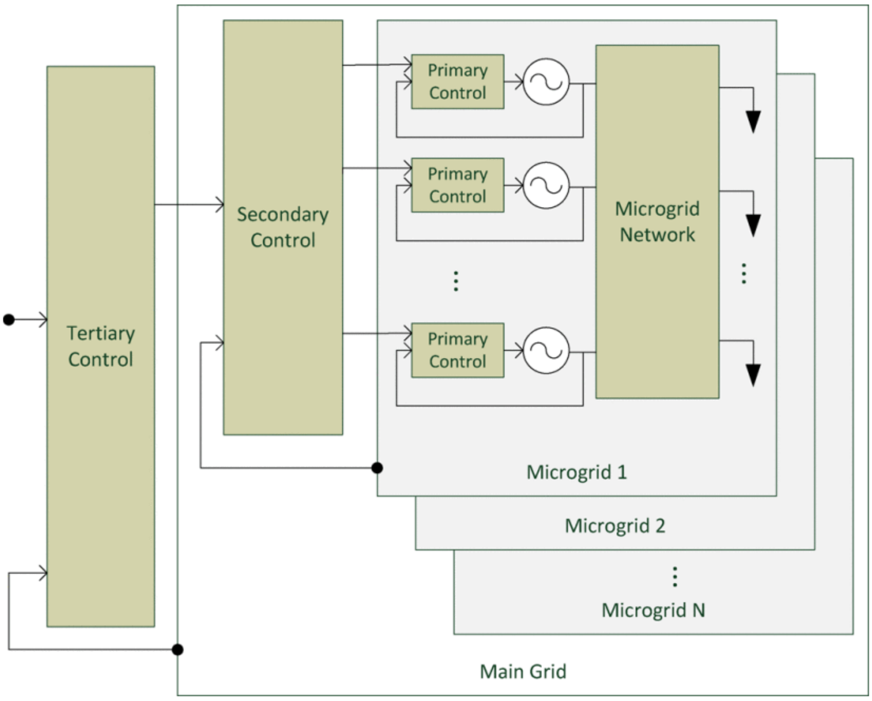


Figure 5.2. *Hierarchy for microgrid control system*

Tertiary control sits in the top layer of the microgrid control hierarchy and it will coordinate the operation of multiple microgrids that interact with each other in the same main grid [37].

5.2 Microgrid laboratory

The microgrid laboratory was first set up in 2014 with the purpose to simulate the energy management in the household. The diagram is shown in Figure 5.3. Seven 3-phase channels have been built for this AC microgrid, which can be utilized to connect with electrical appliances, home energy storage, and distributed generations such as PV arrays and micro wind turbines. This setup offers a realistic testing microgrid system. Each channel is equipped with two connectors to control the operation. The top connector is controlled by the HEMS computer using wireless Z-Wave and the other one is controlled by the dSpace computer. The dSpace enables Simulink models to communicate with peripherals via CAN or other protocols in real-time. Compatible with the transducers mounted in each channel, dSpace computer can collect the real-time information such as voltage, current, and power of each channel and emulate the energy consumption by changing the operation state of the connectors. HEMS computer is considered as a centralized controller of AC microgrid, where data acquisition and analysis take place between energy storage systems, distributed generations, and household appliances. HEMS computer is utilized to optimize the energy consumption in the residential building via analyzing the collected data such as weather forecast, real-time electricity pricing, and energy consumption. The algorithm is the key part of the optimization process and some control algorithms have been presented in the previous chapter.

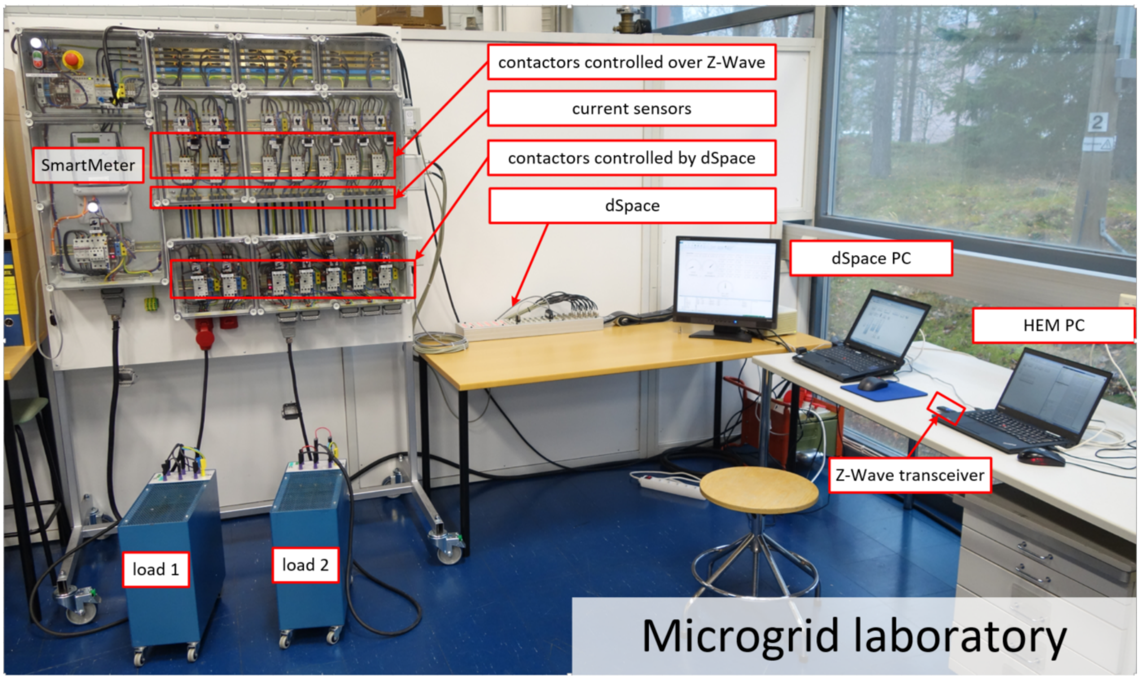


Figure 5.3. *The microgrid lab for implementation*

5.2.1 dSpace

dSpace is used to emulate the consumption pattern in residential households by controlling the bottom connector. The driving signal or command in the decimal form first generates in workspace and then is loaded to dSpace in binary form, which can be used to represent the state of the switch easily. "1" in binary form represents the "ON" state while "0" represents the "OFF" state[14]. dSpace will be used to model the dissipation power as the hot water demand for the customers while the HEMS is used to control the boiler.

5.2.2 Z-Wave

The operation of the household appliances can be controlled by HEMS computer switching the state of the top connector in each channel using Z-wave which enables smart appliances to interface and exchange information with each other in smart home automation systems. Z-Wave USB adapter can easily take part in the Z-Wave network when connecting to a host controller. The connector is controlled by a Function programmed in the Z-Wave protocol in Simulink. Similar in dSpace, the binary format has to be used for signal transmission in Function due to only one input available and the signal or command is transmitted from the transmitter to the receiver equipped with the connector [14, 45].

