Integration of Hybrid Energy Storage and Organic Rankine Cycle into the Trigeneration System

Thesis By

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Abstract

An investigation of a distributed and integrated system of a trigeneration with a hybrid energy storage unit and an Organic Rankine Cycle (ORC) has been conducted using experimental tests and modelling simulation. A detail background study and literature review was carried out which covered the related studies of the similar trigeneration systems.

The design of the whole system was displayed, the operation mode was formulated and the control strategy was proposed for meeting the dynamic power demand of selected case studies. Detailed simulation models for the integrated system were developed. The models were validated using experimental test results and the accuracy of the models were guaranteed (within 1.81%). The integrated model was then used to evaluate the overall performance of the system and the results showed that this system could meet the dynamic demand of the households. The system's overall efficiency was 48.3% and 52.2% in two case studies. A further study on the optimal operation of the system was carried out, and it is found that the integrated system's efficiency was improved from 3% to 22%.

It was found that the integrated system of a trigeneration with a hybrid energy storage unit and an ORC has the potential advantage over the conventional trigeneration in terms of overall energy efficiency and operational flexibility. The main challenge lies within the area of operation control of such an integrated system and further research into this control issue is needed. Future study into exploring other renewable energy sources for the system and more experimental tests on the integrated system are suggested.

Publications from this research

i. Jie Ji, Chunqiong Miao, Cui He, Zheng, Xiao, Liqi Luo, Haisheng Chen, Xinjing Zhang, Huan Guo, Yaodong Wang, Tony Roskilly. System performance of an ORC unit integrated with a trigeneration *Special Issue of The 8th International Conference on Applied Energy – ICAE2016 In press (2017)*

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vi. Cui He, Jie Ji, Yaodong Wang, Tony Roskilly. Control Strategy for a Micro Smart Grid to Meet the Energy Demand of a Household *Advances in Engineering Research, volume 93 International Symposium on Mechanical Engineering and Material Science (ISMEMS 2016)*

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Nomenclature

CCHP	Combined Cooling, Heating And Power
CHP	Combined Heating And Power
CHPA	Combined Heat And Power Association
EPA	Environmental Protection Agency
GDP	Gross Domestic Product
PEC	Primary Energy Consumption
QHO	Qualifying Heat Output
UNFCCC	United Nations Framework Convention On Climate Change
VRLA	Valve Regulated Lead Acid
GDP	Gross Domestic Product
QHO	Qualifying Heat Output
QPO	Qualifying Power Output
COP	Conference Of The Parties
GWP	Global Warming Potential
MGT	Micro-Gas Turbine
IEE	Integrated Energy- Exergy
ZBB	Zinc Bromide Battery
VRB	Vanadium Redox Battery
FTL	Following The Thermal Load
FEL	Following The Electric Load
EDM	Electric Demand Management
HEES	Hybrid Electrical Energy Storage

P_{fuel}	Fuel consumption (primary energy consumption) of the trigeneration system
η_{engine}	Efficiency of engine
P_{engine}	Power output of engine generator
P_s	Power output of energy storage system
P_{SU}	Power output of supercapacitor
P_{BT}	Power output of batteries
P_{LOAD}	Electrical power demand (load)
SOC	Batteries' state of charge
te	At the end of operation time
C_S	Batteries' capacity
DG-ES	Distributed power generation with energy storage system
P_R	Power output of the recovery system
P_{T-ST}	Power output of the thermal storage system
P_{ET}	Power consumption of transferring from electricity to thermal energy
P_{EC}	Power consumption of cooling generated by electricity
P_{OE}	Power generated from ORC system
P_{OT}	Rate of low level heat from ORC
P_{ORC}	Power output of the ORC system
P_{C-L}	Cooling load

1. Introduction

1.1World energy consumption

The global energy state has gone through a significant change from the year 2014 to the year 2017 because of a sharp fall in oil prices[1-2] [3] [4]. A comprehensive introduction about the background of the global energy consumption state is introduced as the initial part of this energy system's research.

Because of an increasing world's population and the establishing of higher living standard for human beings in the recent decades, the energy consumption of human activities has been growing continuously during the past years. Specifically, the energy consumption for the human activities have been recorded as an increasing number from 7140.7 Mtoe in 1980 to 12875.6 Mtoe in 2010 (shown in Figure 1) [5]. Among the changing of energy consumption, Asia and Oceania contributes the largest contribution. At the same time, Oil, Natural Gas and Coal were still the dominant resource of the global energy consumption during the time in the survey. Compared to the main energy sources, Hydro Power and Renewables only provided 6.6% and 1.9% of the energy consumed [6].

The above information indicates that the human activities are consuming an increasing amount of energy currently. The natural resources have been consumed rapidly for the modern society's developing especially in the region with high speed development [7]. There is an urgent requirement, which is making the development of the world to be sustainable. In the one hand, the renewable energy is required to be a larger part of energy supply sources, on the other hand, the energy consumption efficiency has potential space to be improved. A brief information about world's recent changing on population and energy consumption are displayed in the Table 1[8]. A significant change is recognized as that technology has become the most important driver of social and economic development [9]. Rapidly developing information technology in the recent years plays an important role that has been transforming people's acting and thinking. Currently, the energy demand is closely connected with people's activities. The Table 1 shows some key indicators including some recorded values and estimated values.

	1993	2001	2020	Growth 1993-2011
Population, billion	5.5	7	8.1	27%
GDP				
Trillion USD	25	70	65	180%
TPES Mtoe	9532	14092	17208	48%
Coal Mt	4474	7520	10108	68%
Oil Mt	3179	3973	4594	25%
Natural Gas Bcm	2176	3518	4049	62%
Nuclear TWh	2106	2386	3761	13%
Biomass Mtoe	2286	2767	3826	21%
Other renewable* TWh	1036	1277	1323	23%
	11	515	1999	n/a
Electricity Production/year				
Total TWh	12607	22202	23000	76%
Per capita MWh	2	3	3	52%
CO_2 emissions/year				
Total CO_2 Gt	21	30	42	44%
Per capita tonne CO_2	4	4	n/a	11%
Energy intensity koe, 2005 USD	0.24	0.19	n/a	-21%
*Includes figures for all renewables, except hydro				

Table 1 Key indicators of energy consumption sacle from 1993 to 2020 [10]

The population growth always has a positive correlation with the energy consumption during the process of the human society's economic development[11]. In the past two decades, the global population has 1.5 billion increase which indicates the corresponding energy consumption has been increased. Although the overall growth rate of the global population is slowing down, the economic activities and the energy consumption by the human activities have increased significantly during the past decades. Based on the latest estimation on the world's population, there will be 2.7 billion increase in total by the end of 2020 [12]. From the indicators' estimation, the renewable energy resources also have an obvious development by the year 2020. Before 1993, hydro power and biomass were regarded as renewable energy resource application. The ratio of renewable energy resources to the total energy supplying was nearly negligible. After decades of developments, the contribution of the renewable energy has increased significantly and been counted individually then. The actual values of indicators in 1993, 2011 and the estimations in 2020 are made in the Figure1. The estimation made in the Table 1 shows the energy demand in the future will be much larger. The driving power to fill the gap between the capacity of energy generation and the huge energy demand is the new energy generation technologies.

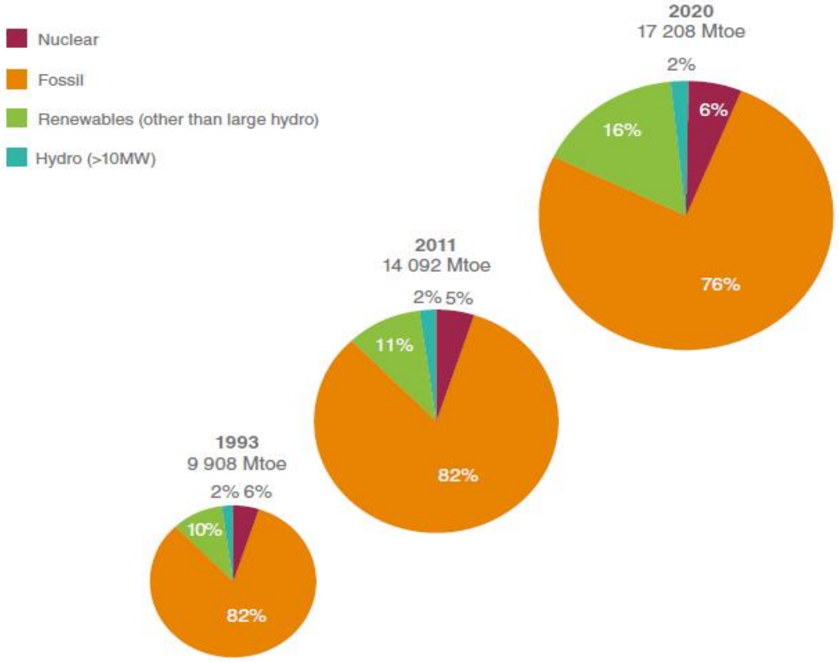

Figure 1 Energy consumption categories statistics in 1993, 2011 and 2020 [137]

Energy supplying for the human activities results in severe environmental, economic and social impacts. In the modern society, the energy supplying resources are still mainly fossil fuels. From the Figure1 shown, from 82% in the year 1993, 82% in the year 2011 to estimated value 76% in the year 2020, the fossil fuels have been taking a great part of energy supplying resources [13]. Relying on this traditional energy resources to fulfil the energy demand indicates that the modern society is still having large amount of demands of the unsustainable energy resources. This situation makes a high efficiency approach of consuming primary energy resources to have a significant meaning in the future. Based on the investigation of the energy consuming scale, in most of the area in the world especially in the developing countries, the fuel wood and biomass are largely applied by people in their daily life. The accessing to the commercial energy using is still a target in the future for the world. Researching and a developing a distributed energy supplying system with high operation efficiency shows a significant meaningful way to contribute this long-term task.

Lots of technologies aims on enhancing the energy utilizing efficiency are proposed in recent decades of years. They are applied For protecting the environment and making a higher efficiency of energy consumption in the global range [14]. The energy systems consume the primary energy resource with high efficiency and low carbon emissions are encouraged in regions all over the world. Innovated policies are in the process of being created to promote this high-efficiency and low-carbon systems. Combined cooling, heating and power systems (CCHP system also named trigeneration system) are admitted as one alternative way to solve the energy crisis for the current society because of its high energy transferring efficiency.

1.2 trigeneration system research – a brief introduction

Based on a government's report on the current energy consumption statements, a large part of energy consumption (over 52.3% of electricity and heat) is used for energy supplying for the domestic and small scale commercial buildings in the UK[15]. After investigating the heat and electricity consumption of the domestic load, most of energy consumed for the domestic application is generated by the traditional energy plants which is generated with efficiency within the range of 35%-40% [16]. Due to the low efficiency of conventional energy generations, combined heat, trigeneration was introduced in recent years [17]. It allows the power, heat and cooling being generated simultaneously in a single process. Trigeneration has been proven as a reliable technology to provide three formats of energy with a high efficiency [18]. Compared to conventional energy suppliers, the efficiency of trigeneration increases dramatically especially in cold climates where the heating demand is necessary for long time in a year. Besides the real climate conditions, people in many regions have an increasing demand for cooling and air conditioning due to longer time of daily activities and higher life standards. A conclusion is obtained from several of researches on trigeneration system, trigeneration systems have a number of advantages which are widely admitted by the researchers such as economic savings, lower carbon emissions, less consumption of primary energy source and high quality of energy supplying. Compared to the traditional separate power and heat generation system, better performance could be evaluated by those parameters such as operation cost, carbon dioxide emissions, or primary energy consumption (PEC). Better performance on all the key parameters is verified in many recent researches. The benefits of applying trigeneration system are roughly divided by the business benefits and the environmental benefits which will be introduced separately in the following sections.

1.2.1 Trigeneration system has business benefits

Compared to the traditional energy systems, low cost is a significant benefit for trigeneration systems [19]. Trigeneration system brings a reduction of cost on supplying the desired electrical power, space heating and cooling [20]. Compared to the conventional energy generation systems, the trigeneration systems have lower operational cost, lower maintenance cost and lower unit cost of per energy production [21]. The cost of trigeneration systems is usually determined by calculation of efficiency and fuel consumption. The amount of energy consumption is used to evaluate the operational cost of the trigeneration systems. The payback period of trigeneration system is also another evidence which shows the trigeneration system has an advantage compared to the separate energy generation systems [22]. Spark spread which means the difference between the price of the fuel and the price of purchased electricity is another important indicator of evaluating a trigeneration system. The spark spread of the combined cooling, heating and power (CCHP) systems shows applying them into energy supplying brings a great value compared to purchasing energy from the conventional plants. A detailed expression has been developed to investigate if the trigeneration system is an investable program and what is the payback period of the system. Saving primary energy is another key feature of trigeneration systems. The definition of the primary energy consumption is the amount of site energy consumption, plus losses which may occur in the duration of energy's generation, transmission and distribution process. PEC of a trigeneration system is related with the site-to-primary energy conversion factors. Compared to the PEC of traditional energy generation system or separate energy generation systems, the value of the trigeneration systems' PEC is normally evaluated lower. As a matter of fact, a trigeneration system produces more energy with the same amount of fuel compare to conventional systems with the help of its waste heat recovery process. By applying a trigeneration system, a minimum 10% energy saving is a widely admitted number. In most of the cases, the saving is markedly higher [23]. About 15%-40% saving on the primary source and over 60% overall efficiency make a trigeneration system is a guarantee of economic friendly choice [24]. Besides the discussion, a trigeneration system is also a reliable system which maintains a high level of stability. A trigeneration systems normally work with a control system which makes the security of system's operation be guaranteed by the own system's controlling process. Removing its connection with the Grid, the energy generation of a trigeneration system is more flexible. As a summary, high efficiency of energy product's production, reduction of the primary fuel's consumption, lower cost of maintaining, high stability and more flexible system operation make the trigeneration systems are potentially better economic choice for the future energy suppliers.

1.2.2 Trigeneration system has environmental benefits

The trigeneration systems also have environmental benefits. Environmental problems occur since the human activity breaks the balance of nature. The most famous environmental problems are greenhouse effect, changing of climate, water pollutions, and carbon emissions (mainly CO_2) and so on [25]. Most of them problems are related to the process of the exploitation of the energy sources or the using of energy sources. During all the environmental problems, carbon emissions is the closest problem related with the energy supplying. This problem has caused the attention of the government for decades.
In 1992, countries gathered by the international treaty held by the United Nations Framework Convention on Climate Change (UNFCCC) agreed to cooperate for limiting average global temperature increasing. By 1995, negotiations were launched to strengthen the global response to climate change. "Kyoto Protocol" legally binds developed countries to the mission of emission reduction in the period from 2013 to 2020. Carbon emission reduction is a trend for all developed countries since that specific time. In the <Planning our electric future: a white paper for secure, affordable and low-carbon electricity> by the UK government energy department, low-carbon generation will be provided stronger support and emission performance standard is set at 450g CO_2/kWh. Generally, the carbon dioxide emission can be reduced by applying renewable energy or increasing the burning efficiency of fossil fuel using [26].

Trigeneration systems are one of effective solutions to the environmental problem because of waste heat recovery and low carbon emissions. In most cases, the energy for the load is either obtained from the grid or generated by some energy systems. When the energy is generated by the trigeneration systems, the high energy conversion efficiency during the process transferring fuel to energy decrease the emissions and make the energy supplying to be more sustainable. A usual efficiency for the trigeneration systems to generate electricity and thermal energy varies in the range between 60% and 80%. The waste heat recovery technology integrated in the trigeneration system recycle part of waste energy form engine. This part of waste energy cannot be utilised in conventional systems. The operation of the system and the efficiency of the components decides the ultimate efficiency of the trigeneration system. The combination of thermal output and electricity generated by the trigeneration systems are normally higher than a traditional system with same amount of primary energy consumption. In the other words, the carbon emissions will be decreased. When comparing the carbon emission between the conventional energy plants with the trigeneration systems, advantages of transmission and distribution losses are avoided when the power is generated by the trigeneration systems. When the trigeneration systems' scale is large and the system is used to support large load such as a community's energy demand, avoiding the transmission and distribution losses are the additional benefits. From the numbers in the Table 2, the carbon's saving brought by trigeneration systems increase annually. The data in the Table is the evidence of that the trigeneration systems can reduce carbon emissions.

1.3 Developments of CHP systems and trigeneration systems in UK

	2010		2011		2012	
	$MtCO_2$	$MtCO_2$/1000 MWe	$MtCO_2$	$MtCO_2$/1000 MWe	$MtCO_2$	$MtCO_2$/1000 MWe
Carbon savings against all fossil fuels	13.23	3.22	13.27	2.22	15.73	2.56
Carbon savings against all fuels (including nuclear and renewables)	9.26	1.56	9.04	1.51	10.25	1.57

Table 2 Reduction of carbon dioxide by trigeneration systems[27]

The CHP systems and trigeneration systems have made a contribution to a high efficiency energy supplying in the UK [28]. There are data supporting the growing market share of the trigeneration systems [29]. In those corresponding cases, the information of the systems is also recorded. Besides personal investment in the UK, the government has also been promoting the development of the trigeneration system. CHP Quality Assurance programme (CHPQA) is set by the UK government which offer the methods and procedures to evaluate the quality of a wide range of trigeneration systems [15]. The trigeneration systems in the UK uses large categories of fuels and technologies. They are involved in a large range of sizes and applications. The most fundamental component of the trigeneration systems is the prime mover. A trigeneration system could contain one or more prime movers which are usually gas turbines, steam turbines or reciprocating engines. With the driving of the prime movers, the system obtains electricity, heat and cooling during the system's operation for different application purposes [30].

Normally, the size of a trigeneration system is specially designed for the target load. According to the energy demand of the load, the available electricity and heat are generated and stored in the system. In some locations, the trigeneration system is also connected with low distribution systems. Differing from the conventional generation system, a large amount of transmission and distribution losses are saved by applying trigeneration systems and these saved losses also lower the carbon level. High power quality, flexible capacity and low carbon emissions make the trigeneration systems have a rapid development in the UK in the recent decades [31].

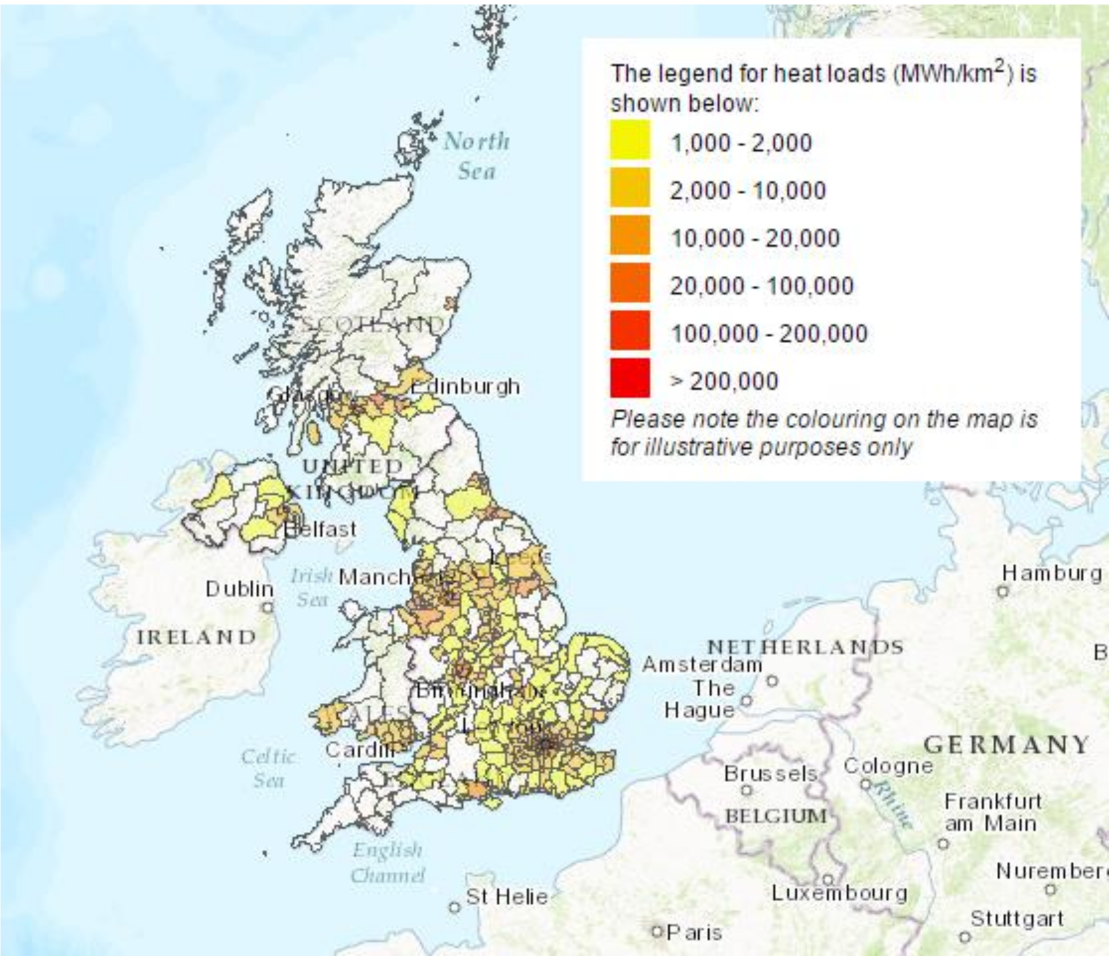

Figure 2 CHP Markets in UK[32]

The CHP systems market distribution is shown in the Figure 2. Dark colour represents high density of heat loads. Among the UK energy market, two most important factors which have the largest influence on the development of the trigeneration systems are the cost of fuel and value. The economic value could be measured by calculating the spark gap of the specific system. In the UK, trigeneration system is mainly installed in the south and in the middle in England. The north Ireland and the south of Scotland also have a quite amount of trigeneration system because of abundant wind power resource.

	Unit	2010	2011	2012	2013	2014
Number of schemes		1459	1791	1955	2054	2066
Net No. of Schemes added during year		80	322	164	99	12
Electrical capacity(CHPQPC)	MWe	5950	5969	6175	6190	6188
Net Capacity added during year		458	19	206	15	-72
Capacity added in percentage terms	Per cent	8.3	0.3	3.5	0.3	-1.1
Heat capacity	MWth	22204	22167	22970	22750	22539
Heat to power ratio		1.8	2.1	2.1	2.3	2.1
Fuel input	GWh	112559	98195	99421	93658	90707
Electricity generation(CHPQPO)	GWh	26768	22767	22950	20400	20281
Heat generation (CHPQHO)	GWh	48267	48184	48244	46076	43306
Overall efficiency	Per cent	67	72	72	71	70
Load factor (CHPQA)	Per cent	51	44	42	38	38
Load factor (ACTUA)	Per cent	55	58	53	53	52

Table 3 A summary of the recent development of CHP[33]

The data shown in Table 3 is a review on the recent development of CHP systems in the UK. For the last a few year, the CHP and trigeneration system have a rapid development especially in the year 2011 and the year 2012. For the capacity of CHP system, the year 2010 has the largest growth during year 2010 to 2014[34]. In the Table 3, the heat to power ratio is obtained by the relationship's calculation between qualifying heat output (QHO) and the qualifying power output (QPO) [33]. This indicator shows the utilisation of available heat by the CHP system. During the development of the CHP system, the heat energy transferring ratio has increased from 1.8 to 2.1. The electricity capacity and the heat capacity are two fundamental capacity of CHP systems. With an increase in the overall efficiency, the energy generation amount of CHP system has a trend of reduction in the recent years. The CHP systems were widely applied early in the 1990s. From the installation capacity of 3000 MWe in the 1990s to over 6000 MWe in the 2010s. As shown in the Table 3, the peak of the capacity accessed to 6190 in the year 2013. According to the information of the overall CHP market, the CHP schemes contributed 20281 GWh in 2014 of electricity generation[33]. This amount of electricity takes 6.0% of total electricity generation in the UK. On the other hand, the CHP system supplied a total amount of 43306 GWh of heat in the year 2014. Comparing

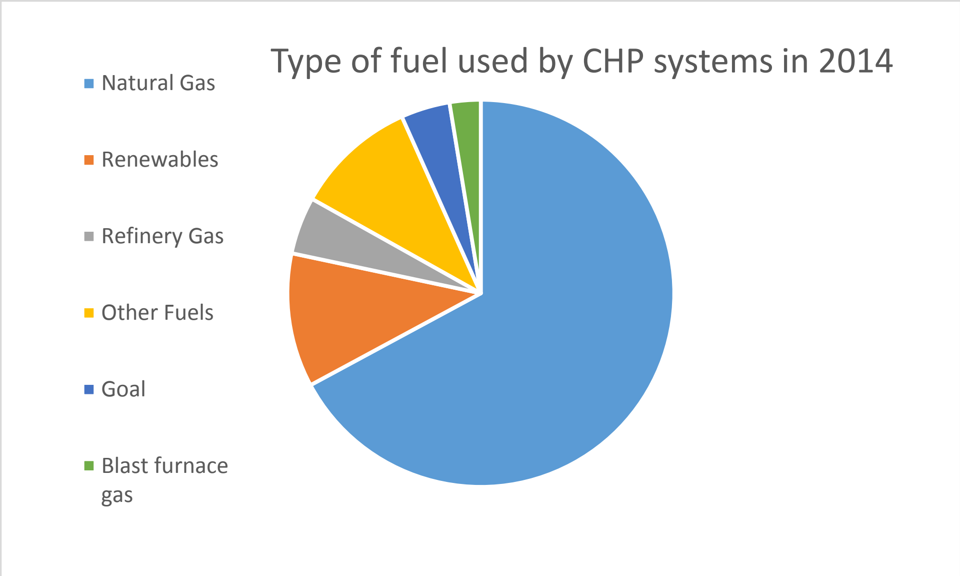

Figure 3 Fuel used by CHP systems in 2014[2]

the heat energy generated by CHP systems, in the year 2013 and 2014, the number reduces 6%. The capacity of energy generation by CHP systems reached the peak at 2013 and had a slight reduction in the year 2013 and 2014 in both heat and electricity generation. The fuel's utilisation is another key factor for investigating the trigeneration system. The Figure 3 gives an over fuel utilisation information of CHP systems in the UK. The most widely used fuel is a natural gas which takes the amount of 67%. The renewable energy sources is also connected closely with CHP systems. It supplied 11.2 % of primary energy source for the CHP systems which indicates that there are a large amount of CHP system combines renewable energy source as one of their prime movers. Besides the energy source in Figure 3, the refinery gas, coal and blast furnace gas are also energy consumption options for the CHP systems. In the UK, different format of fuel includes liquids, solid and gases accounted for 27.2 % of all the fuels used in CHP in 2014. Compared to 25.1 % in 2013, the increased number exposes the CHP systems are accelerating its combination with the renewable energy[33].

The CHP systems and trigeneration system in the UK show a performance variance based on their different type of prime mover. The gas turbines and steam turbines are the most widely used prime movers. In 2014, the average operating hours were roughly 9 hours per day (3315 hours annually). Compare to 3296 hours in 2013, the load for the CHP and trigeneration system did not change much in the recent several years.

	Average operating hours per annum (Full load equivalent)	Average electrical efficiency (%GCV)	Average heat efficiency (%GCV)	Average overall efficiency (%GCV)	Average heat to power ratio
Main prime mover in CHP plant					
Back pressure steam turbine	4360	13	65	78	5.2
Pass out condensing steam turbine	2325	13	56	69	4.4
Gas turbine	5382	23	51	74	2.2
Combined cycle	3208	24	47	71	2
Reciprocating engine	3515	26	37	62	1.4
All schemes	3315	22	48	70	2.1

Table 4 A summary of scheme performance in 2014[35]

As shown in the Table 4, the average CHP system's electrical efficiency was 22% and 48% heat efficiency at the same time. The theoretical calculation shows the overall efficiency should be over 70%. The overall efficiency was 71% in 2013. The high overall efficiency (over 70%) in the recent years shows the technology of the CHP and trigeneration systems are tended to be mature.