5.2.3 Water heating system and cooling system

The water heating system and cooling system used in the microgrid laboratory are powered by connecting to two channels separately on the switch board. As can be seen in the figure below, the system includes a water boiler, energy meter, control unit, air cooling system with a fan and water pump. In this thesis, the water boiler is the only controllable load while the cooling system and pump are utilized to model the hot water demand, which should be controlled by dSpace.

Ariston Pro R water boiler with a capacity of 29 liters is used, which has good features like high efficiency and high precision temperature sensors. The rated power of this boiler is $1800W$. The water boiler is cylindrical with a single-phase electrical resistance inside. The indicator mounted on the container displays the water temperature and the LED light located at the bottom shows the operation state. There is one thermostat inside the container for overheating protection, which can switch off automatically at the maximum temperature. The expansion cap on the top of the container can be used to fill water which can be drained from the valve at the bottom.

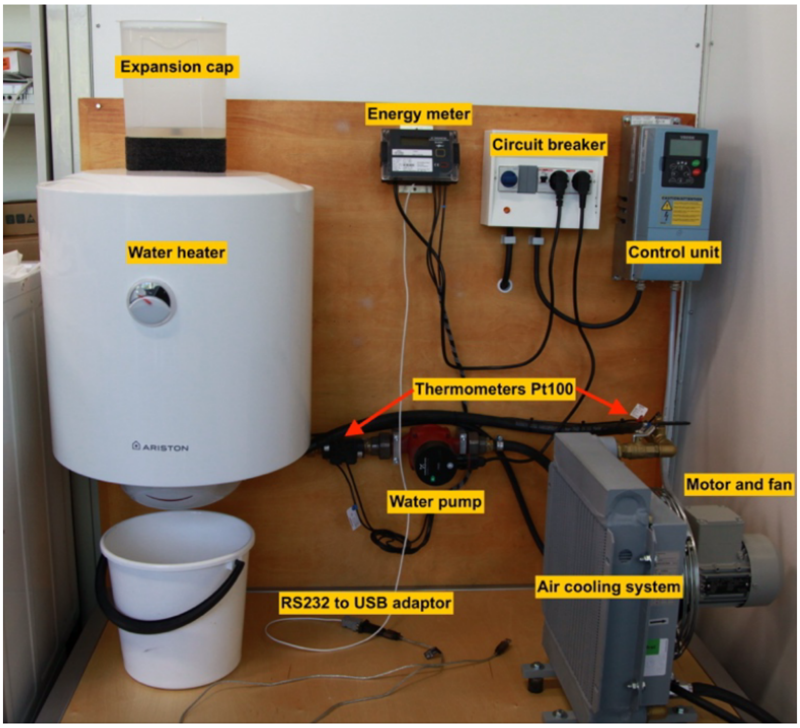


Figure 5.4. *The water heating and cooling system in microgrid laboratory*

The air cooling system used in the microgrid laboratory consists of four parts, namely radiator, cooling fan, control unit and water pump, which are shown in Figure 5.5. The radiator is designed by AKG and made of aluminum. The water coming from the heater can be cooled down when going through the radiator by convection and conduction with the coolant in the air system. There are a fan and motor attached to the air system, which can increase air convection. Additionally, the motor could be controlled by the control unit manufactured by Vacon. Users have two ways to adjust the frequency of the motor, one is to modify the parameters in the control panel of the control unit, the other way is to use the external device by establishing the communication by the RS232 interface. In this thesis, the air cooling system is used to emulate the heat demand of the households.

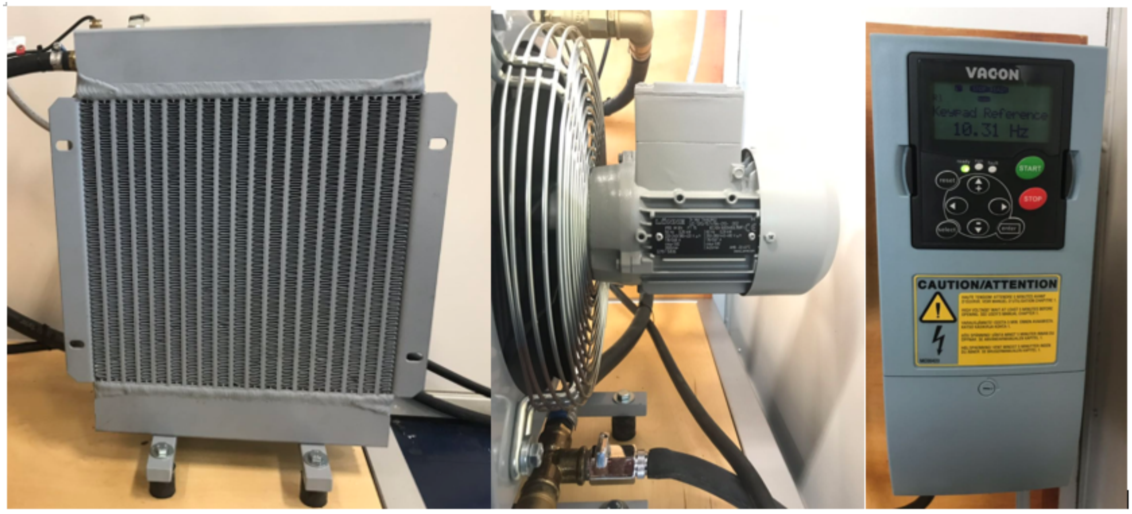


Figure 5.5. *Air cooling system*

The water pump also takes a crucial part in the cooling system and can be used to force the warm water entering the radiator. It can work permanently, and if the water pump stops working, the thermometer will not measure the temperature of the heated water. There are seven modes designed for this pump to operate, namely CS1, CS2, CS3, PP1, PP2, CP1, and CP2. "CS" refers to constant speed, which means the pump runs at the constant speed, while "CP" means constant-pressure mode, which controls the pump to operate based on the actual heat demand in the system keeping the same pressure at the same time. The mode "PP" refers to proportional pressure, and this mode controls the pump to work based on the actual demand in the system. From Figure 5.6, there is only one button on the control panel for switching different models.