The CHP and trigeneration systems in the UK are contributing to the reduction of the carbon emissions these years. The saved carbon emissions could be calculated by applied in the category of fuels, technologies and size of the plant. According to an estimated calculation, the CHP and trigeneration system save 7.55 Mt CO_2 annually which equates to 1.23 Mt CO_2 per 1000 MWe installed capacity. Attracted by the CHP and trigeneration systems, the EU governments have established a number of policies which promote the development of CHP and trigeneration systems in the UK. The current CHP and trigeneration systems in the UK are mostly large and super large scale systems. The CHP and trigeneration system lower than 100 kWe take the amount of 0.8% total capacity in 2010 and 0.63% capacity in 2014. There is great potential for the small scale of CHP and trigeneration system to develop and to supply high quality of energy products for the individual small loads. This section introduces information of the CHP and trigeneration systems statement in the UK. In this research, the small scale of trigeneration system will be designed and researched by several case studies.

1.4 Research aims and objectives

1.4.1 Aim and objectives

The challenge facing the current stand-alone systems is that it cannot meet the energy demand at high efficiency and hence it is necessary to have energy storage. The aim of this study is to find a feasible solution to tackle the challenge, i.e. to investigate and develop an integrated system of combined trigeneration, energy storage and ORC to generate multi-energy products (power, heat and cooling) with high efficiency; to reduce the energy consumption and reducing the carbon emissions from the stand-alone systems.

The detail of objectives of the research are:

1) Investigating the state of art of current energy systems. Considering what types of energy system and which technologies can reach the aim of the research; and select the energy system and technologies for the study;

2) Selecting the case study of a stand-alone user demand; designing an integrated system which can meet the demand; and set up computational models to simulate and evaluate the system's performance; i.e. using the system to supply the small scale of loads with high efficiency under several scenarios;

3) Carrying out experimental tests; evaluate the system's performance and validate the computational models;

4) Carrying on further simulation using validated models for several scenarios; to find the best/optimisation of the system's performance achieving high efficiency."

1.4.2 Milestones

Phase one: system design

For developing a novel system which produces various kinds of energy products, the design work is significant for the system's operation and performance. In the first phase, the main work is investigating similar trigeneration systems and the integration between the trigeneration systems, energy storage and ORCs. The fundamental components which includes the prime movers, energy storage units (including electrical and thermal), waste heat recovery system, ORC, energy transferring components and other auxiliary components are chosen in the design phase. The integration of the electrical energy storage which consists of batteries and supercapacitors. The two storage devices showed different characteristics during the operation process. The integration of the hybrid electrical energy storage system (HEES) improves the system's ability to supply electrical energy. In the integrated system, part of the waste heat is still available. The integration of the ORC system helps the system to utilise the waste heat for electricity generation when the demands of heat and cooling are less and extra heat is available from the engine. Management of the system's operation is another important task to ensure the system work properly to supply the electricity, heat and cooling energy to meet the dynamic demand in different scenarios.

Phase Two: system model building, tests and validation

After the design work of the system, several experimental tests are designed to evaluate the system's performance on supplying the dynamic load. The experimental results are either used to measuring the system's parameters and analysing the system energy performance. The system's model is set up based on the design of the system and its operation. The mathematical models for each component are the theoretical foundation of the models' developing. The simulation model of the system is built in the Matlab software where the system's performance was predicted at high accuracy. Most of the components in the system are available in the Swan centre's laboratory. The fundamental tests are carried to get the primary test results for some key parameters. The system model is also adjusted and validated by the test results of those components.

Phase three: case studies

Case study one: experimental tests on the system.

The first case study consists of experimental test of supplying a domestic load with electricity by the integrated system. The dynamic electrical energy demand of the household is recorded by the previous research project in Swan centre. Based on the specific information of the household, the heat demand is estimated. During the energy supplying process in this case study, the performance of the system is evaluated which includes the efficiency, the dynamic parameters during the energy supplying and energy flow analysis.

Case study two: simulation studies

The simulation of the system is displayed in this case study. Each simulation model is built and validated separated. After system's model building, the system's performance is simulated. The simulation results are used to compare with the results of experimental tests. Confirming the accuracy of the models are necessary for the system's optimisation process.

Case study three: optimisation on the integrated system

The optimisation study on that part of system's operation is also simulated and analysed. The optimisation process includes the optimisation on the electric system and on the integrated system. This case study designs a set of loads under different scenarios. The system is adjusted to a different mode to supply these loads for testing the system's performance. The recorded simulation results are shown for analysing the system's performance. The results of the system's operation in various scenarios are listed for evaluating the integrated system' performance. The optimisation of the system and the simulation results are shown as part of the results of the case study.

1.5 Novelty of this research

Facing the urgent demand of high efficiency energy generation, the aim of this research is to develop a system which combines several mature technologies. For small scale energy demand. Designing an integrated system is a feasible approach to engage these mature technologies. The integrated system studied in this research combines the trigeneration system, a novel electricity storage system and the ORC system. In the area of trigeneration system investigation, this system structure is novel because of the integration of hybrid energy storage unit and ORC system. There are trigeneration systems integrated either ORC system or energy storage unit. However, combining the ORC system and energy storage unit (including supercapacitors) with the trigeneration system is the first attempt. The research focus on building these integrated system and evaluating it. Therefore, the study begin with the experimental tests on the system's components. Simulation s on this integrated system is built from the results of the experimental tests. Based on the simulation and experimental tests results, the optimisation process is also an important part. In conclusion, the novelty of this research is the investigation of a new structure of an integrated system and the performance evaluation on the system.

1.6 Summary

This chapter describes the energy background of the research. The fossil fuels are unsustainable resource and facing a crisis of being over consumption. In the rapidly changing world, high-efficiency energy generation approach is a necessary demand for human being's sustainable activities in the future. In the world wide especially in the UK, the trigeneration systems are taking larger part of market share in the energy supplying area. The current global development of the trigeneration systems is introduced focusing the topic of capacity and benefits. From the brief introduction displayed above, the trigeneration systems have environmental and economic benefits compared to the conventional energy generation systems. In the UK, the huge and large scales of trigeneration system are fully developed. However, the small scale of trigeneration system lack attentions relatively. Facing the changing demand of the small scale load, the trigeneration system may has problems to fulfil the power demand. An integration with an energy storage unit can solve this problem. Using part of low temperature heat source form the engine's waste heat make a traditional trigeneration system possible to generate energy with a higher efficiency. Because of that, a trigeneration integrated with an ORC is studied in this project. As a new structure of integrated energy system, the trigeneration system is combined with an ORC system and novel energy storage units for better performance. The objectives and the process of the study were also introduced in this chapter. It indicated the basic route of this research.

The structure of the thesis is listed as follows:

Chapter 2 shows a detailed literature review about the related knowledge of this research. This chapter contains the recent development of the trigeneration systems, the basic technologies and updated technologies of trigeneration system, trigeneration systems' integration with other components, the energy storage units for the trigeneration systems and the control strategies. This chapter discussed the gap between the current trigeneration system and the demand of the domestic small-scale load. The reason of the system's design is included in this chapter.

Chapter 3 discusses the methodology of the research. The research approaches design is displayed in this chapter. A case study targets on the domestic load is discussed in the first half of this chapter. The main research approaches consist of experimental tests and simulations which are evaluation method on the system's performance. The optimisation process is also introduced I this chapter.

Chapter 4 introduces the experimental tests on the system. The installation of the system's test bench is introduced. Experimental tests on both the electrical energy storage system and the whole system shows the system's capacity of energy supplying. Besides the analysing of the storage system's tests results, the control strategy designed for the electrical system are also discussed .

This chapter also presents the experimental tests and simulation study on the electrical part of the system. The optimisation of the system's operation is shown in detail.

Chapter 5 expressed the system's modelling building which includes the computer modelling building in the Matlab software environment. The validation contains the comparison between the simulation results and the primary experimental results are displayed. After the model building, a simulation study on a domestic load supplying is curried out and the results shows a primary prediction of the system's performance.

Chapter 6 is the optimisation study on the integrated system. The first part of chapter introduces the theoretical efficiency boundary of the integrated system. Then the optimisation of the electric part of system is expressed. This chapter also shows the simulation of the integrated system in different scenarios. By supplying the designed load and processing the optimisation on the system, the system's energy performance is analysed.

Chapter 7 shows the conclusion of the study and the future work of this project.

2. Literature review

2.1 Background of trigeneration system researching and government policies

The integrated trigeneration system generates electricity, heat and cooling. The main products are the heat and the electricity. It has similar construction to CHP systems. The development and current shares of CHP system, are closely related to the research of this project.

The world is facing one urgent environmental problem- the climate change. In 1995 when the first conference of the Parties (COP) was held, global warming caused by the carbon emissions has been a serious problem in the research years. One fundamental element for developing a stable and sustainable economy is the reliable and affordable energy systems. The urgent challenges for the current world includes the climate change[36], the erosion of the energy facilities and the increasing expanding energy demand. Carbon dioxide emissions, the closest global environment related parameter, has been increasing by over 20% during the past twenty years[37], which requires necessary actions to be done to prevent future deterioration of this situation. Since the world is mainly relying on the energy from fossil fuels, it indicates that emission of burning fossil fuels is a primary cause of global warming emissions. For reducing the carbon emissions, two alternative approaches are either developing existing technologies to expand clean energy source or improving the energy consuming efficiency. There are plenty of plans designed for improving the energy consumption efficiency in related researches[38] [39] [40]. For example, enhancing the fossil fuel’s processing (using pulverised coal under supercritical condition), developing clean energy generation technology, and novation of technology of traditional energy plant. Among all the options for solving the energy crisis, applying the multi energy products generation system is regarded as a proven, cost-effective solution for every energy consumption area. The trigeneration system an effective method in the large amount of extensive options. CHP system has similar theoretical operation with the trigeneration system. Since utilizing the energy in the heat and electricity formats simultaneously can enhance the efficiency to a much higher level, The CHP technologies in industrial, commercial and residential sectors are drawing attentions these years[41] because of the advantages of the kind of systems. The benefits of supplying energy by the CHP systems are summarised briefly as lower cost for energy consumption, lower carbon emissions, lower fossil fuels consumption, money saving by reducing infrastructure, higher stability of energy supplying and healthier energy consumption pattern for local environment.

There are several countries, which developed high level of CHP technologies to supply their energy demand. Denmark, Finland, Russia, Latvia and the Netherlands have expanded CHP system up to 30%- 50% of the power generations. In these countries[42], Denmark has an obvious growth on the CHP system's promotion in the past decades. The growth of developing CHP system contributes to the carbon emission reduction in Denmark. The carbon emission by final energy drops from 80 million tonnes in 1990s to around 52 million tonnes in 2006 [43]. The government's promotion on the CHP system indicates that the CHP systems bring benefits to the society [44].

Governments have been launching polices to encourage CHP systems development. Because of variety energy production, low environment impact, economic benefits and mature technologies, CHP system as widely applied energy generation systems has large share in global market. [45] For example, in America, CHP systems have reduced 400 MT carbon dioxide emissions annually. In the EU, CHP systems contributes to 15% of the carbon emission's reduction since 1990s[46]. In the EU counties, CHP systems have been one of the primary solutions to the climate change problem. In China, trigeneration systems are promoted to apply in the domestic and industrial use[47]. The government encourages trigeneration systems operate in the off-peak time to work with the grid together which realise a large part of grid's pressure in the energy supplying crisis. Based on the recent researcher's review's and the governments' reports, increased policy attention are addressed in EU, USA, japan and other counties. The contribution of power generation from CHP systems are increasing in the past decades [48].

One conclusion obtained by the recent researchers is the economic benefits of the CHP systems. Not only an enhanced efficiency attracts the energy market, the profits is another key factor for the investors to choose the CHP systems. A clear economic benefit of the CHP systems leads to a growing number of CHP system's installation. CHP systems as a supplement to the main energy supplier market, the new effective way supplies energy with lower carbon emissions and has potential benefits for the environment for the forward years. Study from Mckinsey pointed out that the CHP systems achieved the carbon emission reduction goal in the USA[49]. Based on the investment and data collected, the CHP systems provided 13% of carbon dioxide reduction. In the future, the CHP systems have ability to contribute up to 53% carbon emission reduction in the next 20 years[50]. Another evidence is a study focusing on the carbon abatement policies in the Netherland. The CHP systems were proven as the less cost energy suppliers at EUR 25/Tonne CO_2. In the study, CHP systems are proven betters than boilers and wind power system in case studies. [51].

Combining the current energy consumption background nowadays and the feature of the trigeneration systems, wide range of researches have considered applying the trigeneration system to fulfil the energy demand in higher efficiency. In this project, a novel structure trigeneration system is design and simulated, the literature review of the subject will be shown in the flowing sections.

2.2 Tendency of worldwide Trigeneration states

Trigeneration is widely considered as a key method to enhance the energy consumption efficiency and reduce carbon dioxide emissions for small-scale energy users. Since the first trigeneration idea is introduced, the researches on trigeneration system develops rapidly with the promoting of government's policies [52]. A framework for the development of highly efficiency combined heat and power generation system was established in the EU Drective 2004/8/EC aims at saving primary fuel in the energy market [53]. After a few years' development after that, the total CHP system's capacity exceeded 105 GW in the EU. Among these CHP systems, Germany took the lead with 22% of the whole capacity. Poland and Denmark also took 9 % of the CHP overall capacity. The Table 5 shows the capacity of CHP system installed in the UK. CHP and trigeneration systems are widely applied in UK and the state is introduced in following part.

A summary of the recent development of CHP(1)

	Unit	2008	2009	2010	2011	2012
Number of schemes		1,327	1,380	1,460	1,794	1,929
Net No. of schemes added during year (2)		13	53	80	334	135
Electrical capacity (CHP_{QPC})	MWe	5,323	5,492	5,950	5,970	6,136
Net capacity added during year		5	169	458	20	166
Capacity added in percentage terms	Per cent	0.1	3.2	8.3	0.3	2.8
Heat capacity	MWth	21,133	22,258	22,204	22,168	22,837
Heat to power ratio *(3)*		1.89	1.82	1.80	2.12	2.10
Fuel input	GWh	118,685	111,291	112,560	98,194	103,181
Electricity generation (CHP_{QPO})	GWh	27,528	26,425	26,768	22,766	23,360
Heat generation (CHP_{QHO})	GWh	51,911	48,092	48,267	48,183	49,134
Overall efficiency *(4)*	Per cent	66.9	67.0	66.7	72.3	70.3
Load factor (CHPQA) *(5)*	Per cent	59.0	54.9	51.4	43.5	43.5
Load factor (Actual) *(6)*	Per cent	65.5	57.3	55.2	57.8	53.3

(1) All data in this table for 2008 to 2011 have been revised since last year's Digest (see text for explanation).
(2) Net number of schemes added = New schemes – Decommissioned existing schemes
(3) Heat to power ratios are calculated from the qualifying heat output (QHO) and the qualifying power output (QPO).
(4) The load factor (CHPQA) is based on the qualifying power generation and capacity and does not correspond exactly to the number of hours run by the prime movers in a year
(5) Overall efficiencies are calculated using gross calorific values; overall net efficiencies are some 7 percentage points higher.
(6) The load factor (Actual) is based on the total power generated and total capacity

Table 5 Summary of recent develpmen of CHP systems[22]

Due to the requirement of low carbon energy, CHP technology is introduced and promoted in UK. A summary of CHP is shown in Table 5. CHP technology as a high efficient generation system grows rapidly in UK [54]. The electrical capacity exceeded 6136 MWe in 2012. The total electricity production exceeds 23360 GWh and the efficiency is 70.3%. The size of CHP generation is growing and a major factor of CHP's developing is the high ratio of energy production. The data in the table indicates the energy produced by the trigeneration meets the standard of high quality. Since 70% of CHP systems are fuelled by natural gas, and the natural gas is limited resources, the CHP system has potential to take bigger amount of energy production [55].

Except EU area, the CHP system becomes popular over the world. Japanese Government installed 5190 CHP and trigeneration units in commercial application by 2006 [56], and for the past 30 years, the capacity of CHP and trigeneration system has grown from 200 kW up to more than 10000MW [57]. That is a homegrown trigeneration energy program, which aims to lower the future carbon price.

Chinese governments also introduced trigeneration and CHP systems since 1990s. Within the encouraging of National energy law set in 1998, the development of CHP and trigeneration systems grows rapidly [58] . The capacity of CHP and trigeneration system reached 28.15 before 2000 and more than 150 MW's trigeneration system are planned to be installed [59] . The trigeneration capacity in USA has increased from 12 GW in 1980 to 45 GW in 1995 [60] . The US Department of Energy(DOE), the Environmental Protection Agency (EPA) and the Combined Heat and Power Association (CHPA) have launched the "CHP Challenge" in 1998 to increase the installed capacity of trigeneration systems to 92GW in 2010 [61] . A challenge also is set up to install 40 GW of new, cost-effective CHP and trigeneration by 2030 [62]. Overall the world, governments and institutions such as Russia, Brazil, Iran, India, Mexico and South Africa are promoting the deployment of CHP and trigeneration systems [63]. The price of natural resources has been growing up in the recent year. Under the promoting of policies, the trigeneration systems has the potential to be one of the largest energy supply method in the future 21th century [64]. Therefore, the technology of trigeneration system deserves to be researched, developed and improved. (a series of systems are checked and shown in appendix 1)

2.3 The configuration and categories of conventional trigeneration

Normally, a trigeneration system consists of five basic units which are the prime mover, electrical generator, heat recovery system, thermally activated equipment, the management and control system [65] .

Prime mover for trigeneration can be divided into 2 types: Combustion-based technologies (Stirling engine, gas turbines, Rankine cycle unit and reciprocating engine) and electrochemical-based technologies (fuel cells) [66]. The most used types of prime movers are studied in detail in the following sections.

A brief introduction expresses the advantages and the disadvantages of these engines. The reciprocating engine has high efficiency and better load performance, it also requires short start-up time. But normally the engine has low movability and has high noise levels [67]. Gas turbines are mostly used in trigeneration system, it has compact and flexible design, and low maintenance levels and low operates output heat temperature. The shortcoming of gas turbine is inefficient part load performance and unsuitable for intermittent use and frequent start/stop application [68] . Sterling engines and fuel cells all have low noise and low emission levels.

Sterling engines are suitable for domestic application. Depending on the types of fuel cells, they may have high output temperature. However, the start-up time of Sterling engines is long. The capital and investment cost of fuel cells is high [69]. Besides single prime mover, there are prime movers' combinations applying in the area of trigeneration system. A number of studies focused on the multi prime mover have been presented. For example, a trigeneration combined gas turbine and solid oxide fuel cells was presented by Velumani [70]. In another research, a trigeneration developed by Saito combined micro-turbine and oxide fuel cells as the prime mover [71]. The combination of prime mover is used to reduce the consumption of primary fuels. In the analysis, the consumption of fuels decreases more than 30% in different application.

The prime mover transfers energy from fuel or other energy resources and transmits the energy to thermal and cooling equipment. Major thermally activated technologies include absorption chillers, adsorption chillers, and desiccant dehumidifiers [72]. These cooling and dehumidification systems can be driven by steam, hot water or hot exhaust gas derived from prime movers. Existing trigeneration systems including laboratory-sized units and models vary from site to site, with diversity in prime movers, cooling options, connecting forms, rated size ranges, heat-to-power rates, and demand limitations [73].

Renewable energy sources apply are getting popular especially in the area of trigeneration. A number of studies have utilized bio-fuels to drive the system's prime mover and to supply the energy [74]. It can be regarded as alternative sustainable energy choice for the trigeneration system. In some research, the renewable energy is adopted to supply the heating demand in the system's operation. Lots of renewable energy-based heating resources are used such us solid fuel cells heating, biomass boiler and solar energy [75].

Lots of researches have been found focusing on the developing of micro-scale trigeneration system. An innovative micro-scale trigeneration system is experimentally investigated by M.Jradi [76]. An organic Rankine-based combined heat and power unit and a combined dehumidification and cooling unit are the main parts of the system. Experimental work tested the system under different operational conditions, and showed that the overall efficiency of the system is about 85%. An engineering/economic model and an interdisciplinary framework have been built to verify the value of the system. Design, technical, economic and environmental performance of trigeneration system for home and neighbourhood refuelling are evaluated by Xuping Li [77]. Thermodynamic analysis of a trigeneration system was introduced by Rui Pitanga Marques [78]. The ability of carbon emissions reduction has been analysed in the paper. A household size trigeneration based on a small-scale diesel engine generator is designed and realized by Lin [79]. Experimental tests are carried out to evaluate the performance and the emissions of the system. In addition, the results showed the size is feasible and the set-up of the trigeneration was successful. For all the micro trigenerations have found, none of them combined the trigeneration system, ORC system and storage unit together. For system integrated with storage has some key issues need to be solved such us system integrating, controlling strategy and efficiency evaluating. These problems are researched and solved in this thesis.

2.4 Prime movers

A number of energy generation approaches have been considered by system creators to apply as trigeneration system's prime movers [80]. Most of these methods are based on fuels, have mature technology, and have certain markets share and wide capacity range. Besides the conventional energy generation technologies, a number of alternative technologies are also taking part of the CHP system's prime movers such as: micro-turbines, fuel cells or renewable energy generators [81] [82]. Applying these mature technologies are changing the future of the CHP system's development. They are also enhancing the system energy capacity and applying range. Depending on the characteristics of various energy demand, the certain type of prime mover is selected for the designed purpose. In this section, current technologies of prime movers are introduced, the advantages, drawbacks of this technologies are also reviewed with the discussion of applications.

2.4.1 Steam turbines

The most common prime mover technology is steam turbine. The exit pressure of the steam divides the turbines to two categories: condensing turbines and backpressure turbines. The condensing turbines are capable of adjusting the thermal power and electrical power independently. The two type of power work with an exit pressure lower than atmospheric pressure. On the other hand, the backpressure turbines' exit pressure is larger or equal to atmospheri pressure, which makes this kind of turbine suitable sites with a steam demand of intermediate pressure. The steam turbines integrated with a boiler in standard configuration to transfer the energy in the fuel. The steam turbine technology is one of the most mature turbine technologies, which indicates the steam turbine usually has long lifetime with reasonable maintenance cost [83]. Although it is a reliable technology, there are some problems, which limits the application range of steam turbines. Most of the steam turbines' electrical efficiency is low and the partial load performance is poor [84].

In the trigeneration applications based on steam turbine, complex systems are designed during most of the cases. Since the steam turbine convert the energy into useful work and waste heat, the exergy analyses becomes a very popular topic in the steam turbine related trigeneration projects. In a hybrid power system, the steam turbines was integrated with ORC cycle and absorption refrigeration cycle [85]. The parametric analysis showed that the hybrid system was capable of supplying electrical power, cooling and hot water with an efficiency of 67.6%. In another research, the gas turbines and the steam turbine were evaluated with the performance on the integration with CHP systems [34]. For the small scale of CHP systems, when the heat demands is low, the operation strategies was proven to be necessary to adjust for satisfying the particular energy demand. In a cogeneration system designed for industrial energy demand, for enhancing the environmental sustainability, higher efficiency of system operation was set up as research target in the project. A novel algebraic technique, which applies steam cascade analysis to determine the steam flowrates, and cogeneration potential for a steam distribution network achieve the accomplishment that multi objective functions were processed synchronously [86]. Optimisation of the steam turbine CHP system is also a popular topic. In Chanel's research, CHP operation strategy under three economic cases are discussed based on the carbon price in Australia [87]. From considering for validation purposes, the load equations of steam turbine is analysed combined with the pricing date under various cases. The results show that the steam turbine has economic advantages compared to a natural gas boiler in the CHP system. [88] Simulation model about CHP integrated Steam engine is also established in recent research. In Jean-Baptiste simulation study, a micro CHP system was built as a dynamic model based on experimental data. The energy performance and the emission were predicted as the study results [89]. The research differs normal CHP system as the wood pellet micro CHP system (μCHP) was studied and the μCHP's behaviour for different load ratios were simulated in the study [90]. Steam turbine as the most fundamental and most popular turbines, they are involved with the CHP studies in numerus cases. Simulation and experimental study on the trigeneration systems integrated with steam turbine are all involved in the recent researches. Besides of the system energy performance investigation, the control strategy is another popular topic in this area.

2.4.2 Internal combustion engines

The reciprocating internal combustion engines are divided by two types, which are spark ignition engines and compression ignition engines. The spark ignition engines mainly applies natural gas as the primary fuel in energy generation, sometimes the biogas air landfill gas are also compatible [91]. On the other hand, the compression ignition engines mainly use diesel fuel and other petroleum products. During a number of engine technologies, the reciprocation engines have the lowest first capital cost on the trigeneration systems [81]. The reciprocating internal combustion engines have several advantages such as fast start-up capability, high-level reliability and high efficiency. During all the trigeneration systems, the reciprocating engines are the widely applied engine in the system capacity range under 1 MW [92].
There are some drawbacks on this mature technology, which could not be neglected. The maintenance is one significant issue for reciprocating engines. The moving components in the engine requires regular maintenance to keep functions. The high vibrations of reciprocating engines need shock absorption components to balance the machine's movement. High level of noise is another problem of reciprocating machines. The reciprocating machines in the trigeneration applications make the machines has lower emission. The most significant point for enhancing trigeneration system efficiency is utilizing the waste heat produced by the reciprocating is operation [93].

2.4.3 Combustion turbines

Most of the combustion turbines operates to supplement power supplying especially for electricity demand. The combustion turbines are technology applied in the large range of power system because of the high reliability [94]. When the system size is smaller than one MW, the low efficiency of energy generation and the high cost on per kW_e energy producing make the combustion turbines become uneconomical. Compared to steam turbines and reciprocation turbines, the combustion turbines have easier installation process, which make the combustion turbines to be less area intensive and its capital cost is not the highest [95]. Compared to reciprocating engines, the combustion turbines are easier to be maintained. But the electrical efficiency also lower. The emission of combustion turbines is lower than that of reciprocating engines. The disadvantages of combustion turbines are not negligible. The combustion turbines have requirements of premium fuels. In most of the cases, the primary energy fuel is natural gas, which keeps a high price [96]. The operation temperature of combustion engines is much higher than many other engines. Higher temperature make the engines needs better quality of materials. As results, the operation cost is high and the performance is limited in high temperature operation.

2.4.4 Stirling engines

The Stirling engine differs from conventional internal combustion engines in that it is an external combustion device. During the cycle medium of Stirling engines, the helium or hydrogen is not exchanged in each cycle. The driving energy is applying externally [97]. Most of the fuels such us natural gas, alcohol, gasoline or butane are available to Stirling engine. Because of the combustion, process is occurred externally, the process could be controlled to limit the emissions. Controlled external process of combustion makes lower noise and lower emissions. Compared to conventional engines, there are fewer moving parts, which make the vibration level of Stirling engine to be lower [98].

However, the Stirling engine has high efficiency theoretically. This kind of machine is still in developing process. In the energy transferring process, Stirling machine could get as high as

80 % thermodynamic efficiency in experimental test [99]. However, the working gas and the materials of the engine limit the engine's operation. The friction, thermal conductivity, tensile strength and melting points all have significant influence on the engine's performance. For certain rate engines, the investment cost of Stirling engines is higher than combustion engines [100]. Additionally, the Stirling machines are heavier than conventional engines. As a result, the wide range of available primary energy source and high efficiency is the biggest advantages for Stirling machine. There are reports focusing on combining Stirling engine with trigeneration system. For example, a methodology for optimal sizing of a CCHP system with Stirling machine as its prime movers is developed for a residential application. The system is analysed from the aspect of energy environment and economic.