Figure 5.6. *The control panel pump used in the air cooling system*

5.2.4 Energy meter

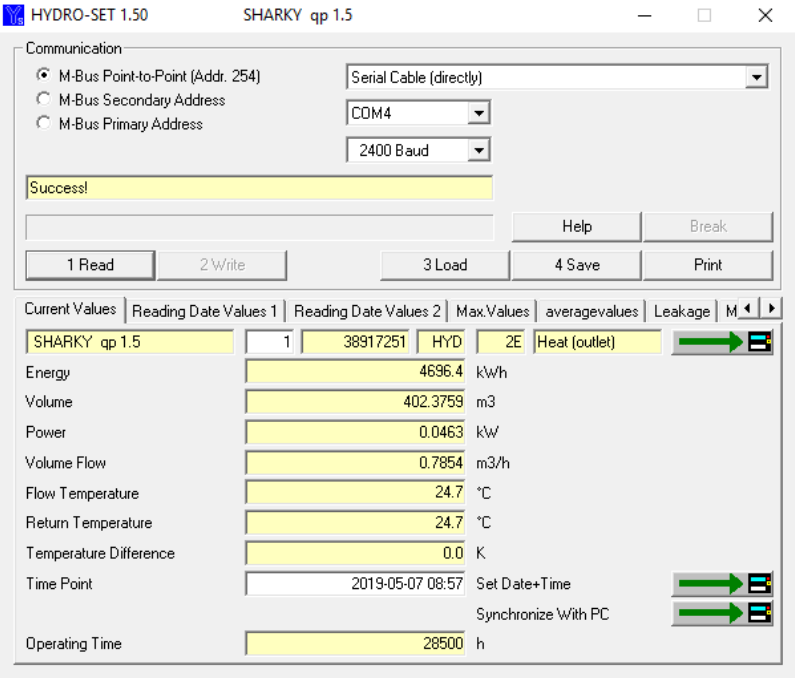
The smart meter used in the microgrid laboratory is Diehl Sharky 773 that made in Germany and it is illustrated in Figure 5.7. This digital meter can not only read the temperature of water by using the thermometers and also can display the energy dissipation. To measure the water temperature and flow rate, two thermometers, and one flow meter have been equipped in the water heating system. Otherwise, this energy meter can use multiple interfaces to display information on external devices. As can be seen from Figure 5.7, there is only one button in a yellow circle on the panel, which can be used to navigate the information to display on the screen. The displayed information consists of flow rate, operation time, flow temperature, end-users can select other loops to display if they need other information such as maximum flow or maximum power of the month. There are six loops for Sharky smart energy meter display and the users could select which loop to be displayed on the screen by Hydro-Set software which is developed by Diehl. The energy meter acts an important role in information exchange in microgrid. According to Sharky 773 manual, there are three available communication options including radio module, M-bus module, and RS232 module. The RS232 module is a serial interface that allows information exchange with the meter. With the purpose of communication via RS232, a special cable is needed. Besides, due to the lack of RS232 port from the computer, an RS232-to-USB adapter is utilized for connection with the smart meter and external device. In this research, RS232 is used to collect the data remotely by using Hydro-Set software.

Figure 5.7. *Diehl Sharky 773 energy meter*

For the two thermometers, Pt500 is selected as the sensor to measure the temperature of the water coming out and returning to the boiler. Pt500 sensor is a kind of platinum resistor, which is usually used for precise temperature measurement because of the linear relationship between temperature and resistance. Pt500 means this type of platinum has a resistance of 500 Ohms at the temperature of 0$^\circ C$. The sensor can measure the temperature with the range from 0$^\circ C$ to 150$^\circ C$. The thermometer with a red label is located near the radiator to measure the temperature of water following out from the heater while the thermometer with a blue label positioned next to the pump is utilized to measure the temperature of the water returning to the heater.

5.2.5 Hydro-set software

The hydro-Set software is developed by Diehl Metering and is also a convenient tool for supporting the meter. It can operate on the Windows Operating System and is used for reading out different memories, meter configuration and taking meter into operation. The operation interface of this software is presented in Figure 5.8.


HYDRO-SET 1.50 SHARKY qp 1.5

Communication

● M-Bus Point-to-Point (Addr. 254)
○ M-Bus Secondary Address
○ M-Bus Primary Address

Serial Cable (directly)
COM4
2400 Baud

Success!

SHARKY qp 1.5 | 1 | 38917251 | HYD | 2E | Heat (outlet)

Energy	4696.4	kWh
Volume	402.3759	m3
Power	0.0463	kW
Volume Flow	0.7854	m3/h
Flow Temperature	24.7	°C
Return Temperature	24.7	°C
Temperature Difference	0.0	K
Time Point	2019-05-07 08:57	Set Date+Time
		Synchronize With PC
Operating Time	28500	h

Figure 5.8. The operation interface of Hydro-Set software

Before starting up the software, the adapter for converting RS232 to USB should be connected to the computer and several parameters should be determined. As can be seen from the figure, serial cable is selected, if the communication between the computer and meter is established via the cable directly. And the serial port also should be selected when the cable is connected. The port varies so the actual active port should be checked from "view devices and printers" in control panel in Window 10 system. The default baud rate usually uses 2400 when the cable is not too long or the connection is not so noisy. Otherwise, the device connected with the meter can be addressed in three ways, including Point-to-Point, Secondary, and Primary. In this research, the mode "Point-to-Point" is used.

After selecting the parameters, the program can be operated by pressing the Read button. During the process, the communication between the device and the energy meter is established. The data can be fetched and displayed on the screen of external devices.

It takes about 30 seconds for the process to fetch and display the data. There are many options to display in the interface of the software and the users can select the data based on their needs. The information about flow temperature, return temperature and flow rate is used in this thesis research.

5.2.6 PV inverter

PV inverter is utilized to emulate PV production. It is one of the most important devices that can convert DC output into AC current to power the electric appliances in the households. The model of this device manufactured by ABB is TRIO-5.8-TL-OUTD-S-400 with the maximum DC current of 18.9 A. The irradiance data can be emulated by dSpace controlling DC source which can be supplied by the DC generator manufactured by PowerFinn. Power control such as power factor or power curtailment can be achieved.

5.3 Experiment in the Microgrid laboratory

The optimal strategy of how the water boiler operates in the smart building or house will be made by HEMS and is based on the estimated demand of hot water, estimated PV production and the Nord-Pool market price. When the market price is determined and then HEMS will make a schedule for the next day. The schedule will be executed from 0 o'clock by using Z-Wave to control the upper switch on the switch panel. The goal of applying this schedule is to save the energy cost without sacrificing the user's preference by keeping the temperature of the water at a specific range. The detail for the strategy or algorithm has been addressed in the previous chapter.

This chapter presents the implementations that have been conducted on the operation of the water boiler to verify the strategy or algorithm which can save the energy cost due to the optimization.

5.3.1 Preparation for the experiment

The aim of the experiment is to verify the algorithm used for the optimization can achieve energy bill saving compared with the operation of the boiler without controlling by HEMS. Before optimization, all the parameters should be determined. The value of the temperature measured by the thermometers and dissipated energy can be read from Hydro-Set software. The dissipated energy means the energy loss when the hot water come through the cooling system. Otherwise, the mass of water in the system need to be calculated. The accurate quantity is difficult to determine from the volume according to the equation $m = \rho \times V$, because the volume of the whole system including boiler, pump, radiator and rubber hose cannot be calculated accurately. By applying equation 5.1, 5.2 and the experiment, the mass of water can be gained.

Generally, the energy needed for the water to increase the determined temperature can be calculated from the equation presented below.

$$Q = c \times m \times \Delta T \tag{5.1}$$

Where,
Q is the heating energy needed for the water when temperature change
c is the specific heat capacity of water
m is mass of water
ΔT is temperature change of the water

Meanwhile, the energy is provided by an electrical resistor in the water heater, and it can be known by the equation stated below.

$$Q = P_b \times t \tag{5.2}$$

Where,
Q is the energy provided by water heater
P_b is the power provided by the water heater
t is heating time

Based on equation 5.1 and 5.2, the equation for mass can be gained.

$$m = P_b \times t/(c \times \Delta T) \tag{5.3}$$

These equations are based on the idea condition that there is no heat loss or dissipation to surroundings. But actually, heat loss occurs in the whole process of water heating and cooling in the way of thermal conduction and air convection. Thus, the dissipation energy should be considered. When the heat losses in the radiator are taken into account, the equation for the mass can be stated below.

$$m = (P_b \times t - Q_{radiator})/(c \times \Delta T) \tag{5.4}$$

To determine the mass of water in the system, the experiment for heating has conducted when the pump is operated at the mode of "CS1" and the water is heated from an initial temperature of 25.7$°C$ to the temperature at 51.7$°C$. And the temperatures have been documented every 10 minutes and presented in table 5.1.

As presented in table 5.1, the water needs 80 minutes for heating from 25.7$°C$ to 51.7 $°C$. Otherwise, the actual power supplied to the boiler can be measured by the meter because the power varies due to the variation of voltage, hence, the rated power cannot

Table 5.1. *Temperature against time for heating*

Time (Mins)	0	10	20	30	40
Temp ($°C$)	25.7	29.3	32.3	35.7	39.2
Dissipation Energy (kWh)	0	0	0	0.1	0.1
Time (Mins)	50	60	70	80	
Temp ($°C$)	42.2	45.6	48.7	51.7	
Dissipation Energy (kWh)	0.1	0.2	0.2	0.3	

be used directly in the calculation. And the dissipated energy can be calculated according to the figures from the energy meter.

The dissipation energy in the radiator is the difference between the dissipation energy at the end and the beginning and equals 0.3kWh (0.3 - 0 = 0.3kWh) according to table 5.1. The energy supply to the boiler consists of energy for heating water and dissipation energy in the process. Based on equations 5.4, the determined mass is 48.32kg when the specific heat capacity of water c is $4184J/kg.K$.

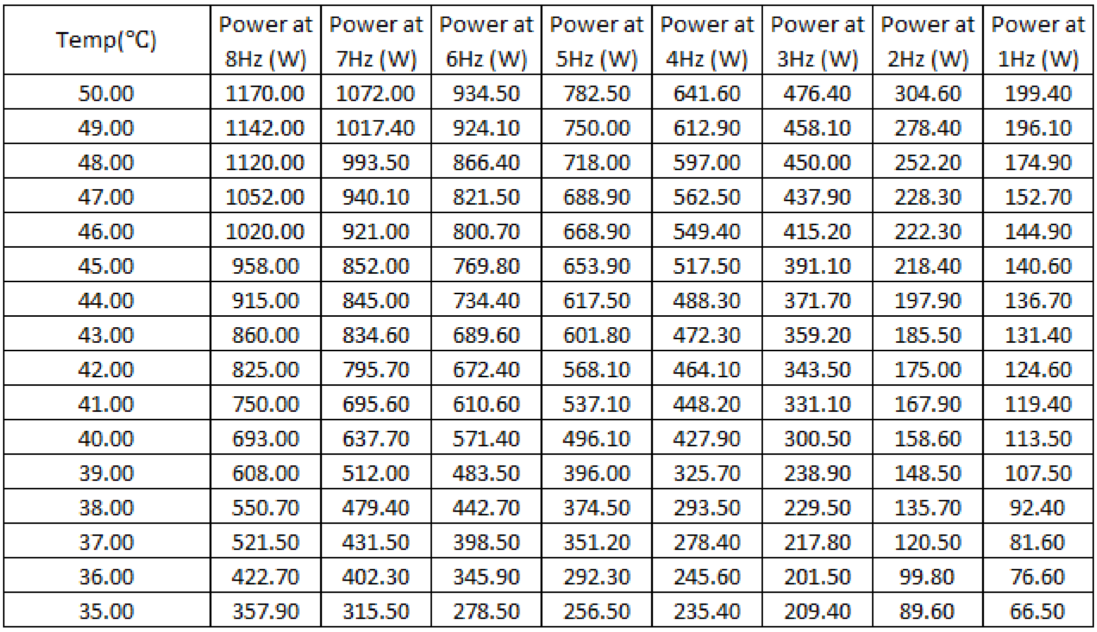
According to the law of thermodynamics, heat energy always transfers from objects with higher temperatures to objects with lower temperatures spontaneously. The energy dissipated to surroundings is regarded as heat loss. And the factors that result in heat loss in the heating system are discussed and addressed as below:

- Heat dissipation in the boiler: the heat energy will still dissipate due to thermal conduction of its insulation layer, inner and outer shell even though it has good insulation.
- Heat dissipation in the radiator: When the hot water goes through the radiator, the heat will be dissipated to surroundings by air convection. The rate is dependent on the difference in the temperature between the water and the surroundings. The bigger the difference, the faster the rate is.
- Heat dissipation in the rubber hose and valves: Some heat energy is transferred to surroundings by these things which are used to connected the water boiler with the air cooling system.
- Heat dissipation in water pump: Heat loss occurs when the water goes through it.
- Heat dissipation in the cap attached on top of the boiler: The level of water rises when the water is heated. And heat energy will be dissipated to the surroundings easily.
- Heat dissipation in the thermometer: The thermometer measures the temperature by using the heat from the water, so there is some energy loss here.

Before experiments, the limitation and assumption also should be stated. The sensor of thermometers used in the water heating system is Pt500, which has high precision with the sensitivity at 0.125K. But the figure from the meter is a rounding value with one decimal place. This means it is not so accurate due to rounding. Additionally, the pump generally operates constantly for reading the temperature, so the heat dissipation always exists in the heating process. The microgrid laboratory sits in a large hall with good air circulation due to good ventilation. Thus, it is assumed that the ambient temperature of the hall is constant for the whole day. The heat dissipation from the heating system will not affect the temperature inside the hall. The thermometer cannot measure the temperature of the water inside the boiler directly because none of the thermometers locates inside the boiler. The thermometer with a red label is located near the radiator to measure the temperature of water following out from the heater. And this temperature will be used as the water temperature inside the boiler.

Generally, dSpace is used to control the dissipation power as the hot water demand, but in this thesis, the dissipation power has to be controlled manually because there is some problem in the communication part between dSpace and dSpace computer, so it cannot be used for the research to model the constant dissipation power as the hot water demand by adjusting the frequency of the propeller. Besides, the rate at which heat transfers from the hot object to the cold one depends on the temperature difference between the objects when the difference is larger, the rate will be more bigger, this makes it difficult to emulate the constant dissipation power.

To control the dissipation power as constant as a long time, some experiments to determine the power at the fixed speed of the fan have been conducted. And Figure 5.9 below shows the dissipation power related to temperatures when the fan operates at different frequencies, namely 8Hz, 7Hz, 6Hz, 5Hz, 4Hz, 3Hz, 2Hz and 1Hz. The power can be read from the Hydro-Set software when the fan operates at those frequencies.