2.4.5 Microturbines

The microturbines are a new class of small gas turbines. Several manufacturers for the power range from 25 kW to 250 kW have developed this kind of turbines. Normally, this kind of turbines are integrated in a multiple system to generate certain part of the electricity for higher system reliability [101]. Most of the Microturbines are applied single shaft design where in the compressor. The turbine and the generator are mounted on a single shaft. The power source of the turbine could be either gas, gasoline, diesel or alcohol. There is also dual shaft design, which has lower operation speed compared to single shaft design. This kind of turbine is a relatively new entry in the CHP and trigeneration industry. The research on this turbine integrated in trigeneration system is a popular topic in recent years.

During most of the designs, with recuperation, the efficiency is ranged from 20% to 30% LHV range [102]. Compared to other turbines, the establishing cost of Mircroturbines is not high. This turbine also has high level of availability. A significant advantage of this turbine is the lower combustion temperatures assuring low nitric oxide emissions [103]. Low emission and low noise make this turbine has few impact on the environment. Because of these technologies is not mature currently, the reliability of this system is guaranteed. Compared to other reciprocating engines, the first cost is also higher. The low electrical efficiency and the strict requirements on the ambient operation condition are the main issues of drawbacks.

2.4.6 Fuel cells

The fuel cells are a type of electrochemical cells, which converts the chemical energy from a fuel into electricity. The fuel is input of the electrochemical reaction. Unlike the batteries, the fuel cells demands a continuous sources of fuel and oxygen to keep the chemical reaction. This new type of cells provide clean, quiet and high efficiency power generation. An outstanding environmental benefits drives their developments of the fuel cells in the recent decades. Normally, in CHP systems, the efficiency of the fuel cells excess up to 85% [104]. Over 40 years developments on this technology make the fuel cell be expanded from stationary power and transportation applications to a various types of applications [105]. Among all type of fuel cells, only the phosphoric acid fuel cell (PAFC) is a mature commercial product, and the price of the kind of cell is around $3000/kW. The payment of energy generation is too high for most of industrial and commercial applications [106].

The fuel cells produce a direct current through an electrochemical process. In this way, they are similar with the traditional batteries. An electrolyte uses the charged ions to produce heat and electricity. The DC electricity output of each individual fuel cell is ranged from 0.5-0.9 volts.

The main types of fuel cells share a similar design. They are distinguished by their electrolyte. The five types are alkaline, phosphoric acid (PAFC), Solid oxide (SOFC), Proton exchange membrane (PEMFC) and molten carbonate (MCFC) fuel cells. During all the types of fuel cells, the MCFC is designed to target 1-20 MW stationary power generation which is the most suitable application for CHP system [107].

As a novel energy generation approach, the maximum efficiency is possible to reach 85% when the thermal by-product is recovered. However, the capital cost of the fuel cells is too high for large range application. The current commercial PAFC fuel cell costs lots of money for per kW's generation, the price of the fuel cells are expected to keep above 700£/kW in the next decade. Even with a high availability, the fuel cells are not reasonable choice for the current CHP systems and trigeneration system.

	Diesel Engine	Natural Gas Engine	Steam Turbine	Gas Turbine	Micro-turbine	Fuel Cells
Information source	[43,47,49]	[51,57]	[51,53-55]	[38,57]	[62,63,64]	[39,65-68] [98]
Electric Efficiency (%)	31-36%	25-39%	30-38%	25-36%	20-30%	40-65%
Size (MW)	0.05-5	0.05-5	Any	3-200	0.025-0.25	0.0-2
Uses for Heat Recovery	hot water, LP steam, district heating	hot water, LP steam, district heating	LP-HP steam, district heating	direct heat, hot water, LP0HP steam, district heating	direct heat, hot water, LP steam	Hot water, LP-HP steam
Fuels	Diesel and residual oil	natural gas, biogas, propane	all	natural gas, biogas, propane, distillate oil	natural gas, biogas, Propane, distillate oil	natural gas, biogas, propane
O&M Cost (£/kWh)	0.0042-0.0067	0.0058-0.0125	0.0033	0.0016-0.0066	0.0016-0.0083	0.0025-0.0125
Availability	90-95%	92-97%	Near 100%	90-98%	90-98%	>94%
Hour Between overhauls	25000-30000	24000-60000	>50000	30000-50000	5000-40000	10000-40000
Nox Emissions (ib/MWhr)	3-33	2.2-28	1.8	0.3-4	0.4-2.2	<0.02
Fuel Pressure (psi)	<5	1-45		120-500	40-100	0.5-45
Life Cycle (year)	20	20	25-30	20	10	Over 80
Start-up Time	10 sec	10 sec	1 hr-1 day	10 min - 1 hr	60 sec	3 hrs - 2 days
Noise	Mid to high	Mid to high	Mid to high	Mid	Mid	Low
Footprint (sqft/kW)	0.22	0.22-0.31	<0.1	0.02-0.61	0.15-1.5	0.2-2
CHP Output (Btu/kWh)	3400	1000-5000		3400-12000	4000-15000	500-3700
Useable Temp For CHP (F)	180-900	300-500		500-1100	400-650	140-700
CHP (£/kWh)	750-1350	750-1350	660-830	580-750	420-1080	>2500

Table 6 Comparison of the prime movers

2.5 Cooling technologies of trigeneration systems

Cooling is one of energy products supplied by trigeneration systems. The cooling demand of the target is normally satisfied by integrated components using transferred waste heat from the prime movers. There are several cooling technologies widely applied in the current trigeneration systems [108]. They fulfil the cooling demand for air conditioning demands by transferring recovery heat in the trigeneration system. Exhaust flue gases, steam and hot water are all heat sources for the cooling components in trigeneration systems. These technologies can be divided by two categories, which are thermally active technologies and traditional vapour compressions cooling technologies. In the next section, the cooling technologies are introduced in details.

2.5.1 Absorption cooling

The technology of absorption cooling is introduced early in 19th century. The absorption cycles are similar to vapor compression cycles. In the absorption cycle, the compressor is taken place by a chemical cycle between the absorber, pump and regenerator. After long times of researching and enhancing, the absorption cooling technology is a mature and well-established cooling technology which has been applied into energy systems for years [109]. A basic absorption cycle includes an absorber, generator, condenser and evaporator. An absorbent and a refrigerant also form a working pair. Absorption system applies heat to compress the refrigerant vapor. In a basic absorption cycle, the evaporator of absorption chiller generates the cooling power. A liquid absorbent absorbs the vapor generated in the evaporator. After that, the absorbent is pumped to the generator. During this step, the absorbent either takes up refrigerant with spent or weak absorbent. Then the waste heat from the steam, hot exhaust gas or hot water releases the refrigerant as vapor again. The vapor release is condensed in the condenser. During this step, the regenerated or strong absorbent is transported to the absorber for delivering the refrigerant vapor. In the cycle, the high temperature heat is supplied at the generator side and the low temperature heats is rejected from the absorber [110].

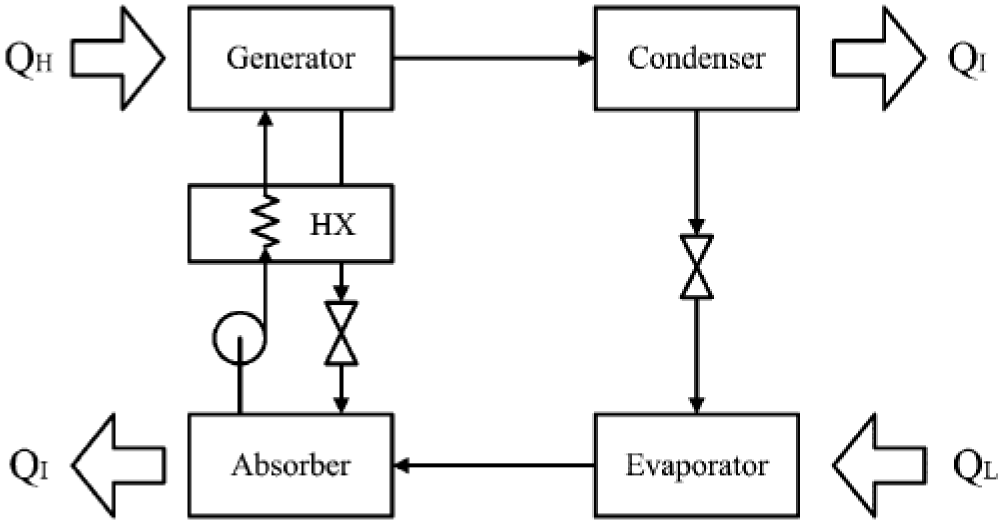

Figure 4 Absorption cooling operation schematic diagram [111]

The absorption chillers are supposed to operate supplying a high demand of cooling energy demand. When the cooling load has sharp spikes in the building's electric load profile and the demand is large, the efficient of absorption chiller is high [112]. When the cooling demand is only base load, the cooling demand is better to be supplied by the electrical cooling appliance. The absorption chillers are working as individual system or integrated system in synthetic energy system.

There are a few features the good applications for absorption chillers have which are: 1, acceptable maintenance and service cost; 2, coincident demand for air conditioning and heat; 3, high demand charges. The absorption chillers are simply divided by direct or indirect-fired. They are also categorised as single, double- or triple-effect. When the heat source (gas or some other fuel) is burned in the units, the chiller refers to direct fire. When the units use steam or some other transfer fluid which obtain heat from a separate source, it refers to indirect-fired units.

2.5.2 Efficiencies of absorption chiller

The parameter used to evaluate the efficiency of absorption chiller is coefficient of performance (COP). The COP is defined as the refrigeration effect divided by the net heat input. For single effect absorption chillers, the ideal COP is 1.0. The COP is approximately 0.6-0.8 in reality. In real applications, the COP is always less than one[113]. The single-effect chillers are mostly used in applications which applies recover waste heat. For example, in a research, the single effect chilling is applied to supply cooling generation a CHP system. The theory of this chilling is using waste heat from steam or exhaust gas as the energy source of the chiller. [114]

The COPs of double-effect absorption chillers is approximately 1.0 out of an ideal 2.0. The triple effect absorption chillers are not commercially available currently. The COP calculated ranged from 1.4 to 1.6. The COP is also available on evaluate the electric chillers. The problem is the COP is based on the site energy. The comparison of gas and electric chiller efficiencies is not appropriate in that case. Another term Resource COP is better for comparison the electric chillers and absorption chillers. The Resource COP accounts for the source to site efficiency of the fuel. The electricity generated and the losses are accounted. The Table 7 explains the typical values of the evaluation performance between the electric chillers and the absorption chillers.

Chiller	Site COP	Source-to-Site Factor	Resource COP
Electric	2.0-6.1	0.27	0.54-1.65
Absorption	0.65-1.2	0.91	0.59-1.1

Table 7 COP Comparison [72]

2.5.3 Benefits and limitations of absorption chiller

For the gas cooling system, one of the obvious benefits is reduction in operation cost by operation at certain period. It has a primary energy benefits which is saving peak electric demand charges. Instead of high cost of electric cooling, use of gas absorption chillers is a economic choice [115]. Between applying the electric chillers and applying absorption chillers, flexible operation of gas cooling system is the key to save the primary energy sources. Applying the absorption chiller to an energy system make this hybrid system maximize the benefits and has high flexibility. The natural gas cooling systems have higher resource efficiency than similar electric systems [55]. For a normal electricity generation and distribution system, the normal efficiency is 25% -35% in the initial energy resource of the fuel. On the contrary, the gas system only has 5% to 10% of fuel resource lost in the same case [116]. On the other hand, the utilizing of the waste heat is a key factor to increase the cost-effectiveness of the system. Besides the primary energy benefits, the gas cooling technologies also have some relevant benefits such us quite, vibration-free operation, lower pressure system with no large rotating component, low cost on maintenance and high reliability. With higher energy consumption efficiencies, the absorption cooling technologies contributes to reducing the emissions and improving the environment sustainability. The direct-fired absorption system can also supply hot water when an auxiliary heat exchanger is equipped in the system. Using certain control devices, the auxiliary heat exchange could manage the hot water circuit using the chilled water.

However, the thermal efficiency of the single-effect absorption system is low which has negative effect on the system's operation during recovering the waste heat resources [117]. The double effect system is also not effective in many applications. The operation patterns make the absorption chillers only have high efficiency at certain scenarios [118]. For high economic efficiency, the application of the absorption chiller must be applied in the right situation. Compared to the electric chillers, the absorption systems have higher demand on the pump energy. The size of condenser water has relations to the flow rate per unit's cooling capacity. Lower COPs cooling technologies requires a significant higher condenser water flow rate. Therefore, the absorption chillers need larger cooling water than electric chillers because of the volume of water used in the system.

2.5.4 Adsorption cooling

Similar with the absorption systems, the adsorption cooling technology is also thermally driven. The adsorption refrigeration is processed in a thermal compressor and a sorbent instead of in the conventional mechanical compressor of the common vapour compression cycle. In the adsorption refrigeration system, there are an inherently cyclical process and a number of adsorbent bed to offer continuous capacity for the refrigeration process [119]. During the adsorption process, large heat transfer surface is necessary which leads to a cost issue. In the adsorption cooling systems, to obtain high efficiency, the recovered heat is used to provide energy to regenerate the adsorbent, which means in the system, the regenerative cycles have multiple of two-bed heat exchangers and the heat transferring loops in the system[120]. With appropriate control and the usage of the waste heat, larger amount of heat is utilized in the heat exchanger cycle between adsorbing and desorbing refrigerant. Currently the adsorption systems are not fully commercially available for a wide range of applications. As a novel, environmentally friend chiller technology, the adsorption chiller are capable using low-grade heat sources [121]. In a basic adsorption cooling cycle, there are four phases, which are shown in the schematic figure 5. 1-2 is a heating-pressurization process. In this process, the adsorber is isolated from the evaporator and the condenser. The internal pressure of the adsorber rises to the condensation press supported by an external heat source. 2-3 shows an isobaric condensation process. In this process, the adsorber is transmitted into the condenser by the refrigerant vapour. There is also a simultaneous heat process combined with the condensation process make the system's operation to be isobaric. 3-4 is a cooling-depressurization process. In this period, the adsorber is connected with either the evaporator or the condenser. The temperature of the adosrber decreased back and the pressure also becomes to a lower level. In the last process, the adsorber is transmitted to the evaporator and isolated from the condenser. The evaporator heats the low-press liquid using the latent heat. The adsorbent in the adsorber is reactivated in the process [122].

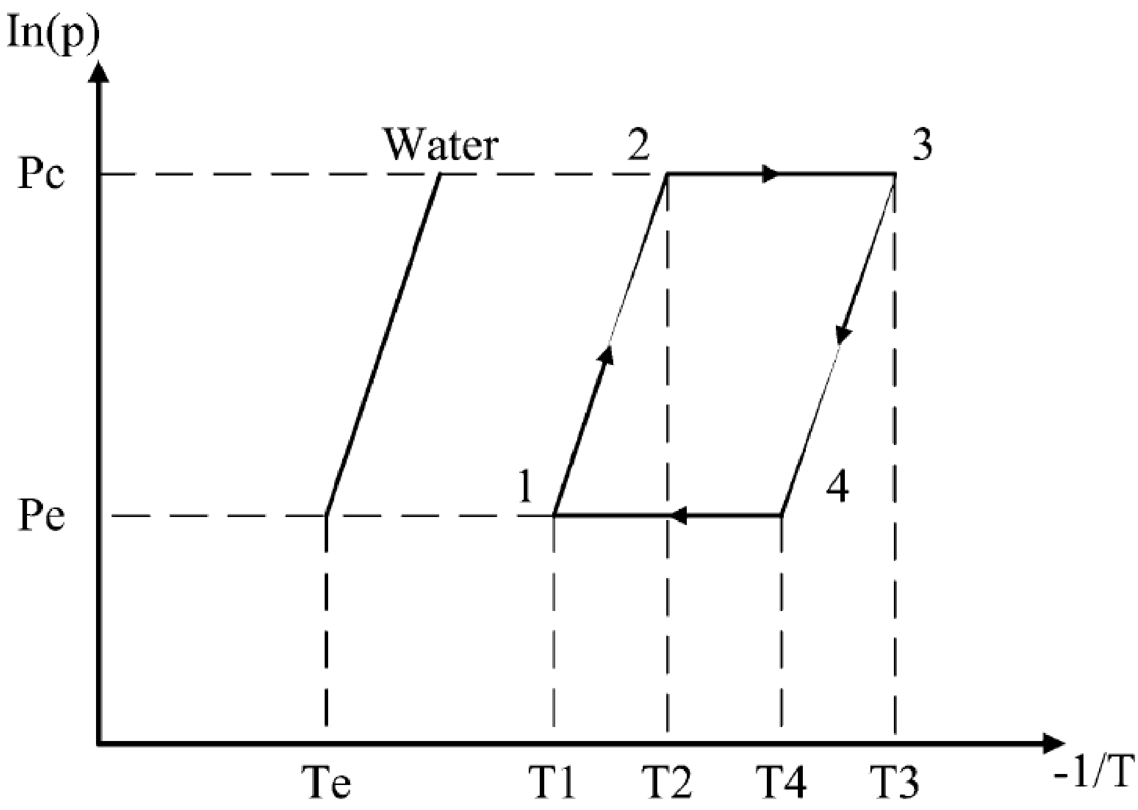

Figure 5 Standard Clapeyron's Inp-1/T diagram of basic cycle [123]

There are few applications which combines CHP, trigeneration systems with the adsorption chillers. One research expresses a 10 MW biomass-fuelled CHP plant which applies the adsorption chiller. In the research, a pre-combustion adsorptive capture process and conventional post-combustion amine process are compared and analyzed [124]. The adsorptive carbon dioxide process boots the carbon capture rate up to 59%. The research indicates the adsorption technology could make the CHP system become more environmentally friendly.

2.5.5 Discussion about cooling load of the UK

The cooling load in the UK especially for the domestic use is not high in common sense. However, following the Japanese Cool Biz campaign which advocated relaxed dress codes and indoor set-points of 28 degrees, the other counties claimed similar policies. The temperature level for office using in UK is suggested to set as 22±2 degrees by the British

Council [125]. At the same time, the temperature measured hourly in a summer day in London indicates kept above 30 degrees for over 10 hours [126]. These two findings indicates a developing living standard of modern society requires higher cooling energy demand currently. In the foreseeable future, this part of energy demand may increase continuously.

In the recent researches, trigeneration systems are proposed for office using or for domestic using [127] [128]. Whenever the energy generation is involved, the cooling demand is always companied. In Ameri's research, 137 buildings' energy demand is estimated and summarised. The results shows there is a high cooling demand at the summer in Shahid Beheshti Town [128]. Korilijia's article also presented that there is cooling demand from the UK office when the cooling temperature was set as 24 degrees [129]. For a single household, there is a basic demand for refrigeration. This function is possible to be realized by applying the recovery heat from the waste heat.

From the discussion about cooling demand, the integration of the cooling generation is necessary. The design is an attempt on a new structure of energy system. Although the energy system in this research focus on energy supply for small-scale load, this design's size is not limited. The design could be applied with other size or other application such us office using or commercial energy supplying. When the initial design lack a certain function, it will cost a much higher payment to compensate the lost function. Because of this, the cooling energy supplying is integrated and it could be more practical when this design is further applied in different scenarios other than domestic using.

2.6 ORC systems applied in trigeneration systems

In this section, the research background of the ORC system, the working fluid and the integration with trigeneration systems are studied and discussed. Researches about Potential applications for the ORC system and the direction of integrated system combined with ORC systems and trigeneration systems are also investigated in this part.

For the recent years, the ORC has drawn increasing interest in the renewable energy's researching. The ORC can be driven by relative low-temperature heat sources such as recovered thermal energy from liquid coolant and geothermal source. This feature makes the ORC to be extremely useful for the waste heat. The ORC is different from the steam power cycle. The hydrocarbons, solvents and refrigerators could all be applied with the ORC [130].

Since the operation of ORC allows the using of the low temperature heat source, working fluid in the heat exchanger absorbs the thermal energy from the waste liquid or gas, and this part of energy is transferred by ORC to electricity. Combining the ORC with the trigeneration system is a new topic for research. In the traditional trigeneration systems, the waste heat is recovered by the heat recovery system. Since part of low temperature heat is available as ORC system's heat source, the combination of ORC system and trigeneration system draw the interests of many researchers [131].

2.6.1 ORC working fluid selection

In theory, the Rankine cycle is less efficient than the idealized Carnot cycle. For practical application, Rankine cycle is still adaptable since that it has the advantages of using organic fluids at lower temperatures and avoid superheating. The selection of the ORC system's working fluid is a key subject in the application of the ORC system. A number of former researches have discussed this topic. Most of the former researchers focus on the optimization of the ORC's operation efficiency. However, the chosen of the working fluid must be referring to the characteristics of the certain application. The selected working fluid must have a proper thermodynamic property for accessing high efficiency and a suitable working temperature for the applications of the ORC system. As the figure 6 shown, in the certain range of heat sources, the optimal working fluid selection has multiple options, which depends on the characteristics of the working fluids [132]. For the ORC system's operation, the working fluid has significant influence on the system performance, the size and initial cost of the system. Based on these reasons, the selection of the working fluid has impact on the design of the ORC plant.

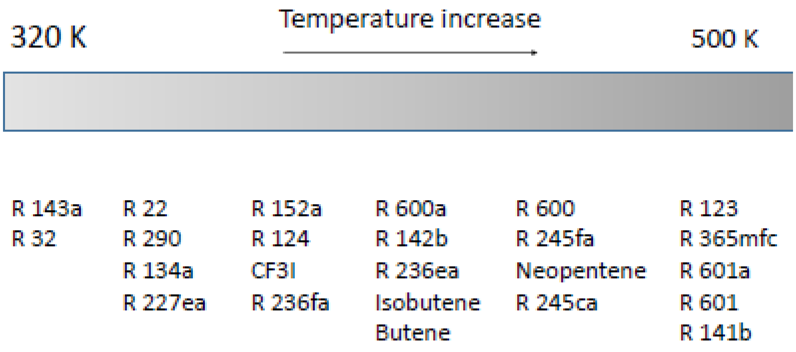

Figure 6 **The chart of optimal working fluid section based on the heat source temperature [133]**

The discussion of the selection of working fluid can be divided by two parts. Firstly, some common methodologies validated by ORC system experts to solve the question of working fluid section are displayed. Subsequently, the influence of the working fluid thermal physical parameters related to the ORC system' design is analysed.

There are a numbers of working fluids referring to the best option for an ORC system. The backup options differ each other from their chemical properties. These working fluids can be divided by different groups. The first categorization is based on the chemical composition. The Organic compounds can be defined as alkanes, ethers, fluorinated, aromatics, fluorinated, linear siloxanes, PFCs, HFOs, HFCs, etc. other category is based on the fluid's properties of saturated vapour curve[134]. In this category, the compounds are divided as wet, isentropic and dry. They represent a negative slope (wet fluids), an infinite slope (isentropic fluids) and a positive slope (dry fluids) of the saturated vapour curve. According to the former studies, the isentropic and dry working fluids are more suitable for the ORC applications. Different from the wet fluids, the isentropic and dry fluids remain the vapour phase after the expansion process, which avoids the erosion of the blades. Additionally, the de-superheating level is also minimised by these two types of fluids, which leads to a reduced overall heat transfer surface. A reduction of the over heat transfer surface saves the cost of the system. The using of extremely dry working fluids was also addressed as the regenerated cycle improves the system's performance. Although at the same time, the system's size and cost could be increased, the trade-off option is still attractive and affects the selection of the working fluids strongly. The global warming potential and Ozone Depletion Potential also limits the selection of the working fluids as a consideration of the surrounding environment protection. A system is also developed to evaluate the equivalent heal, flammability and the reactivity for the chemical compounds used in the industry. A number of handbooks are published to offer the guidance of selection of suitable working fluids with minimum environmental effects[135, 136].

Before the choosing of the working fluid, meeting the requirements regulated by the government should be concerned firstly. After that, the thermo-physical properties should be considered to fit the operation of the target application. Several factors such as the deterioration temperature, the freezing point and the autoignition temperature are always check to fit the thermodynamic conditions of the energy source. Among the thermo-physical properties, the deterioration temperature takes a key part of the evaluation of the reliability of the ORC plant. The deterioration markets the ORC have to change the working fluid. There is research pointing out the long life span fluids can reduce a large amount of system cost. During the operation of the ORC plants, the thermodynamic analysis detects the performance of a working fluid [137].

One factor must be considered. Because of increasing concern about global warming, the HFC-134a (R134a) is replacing by R1234yf for avoiding the former fluid's high global warming potential (GWP). HFE 70000 is also an option as a replacement of R123 for minimizing the depletion to the ozone layer. R123 will be forbidden at the latest of 2030 depending on national legislations[138]. There is results showing that the n-butane, R245fa, R123 has the highest efficient performance in the thermodynamic optimization process in former researcher's tests. Among the isentropic fluids, the R245fa is a reasonable choice for this system [139]. Therefor R245fa is selected as working fluid in the ORC system.

2.6.2 The ORC system integration applications

Researchers' interest in ORC technology have been increasing with a remarkable rate especially in the recent 10 years[140]. A number of literature have been found describing CHP or CCHP systems integrated with ORC system. Trigeneration systems utilises the waste heat for heating and/or cooling. However, the user demands are always changeable in different scenarios. Part of low temperature heat is always wasted in a trigeneration system's operation. There is economic analyses showing that medium scale ORC technologies is suitable to be integrated with CHP and trigeneration systems [141]. In this section, the combination of ORC system and trigeneration system is studied. Through the previous experience from other research, the structure is evaluated by their results.

A trigeneration system based on a micro-gas turbine (MGT), ORC and ejector cooling system is presented by Ebrahimi, et al [142]. A function named integrated energy- exergy (IEE) was applied in the system's operation, which was optimised by genetic algorithm. The final results show a 37% and 24% saving in summer and winter after a working cycle [142]. Fang [143] stated that the proper ratio of electricity to the thermal energy output was the key to optimise the system's performance. Setting the energy output ratio as an important factor, a trigeneration-ORC system is developed to supply energy for a hotel in Beijing. The results showed the operation cost was much lower than conventional trigeneration system[143]. An optimum design of a trigeneration generation with ORC is presented by Mago to access the optimum prime mover [144]. The system used the Real Parameter Genetic Algorithm (RPGA) to adjust the energy generation ratio to supply different load demand. Another solar combined trigeneration system integrated with ORC for winter and summer season's system was studied by Boyaghchi [145]. The efficiency and operation cost were the main aims of that study. After optimisation process of a genetic algorithm, both single and multi-objective optimisation improved the system's efficiency[146].

An analysis and optimising the use of CHP-ORC system for small commercial buildings was done by Farrokhi in 2010 [147]. Research about the reducing primary energy consumption, cost and carbon dioxide emissions is presented. The load of that research was a small commercial building. In the research, the controlling method was following the electric load. The recovered exhaust heat was more than the demand which lead the ORC to generate extra electricity. Liu [148] presented experimental investigations of natural gas-fired ORC based micro-CHP system for residential buildings. The residential building was highly related to the project of this research. Experimental investigation of a natural gas-fired micro-CHP system for a residential building based on an organic Rankine cycle was done. Isopentane was the working fluid and the performance of for different heat source is evaluated. Primary tests were done in the research, the research is limited to the efficiency measures in the experimental work, and the ORC has not been applied to the study of enhancing the energy supply with a residential load. A comparative analysis between Solar-ORC and ORC-based

Solar-CCHP is presented by Ying et al. the research managed to obtain an optimal configuration parameters to access a maximum thermal performance of the two structure of the system. [149]

Although lots of studies have addressed on the performance of the ORC system with different working fluids under various operation conditions and a lot of successful example of CHP system integrated with ORC systems, there are still not research focusing on the small scale of trigeneration system integrated with ORC system. The aim of this research is to investigate the integrated system's performance. The investigation on the integrated system helps the future researches to have comprehensive understanding of the structure of ORC system combined with trigeneration system and energy storage.