Temp(℃)	Power at 8Hz (W)	Power at 7Hz (W)	Power at 6Hz (W)	Power at 5Hz (W)	Power at 4Hz (W)	Power at 3Hz (W)	Power at 2Hz (W)	Power at 1Hz (W)
50.00	1170.00	1072.00	934.50	782.50	641.60	476.40	304.60	199.40
49.00	1142.00	1017.40	924.10	750.00	612.90	458.10	278.40	196.10
48.00	1120.00	993.50	866.40	718.00	597.00	450.00	252.20	174.90
47.00	1052.00	940.10	821.50	688.90	562.50	437.90	228.30	152.70
46.00	1020.00	921.00	800.70	668.90	549.40	415.20	222.30	144.90
45.00	958.00	852.00	769.80	653.90	517.50	391.10	218.40	140.60
44.00	915.00	845.00	734.40	617.50	488.30	371.70	197.90	136.70
43.00	860.00	834.60	689.60	601.80	472.30	359.20	185.50	131.40
42.00	825.00	795.70	672.40	568.10	464.10	343.50	175.00	124.60
41.00	750.00	695.60	610.60	537.10	448.20	331.10	167.90	119.40
40.00	693.00	637.70	571.40	496.10	427.90	300.50	158.60	113.50
39.00	608.00	512.00	483.50	396.00	325.70	238.90	148.50	107.50
38.00	550.70	479.40	442.70	374.50	293.50	229.50	135.70	92.40
37.00	521.50	431.50	398.50	351.20	278.40	217.80	120.50	81.60
36.00	422.70	402.30	345.90	292.30	245.60	201.50	99.80	76.60
35.00	357.90	315.50	278.50	256.50	235.40	209.40	89.60	66.50

Figure 5.9. *Dissipation power related to temperature at different frequencies*

According to the table about dissipation power related to temperatures at different frequencies, the frequencies limits for fixed power to be modeled can be determined and maintaining constant power for a long time manually becomes easier.

5.3.2 3-Hour laboratory implementation

To verify the optimization algorithm of the HEMS, a 3-hour test has been implemented. Before the experiment, the initial temperature is measure at 43.8$°C$, and the temperature limits are set between 40$°C$ and 50$°C$. The prices used in this case are [41.84, 41.05, 40.97]€/MWh and the dissipation power used for each hour is selected randomly. For this implementation,it is [0.5, 0.7, 0.5]kW, which are presented in Figure 5.10. As depicted in Figure 5.11, the schedule is generated by HEMS when the parameters are ready. The boiler operates when the power is 1.8kW and stops operating when the power is 0kW.

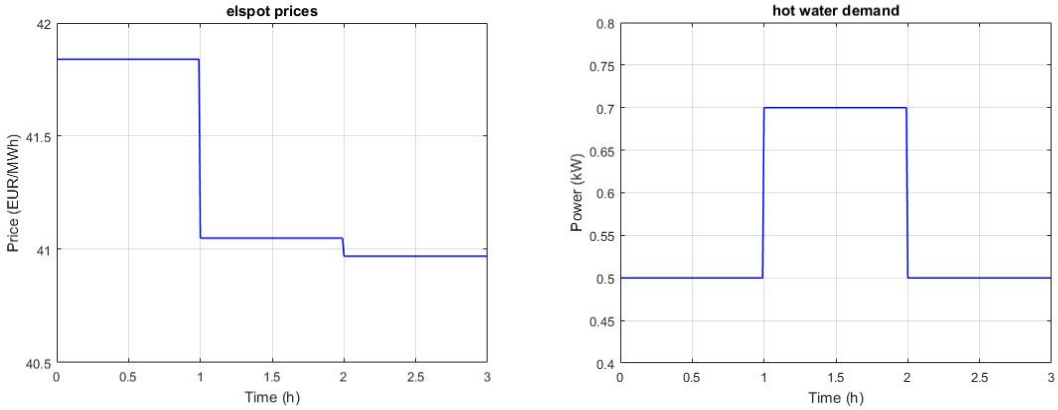


Figure 5.10. *Elspot prices and hot water demand used for 3-h implementation.*

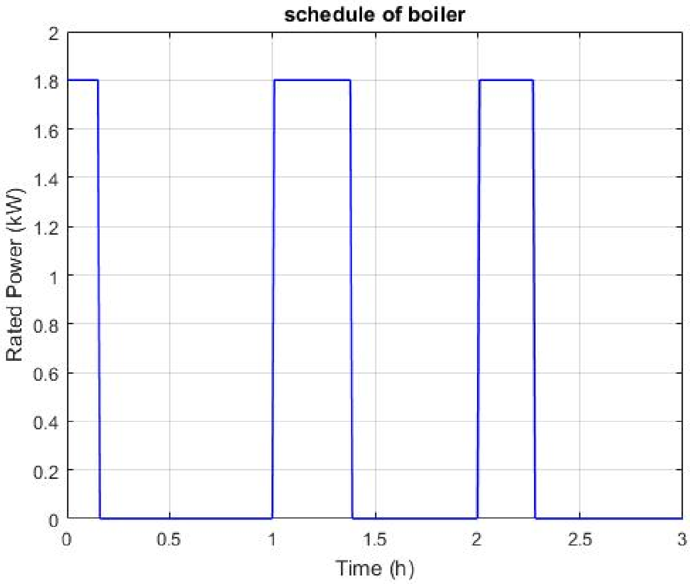


Figure 5.11. *Generated schedule for 3-h implementation*

According to the schedule, the implementation will be conducted. The temperature and

Table 5.2. *3-Hour laboratory test*

Time (Min)	Temp ($^{\circ}C$)	Dissipation Energy (kWh)	Dissipation Power (W)
0	43.8	0	500
13	47.9	0.1	
35	44.5	0.3	
50	42.1	0.4	
60	40.1	0.5	
70	43	0.6	700
90	48.9	0.9	
105	44.1	1.1	
120	40.8	1.3	
135	44.1	1.5	500
150	46.3	1.6	
165	43.8	1.7	
180	42.1	1.8	

dissipation energy can be read from hydro-set software and documented in table 5.2. The figure for dissipation energy in the table is the cumulative number. The temperatures in the three hours are maintained between 40$^{\circ}C$ and 50$^{\circ}C$, and the temperatures at the end of each hour are namely, 40.1$^{\circ}C$, 40.8$^{\circ}C$, 42.1$^{\circ}C$. According to the optimization and the measured temperatures, the average temperatures for optimization and measurement can be calculated and shown in table 5.3. Moreover, the errors for each hour also are also included.

Table 5.3. *Average temperatures for optimization and measurement in 3-hour implementation*

Time (H)	Average Temp ($^{\circ}C$) (optimization)	Average Temp ($^{\circ}C$) (measured)	Error
0-1	44.1	44.5	4%
1-2	43.82	44.48	6.6%
2-3	43.21	43.64	4.3%

From table 5.3, the error in the second hour is bigger than that in other hours and the cumulative error is 4.3%. According to table 5.1, the power in the second hour was not controlled as constant as the other two hours, that is the reason why the error is bigger. Besides, the variation of power may result from the supplied voltage from the distributed grid, which varies all the time, but this has little impact on the result in the laboratory.

5.3.3 6-Hour laboratory implementation

The 3-hour implementation works fine, however, an implementation for a long time is still needed to verify the optimization algorithm. Before optimization for 6 hours, the parameters should be determined. The initial temperature is 40$°C$ and the range for temperature limits of this test is [35, 50]$°C$. Compared with the range of 3-hour implementation, the range used here has been relaxed to reduce the errors. As presented in Figure 5.12, the prices used for this case are [41.84, 41.05, 40.97, 41.67, 42.40, 41.34]€/MWh. The dissipation power for 6 hours is also selected randomly and it is [0.5, 0.3, 0.5, 0.4, 0.5, 0.7]kW. The generated schedule for the 6-hour implementation is shown in Figure 5.13.

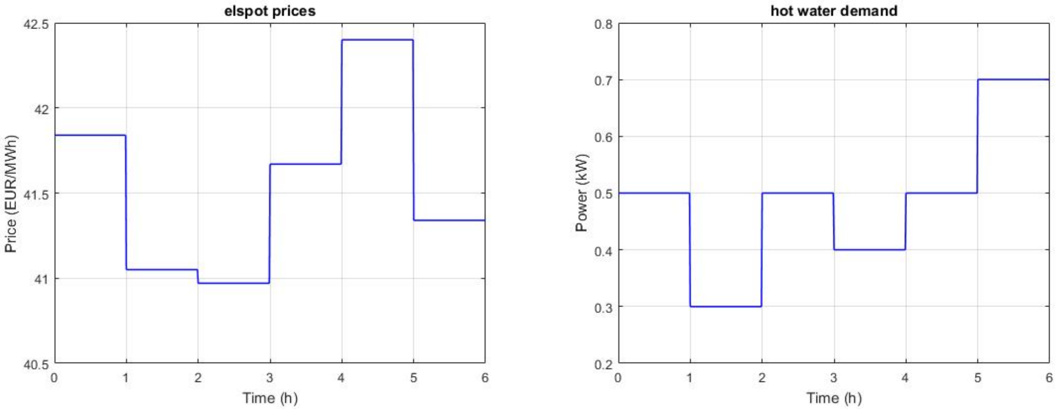


Figure 5.12. *Elspot prices and hot water demand used for 6-h implementation.*

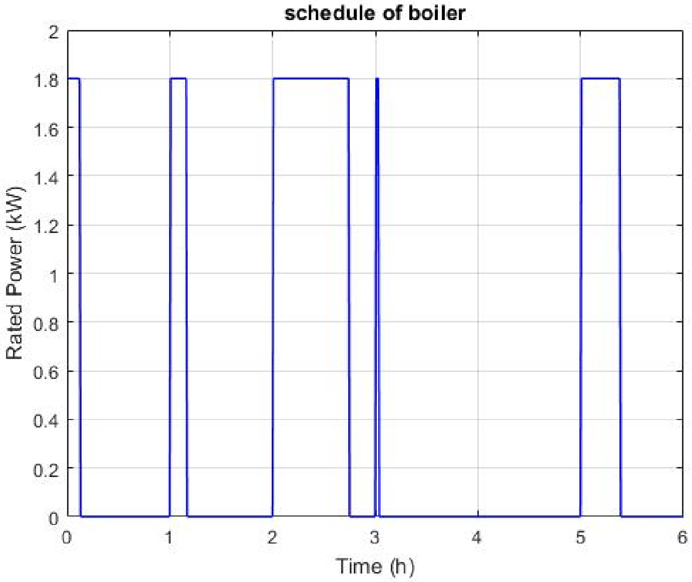


Figure 5.13. *Generated schedule for 6-h implementation*

When optimization is ready, the boiler will be controlled by using Z-Wave according to schedule. Table 5.4 shows the temperatures are documented at an interval of 15 minutes. The temperature was 51.7$°C$ at 165 minutes. From the generated schedule from HEMS, the water boiler would work for 2685 seconds (nearly 45 minutes) in the third hour. This temperature was measured at 45 minutes in the third hour, so the temperature of the water was nearly at the highest. Otherwise, the price is the lowest in the six hours, that's why the heating time of the boiler is the longest.

The average temperatures for optimization and measurement in 6 hours are presented in table 5.5. The table also shows the errors in average temperatures between optimization and measurement. According to table 5.5, the cumulative error is 2% even though the error in the fourth hour is 4%. Moreover, the temperatures from measurement are nearly the same as the temperatures from optimization. Based on the implementations for 3-hour and 6-hour, the HEMS works well and the 24-hour test can be implemented.

Table 5.4. *Temperatures for each 15 minutes in 6-hour implementation*

Time (Min)	0	15	30	45	60	75	90	105	120
Temp ($^\circ C$)	40	41.5	39.2	37.0	35	38.9	37.9	36.5	35.1
Time (Min)	135	150	165	180	195	210	225	240	255
Temp ($^\circ C$)	40.6	46.2	51.7	49.6	48.5	47	45.3	43.7	41.6
Time (Min)	270	285	300	315	330	345	360		
Temp ($^\circ C$)	39.4	37.4	34.9	39.9	41.2	38.0	35		

Table 5.5. *Average temperatures for optimization and measurement in 6-hour implementation*

Time (H)	Average Temp ($^\circ C$) (optimization)	Average Temp ($^\circ C$) (measured)	Error
0-1	39.2	38.8	2.7%
1-2	37.23	37.03	1.3%
2-3	45.54	45.21	2%
3-4	47.44	46.86	4%
4-5	39.45	39.43	0%
5-6	38.81	38.51	2%

5.3.4 24-Hour implementation

The purpose of this research is to develop the optimization algorithm based on day-ahead prices to achieve energy bill reduction. Hence, a 24-hour test for the operation of the boiler with control by HEMS and one 24-hour test without control by HEMS need to be implemented.

For 24-hour optimization, the parameters also need to be prepared. The temperature limits are set between 35$^\circ C$ and 50$^\circ C$ and the initial temperature is 50$^\circ C$. Figure 5.14 illustrates the prices used in this optimization which are hourly prices for the 9^{th} of May from the day-ahead market and the dissipation power profile based on the profile for general Finnish households [11].

For a normal household in Finland, a boiler with the capacity of 300 litters is equipped. And for the system used in the laboratory, the total capacity is nearly 50 litters. So the dissipation power implemented in the laboratory should be one-sixth of the hot water demand in normal Finish household. The normal dissipation power for 24 hours is [0, 0, 0, 0, 0, 0, 0, 1.4456, 0.3766, 0.1880, 0.0943, 0.1880, 0.2823, 0, 0.0943, 0.0943, 0.0943, 0, 0.2823, 0.0943, 0.6584, 1.3487, 0, 0 $]kW$ according to domestic hot water demand profile (15316-3-1:2007). Hence, the dissipation power for implementation is [0, 0, 0, 0, 0, 0, 0, 0.2409, 0.0628, 0.0313, 0.0157, 0.0313, 0.0470, 0, 0.0157, 0.0157, 0.0157, 0, 0.0470, 0.0157, 0.1097, 0.2248, 0, 0 $]kW$.