2.7 Energy storage units

In this section, the energy storage technology related to the CHP and trigeneration energy systems discussed and summarised. Several of energy storage technologies, which are currently applied or possible for further deployment, are involved in this section. The review mainly focus on the electric storage. A comprehensive evaluation on the energy storage technologies is implemented combined with existing power system and energy sources. Review of the current technology and the present research on related area is a significant preparation for the project. The technical literature will be reviewed in this section based on the information collected. The technologies will be introduced in the examples will be analysed. From the background of the present research, suitable technology for this project will be selected.

2.7.1 Batteries

In the electric energy storage parts, several batteries are discussed and compared. The most suitable solution for energy's storing should be selected and applied in this projected. Batteries are an admitted appropriate energy storage solution for many scenarios. For the electric energy storage approaches, the options includes mature technology and newly developed devices. Detail information express the theory and advantages related to the energy system developing.

2.7.1.1 Batteries

In the current energy systems, the batteries are integrand with a variable renewable energy source or a distributed power source. The operation period for batteries is flexible which last from a few hours to days. Higher capacity of batteries indicates larger capacity and more maintenance charge. Generally, the batteries are limited by its quantitative capacity, high initial cost, high maintenance demand and irreversible lifetime [150]. During the CHP and trigeneration energy systems, the large amount of energy demand increase the capacity of batteries. Normally large capacity of traditional batteries have low movability. The recovery processing of the batteries is also a complicated procedure which requires cost to remove the toxic material when the batteries' life ends.

2.7.1.2 Lead acid batteries

For all the current batteries technologies, the lead-acid batteries are the most mature and widely applied batteries. The usual application of this batteries are uninterruptable power engines, automobiles or renewable energy systems (such as wind turbine, tide turbine, photovoltaic systems). Among the various of applications, the lead-acid batteries are suitable for the distributed energy systems [151]. The lead-acid batteries have the ability to offer high surge current. As a fully developed batteries, the cost of lead-acid batteries are also lower compared to other type of batteries. And that they are inexpensive and widely available compared to other types of batteries. However, the life-span of the lead-acid batteries is limited by its operation mechanism. High frequency of mechanical reaction make the energy wastage inside the batteries to increase as during the batteries' service. The operation of the lead-acid batteries also needs stable outside environment. The temperature has an influence on the batteries' operation. After the lead-acid batteries' lifespan, the recycle process is also difficult because of its high weight. Low movability is another disadvantage of the lead-acid batteries.

The lead-acid batteries also have flexible sizes. For the large-scale power application, they have two categories which are valve regulated lead acid (VRLA) and flooded batteries [152]. These two type of batteries differ from whether it can spill. Currently, the flooded type of lead acid batteries is a widely applied and mature technology. Applying this technology into energy system requires a frequent monitoring on the devices. The VRLA cells are lighter than the flood lead-acid batteries. Compared to previous type of lead-acid batteries, VRLA batteries has lower maintenance cost [153]. The short lifespan is its disadvantage which make the energy system needs to exchange the batteries more frequently.

2.7.1.3 Flow batteries

In the flow batteries, the energy is stored as a format of liquids. When the batteries are operating, pumps are necessary for pushing the liquid electrolyte to move across the membrane for electric current generation. The operation mechanism is similar with the fuel cells. The power rate of the flow batteries is flexible. Adjusting the surface area of the membrane can change the electrolyte flow rate [154]. The energy capacity of the flow batteries is directly related to the size of the liquid electrolyte storage tanks. Theoretically, the flow batteries have the ability to supply energy for a number of hour which make this equipment is suitable for seasonal storage systems. The disadvantage of this batteries is the discharging rate. Compared to the capacitors, lead acid batteries or flywheels, the flow batteries' rate of discharging is slower.

There are two main types of flow batteries which are Vanadium Redox Battery (VRB) and Zinc Bromide Battery (ZBB) The VRB battery store the electric energy as the a format of chemical energy in the ionic forms of vanadium[155]. In the practical application of the VRB batteries, the efficiency was measured as high as 70% in in an energy test [156]. During the operation of the VRB batteries, chemical failure may occur which cost more maintenance fee. Besides the maintenance problem, the toxic electrolyte liquid also danger the environment round the battery set which needs specific solution to control the risk of hazardous spilling. The application of the ZBB batteries needs temperature control.

2.7.1.4 Nickel Cadmium Batteries

The Nickel Cadmium batteries have similar operation theory with the lead-acid batteries as chemical batteries. Compare to the lead-acid batteries, NiCad batteries have discharge ability. Larger energy density and lighter weigh make the Nicad batteries to have advantages compared to the lead-acid batteries. In the low temperature operation environment, the Nicad batteries have a decent performance [157]. The disadvantage of the Nicad batteries is the cost. The technology of the Nicad batteries is very mature which has been applied to lots of energy systems.

2.7.1.5 Sodium sulphur batteries

The NaS batters operates in the high temperature (as high as 300℃) operation energy systems. In the NaS batteries, both sulphur and molten salt are the electrodes. These batteries are deeply developed and widely applied in Japan. Over 200 utility-scale NaS systems are in service there. For the NaS batteries system, the power is up to 245 MWh energy capacity and as high as 34 MW power capacity currently [158].

2.7.1.6 Lithium-ion batteries

The Lithium-ion batteries is also a deeply developed technology currently. This kind of batteries has a wide application range. From electric vehicles to mobile phones and personal computers, the Li-ion batteries are mostly applied in the electric appliance because of its high power density and efficiency. Compared to other types of batteries, the initial cost is also higher. The application on the electric vehicles attracts lots of researchers’’ attention. For the domestic load, this batteries is not suitable for its high cost [159].

	Lead acid batteries	Flow batteries	Nicke Cadmuim batteries
Overall efficiency	From 70% to 75%	From 60% to 85%	From 75% to 85%
Discharge time	From a few seconds to several hours	From a few minutes to several hours	From a few minutes to several hours
Lifetime	300-2000 cycles (75% depth of discharge)	1800-5500 cycles (75% depth of discharge)	1000-5000 cycles (75% depth of discharge)
Energy density	30-50 Wh/kg	15-30 Wh/kg	35-75 Wh/kg

Table 8 Batteries Comparison table [151-157]

2.7.1.7 Battery storage technology summary

Types	Advantages	Drawbacks
Lead-acid batteries [140]	Mature technology;	Low cycle life and operational lifetime
	High energy efficiency; (85%-90%)	Be affected by depth of discharge and temperature
	Low level of maintenance and investment cost;	
	Very low self-discharge rates(2% per month)	
Nickel-based batteries [141]	Superior operational life and cycle life(1500-3000)	10 times than lead-acid
	Higher energy densities than lead-acid one(50Wh/kg – 80Wh/kg)	Lower energy efficiency
		Inferior self-discharge rate(10% per month)
Lithium-based batteries (lithium-ion &lithium-polymer) [142]	Higher energy density(100Wh/kg – 150 Wh/kg)	High cost
	Energy efficiency (90%-100%)	
	Lower self-discharge rate(maximum 5% per month)	
	Extremely low maintenance	
	High power density(500W/kg-2000W/kg)	
Sodium sulphur (NaS) battery [143]	High power density	Highly operating temperature/ highly corrosive nature of sodium
	High energy efficiency (89-92%)	

Table 9 Batteries information

According to the reviews, the batteries technology is a widely used energy storage device associated with electrochemical reactions to store electricity. During the listed technologies, common devices include lead acid batteries [160], nickel cadmium batteries, sodium sulphur (NaS) [161], sodium nickel chloride, and lithium ion batteries. Operation of some batteries can be controlled.

However, usually used battery storage devices are lead-acid and nickel cadmium batteries. Devices with superior power capability are more suitable for application where requires high power quality and peak shavings for example sodium sulphur battery. Sodium nickel chloride battery is a new type of battery. It has been applied into hybrid electric vehicle. In most cases, it is used to store renewable energy and levelling load in industry. Lithium ion battery has extreme high efficiency and relatively high cycle life [162]. Although the cost of lithium ion battery is relatively high, it is widely employed in portable electrical and electronic devices. Information about rechargeable batteries are collected in the form

2.7.2 Supercapacitors (electrochemical capacitors)

Super-capacitor is also names ultra-capacitor. Using special electrodes and electrolyte makes the modern super-capacitor crosses the boundary into battery. It is charged by applied the voltage differential on the positive and negative plates. The super-capacitor has the advantages of short charge time, long cycle life and high power capacity. The power density can up to 10kW/kg [163]. But the energy density of super-capacitor is low normally 2-5Wh/kg. Because of that, the mainly adopted area is power quality application such as ride-through, bridging, and energy recovery in mass transit system. More than 90% efficiency of energy transferring make super-capacitor has great penitential to replace traditional batteries in the future.

As mentioned in this chapter, trigeneration system usually does not contain an energy storage unit. For a stand-alone trigeneration system in this project, the energy storage unit is important for the system's stability and capacity. For distribution system, energy unit is combined with system in many occasions. Based on some related researches on system with energy storage, performance of the energy storage will be tested and alternative options for energy storage unit will be researched and discussed [164].

2.8 Control system

As an advanced, high efficiency and clean provision of energy, trigeneration systems demonstrate vast potential for energy savings and emission reduction. In the trigeneration's operation design, certain issues should be taken into account, such us system operation strategy, individual units sizing, efficiency, system configuration and load profile. Among all the factors, the operation strategy is the critical factor related to the trigeneration's performance [73].

Energy management method developing is one of the major objectives of the research. The operation strategy is the key part for the system to seek the highest efficiency. Depending on different requirement, the controlling strategy varies a lot during the controlling progress on the trigeneration system. Commonly, the controlling strategy for the trigeneration system have 3 goals to achieve, which are reducing the system primary energy consumption, reducing the operation cost and cutting the carbon dioxide [165].

The most popular two investigated controlling strategies are: following the thermal load (FTL) and following the electric load (FEL) [60]. The two strategies can be described as the thermal demand management (TDM) and the electric demand management (EDM) [166]. The FTL is to fulfil the thermal loads first, and the additional energy is supplied from other energy resources if the trigeneration yield is not sufficient to meet the electric load. Similar to FTL, the FEL operation strategy will satisfy the electric load first, and the heat energy demand are considered secondly. Normally the heat is provided by an auxiliary conventional boiler [167].

Choosing control strategy for the system depends on the profile of loads. From the study of domestic energy demand in the UK, the FEL controlling strategy is suitable for the trigeneration of this project. The comparison of electric demand and heating demand is shown in the Figure 7-9. The study of domestic energy demand indicates the electric demand keeps at certain range for the whole year. But the electricity consumption varies markedly according to people's activity. By the contrary, the heating demand has seasonal varying and keeps relatively constant during a day. Based on this situation, the controlling strategy takes FEL in this project.

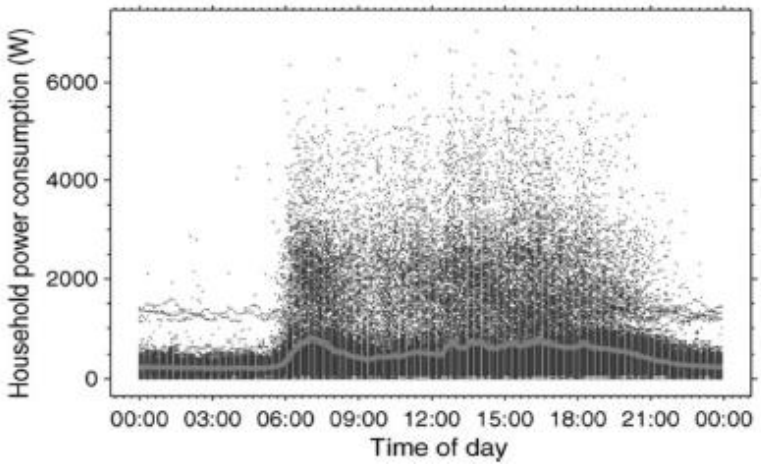

Figure 7 Domestic electric energy demand for 24 hours[120]

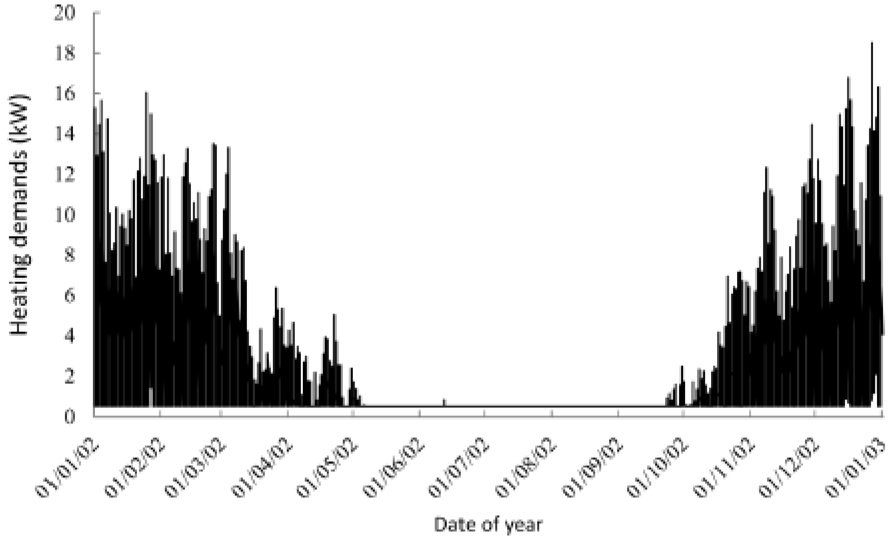

Figure 8 Yearly Heat consumption profile in a UK household[121]

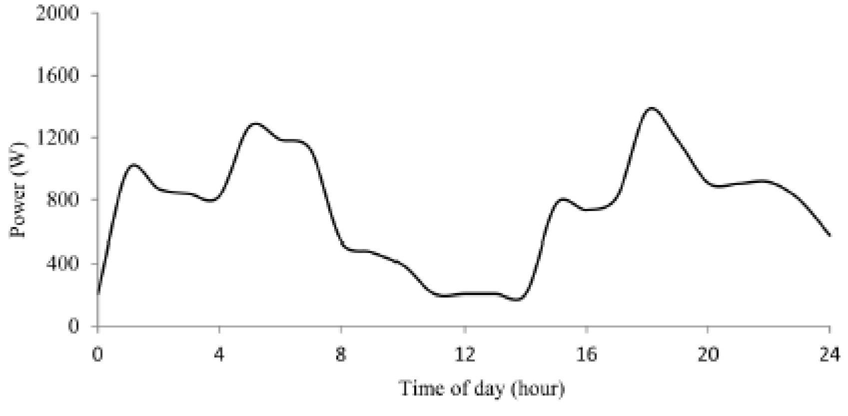

Figure 9 Daily heat consumption profile in a UK household[121]

In the former researcher's experimental work, the controlling strategy decides the system's operation to several time periods. The controlling method was trying to charging the system to meet the peak energy demand. The domestic load was supplied with sufficient energy under the controlling [168]. A CHP model was established by Amir Nosrat and Joshua M. Pearce, they combined PV array with the trigeneration system for residential-scale energy supplying [169]. This hybrid system was designed to follow electricity load first. The control strategy combines the state of charge of the energy storage units with the profile of loads. The results indicate the system had 50% improvement on efficiency compared to traditional energy generation set [170].

Various optimisation algorithms associated with different trigeneration models have been proposed by former researchers. Those algorithms are designed for seeking higher efficiency for the system's performance. The Table 10 shows different algorithms and their objectives.

Algorithm	Optimisation objective
Genetic algorithm [171]	Minimizing operational costs or emission
Multi-objective evolutionary algorithm [33,34,35] [172]	Energetics efficiency, total liveliest cost rate of the system product, the cost rate of environmental impact
Decomposition technology [173]	Cost-efficient operation
Lagrangian relaxation [174]	Minimizing annual costs
Optimal energy dispatch algorithm [175]	Minimizing operational costs, PEC, or CDE
The particle swarm optimisation algorithm [176]	Minimizing costs
Fuzzy multi-criteria decision-making [[177]	Energy saving potential, carbon dioxide emission reduction and annual total cost savings

Table 10 Algorithms summary

Since it was reported that both FTL and FEL operation strategies lead to a considerable energy waste. Adopting only one controlling strategy (FTL or FEL) is not enough for seeking the highest efficiency. There are plenty of researches investigating and developing optimized operation strategies for trigeneration systems to enhances energy saving and reduce operation costs and emissions. Nevertheless, controlling strategy for system with an energy storage will be different. The controlling system must meet the demand as the same time consider the efficiency and capacity of the energy storage [178]. Only with appropriate using of energy storage unit, the higher efficiency can be reached. This project develops a control system for integrated system to reach the maximum efficiency.

2.9 Chapter summary

The above review shows a detailed literature review about the related knowledge of this research. This chapter contains the recent development of the trigeneration systems, the basic technologies and updated technologies of trigeneration system, trigeneration systems' integration with other components, the energy storage units for the trigeneration systems and the control strategies. Nowadays, the trigeneration system are widely applied for high efficiency energy supplying. However, how to optimise the system's efficiency is a core problem for such a promising system. When the system's application refers to small scale loads, tor all the prime movers, the diesel engine as a stable primary mover is selected to supply most of the energy in the project. The previous review suggests this single energy source is not enough for dynamic energy demand. For fulfilling all the energy demand which includes electricity, heat and cooling， some energy storage units especially for electricity storing must be integrated in the system. During all the energy storage technologies, hybrid energy storage system consists of the lead-acid batteries and supercapacitors can make up the gap between the diesel engine's power and the energy demand of the dynamic load. From the plenty of researches focusing on the development of the trigeneration systems, the evaluating approaches of the trigeneration systems under different conditions are fully developed. Additionally, investigation on complex integrated system is still required. Among the reviewed systems in the recent years, there is no system integrating a trigeneration with a hybrid energy storage system and an ORC system.

This kind of integrated system designed for small scale loads has been developed for years. Similar structures have been posted such us CCHP-ORC, solar based CCHP-ORC or CCHP system based on fuel cells. However, an integrated system combined trigeneration system, ORC system and energy storage system has never been addressed and fully evaluated. How does this new system work? What is the efficiency? What kind of control strategy is suitable for this integrated system? These problems needs to be solved during developing this new structure of system.

Therefore, it is necessary to carry out an investigation into the configuration of the system and the evaluation on the integrated system. In the next chapters, the details of this study are described, e.g. experimental tests and computational simulation evaluating and analysing the system's performance for different scenarios.

3. Methodology

The methods used in this study are summarised in this chapter. It consists of three parts: a) analysis of the patterns of the domestic energy consumption, b) experimental tests and c) computational modelling and optimisation. The selected domestic application is one of the main load target for the designed system. The background research on the domestic energy consumption are displayed as case study in the first part of this chapter. The research approaches on the integrated system are experimental tests and the computational modelling which are introduced in details in the following sections.

3.1 System design

The overall system structure is shown in Figure 10. The main components which are a trigeneration system, an ORC system and an energy storage system have been mentioned in the last chapter. For investigating a complex structure of an integrated system, the system's design is important. For satisfying the various energy demand, all the components in the system must be balanced from the angle of the design. The objective of the project is designing this new structure of system to apply energy for small scale loads. During the energy supplying process, system's performance evaluation, efficiency optimisation of the system are the main objectives in the research. Prime mover of the system is diesel engine. The energy source is the chemical energy in the fuel. This integrated system is responsible for transferring the stored chemical energy in the fuel to three energy products. The generated electricity, heat and cooling are used to supply the load. Each energy product belongs to a part in the system. The system design must consider every aspect in the system for a balance operation. In the system design part, each components' engagements in the system's operation are introduced from the primary energy's consuming to the system's terminal.

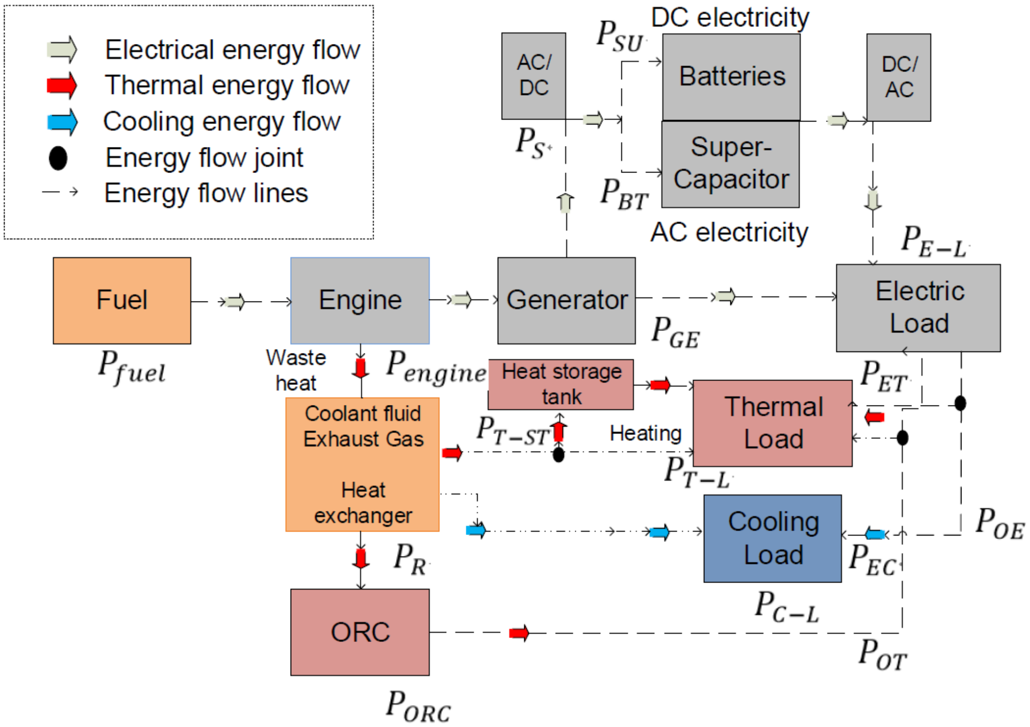

Figure 10 System design

3.1.1 Electrical part of the system

Electricity from generator and energy storage are the main electricity output. The electricity generated from the ORC is auxiliary output in the electrical part of the system. At the same time, waste heat generated by the engine is transported to the heat part. The electricity generation of the system is given the highest priority in the system design because of the frequent changing electricity demand in small scale load. The electricity generated from the generation and stored in the smart electricity storage could also be a support for the heating part. The main components for the heating part are the ORC and the thermal energy storage equipment. Most of the heating demand is satisfied by the waste heat generated by the engine. Waste heat generated from the burning of the fuel is transported to the high-temperature phase change material thermal energy storage.

3.1.2 Thermal and cooling part of the system

The heat demand is designed to be supplied with recovered waste heat. The waste heat is the energy source of recovery system which supports the heat and cooling energy generation. Part of the low temperature heat is transported to the ORC system. An electric heater is integrated as auxiliary heating source to increase the system's flexibility. The adsorption refrigerator produce the cooling energy. Cooling part's operation is considered after the other two energy parts. From energy injected in the system to the energy output, the key points for the research are the variables in the system. Several important variables have influence on the efficiency of the system. The energy output, electrical energy stored, the electrical demand, the thermal energy demand and the thermal energy source could all both interactive and variable. One important factor of the system is the ORC's performance. The efficiency of ORC has an influence on the balance of the system. The performance of ORC should be included in the controlling strategy for this system.

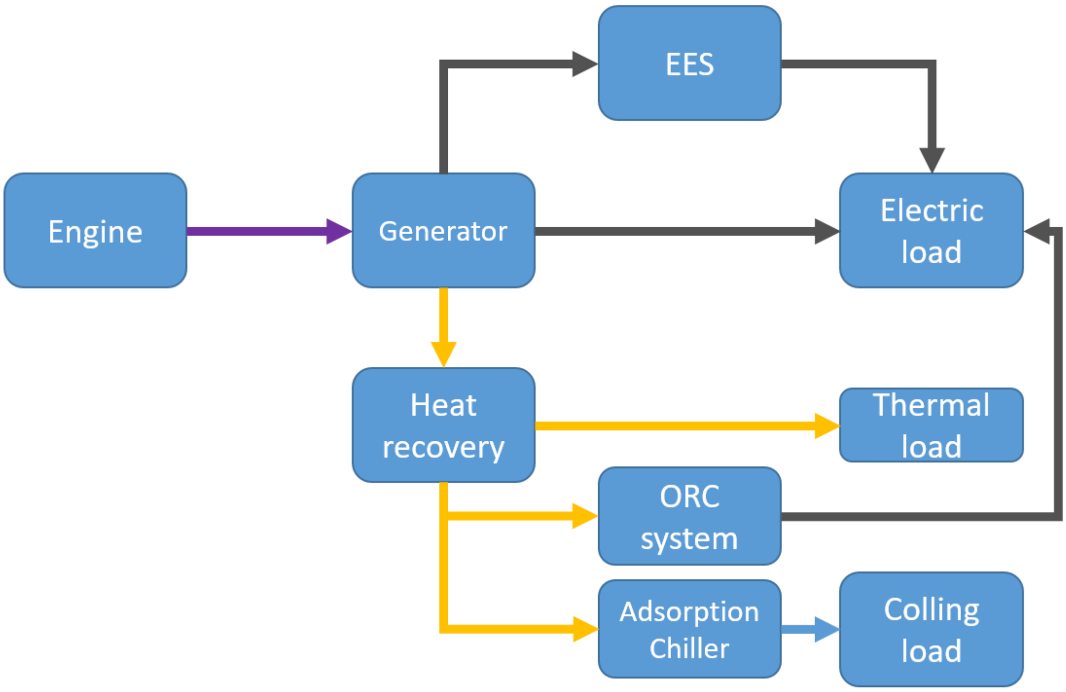

Figure 11 energy distribution of the system

3.1.3 Energy flow of the system

The energy flow of the system is displayed in the Figure 11. As section 2.8 discussed, the control strategy of this integrated system apples FEL. Supplying the electrical energy demand has the highest priority. Therefore the energy is transferred by the engine to generate electricity for the load. The allocation of electricity's storing and consumption depends on the power demand of the load. When the engine is operating, the waste heat is used to drive the thermal part and cooling part. The thermal load is satisfied by the recovered waste heat. The cooling energy is also supplied by the adsorption chiller which uses the recovered waste heat as energy source. Since the electricity demand has the highest priority, when the electricity demand is not fully supplied, the ORC system use the recovered heat and transfer them to electricity. When the electricity demand is fully supplied, the integrated system supplied thermal energy secondly. The suppling of cooling energy has the lowest priority. When the thermal energy generated is not sufficient for the load, the energy stored in the energy storage system supports the generation of thermal energy.

3.2 Size of the system

The system is designed for small scale load. Among all the small load, domestic load is a big part of energy demand which is involved with electricity demand, heat demand at the same time. For the domestic load in the UK, the cooling demand is relatively low. Because of the cooing part in the system take a low proportion of the total load, the size of the system is selected mainly based on the electricity and heat demand.

3.2.1 Domestic energy consumption

The integrated system is designed as a distributed energy system for small scale load. The state of domestic energy is important for the researching of the trigeneration system for size selection. Policy landscape for housing is changing fast in the recent years. The EU Renewable Energy Directive requires the UK to obtain 15 % of all energy from renewable source by 2020 [179].On the other hand, the 2008 Climate Change Act requires that: A 34% cut in 1990 greenhouse gas emissions by 2020. At least an 80% cut in emissions by 2050

Energy consumption of the household takes 32% of all the energy consumption of the UK and housing is responsible for a quarter of the UK's greenhouse gas emissions. For gaining this goal, the emissions from the homes must be reduced [180]. A twenty-year program named Green Deal is designed to improve the efficiency of energy supply. From the domestic energy consumption, the tendency of the domestic energy demand can be detected and the trigeneration can be designed based on the analysis of the domestic demand [181].Samples of energy using from more than 14000 homes are collected in the Energy Using Fact file [182]. More than 30 years energy use for housing and all sectors are collected for analysing. Data is ranged from 1970s to 2012. Housing energy consumption crept up from 1970 to 2004, and then it fell down 10 % to 2009.