But the power below 0.050kW is difficult to simulate because it is less than the ambient dissipation which means the dissipation power when the pump and propeller stop working. So the dissipation profile should be transformed and cannot be used in the optimization directly. The dissipation power below 0.050kW in the profile can be changed with ambient dissipation power. Actually, the rate of heat transfer increases with the difference between the hot water temperature and the ambient temperature, so it cannot use the same ambient dissipation power to substitute the norm dissipation power in the profile. In this profile, three kinds of ambient dissipation power will be used, namely, the dissipation power of the first 7 hours, the dissipation power from 8^{th} hour to 20^{th} hour and the ambient power for the last two hours.

To measure the ambient dissipation, three implementations have been conducted. Hence, there are three kinds of ambient dissipation power used in the profile. The implementations start at three different initial temperatures, namely 50$^\circ C$, 40$^\circ C$, and 35$^\circ C$ and last for 6 hours, 12 hours and 3 hours. The temperatures drop 6$^\circ C$, 5.5$^\circ C$, and 1.8$^\circ C$ respectively. According to heat equation, the three kinds of dissipation power are determined at 0.0562 kW, 0.0248 kW, 0.0323 kW. The actual dissipation power profile for optimization should be [0, 0, 0, 0, 0, 0, 0.3934, 0.2409, 0.0248, 0.0248, 0.0248, 0.0248, 0.0248, 0.0248, 0.0248, 0.0248, 0.0248, 0.0248, 0.0248, 0.0248, 0.1097, 0.2248, 0.0323, 0.0323 $]kW$. Based on these parameters, the mean power of the boiler will be determined in optimization and the schedule for the next 24 hours will be made and presented in Figure 5.15.

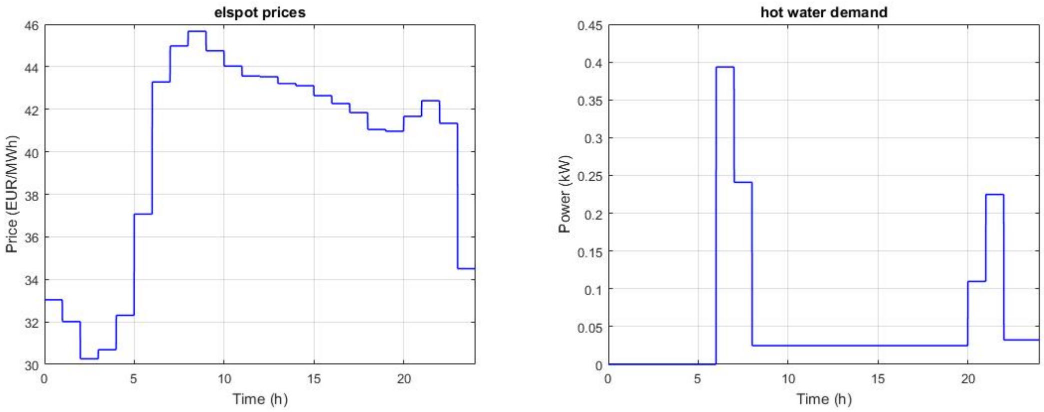


Figure 5.14. *Elspot prices and hot water demand used for 24-h implementation.*

In the implementation, the power [0.2409, 0.1097, 0.2248]kW in 8^{th}, 21^{st} and 22^{nd} hour need to be modeled manually and the other is modeled as ambient dissipation power. Then, the temperature cannot be documented for each hour due to stopping the operation of the pump. If the pump is operated at the beginning of each hour to read the

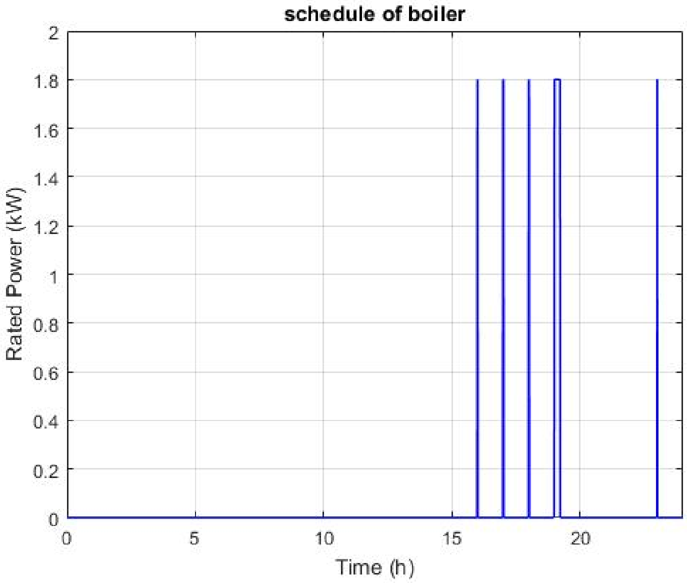


Figure 5.15. *Generated schedule for 24-h implementation*

temperature, the temperature will be accurate after the water mixing evenly between the water boiler and the cooling system. But in this case, the dissipation power will be increased and this will affect the result of the experiment. Hence, the temperature will not be documented in each hour. Table 5.6 shows the temperature recorded at the time when the pump operates.

Table 5.6. *Measured temperatures in 24-hour implementation*

Time (H)	0	7	8	20	21	22	24
Temp($^{\circ}C$)	50	43.4	39	41.8	39.7	35.7	35.6

Table 5.7. *Average temperatures for optimization and measurement in 24-hour implementation*

Time (H)	Average Temp ($^{\circ}C$) (optimization)	Average Temp ($^{\circ}C$) (measured)	Error
0-7	46.5	46.7	1%
7-8	40.85	41.2	2.3%
8-20	40.15	40.4	1.7%
20-21	40.63	40.75	1%
21-22	37.65	37.7	0.3%
22-24	35.33	35.65	2.1%

The errors for average temperatures between optimization and measurement have been presented in table 5.7 and the cumulative error is 2.1%. As presented in the previous part, the switch of the boiler is controlled by HEMS using Z-Wave, so the heating time is based on the schedule according to the optimization. Hence, the energy bill for optimization can be calculated and presented by HEMS, and it is 0.0199€ for this implementation.

The boiler starts heating when the temperature is below around 48$°C$ and stops heating at around 56$°C$ without control by HEMS and the implementation started at the same initial temperature at 50$°C$ and ended at the temperature of 50.3$°C$. For the implementation without control by HEMS, an external meter is needed to measure the energy consumption to calculate energy cost. In this case, PowerXplorer is utilized in the laboratory demonstration, which has advanced features in power monitoring. This meter can be set to record the power for each minute and then according to the equation $Q = P_b \times t$, the energy used in each hour can be calculated. By applying the prices for each hour, the energy bill will be determined. After implementation, the recorded profile can be read using the compatible software with the meter. According to the profile, the water is heated for 16 minutes in the 1^{st} hour, 16 minutes in the 21^{st} hour and one minute in the 22^{nd} hour. Based on the mean power provided by the profile, the calculated energy consumption for these three hours is 0.4519kWh, 0.4717kWh, and 0.0077kWh. The hourly prices for these three hours are 33.04€/MWh, 41.67€/MWh, 42.40€/MWh respectively. Hence, the energy bill for 24-hour is 0.0349€.