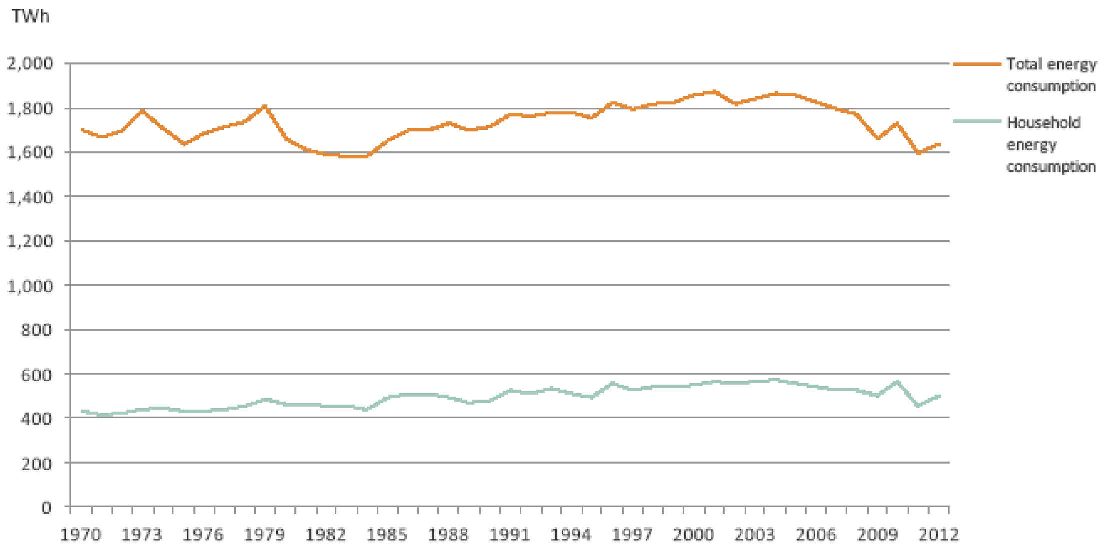

Figure 12 Final Energy Use for Housing and all sectors [131]

The Figure 12 shows the total energy consumption and the household energy consumption. An obvious fluctuation occurred around 2010 to 2012 [183], which is related to the heating demand of winter. The total energy consumption remains at a certain level and has similar shape with the housing energy using. This graph indicates the housing energy consumption keeps in the range of 600 TWh, and for the next decades of years, it has a trend of slight increasing.

Carbon dioxide is a general greenhouse gas came from domestic energy using. As the population increases, higher pressure is generated on the carbon emission. Great effort has been down including changing in heating system, transforming appliances and energy saving technologies. However, the most important factor of carbon dioxide producing is the efficiency of energy using.

The Figure 13 shows the average temperature in UK over the past 40 years. The heating demand is closely related to the outside temperature. The consumed energy is used fill the gap of transferring indoor temperature to a comfortable temperature. Heating is the biggest energy consumption of UK's household energy use [184]. From the Figure 13, the temperature of the UK has kept under 10 degrees especially in winter. It indicates the heating demand is continuous for long period of a year in UK. For the emission cutting, solutions for higher efficiency heating must be presented [8]. The electric using can be divided by several parts such us water heating, appliances and cooking. States of energy using for different area are collected for analysing.

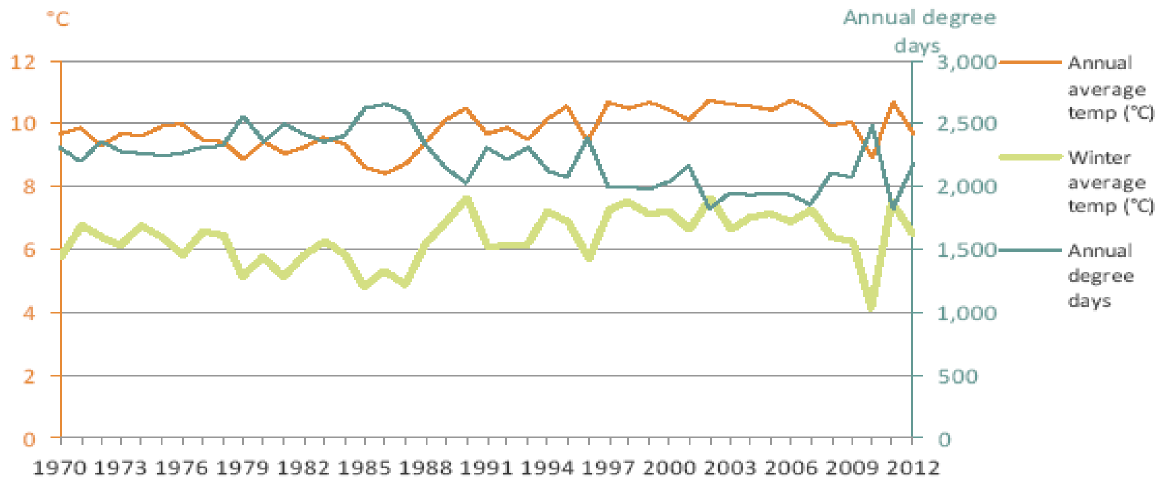

Figure 13 Average UK Air Temperature for over 40 years [132]

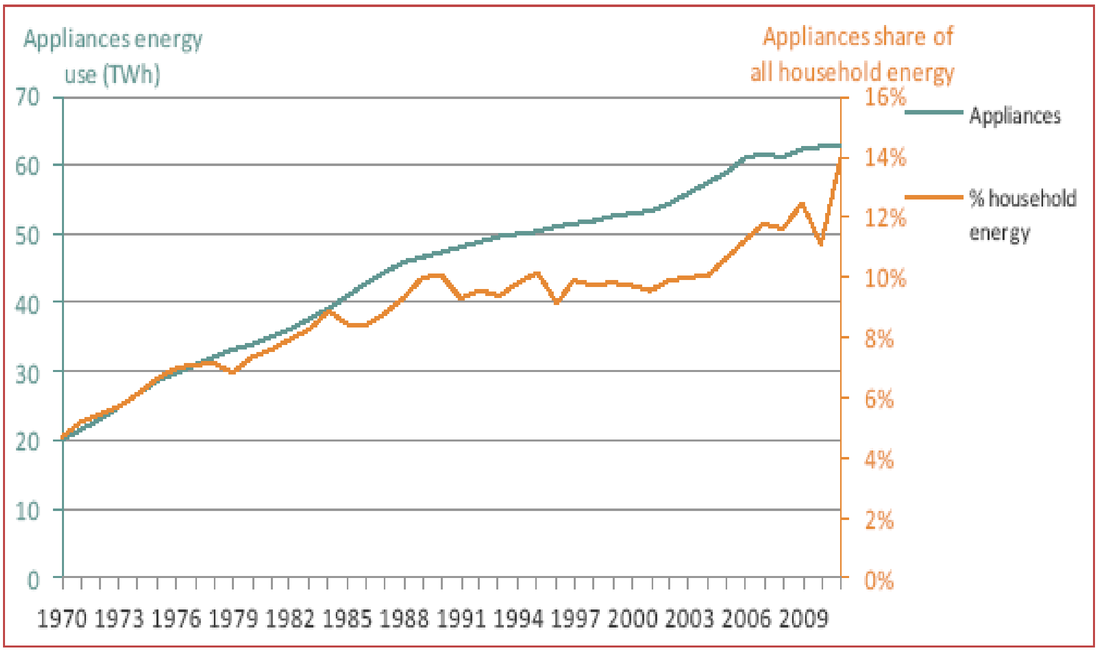

Figure 14 Household Energy use for water heating [131]

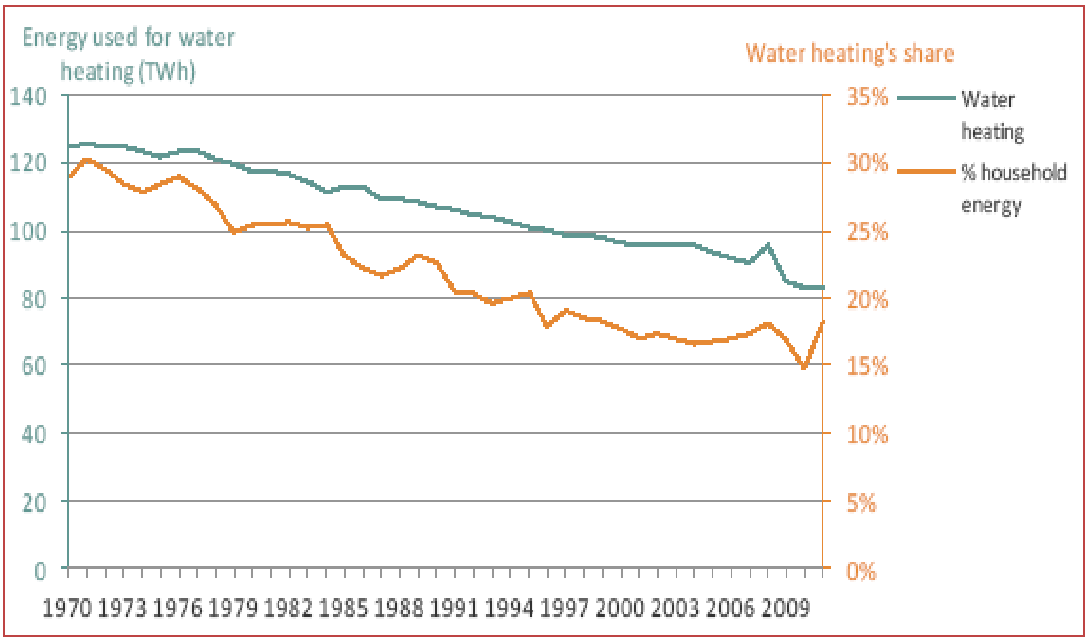

Figure 15 Household Energy use for appliances [131]

The Figure 14 and Figure 15 shows the energy use of appliances and water heating from households. The energy used for the water heating has been dropping from 30% to 18 % in the 40 years. The main reason is loss reduction from the hot water storage. Even with this state of efficient hot water supply, there is still place for more significant saving. Lighting energy is a small proportion of the total household energy demand. Appliances are also a big part of domestic energy use. Energy consumed by the appliance has tripled in 40 years and has a 3 % annual increasing. More electric appliances have come to people's live in the last decade of years such us washing machines, entertainment devices, computers and hairdryers. Energy for cooling has transferred to appliances energy. It took 6% of domestic energy at 1970 but reduced to 3% at 2012. The three figures shows the changing tendency of the household energy consumption. The heating demand and water heating energy demand shows a trend of reducing. At the same time, the appliances consume an increasing amount of energy. From the information shown in Figure13-15, the UK domestic energy using kept a certain level after year of 2000. Because of this, using the data from measurements at year 2009 is still applicable for evaluating a system.

3.2.2 Typical case study

Domestic energy use takes more than a quarter of the UK's total energy consumption. From the domestic energy consumption shown in the last section, a small scale integrated system is suitable to supply energy for domestic load.

3.2.2.1 Domestic energy Data Analysing

Domestic load is one of the most important application for this system. Using from different area has been collected for analysing. More than 10 typical areas are involved in the data sheet. The annual mean household energy consumption annual and the annual electricity consumption are collected in the energy using report from Energy Department of UK government[185]. Other part of data is calculated based on the energy using.

Region Control	Mean household energy consumption (MWh/year)	Electricity consumption as a percentage of total energy consumption (%)	Electricity consumption Per Year MWh/year	Electricity consumption Per Year kWh/day	Electricity Consumption Per Hour kWh/Hour	kWh/h (Peak hours only)
North East	16.9	20.9	3.52	9.65	0.40	1.21
North West	16.8	23.5	3.95	10.83	0.45	1.35
Yorkshire and The Humber	17.0	22.4	3.80	10.42	0.43	1.30
East Midlands	16.5	24.4	4.02	11.02	0.46	1.38
West Midlands	16.5	24.9	4.11	11.26	0.47	1.41
East	15.6	28.1	4.39	12.04	0.50	1.51
London	16.4	24.1	3.94	10.80	0.45	1.35
South East	16.6	26.6	4.41	12.08	0.50	1.51
South West	13.4	32.3	4.32	11.83	0.49	1.48
Wales	14.9	25.8	3.85	10.56	0.44	1.32
England and Wales	16.1	25.4	4.08	11.19	0.47	1.40

Table 11 Data of domestic energy consumption [140]

The Table 11 indicates the demand of energy using by dwellings. From the energy using amount of the whole year and the ratio of electric using, the annual electric energy demand can be calculated as shown. Although the energy demand is sight different during different areas, but the amount is ranged from 13.4MWh to 17 MWh. The electric energy using per day ranges from 9.65kWh to 12.08 kWh which can be transferred to 0.40-0.50kWh per hour (the day consumption number divided by 24 hour). From the Data, the electric energy using for dwellings is not high. For normal human activities, peak energy using time is 8 hours during a day. If the electric energy demand is supposed to be met by trigenerations, 3.35kWh energy is normally needed (3 times of average energy demand). The rated electric output of the prime mover in this project has more than 6.5kWh capacity generation. This power rate can supply fully energy for the loads in the selected cases.

Domestic energy demand study is the basic part of the research. Since the project is to investigating how the trigeneration can meet the demand of the domestic energy consumption. It is necessary for the system's design. The specific controlling system meets the electrical demand at the first place. According to the power consumptions, the controlling system must have the ability to meet the demand with high efficiency. All the operation strategy and the size of the system are based on the investigation of domestic energy consumption.

3.2.3 Size selection of this system

	Model		YTG6.5S
Alternator	Alternator Model		S20FS160A
	Alternator Weight	kg	50
	Insulation Class		H
	Operation Condition		Ambient temperature not exceeding 50 C
			Attitude not exceeding 1000
Engine	YANMAR		TF 120 M
	Type		Horizontal water-cooled, 4-ccyle diesel engine
	Bore x Stroke	mm	92 x 96
	Displacement	liters	0.638
	Cont. output	kW(hp)	7.7 (10.5)
	Rated output	kW(hp)	8.8(12)
	Revolutions	rpm	2400
	Starting system		Hand Start
	Cooling System		Radiator
	Lubricating System		Fully sealed forced lubrication with trochold pump & hydraulic regulator valve
	Combustion System		Direct injection
	Fuel consumption	lit./h	2.8
	Fuel Tank Capacity	liters	11

Table 12 Information of the engine

	Capacity	KVA	6.5
Generator Set		KW	6.5
	Frequency	Hz	available in either 50Hz or 60 Hz
	Revolutions	rpm	3000 for 50 Hz/3600 for 60 Hz
	No. of phase		Single phase
	Power factor		1
	Excitation system		Brushless, self-excitation system
	Drive system		V-belt derive
	Voltage (standard)	V	220
	Recommend cable dia	mm	6-16
	Recommend earth cable		Equal to the conductor size
	Ampere	A	29.5
Dimension			
	Dimension length	mm	1360
	Dimension width	mm	690
	Dimension height	mm	800
	Net weight (dry)	kg	227

Table 13 Information of the generator

The two tables show the specifications of the diesel engine and the generator integrated with the engine. The power rate of the engine is 8.8 kW and the output rate of the generator is 6.5

kW. Except the generated electricity, part of the power from the engine is contained in the gas emissions and coolant water of the engine. The peak power output of the system including electricity, heating and cooling is estimated 13kW at full load. The peak power demand of the loads selected in this study is 10 kW. Both the simulations and experimental tests carried for evaluating the system's performance are controlled in this power range. The maximum power of the energy storage units reaches 12 kW. The lead acid batteries have maximum 8 kW output power and the supercapacitor has maximum 4 kW output. Since the small scale load has a 10 kW maximum power demand, the selection of the energy storage unit guarantees that no matter the engine is operation or not, the small scale load can be satisfied. The selected size of the energy storage unit make the system be able to deal with sudden power demand change during operation.

3.3 Case study：Individual household analysis

In the next section, the energy consumption of an individual household is displayed and analyses by the four seasons. The original data was tested and collected by former research in Swan centre. After obtaining the access to the data base, the information of the individual household is listed and analysed by the author of the thesis. The data is describing the energy consumption for the selected single house in the 24 hours period. During the four seasons, the energy consumption of the household is recorded in 5 seconds resolution. Each season's data consists of several days. Detail information is shown in the following parts. The energy consumption of the selected house is displayed. The energy consumption introduced of the household includes the electricity consumption and the heat consumption. In the original data, the heat consumption is converted to equal energy in value of electricity. Therefore, the electricity consumption mentioned above is involved with the electricity consumption and the heat consumption. The information obtained is from Swan data base. The high resolution data is the best choice to elevating the integrated system's performance.

3.3.1 Spring

During the full 24 hours recording time, Table 14 shows the complete electric consumption. For all the data collected during the spring season. The data was recorded in the period from 23/03/2009 to 29/03/2009. The low level and high level consumption of electric power is set at 0.5kW and 5 kW. Table 14 shows the characteristics of 4 days' data.

Date	Recording Resolution	High/Low Power (kW)	Average Power (kW)	High/Low Temp (℃)
Mon 23/03/09	30 Sec	9.51 / 0.0	0.368694	10.0 / 3.6
Wed 25/03/09	30 Sec	5.99 / 0.0	0.304038	9.3 / 7.2
Fri 27/03/09	30 Sec	5.81 / 0.0	0.410639	8.7 / 5.4
Sun 29/03/09	30 Sec	4.23 / 0.0	0.441455	10.0 / -4.5

Table 14 Information Extracted from the Full Day (24 Hour) Spring Electricity Consumption Data Sets

The Table 14 recorded the electricity consumption on spring days in 30 seconds resolution. From the characteristic of high-resolution data, the electric consumption varies in a wide range from 0 to 9.51 kW. But the average power consumption is not high. The average value is under 0.4 kW. It indicates the total power consumption is not high for all day's power demand. The state of weather is also recorded in the Table 14 that show the temperature varies in the range of -4.5 degree to 10 degree.

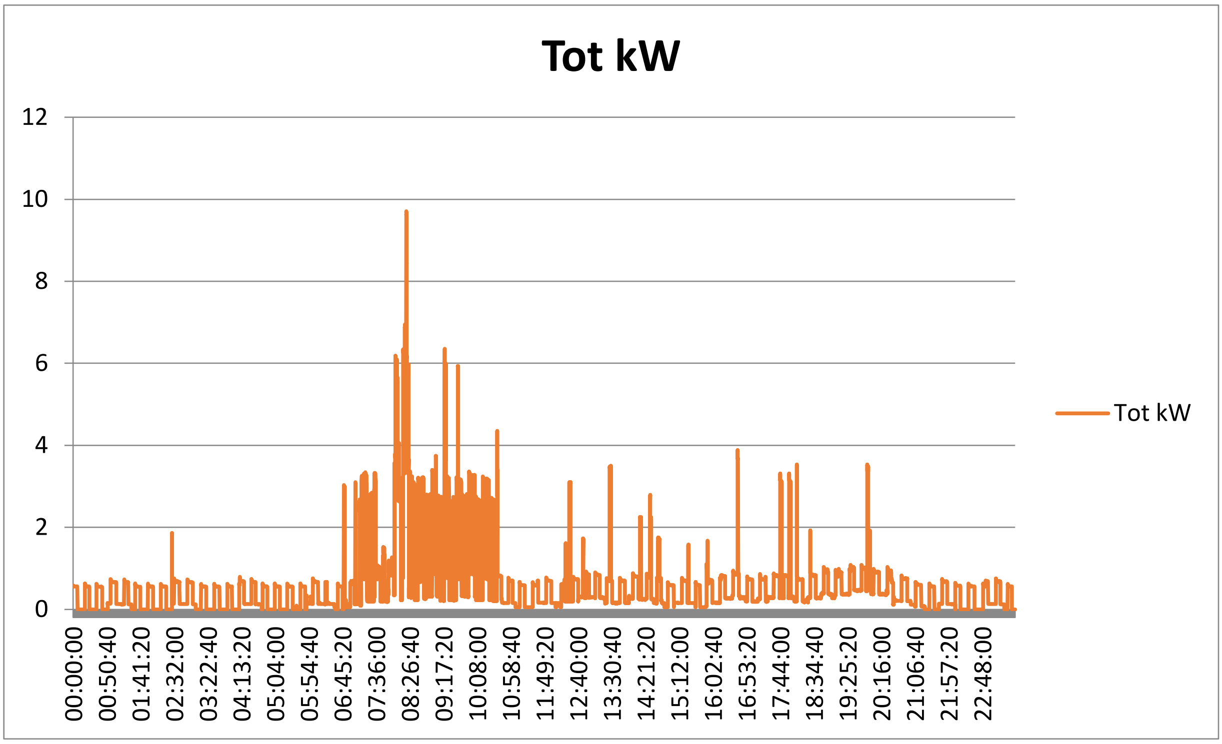

Figure 16 Spring Season 24 Hour Graph Showing House 2 Electrical Power Consumption

The Figure 16 shows a general electrical power consumption on a spring day. A detailed consumption record is shown with labelled time. The maximum power consumption is recorded as 6.66 kW on Saturday 28th March at 07.59.30. Values of 6.66kW actual power were recorded. Time periods of high power use is 06:00-10.40, 12:12-14:29 and 16:30-20:00. Energy consumption peak occurs in the morning due to people's activities. The rest time of the day shows low power demand for this house.

Date	Percentage of the day consumption was below 0.5kW (%)	Percentage of the day consumption that was between 0.5 and 5kW (%)	Percentage of the day consumption was greater than 5kW (%)
Mon 14/03/09	86.7	12.95	0.35
Wed 25/03/09	89.83	10.1	0.07
Fri 27/03/09	82.26	17.32	0.42
Sun 29/03/09	82.47	17.53	0.0

Table 15 Spring Daily Percentage Values about a High and Low Value of Power

This Table 15 shows most of the time; the domestic house's power consumption keeps at relatively low level that is 0.5 kW. Part of the time, power consumption excess to 0.5kW to 5 kW. This period occupies 10%-17.53 per day. Less than 1% of the time of a day, the power demand is larger than 5kW.

3.3.2 Summer

During the full 24 hours recording time, Figure 17 shows the complete electric consumption. For all the data collected during the summer season. Table 16 shows the Characteristic of 7 days' data.

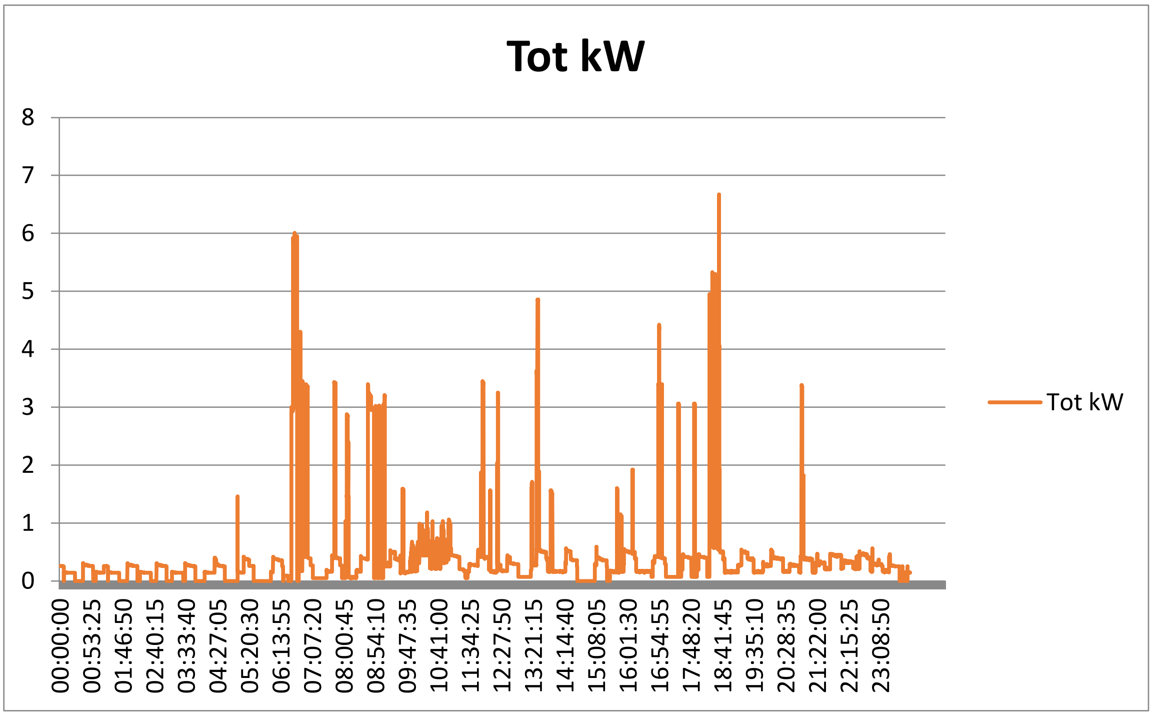

Figure 17 Information Extracted from the Full Day (24 Hour) Summer Electricity Consumption Data Sets

Date	Recording Resolution	High/Low Power (kW)	Average Power (kW)	Total Energy Use (kWh)	High/Low Temp ℃
Wed 15/07/09	5 Sec	5.34 / 0.0	0.348151	8.355625	19.7 / 12.6
Fri 17/07/09	5 Sec	7.45 / 0.0	0.30048	7.211528	16.0 / 11.5
Sat 18/07/09	5 Sec	5.48 / 0.0	0.318587	7.646097	17.3 / 12.4
Sun 19/07/09	5 Sec	6.70 / 0.0	0.392927	9.43025	16.8 / 13.0
Mon 20/07/09	5 Sec	5.54 / 0.0	0.340841	8.180194	18.5 / 10.2
Tue 21/07/09	5 Sec	6.67 / 0.0	0.401311	9.631472	17.9 / 8.5
Wed 22/07/09	5 Sec	6.1 / 0.0	0.433006	10.39214	19.5 / 13.8

Table 16 Summer power using situations

The Figure 17 shows a detailed electricity consumption on a summer day. From the characteristic of high-resolution data, the electric consumption varies in a wide range from 0 to 7.45 kW. But the average power consumption is not high. The average value is under 0.43 kW. It indicates the total power consumption is not high for all day’s power demand. Energy consumption peak occurs in the morning due to people’s activities. The rest time of the day shows low power demand for this house. The reason could be low heating demand during a summer.

The maximum power consumption is recorded as 7.45 kW on Friday 17th July at 18:08:05. Period of high power consumption is 06:50-10.40. Energy consumption peak occurs in the morning due to people’s activities. There are also some power demanding ripples occurs from the afternoon to the evening. During the sec half of the day, the maximum power demand is less than 5 kW. The rest time of the day shows low power demand for this house.

Date	Percentage of the day consumption was below 0.5kW (%)	Percentage of the day consumption that was between 0.5 and 5kW (%)	Percentage of the day consumption was greater than 5kW (%)
Wed 15/07/09	88.59	11.31	0.1
Fri 17/07/09	94.98	4.66	0.36
Sat 18/07/09	89.15	10.71	0.14
Sun 19/07/09	87.52	11.90	0.58
Mon 20/07/09	92.34	7.48	0.18
Tue 21/07/09	87.93	11.67	0.4
Wed 22/07/09	84.09	15.83	0.08

Table 17 Summer Daily Percentage Values about a High and Low Value of Power

The low-level and high-level consumption of electric power are set at 0.5kW and 5 kW. This Table shows most of the time; the domestic house's power consumption keeps at relatively low level that is 0.5 kW. Part of the time, power consumption excess to 0.5kW to 5 kW. This period occupies 4.66%-15.83 per day. Less than 0.58% of the time of a day, the power demand is larger than 5kW.

3.3.3 Autumn

During the full 24 hours recording time, Figure 18 shows the complete electric consumption. For all the data collected during the summer season. Table 18 shows the Characteristic of 4 days' data.