Comparing the energy bills for these implementations, the saving is 0.015€ and the boiler controlled by HEMS operates more economically and 43% of the energy bill will be saved for this case. It is also illustrated that HEMS can optimize the schedule of the boiler in households so that the minimization of the energy bill can be achieved. But actually, there are some factors which will affect the result in the process of implementations. The energy cost can be affected by modeling the dissipation power. It is not precise to control propeller manually comparing with controlling by dSpace. When using dSpace to emulate the hot water requirements for the households, the power will be controlled by the closed-loop control so that the precision is higher than controlling manually. The dSpace computer can be used to read the dissipation power from energy meter, and then the speed of the ventilator will be controlled by using the control unit based on the measured power. Hence, the dissipation power can be controlled accurately.

In fact, it is not fair to compare the two implementations at different end temperatures. The two implementations should have the same initial temperature and the same end temperature as well as the same temperature limits. There are two possibilities or ways, one is to make the end temperature of the implementation with HEMS at the same end temperature with implementation without HEMS of 50.3$°C$, and the other possibility is to make the end temperature of implementation without HEMS at the same end temperature of 35.6$°C$. For the first possibility, the energy consumption and the energy cost for operation of the boiler with HEMS will be increased due to end temperature rising to 50.3$°C$. For the second possibility, the energy consumption and energy cost will be decreased because of the end temperature reducing to 35.6$°C$ compared with the end temperature 50.3$°C$. When the end temperature drops from 50.3$°C$ to 35.6$°C$, the water will not need less energy to heat, this means the energy consumption and energy cost will be reduced. Hence, no matter which way would be used, the saving will be reduced.

The temperature limits and initial temperature will also influence on the energy bill of the implementation controlled by HEMS. When the temperature lower limit rises, the heating time in the schedule will be increased. Hence, the energy cost will go up. Besides, when the initial temperature is set lower than 50$°C$, the energy bill can also be increased. The day-ahead price varies every day, and the variation of the price will also influence the energy cost.

6 CONCLUSIONS AND FUTURE DEVELOPMENT

6.1 Conclusions

The home energy management model based on the Simplex algorithm and the algorithm for the operation of the water boiler has been developed and implemented in this thesis. The study on optimal control of the boiler and scheduling in smart households has been conducted when considering the financial incentive for end-users. The objective of this algorithm is to minimize the energy bill of the customers by optimizing the schedule of the operation of the boiler without sacrificing the preference of the customers based on the hourly price from the day-ahead market.

In this research, a water boiler and air cooling system are equipped in the smart home model. The system for the water boiler is presented in the mathematical model for optimization with related constraints. Otherwise, the algorithm has been implemented in several tests so the effectiveness of the optimization model could be checked and proved.

Two case studies for 24-hour illustrate that the implementation controlled by HEMS using this algorithm can contribute greatly to energy bill savings. According to the two simulations, around 43% of reduction for energy bills can be achieved when the temperature differences in the end were not taken into account. Comparing with the energy cost between boiler controlled by HEMS and boiler without HEMS, the saving from the boiler controlled by HEMS is not attractive for customers to invest in the equipment. However, with more household appliances and distributed energy resources such as roof-mounted PV arrays and BESS integrated into the HEMS, the more can be saved in energy bills. Otherwise, some other factors should be considered. The volatility of hourly prices also can affect the energy bill savings. If the price differences between different hours are big, the energy saving will be increased. The distribution operators may provide some financial support or introduce dynamic grid tariffs for the customers who could sell flexibility services. Another thing to be considered is that the implementations are always based on the non-ideal or realistic performance and the estimated savings are also from the non-ideal models. Hence, maybe better algorithms will appear and be implemented in the future and more energy bill savings will be achieved.

The algorithm and Z-wave interface are implemented in Matlab / Simulink environment. Z-wave makes it possible to control the boiler or other loads in real-time. The algorithm and implementation are expected to be extended. BESS, PV production system and other loads like EV and washing machines need to be applied in the algorithm. When the household behavior of the appliances can be fully emulated, the energy bill will be saved more and the results may be more credible.

6.2 Future development

The boiler and cooling system are generally utilized in basic implementation in my thesis. The extension now has been considered so that more household realistic behaviors can be modeled or emulated.

When the problem of communication part is fixed, dSpace can be utilized to emulate the dissipation power by controlling the speed of the propeller and pump as depicted in Figure 6.1. A dSpace computer will be used to read the dissipation power from energy meter, and then the speed will be controlled by using a control unit based on the measured power. This is a closed-loop system and it will work more accurately than controlling the propeller manually.

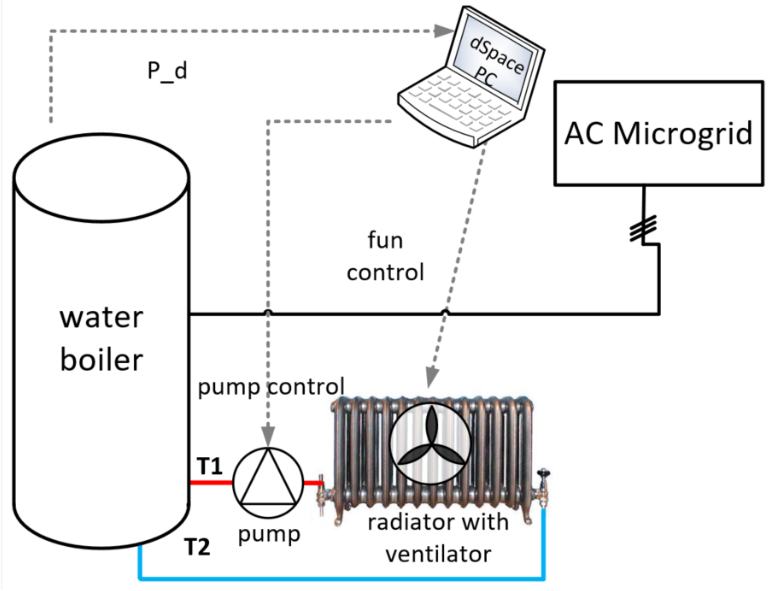


Figure 6.1. *Heating and cooling system*

The emulator of PV production also can be added to the system. PV inverter will be applied to convert DC source into AC source which can be integrated into AC Microgrid. DC source also can be controlled by dSpace so the irradiance will be emulated according to the forecasted profile. The power curtailment and power factor control will be available due to the power control capacity of the PV inverter.

The other system to be added is the battery energy storage system. It will be more economical when applying BESS in the microgrid with a reasonable schedule. And a battery management system (BMS) will be needed to supervise and control the operation of BESS so that the cells of the BESS can retain within the safety range. Besides, the interface should be available for BMS master to communicate with HEMS and charger.

Now there are various of HEMS with different focuses and the technologies in HEMS are still in the process of evolution. The HEMS will be more multi-functional on the basis of the demands of customers. The deployment of HEMS will rely on the development of the technologies and the investment, otherwise, the economic benefit will be another driver. The algorithm used in this thesis is scalable, and as the system expansion in the microgrid, the algorithm will be expanded. For this algorithm, when other devices are integrated, more constraints will be added.

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