Date	Recording Resolution	High/Low Power (kW)	Average Power (kW)	Total Energy Use (kWh)	High/Low Temp oC
Mon 16/11/09	5 Sec	9.71/ 0.0	0.588853	14.13247	12.1 / 8.8
Tue 17/11/09	5 Sec	10.4 / 0.0	0.56856	13.64544	13.2 / 6.9
Wed 18/11/09	5 Sec	8.53 / 0.0	0.617465	14.81915	14.2 / 7.8
Thur 19/11/09	5 Sec	9.63 / 0.0	0.610184	14.64442	14.4 / 12.5

Table 18 Information Extracted from the Full Day (24 Hour) Autumn Electricity Consumption Data Sets

Four typical autumn days are picked to record the electricity consumption. The Table 18 shows a general electricity consumption pattern of this four-day long data. From the characteristic of high-resolution data, the electric consumption varies in a wide range from 0 to 10.4 kW. But the average power consumption is not high. The mean value is under 0.72 kW. It indicates the total power consumption is not high for all day's power demand.

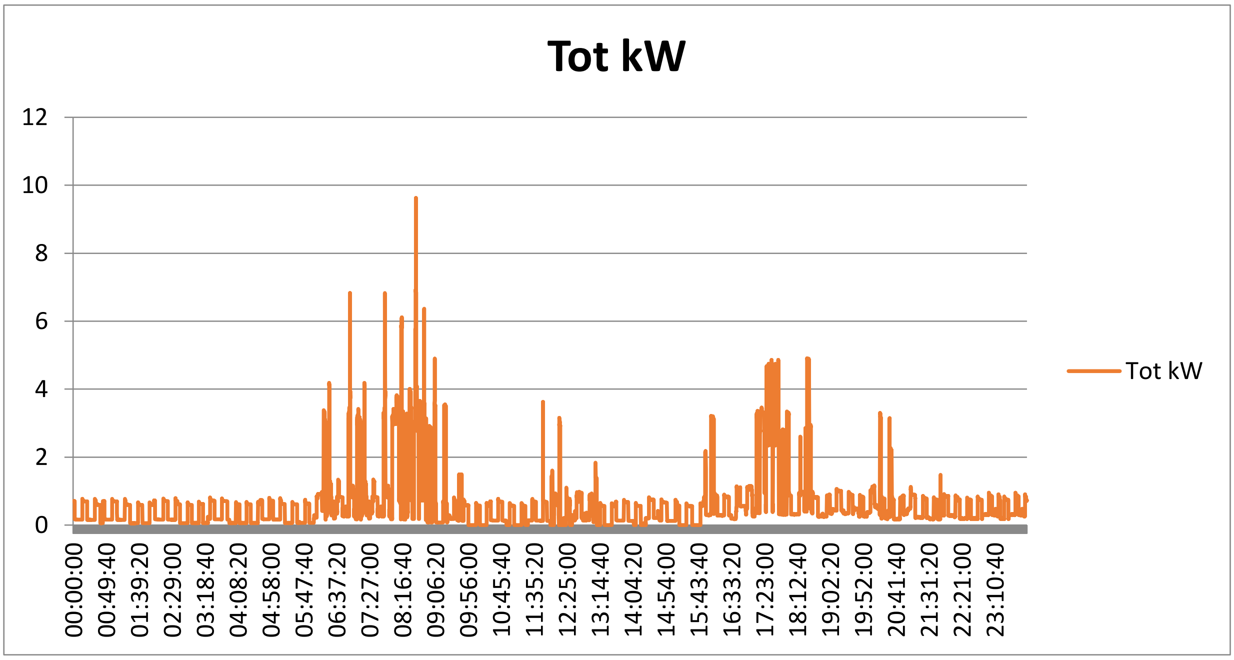

Figure 18 Autumn Season 24 Hour Graph Showing House 2 Electrical Power Consumption

Specific electricity consumption is shown in the Figure 18. The maximum power consumption is recorded as 10.4 kW on Tuesday 17th November at 08:34:35. Time period of high power consumption is 06:00-09.50. Energy consumption peak occurs in the morning due to people's activities. There are also some power demanding ripples occurs from the afternoon to the evening. During the sec half of the day, the maximum power demand is less than 5 kW. The rest time of the day shows low power demand for this house.

Date	Percentage of the day consumption was below 0.5kW (%)	Percentage of the day consumption that was between 0.5 and 5kW (%)	Percentage of the day consumption was greater than 5kW (%)
Mon 16/11/09	55.26	44.09	0.65
Tue 17/11/09	55.93	43.41	0.66
Wed 18/11/09	57.71	41.78	0.51
Thur 19/11/09	56.23	43.59	0.18

Table 19 Autumn Daily Percentage Values about a High and Low Value of Power

The low-level and high-level consumption of electric power is set at 0.5kW and 5 kW. This Table shows most of the time; the domestic house's power consumption keeps at relatively low level that is 0.5 kW. Part of the time, power consumption excess to 0.5kW to 5 kW. This period occupies 41.78%-44.09 per day. Less than 0.66% of time of a day, the power demand is larger than 5kW.

3.3.4 Winter

During the full 24 hours recording time, Figure 19 shows the complete electric consumption. For all the data collected during the summer season. Table 20 shows the Characteristic of 4 days' data.

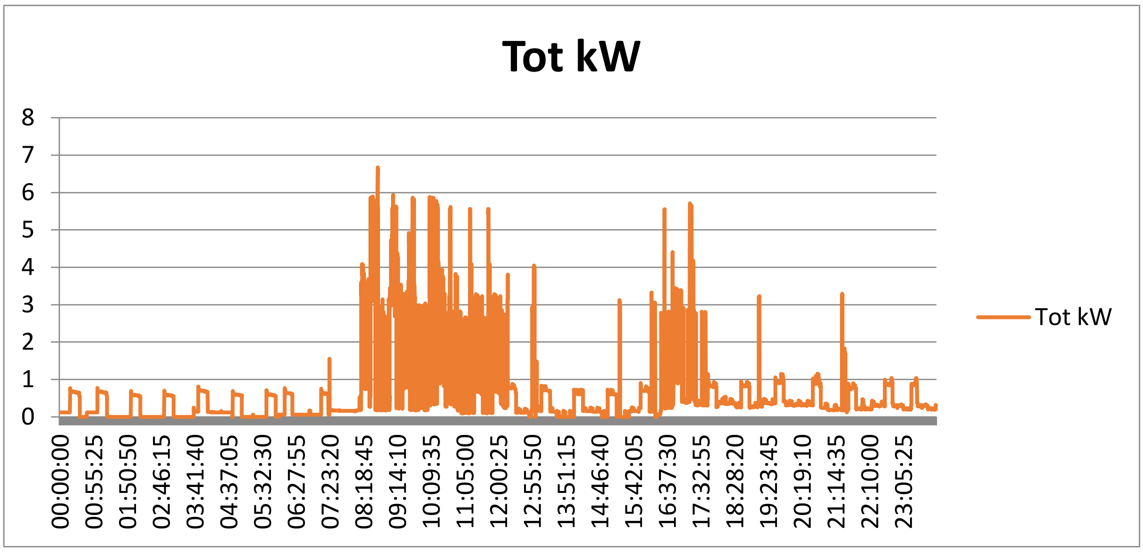

Figure 19 1 Information Extracted from the Full Day (24 Hour) Winter Electricity Consumption

Date	Recording Resolution	High/Low Power (kW)	Average Power (kW)	Total Energy Use (kWh)	High/Low Temp
Tue 02/02/10	5 Sec	6.36 / 0.0	0.455167	10.92401	8.2 / 2.3
Wed03/02/10	5 Sec	10.4 / 0.0	0.515784	12.37881	8.1 / 2.6
Thru 04/02/10	5 Sec	8.91 / 0.0	0.489572	11.74974	10.1 / 0.7
Fri 05/02/10	5 Sec	7.32 / 0.0	0.563631	13.52715	10.2 / 3.6
Sat 06/02/10	5 Sec	7.82 / 0.0	0.423176	10.15622	11.2 / -0.4

Table 20 power using characteristics

From the characteristic of high-resolution data Table 20, the electric consumption varies in a wide range from 0 to 10.4 kW. But the average power consumption is not high. The average value is under 0.62 kW. It indicates the total power consumption is not high for all day's power demand.

The maximum power consumption is recorded as 8.91 kWh on Thursday 4th February at 08:55:55. Period of high power consumption is 08:00-12.16. Energy consumption peak occurs in the morning due to people's activities. There are also some power demanding ripples occurs from the afternoon to the evening. During the second half of the day, the maximum power demand is less than 5 kW. The rest time of the day shows low power demand for this house.

Date	Percentage of the day consumption was below 0.5kW (%)	Percentage of the day consumption that was between 0.5 and 5kW (%)	Percentage of the day consumption was greater than 5kW (%)
Tue 02/02/10	65.51	33.96	0.53
Wed 03/02/10	67.55	31.83	0.62
Thru 04/02/10	66.20	33.49	0.31
Fri 05/02/10	56.23	36.59	0.18
Sat 06/02/10	66.21	33.69	0.1

Table 21 2 Winter Daily Percentage Values about a High and Low Value of Power

The Table 21 shows that the low-level and high-level consumption of electric power are set at 0.5kW and 5 kW. This Table shows most of the time; the domestic house’s power consumption keeps at relatively low level that is 0.5 kW. Part of the time, power consumption excess to 0.5kW to 5 kW. This period occupies 31.83-36.59 per day. Less than 0.62% of the time of a day, the power demand is larger than 5kW.

3.3.5 Summary of the domestic power consumption example

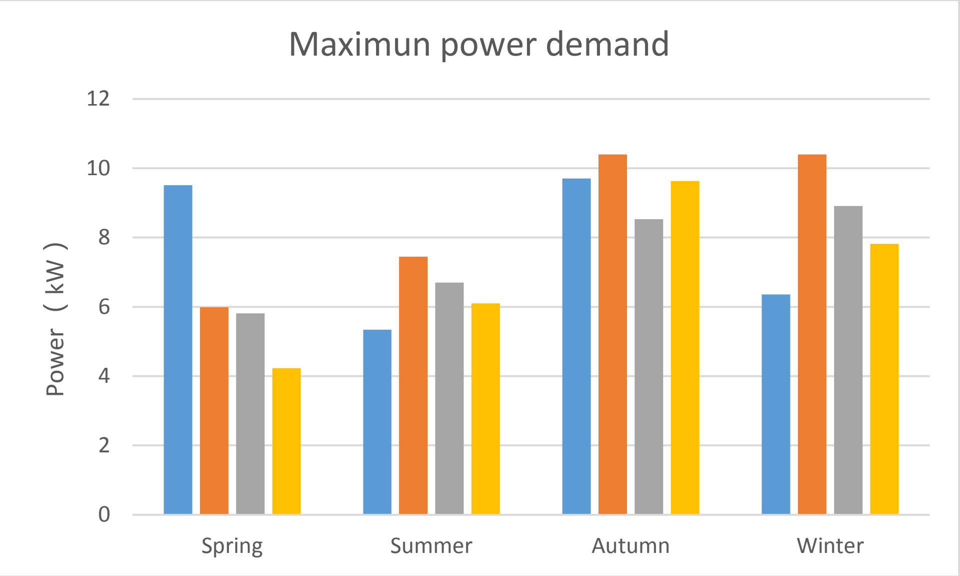

Figure 20 Maximum power demand of the household at different seasons

The Figure 20 shows the maximum power demand of the selected house. In the spring and the summer, because of low heating demand, the maximum power demand on this two seasons is less than the other two seasons. In the four seasons, power demand on autumn days has the maximum power value. The maximum power demand occur in the winter and the autumn days. Generally speaking, on the autumn days, this situation that the house has highest power demand peak point is relevant with high frequent human activity.

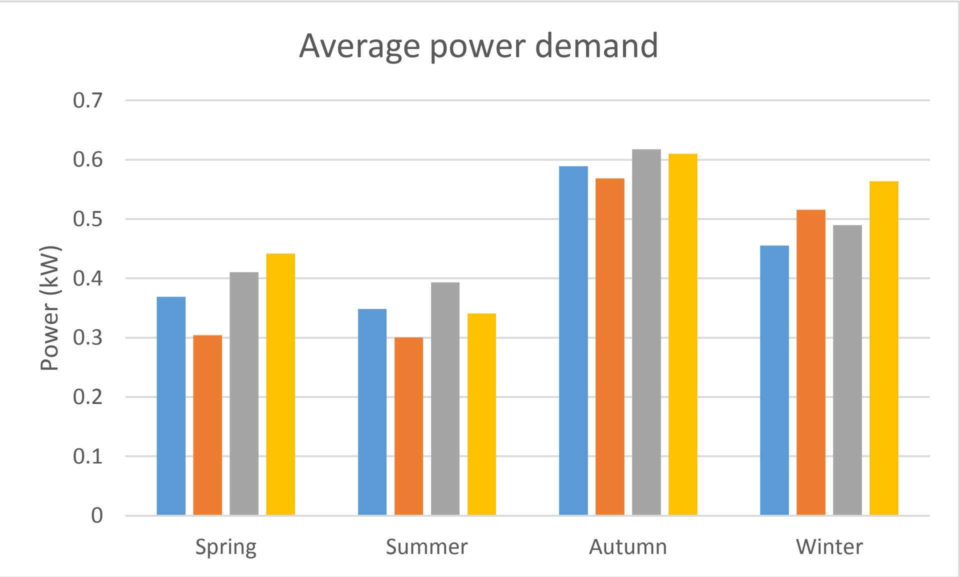

Figure 21 Average power demand of the household at different seasons

This Figure 21 shows the average power demand on the four seasons. The spring and summer days have low power demand because of low heating demand. The power demand of autumn days and winter days are 30% higher than the other two seasons. The maximum power demand occur on autumn days. The heating demand on the autumn days is normally less than that on winter days. However, the human activity is more active on autumn days. Frequent using of electric appliance maybe the reason of high average power demand. The power demand on winter days is less stable than that on autumn days. The fluctuation on the power demand on winter days may has relationship with the changing outside temperature. The key point of this analysing on the household power demand is the selection of appropriate load of the integrated system. Therefore, the specific reason that why does autumn days has highest power demand will not be investigated in this research.

On spring days, the peak time locates in the morning time. From 7:30 to 10:00 has the highest possibility that house demand the highest power during a day time. In the other time of the day, the power requirement on the spring days is much less. Occasional power demand may occur in the afternoon and in the evening. On the summer days, the power demand of the selected house shows large fluctuation in one day time. The highest power demand occur at both morning and evening. There are several power demand peaks in one day: 1, from 6:30 to 9:00; 2, from 12:20to14:00; 3, from 17:00 to 18:30. The power demand of summer days shows a changeable low demand. The power demand on the autumn days are more predictable compared to the other seasons. The peak time locates mainly at the morning time. A high density of high power demand also occur at the evening. For the winter day, because of stable heating demand, large peak time locates from the morning to the evening. From 8:00 to 12:00 and from 16:00 to 20:00, the house has high power demand. Off peak time is the rest time of the day.

Since the house has a changeable power demand on the summer days and high power demand on the autumn days, the load profile of summer days, autumn days and winter days are selected to evaluate the performance of the integrated system on a dynamic load. A sudden change of the load profile helps to elevate the system's stability on the power supplying.

Evaluation of the system on both high power demand occasions and low power demand occasions leads to a comprehensive understanding of the system's performance.

3.4 Experimental tests

As a preparation of a comprehensive researching on the integrated system, the key parameters of the system such as the power rate of batteries, the power rate of supercapacitors, the efficiency of the batteries and the power rate of the engine must be measured and recorded for further modelling building of the system. The experimental tests are necessary for further simulation study. The experimental tests consist of some preliminary experimental tests. They are designed and operated mainly on the system's electric part for performance evaluation on the build integrated system. In the two experimental tests, the preliminary experimental test use the grid to simulate the power output from 6.5 kW diesel oil's engine's generator. Tests are designed for energy storage units' parameter's measuring. Further tests are expanding part on the evaluation of the electric part of the integrated system. In that part, dynamic load is applied in the system's evaluation.

The full size integrated trigeneration system includes: a diesel engine (prime mover), a waste heat recovery system, an absorption refrigerator, a hybrid electricity energy storage unit, an ORC and a controlling system. The preliminary experimental tests can assist the investigating and the prediction of the system's performance. The controlling method is adjusting in the process of the system's operation's analysing. The experimental tests are divided by two parts. The first part concentrates on the energy storage units and the second part carries the performance evaluation on the electric part of the integrated system.

The operation test and the performance evaluation of the energy storage system is the primary goal of the experimental study. The energy storage system for the electricity is a hybrid electrical energy storage (HEES) system. It consists of batteries and super-capacitors. This part is one the core components in this integrated system which is mentioned before in the system design. It is connected with the main energy sources and used to support the energy supply. As a key part of the trigeneration system, the HEES can increase the energy capacity and stability of the system. The performance of the energy storage units is measured during the controlled operation of the system. With sensors installed, the controlled system operation is used to analyse the energy storage system.

The second phase of the experimental tests aims at building an electric part of a trigeneration system. After the success combination of the conventional batteries and the supercapacitor, the energy system is integrated to the electric part of the energy system. Because of the experimental test focus on the electricity supplying, the control strategy follows the electric energy demand. During the peak time, the engine operates to supply the electric load. In this system, the energy storage system operates as auxiliary energy supplier. Engine only operates at high loads for excessing higher overall efficiency. Two sets of loads (one set of summer load and one set of winter load) were tested with an experimental bench which will be introduced in later sections. The tests results are used to evaluating the performance of the integrated system. Limited by the equipment in the laboratory, the engine in the experimental test is simulated by a current limited source powered by grid.

3.5 Computational modelling and optimisation

The main research approach in this study is simulation study on the integrated trigeneration with HEES and ORC systems. The first task in the study is investigating the components which includes the batteries, the supercapacitors, the inverters, the converters in the system. Fundamental tests on the system's key components gives the characteristic of the components. Tests on the engine, batteries, supercapacitors and recovery system shows these components' performance under different conditions. The software of the simulation is Matlab. The components of the system are built individually and validated before building the whole system or further simulation on the system' performance.

Satisfying a small scale changing load by a distributed energy system requires a control method to maximum the operation efficiency of the system. The control strategy must make sure the system produce enough energy for the load with minimum waste. Generally, it is responsible for the energy's sources' operation, energy storage's operation and energy transferring between each part of the system. Following electric load and following thermal load are two popular control strategy for trigeneration system. In this study, following electric load combined with optimisation process is applied to control the operation of the system. In the main circuit of the system, sensors installed on the test bench tests the key parameters such as the current of the energy source, the voltage of the energy source, the current of the batteries, the voltage of the supercapacitor, the current of the supercapacitor, the current of the load and the voltage of the load. The data collected by the sensors helps with the controlling and optimisation of the system's operation.

With the help of the preliminary tests and experimental tests of the system, the system's performance of electricity performance on several scenarios are clear. Next part is using the experimental test results to build simulation model for the system. With the results of the experimental tests, the validation of the system's model is a necessary part of building an accurate simulation model. The validations of the model's accuracy is performed in later part of this study. Since the energy demand depends on the characteristics of the specific applications, a number of scenarios are designed to reflect the features of the trigeneration system. The simulation on the system uses the trigeneration system to supplying the designed load. The system's efficiency results are compared with and without the energy storage units. An optimisation on the integrated system's operation is another part in this study. Based on the purpose of the system and the regulations of the system's operation, a better operation is designed to save the primary energy consumption.

Based on the simulation results carried with current control strategy, analysing on the system's performance is worth further investigating. The optimisation process focus on the system's operation. Through changing the system's operation of key components to maximise the system's efficiency. The optimisation process on the system consists of the optimisation on the electric part of the system and the optimisation on the whole system. In the optimisation of the electric part of the system, the enhanced operation strategy reduces the engine's operation time when the system is supplying the electric load. The optimisation results of system will be the comparison between the simulation results before optimisation and results after the optimisation process. An overall system efficiency and the primary energy consumption will be used to evaluate the optimisation process on the electric part of system.

Another part of optimisation work focusses on the operation of the whole trigeneration system. The optimisation on the integrated system aims at using the least amount of primary energy consumption to meet the dynamic energy demands. Based on the simulation results of the different scenarios, the optimisation control strategy regulated the engine's operation time to maximise the electric efficiency. At the same time, the heat recovery system using the waste heat to meet heating demand and for cooling generation and supply. A comparison between the simulation results and the optimisation results will be discussed after the optimisation process.

3.6 Summary of this part

This chapter introduces the methodology used for this study. As this research is to investigate the performance of the integrated trigeneration system, the energy demand study comes in the first part. In the system design section, collected data supports the current design of system. The 6.5 kW diesel engine is capable to supply the energy for selected small-scale load as the prime mover of the integrated system. Four set of data are selected to study the electricity consumption of a household. The energy consumption pattern, the maximum energy peak and the average energy consumption amount are reviewed in each analysis to the data. The main research approach of the system are experimental tests and computational modelling. The experimental tests include two parts which mainly measures the energy storage units and the electric part of the system. The process of modelling and methods of simulation are also introduced in details in the section. The basic target of the system is satisfying the dynamic domestic energy demand with high efficiency. However, with integration the energy storage system, ORC, heat recovery system, there is opportunity and possibility for the optimisation work for accessing higher overall efficiency. The optimisation work for the system is proposed as two phases-the optimisation on the electric part and the optimisation on the whole system.

4. Experimental tests

For investigating the operation of the trigeneration system, the experimental tests and simulations on the system are necessary. In this chapter, the experimental tests carried on some of the components of the system and on the electric part of the system are introduced and analysed. Limited to the devices in the laboratory, the experimental study is mainly focusing on satisfying the dynamic electricity demand with the integrated system. The electrical part of the trigeneration system is tested in two laboratories with different devices. Each of the experimental bench and the devices are introduced in this chapter. In the two part of experimental test, the first part is used to evaluating the energy storage's performance and measuring its parameters for simulation building. The second part of experimental test is built without the diesel engine. The output form the diesel engine is simulated by the grid.

The experimental test aims at testing the energy storage. Since there is little research focus on the batteries operating with the supercapacitors in the same energy system, and this test researches and analysis using the hybrid system satisfying the dynamic domestic load. Therefore an experimental test focusing on the key components' performance is necessary for understanding the operation of this hybrid electrical energy system. The control strategy follows the electric energy demand. During the peak time, the engine operates to supply the electric load. In this system, the energy storage system operates as auxiliary energy supplier. Engine only operates at peak time for reaching higher overall efficiency. The first test applies four constant load. In the second experimental test, two sets of load (one set of summer load and one set of winter load) are tested with this experimental bench. The results show the system' performance of dynamic energy supplying.

4.1.1 **System description**

The Figure 22 shows the system's construction. The full size integrated trigeneration system includes several components. They are a diesel engine (prime mover), waste heat recovery system, absorption refrigerator and exhaust heat recovery system, hybrid electricity energy storage, ORC and controlling system. The configuration has been shown in the system design. The preliminary experimental tests can assist the investigating and the prediction of the system's performance. The controlling method is responsible for the system's operation.

The engine burns diesel oil to supply energy for the integrated system. During the research, the primary energy is simulated by grid. Waste heat is recovered by the waste heat recovery system. Hot water is utilized to supply heating and hot water for the household using. Heat is exchanged between jacket water and hot water in the heat exchanger in the engine cooling system. The primary goal for the research is to meet the dynamic electricity demand of household. As a results, the hybrid electric energy storage system is researched firstly.

The HEES consists of batteries and super-capacitors. It is connected with the main energy sources and used to support the energy supply. As a key part of the trigeneration system, the HEES can increase the energy capacity and stability of the system. The HEES is designed to be controlled by the control system. In the first step of experimental work, the energy storage units are connected to test the charging and discharging performance. The characteristic of charging and discharging is important for the design of control system.

Some typical cases of domestic energy using are shown. In this project, the trigeneration system are designed to meet the typical domestic energy need first. Then with the help of control system, the trigeneration then meet a changing dynamic domestic energy demand. For exceeding the objectives, the experimental tests are carried to collected system's parameters for further simulation.

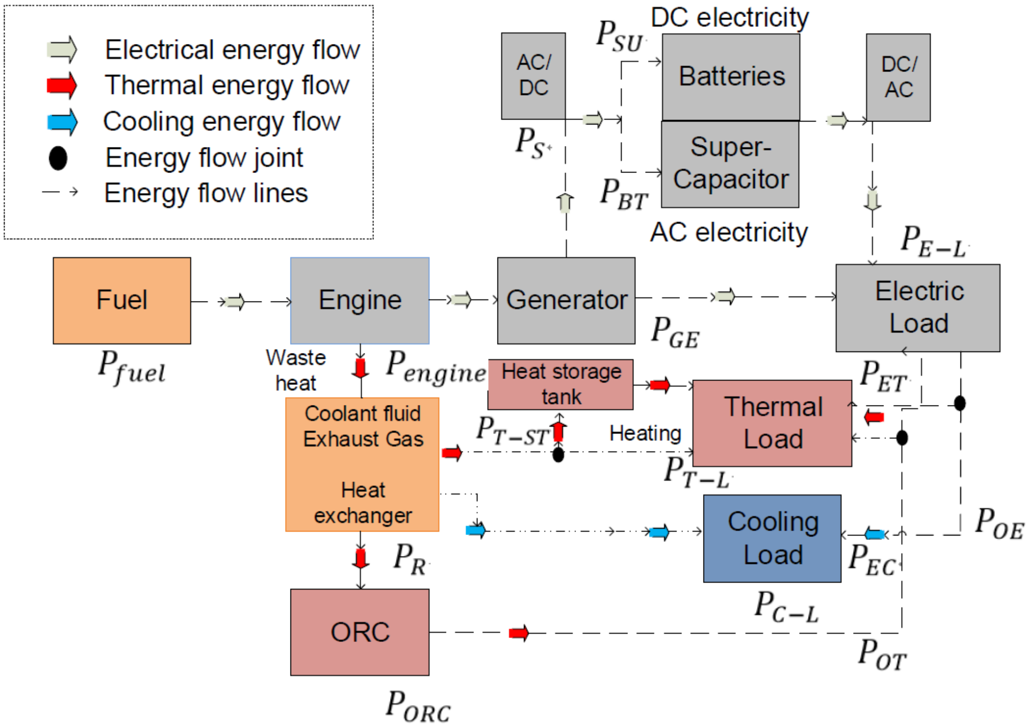

Figure 22 Schematic design of the integrated System

Before comprehensive researching the trigeneration system, some key parameters of the system such as the power rate of batteries, the power rate of supercapacitors, the efficiency of the batteries and the power rate of the engine must be measured and recorded for further modelling building of the system. As a preparation for the simulation study, some preliminary experimental tests are designed and operated mainly on the system's electric part. In this section, some main components on the test bench are introduced. The results of the experimental tests are displayed and analysed.

4.1.2 Sensor installation

The experimental work focuses on the electric circuit in the first phase. Based on the system's design, the test equipment includes the energy source, the energy storage units, the inverters and converters, the loads and the sensors. The basic idea is to use the sensor to detect the system's performance. Several significant measurements for the system are voltages for the energy storage units, the current for both DC and AC loop for the system, the voltages for the energy source and the loads. Since there are AC energy sources, batteries, supercapacitors, electronic converters and loads in the system, eight sensors are used to measure the system's dynamic performance. A configuration for the sensors is shown in Figure 23.

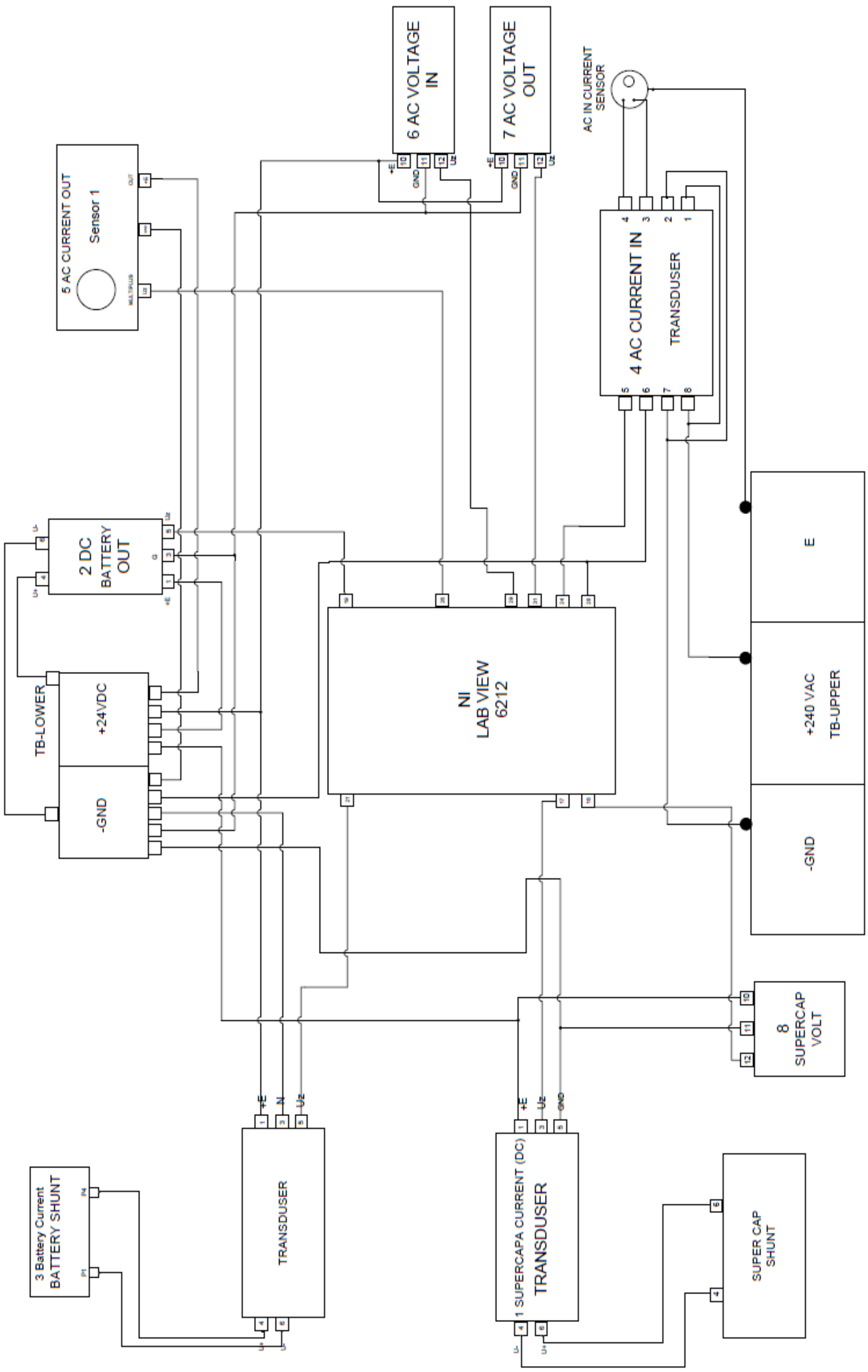

Figure 23 sensors installation figure

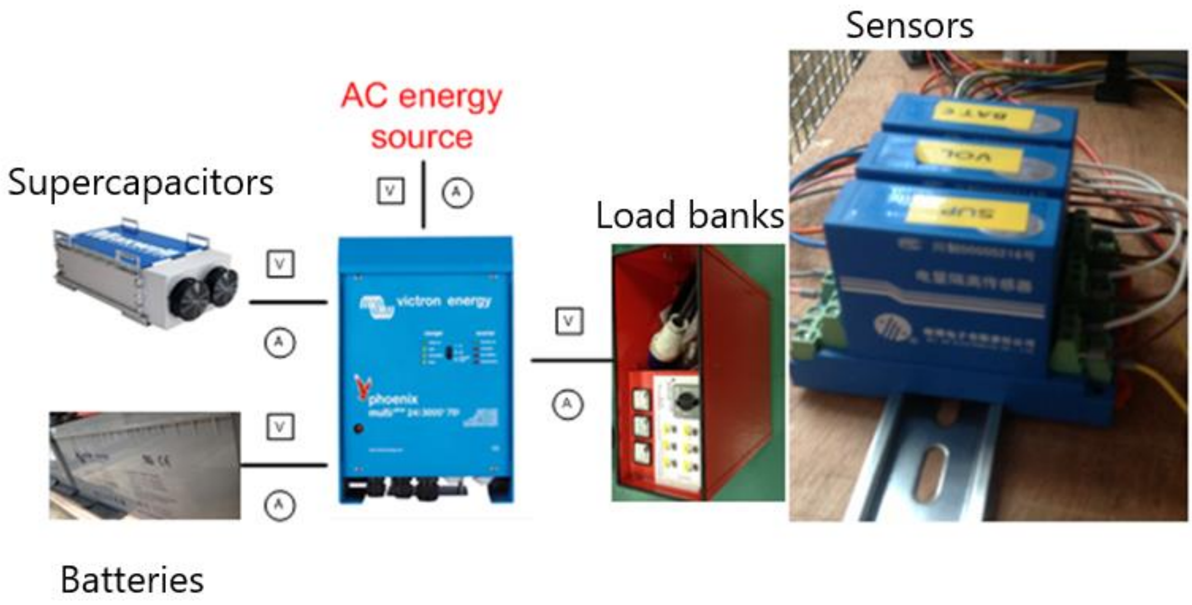

Figure 24 sensor installation

All the sensors are connected with the measurement equipment LabVIEW 6212. There are plugs on the instrument. For the experimental tests I this project, there are 16 plugs being connected with the sensors. Sensors are sorted in order from one to eight. All the current and voltage signals are transferred to a voltage signal and transported to the instrument 6212. After adequate calculation for the signals, the results could be obtained and the performance of the system is expressed by the collected data. In the Figure 24, all the sensors have been allocated to certain plugs on the instrument. All the plugs on the instruments are corresponding to a data source in the software Labview. The data is all collected in the Labview software environment.

4.1.3 Components installation for measurement

Before the test, each component of the system needs to be installed on the test bench. The Figure 25 is the electric configuration of the system including the HEES. Every part of the system is drawn in the graph. The energy can be injected in from the power source (most of the time, the power of engine is simulated by the grid). The MultiPlus inverts the AC power to DC energy storage units. Batteries and super-capacitors are connected in parallel in the configuration. They can be charging and discharging at the same time. For unique energy charging requirement, separate equipment is used to charge the super-capacitor. The energy output can be used on the load from the outlets. There are circuit breakers protecting the whole circle. All the coils are connected in series. There is a security switch to keep safe operation in the system. If any part in the system went wrong, the operation of the HEES will be stopped by the security switch. Since the batteries and the supercapacitors are connected in parallel, in the initial tests, the two parts can operate independently for data measuring. In the test bench, there is diode to make sure the charging from the power supply unit. Between the junctions of the components connection, the sensors are installed to collect the parameters when the system is operating.

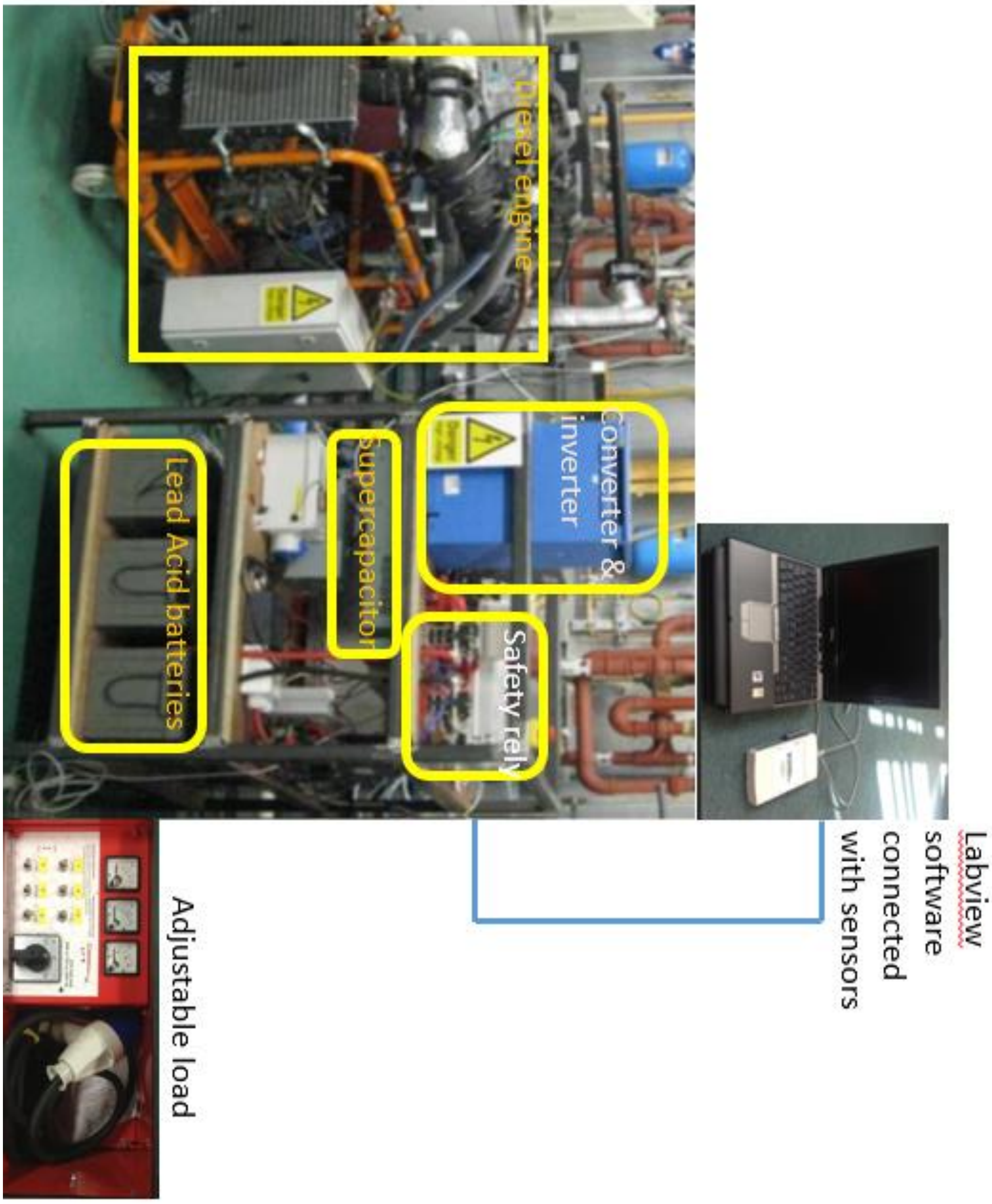

Figure 25 Test bench installation design

4.1.4 Electric components

4.1.4.1 Supercapacitor installation

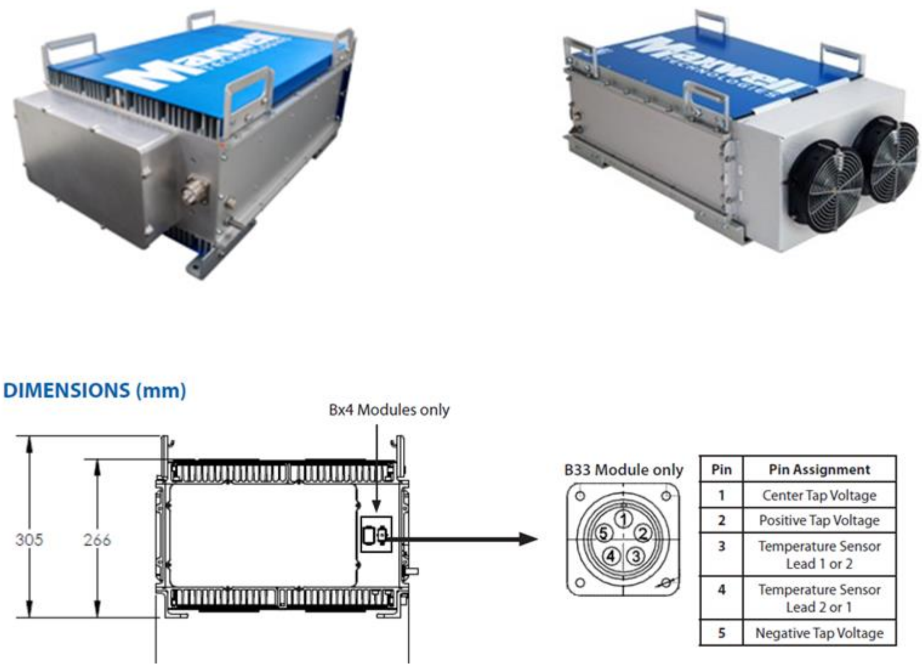

Figure 26 Super-capacitors and dimensions [186]

Super capacitor is one the main storage units of HEES. The super-capacitor used in this HEES is BMOD0063 P125 produced by Maxwell Technologies. The super capacitor is suitable for short time electricity energy supplying. It has digital monitoring and communications. It has high power performance which can be operating over 1 million cycles. The temperature and voltage are also able to be monitored. The Figure 26 shows the super capacitor’s dimensions. From the Pin data sheet, the voltage and the temperature can be monitored from digital pin connections. Some specific information is shown in Table 22

PRODUCT SPECIFICATIONS

CAPACITANCE	B04/B14/B24/B33
Nominal capacitance	63 F
Tolerance capacitance	+20% / -0%
VOLTAGE	
Rated voltage	125 V DC
Surge voltage	135 V DC
Maximum operating voltage	130 V DC
Isolation voltage 50Hz, 1 min. Maximum string operating voltage 1,500 V DC	4,000 V DC
RESISTANCE	
ESR, DC Max., room temperature	18 mΩ
Resistance tolerance	Max.
Thermal resistance (Rth)	0.032°C/W
TEMPERATURE	
Operating temperature range	-40°C to +65°C
Max. ambient operating temp.	+50°C
Storage temperature range	-40°C to +70°C
Temperature characteristics	
Capacitance change	± 5% at 25° C
Internal resistance change	± 150% at 25° C
POWER	
Pd	1,750 W/kg
Pmax	4,700 W/kg
ENERGY	
Emax	2.53 Wh/kg
Energy available Energy Available equals 1/2C (Vnom^2 – 1/2Vnom^2) /3600	101.7 Wh
CYCLES	
Cycles 125 V to 62.5 V DC, RT	1,000,000
Capacitance change Within % of initial specified value.	20% decrease
Internal resistance Within % of initial specified value.	100% increase

Table 22 Specific details of Super-capacitor used in the system [186]

Characteristic of super-capacitors' charging and discharging is shown in the Figure 27. The charging test was done on 27 (2.7V/1200F) series connected super-capacitors. The charging and discharging characteristic graph shows the current keeps constant and the voltage varying linearly during the operation. The test was on a small scale super-capacitor, and more experimental work needs to be done on the BMOD0063 P125.

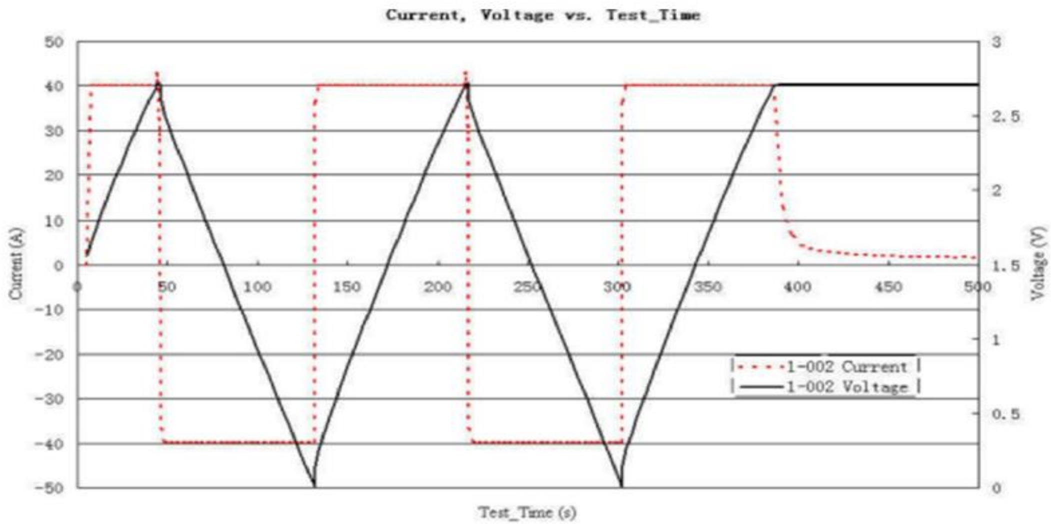

Figure 27 Charging and discharging performance on a simple Super-capacitor unit [187]

The Figure 27 shows a basic test results done on the supercapacitors. The current and voltage changing during the charging and discharging process is shown in the Figure 27. There are two cycles of charging and discharging process. When the supercapacitor is charging, the voltage raise linearly with time's moving. The charging current of the supercapacitor keeps at a stale value which is 40 A in this test. When the supercapacitor is discharging, the current is set as -40 A. The voltage shows an opposite changing compared to before during charging process. This test on a single cell of the supercapacitor shows the supercapacitor device has stable and expected performance.

4.1.4.2 Batteries

Six units of batteries are selected as the main DC source. Every two of them are linked with series and then linked with other in parallel. Each batter is 12V/12 Ah lead-acid battery produced by the Victon Energy. Three series connected battery make the voltage of the battery source to be 36 V. One of the batteries is shown in the Figure 28. They are installed in the bottom of the test bench. Besides the supercapacitor, the batteries are also important component of the HEES. The batteries can offer relative large capacity of energy in long time. The shortcoming of batteries is weight problem. That is the reason they are chose for supplying the domestic household energy. Batteries and super-capacitors are connected in parallel on the DC link box.

Figure 28 Battery unit of the trigeneration system [188]

4.1.4.3 Loads

The loads of the HEES consist of a load bank and some other domestic electric appliance. They are used to simulate the domestic load. From the research on the domestic energy using, the electric load of people's daily load varied from 300W to 10kW. The load band has the capacity from 333W to 6kW. And the other load can be simulated with electric heaters, electric fans, refrigerator and other electric appliance. The loads in the laboratory are shown in the Figure 29.

Figure 29 Load bank in the laboratory

4.1.4.4 Inverter& Converter

Since the energy storage units are DC equipment and the domestic energy using needs AC power. A central control device MultiPlus are adopt in the HEES. The MultiPus performs multiple functions. It is a sinewave inverter, a sophisticated battery charger and a power transfer switch. As shown in the Figure 30, there are LED indicators in the front panel. On different situations, the LED indicators show the operation mode of the MultiPlus. It is also controllable equipment. There a 2 relays which can be used to switch between inverter function and converter function. [189]

Figure 30 MultiPlus Used in the trigeneration [189]

4.1.4.5 Sensors and Data logger

The configuration of the test bench can be simplified as Figure 31 shown. The energy is designed to charge the storage units. Then the energy stored in the units will be consumed by the loads. The sensors shown in the Figure 31 tests the system's performance and collect the data by LABVIEW software. The data can be used to analyse the system energy supplying capacity. The analysing for this data is firstly reflected as waveforms in the labview software which helps the understanding of the controlling system's operation. The test on the energy storage bench is still in preparation process.

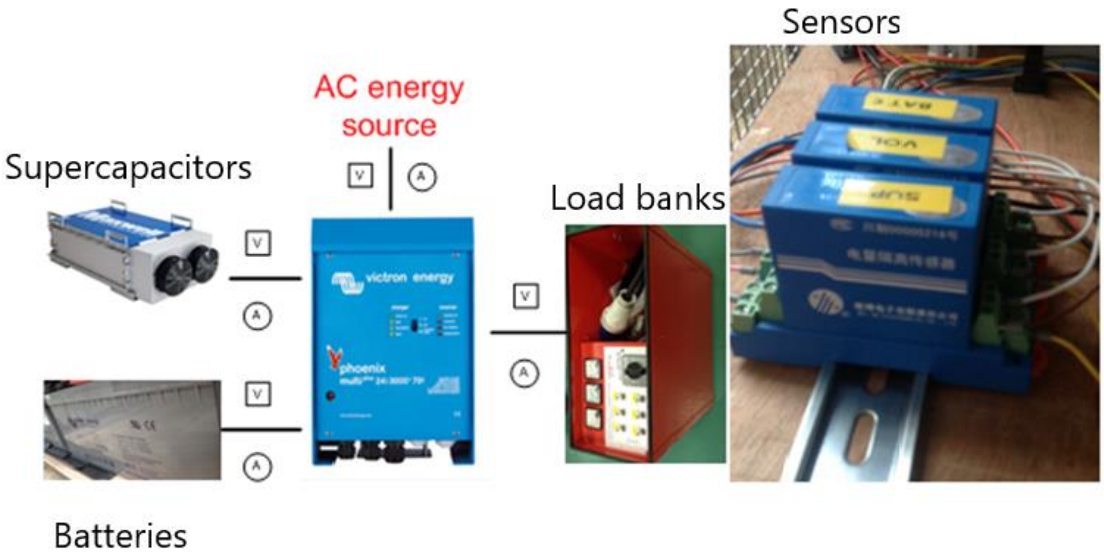

Figure 31 Sensors and the location of sensors(Picture taken in the lab)

The sensors are shown in the Figure 31. Voltage and current sensors are used in the configuration for testing. The sensors can measure the voltage and current with precision of 0.1 mA and 0.1 V.

4.1.4.6 Data Logger and LabView Software

Figure 32 LabView software and the Laboratory use computer

LabVIEW programs are called virtual instruments. It has the function of oscilloscopes and logging the data. LabVIEW contains a comprehensive set of tools for acquiring, analysing, displaying, and storing data. The sensors are connected with the data logger model NI USB-6212 made by National Instruments. Data collected by the sensors can be imported into the Laptop.

4.1.5 Experimental results from the initial tests

This part shows the test results of the energy storage unit. The charging and discharging of the batteries are carried under different load. The program is designed to collect the data. The system's performance could be measured by the data recorder shown below. The DAQ block collect all the electric signals measured by the sensors. All the signals are voltage signals. The voltage signals are transferred to theoretical value by multiply with the certain ratio. The ratio could be found by searching the data sheets of the experimental components. After calculation, the signals are imported to the data recorder block which is used to write all data into excel files. The measurements for battery voltage, batter current, AC voltage in and AC voltage out has been tested and shown with a graph.

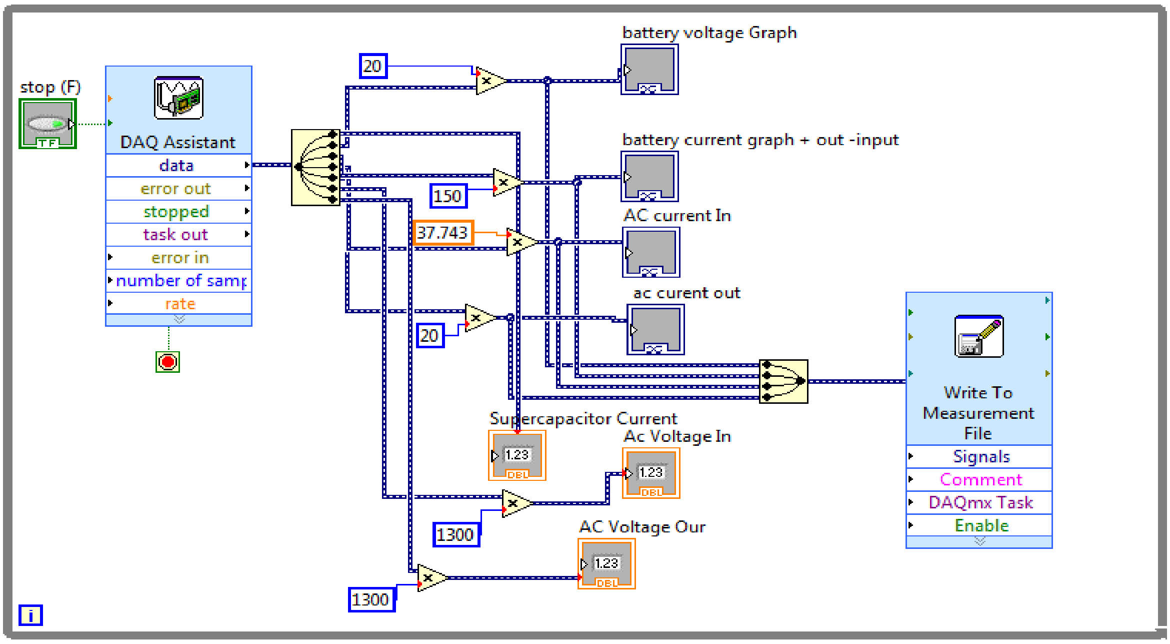

Figure 33 Labview block for measuring

The Figure 33 is the tests results from the Lab View software. The results could be shown in the graph or in a display block. All the data is designed to be written in the files for further analysing. However, exporting the data to the graphs could be a convenient approach to observing the operation of the system. Some results need further tests are shown in graphs, after adjustment for the programme, the system could be used to measure both the batteries and super-capacitors.

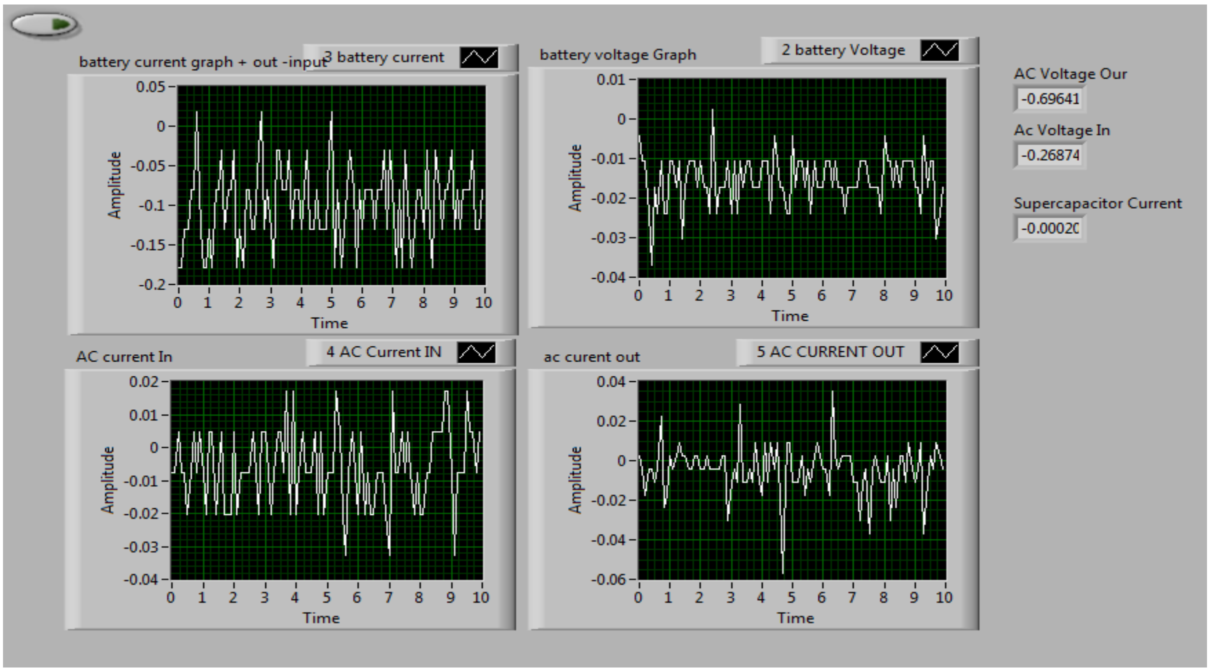

Figure 34 results display in the LabView software

Due to the discharging load for the supercapacitor could not be fully applied in the experimental work. The results for the tests are related with the batteries' performance for the current stage. The batteries were discharging by 4 levels ranged from 1 kW to 4 kW. Each set of experimental tests is designed to operate one charging and discharging cycle for the batteries. As shown in the figures 35-37, all the dynamic measurements for the current and voltages are recorded and shown. During the discharging of the batteries, the current drop from a high value to relative low value. In different levels of discharging, the current changes by portion. The voltages vary in a similar range. In the discharging of the batteries, voltage decrease from 26 V to 19 V which indicates the batteries are nearly over discharge. For the 1 kW discharging, the current kept at a certain range around 50 A. From the begin 46A increase to 52A after about two hours discharging.

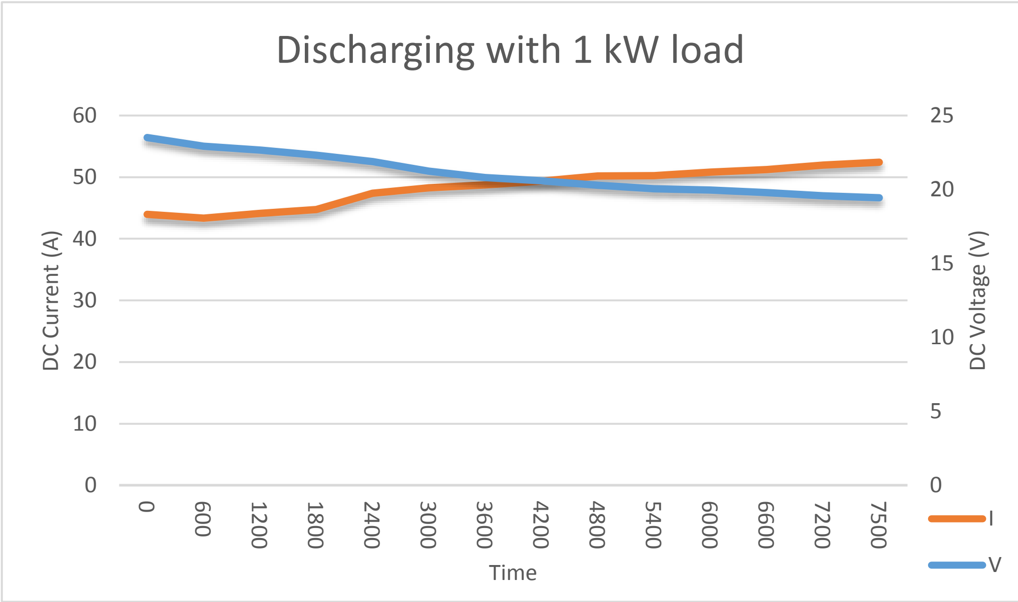

Figure 35 discharging with 1 kW power

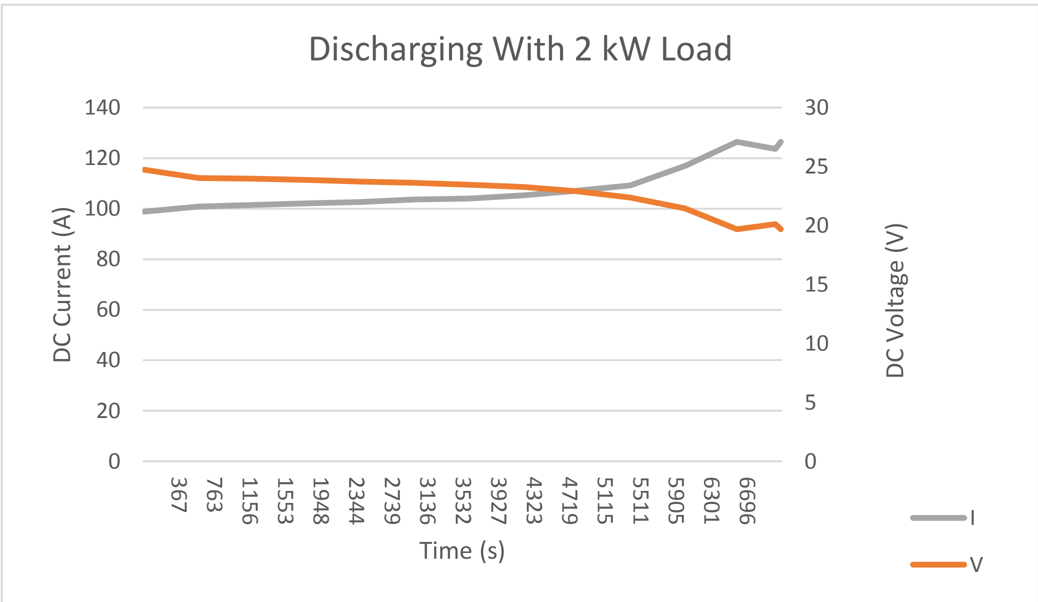

Figure 36 discharging with 2 kW power

For the 2 kW discharging, the current kept at a certain range around 100 A. From the begin 98 A to 120 A after about two hours discharging. For the first one and a half hours, the current kept at stable level around 105 A. At the last half hour, the current had obvious changing for 20 A with fluctuations. At the same time, the voltage had significant changes in the same period. For keeping a constant level of discharging, the voltage and the current have synchronized changes during the batteries operation.

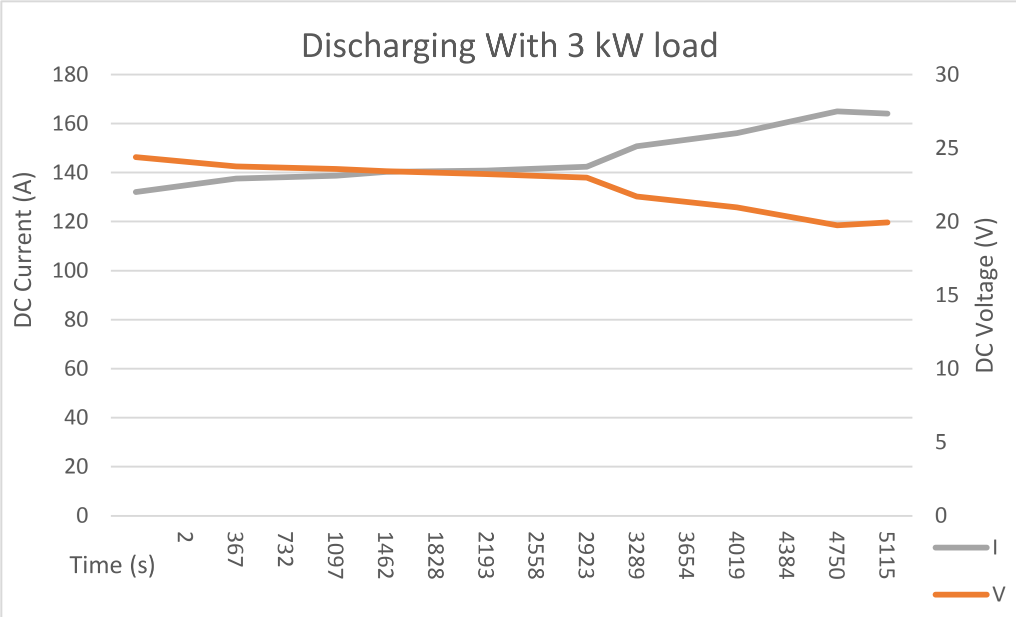

Figure 37 discharging with 3 kW power

The results for discharging' with 3 kW load are similar with results of former tests. The changing trend for the current and voltage are similar with before. The voltage of batteries kept at the same level and had about 5 V change. The current increase by portion. For a higher discharge rates, the batteries' operation time was also reduced.

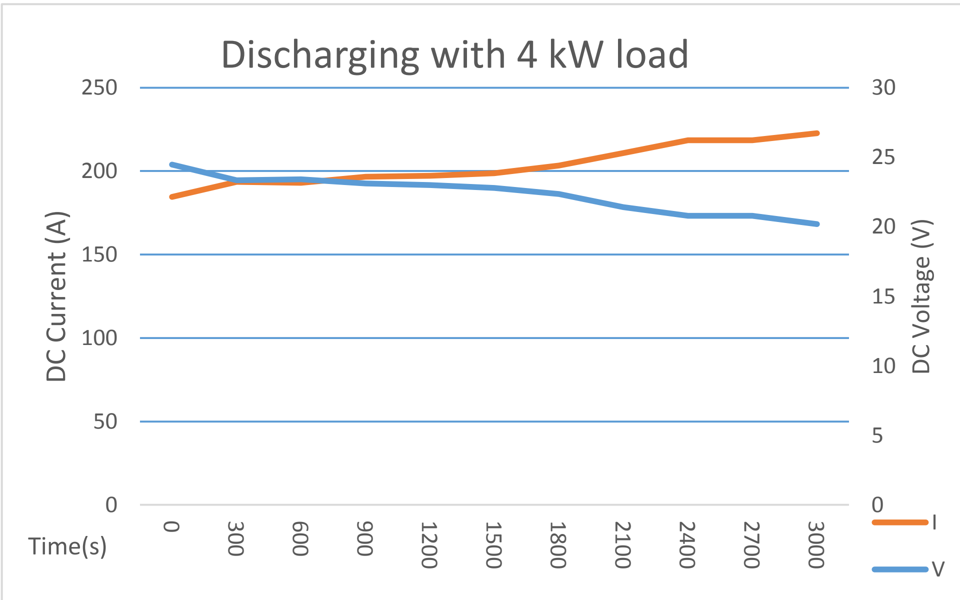

Figure 38 discharging with 4 kW power

The characteristic for the discharging' of batteries at 4 kW shows the batteries has lower efficiency at higher rates discharging. For a 4 kW discharging, the batteries could only last for less than one hour which means the electrical power supplied by the batteries is less than 4 kW.

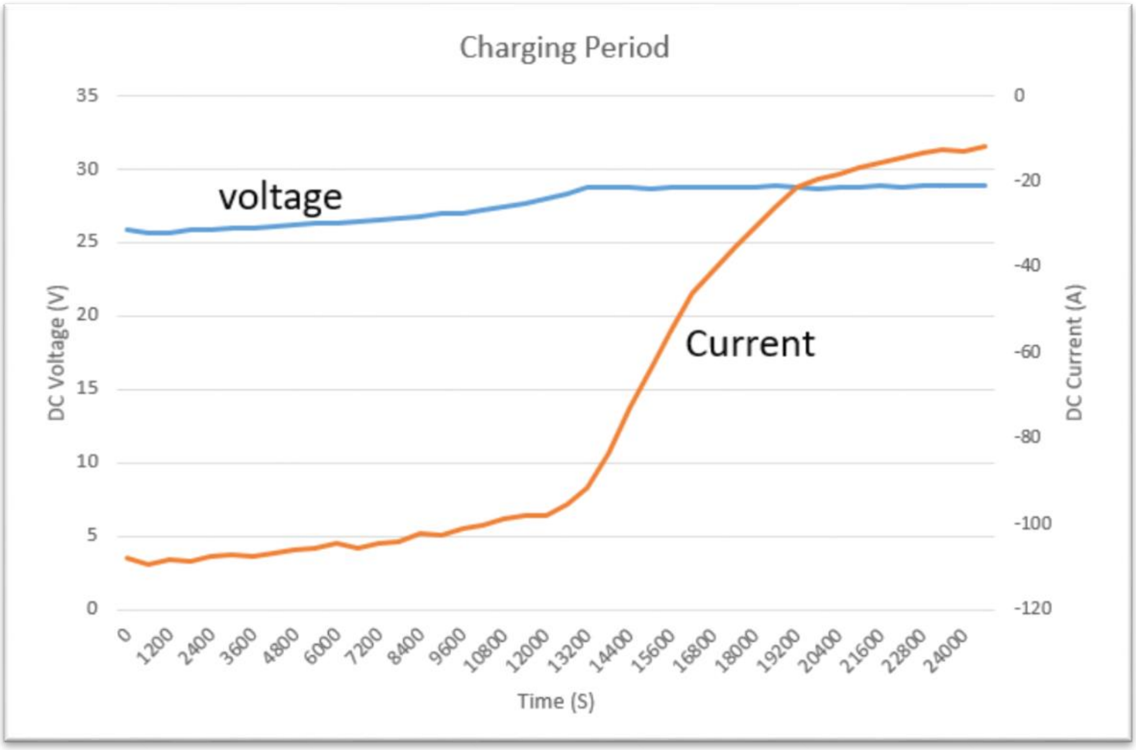

Figure 39 Charging with regulated power

The charging the batteries is regulated by the component Multiplus. It works as converter and inverter in the project. The value of charging current is allocated as 100 A at most of the time. Normally the charging of the batteries could be divided to three stages. The first stage supports the highest amount of electricity charging. During the charging process, the voltage changes from 22 V to 26 V in the first two hours. In the last two hours of the charging time, the voltage kept at a certain level which means the charging process entered the float region.

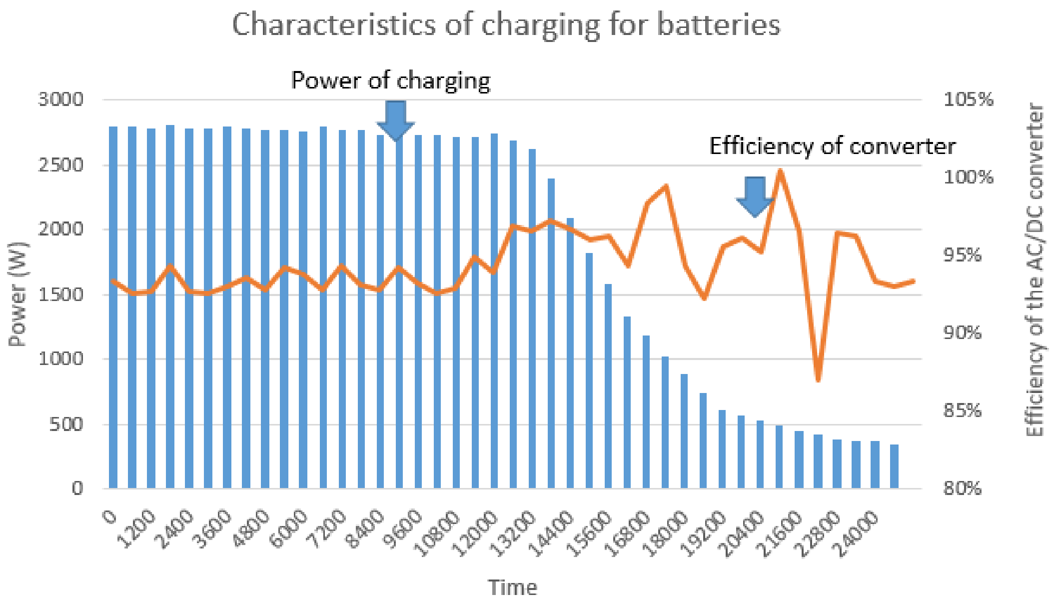

Figure 40 Charging characteristic shown in excel

Since the initial tests are carried out to test the batteries, the most important indicators are voltage and current. A batteries' charging figure with the efficiency is shown in Figure 40. During the charging process, the efficiency of the batteries kept at a high level which exceed more than 90 %. In the charging process, the rate of charging has obvious two phases. In the first phase, the charging power kept at 2.7 kW for 2 hours. In the second phase, the charging power varied as linearly from 2.7 to less than 0.6kW in 1-hour time. When the batteries were nearly fully charged, the charging rate kept at a low level around 0.5 kW for remaining the power of the batteries. At this stage, the batteries are nearly 100% charged.

4.1.6 Energy storage efficiency

This section analysis the energy storage unit's efficiency based on the preliminary test results. In the electric energy storage system, the supercapacitor has little energy waste during the electricity's storing and discharging. Therefore, the efficiency study focus on the process of batteries' charging and discharging.

Traditional batteries in this project for now are lead acid batteries. Lead-acid batteries are one classic type of electrical energy storage units. The electrode of lead acid batteries is made of lead. The lead acid batteries transfer chemical energy to electrical energy. Because of the limitation of the chemical process, the power rate and the efficiency of the lead acid batteries are limited. The batteries in this project are working with the Multiplus which is an equipment charging and discharging the batteries with serval stages. Based on the former research by Mashers, the multi-stage charging and discharging method could improve the efficiency of the batteries[55]. From the experimental test carried on the batteries, the efficiency of the batteries could be illustrated by the Table 23 shown.

Discharge power level Performance indicators	1kW	2kW	3kW	4kW
Energy released (Wh)	8000.3	7296.26	6887.23	6588.06
Energy consumed (Wh)	6846.71	8257.03	7849.10	7516.11
Discharge duration (hours)	7.83	3.50	2.42	1.63
Charge duration (hours)	3.88	3.48	3.32	3.18
Energy efficiency (%)	92.02	88.36	87.75	87.65
SOC at discharge end (%)	41.1	35.5	30.8	25.5
Discharge Capacity (Ah)	325	299	287	284

Table 23 Performance indicators summary Table

The supercapacitor has some advanced features, which are suitable for this system. The supercapacitor has much higher efficiency than normal battery units do. Even with the high current charging and discharging, the Coulomb efficiency is still higher than 99%. Compared to traditional batteries, Supercapacitor uses much less time to charge and discharge which make it produce much less heat in its operation period. Supercapacitors also support high current operation. A Large pulse of energy demand could be satisfied since the supercapacitor could discharge the energy with the much higher current.

With the combination of the batteries and the supercapacitor, the system could have a high capability of supplying the dynamic energy demand. Most lost caused by the energy storage units occur in batteries. The supercapacitor is designed to work only for energy demand peak. Because of the supercapacitor has much higher efficiency than batteries and the working period is much shorter, in the project, the energy loss of the supercapacitor will be neglected.

4.2 Electrical system controlling strategy design

For the design of the electrical part of the trigeneration with ORC, the ORC is added for to the trigeneration system. When the engine is running at half or full load (The SOC of the energy storage units is low or power demand larger than 6.5 kW) heat is available for use to drive the ORC and the ORC unit starts to generate electrical power. The key point of the strategy is to balance energy resources and the energy demand. Once the unnecessary energy consumption is avoided, the maximum efficiency can be obtained. This research aims at designing and implementing adequate controlling by the approach of adjusting the working sequence of the switches in the system in where shown in Figure 41.

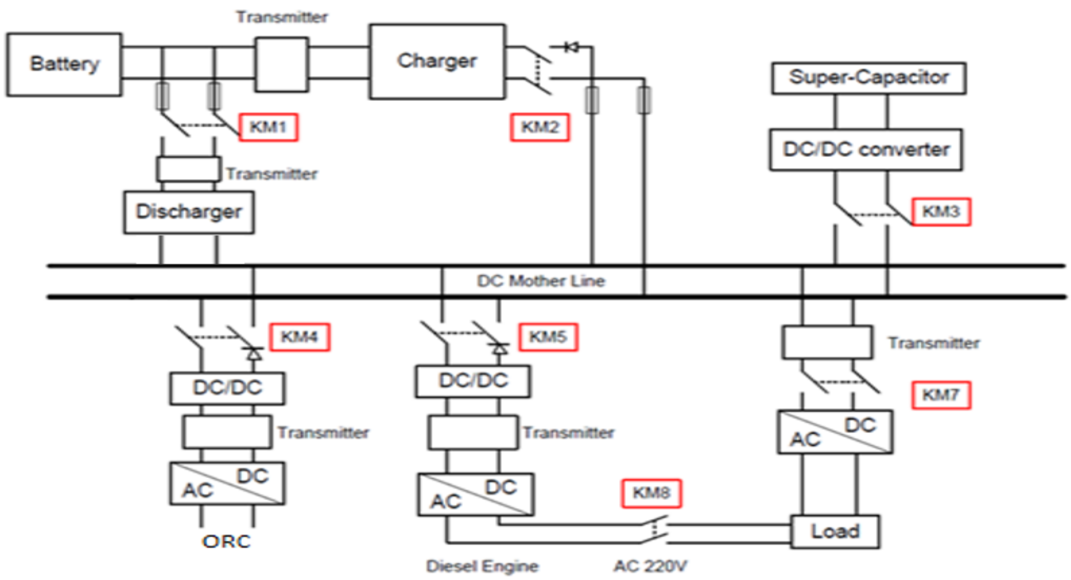

Figure 41 System configuration.

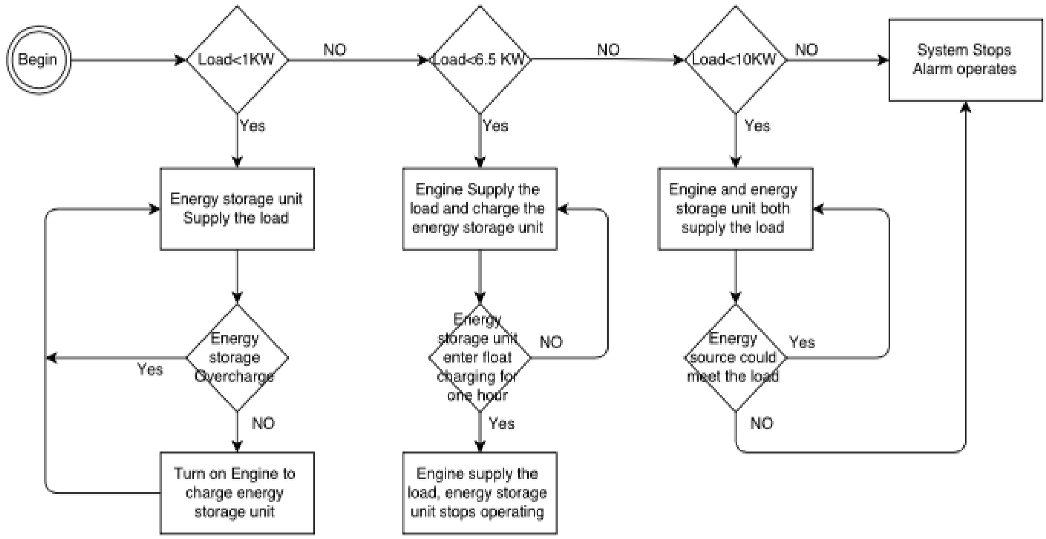

Figure 42 Operation logic map for the system.

All the electrical equipment in the grid system can be controlled by the controlling switch from KM1 to KM 8. KM 8 prepares to stop the diesel engine's operation when a fault in fact occurs. The normal state of the switch KM 8 is off. The energy source in this project includes diesel engine generator and the ORC (generator). Different situations refer to various operation modes.

4.2.1 Control strategy for the system without ORC

1) When the load is less than 1 kW: When the power offered by the batteries and the super-capacitors could meet the energy demand KM1, KM, and MK7 are closed while the others switches are open. In this state, the energy demand is supplied only by the batteries and the super-capacitors. When the energy storage could not meet the energy demand, the diesel engine needs to operate to supply extra energy for the load. In that state, KM2KM3, KM5 and KM8 are closed while the other are open. When the batteries and super-capacitors are fully charged, the system will turn to the former operation state.

2) When the load is larger than 1 kW and less than 6.5 kW, the diesel energy will operate for supplying energy. At the same time, the energy storage will be charged. In

this state, KM1 and KM7 are open while the other are closed. (KM 4 is always open since ORC is not applied)The controlling system will stop charging when the energy storage system finished one hour of floating charging. At that time KM2 and KM4 are changed to open.

3) When the load is larger than 6.5 kW and less than 10 kW, the diesel engine will work with the storage unit together for supplying energy. The maximum energy rate can exceed 10 kW. In this state, KM1, KM3, KM7 and KM8 are closed while the other switches are open KM 4 is always open since ORC is not applied. When the capacity of the energy storage unit is low, alarm will respond and gives a warning. KM1 will be set as closed to protect the energy storage unit for over discharge. If the energy storage unit is in a state of severe over-discharge, then KM 2 will be open with an alarm.

4.2.2 Control strategy with ORC

When the system has multi-energy sources that includes ORC and diesel generator, the operation strategy will have some adjustments because of the output rate of the ORC system.

1) When the load is less than 1 kW: When the power offered by the batteries and the super-capacitors could meet the energy demand KM1, KM, and MK7 are closed while the others switches are open. In this state, the energy demand is supplied only by the batteries and the super-capacitors. When the energy storage could not meet the energy demand, the diesel engine needs to operate to supply extra energy for the load. In that state, KM2KM3, KM5 and KM8 are closed while the other are open. When the batteries and super-capacitors are fully charged, the system will turn to the former operation state.

2) When the load is larger than 1 kW and less than 6.5 kW: The diesel engine will begin to supply energy with the energy from ORC system. The energy storage unit is in a state of charging. The logic state is that KM1, and KM7 are open while the other

switchers are closed. The energy storage unit is a set of floating charging, and the charging circuit will stop one hour after float charging. Then, the KM2 is open in case of over charge.

3) When the load is larger than 6.5 kW and less than 10 kW: All of the energy sources will supply the load. The maximum power rate can exceed 10 kW. The logic state is that KM1, KM3, KM4, KM7 and KM8 are closed while the others are open. When the capacity of energy storage units is not sufficient for supplying energy, KM1 will switch to open with alarm to stop the discharging. A safety relay is responsible for cutting the system when the power exceed 10 kW.

4.3 System configuration in the experiment

The experiment is carried out on the real proportional equipment to meet a domestic fluctuant electric power demand with hybrid energy storage system. The electric part of the trigeneration system can operate separately to supply the electric load in the test. Similar components are adopted in the test. Although the components are not exactly identical with the system's original design, the functions of the components are the same with the original system design. The details of experiment setup is introduced in the following paragraphs. The simulation of the system is implemented in the Matlab software. The model was verified with the experimental test and adjusted based on the parameters of each component in the system. The key components are introduced in the following section.

4.3.1 The second experimental bench configuration

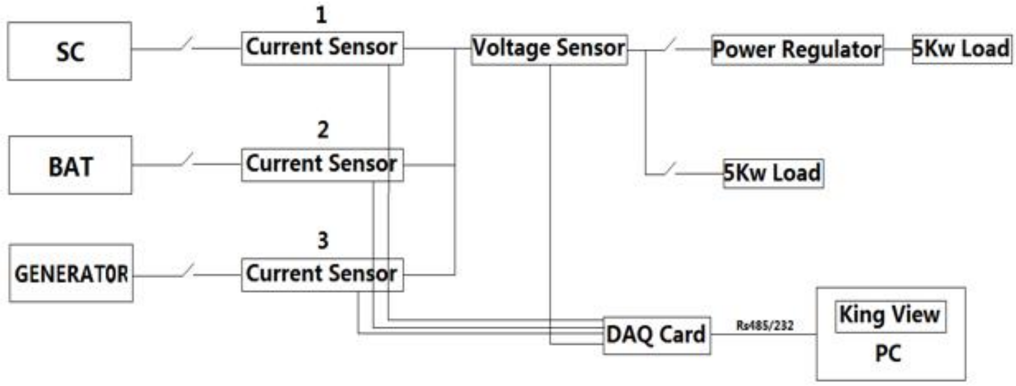

Figure 43 Schematic diagram of the experimental test rig of distributed power generation system with energy storage system

The systematic Figure 43 shows the connection of the electric part of the trigeneration system. The main components of this part of system are the prime mover (electric generator), the batteries, the supercapacitor, the adjustable load and the data logging system. The prime mover is connected parallel with the energy storage. The monitoring equipment on the energy storage system includes of the current and voltage sensors are connected with the data logging equipment's for continuous data measuring. During the experimental test of the system, the signals are transmitted to the data logging card which can be monitored and control by the King View software.

4.4 The electrical loads

The test is designed to supply energy for a continuously changing small-scale load. The load is simulated by a changeable load based on the electricity consumption data collected and analysed in chapter 3. The selected data shows high resolution of electricity demand of a household for 24 hours on a summer day and a winter day respectively. In the test, the changeable load is adjusted manually to simulate the energy consumption of a summer day and a winter day.

4.4.1 Generator

For guaranteeing the safety and the reliability of the experimental test on the electric part of the energy system, a stable energy supplier is integrated into the system. In the distributed trigeneration system, a diesel engine supplies the energy for the system. In the experimental test, the adjustable load simulates the domestic energy demand and this energy demand must be satisfied instantly during the system' operation. In this test, a direct-current power module was used to provide the electric energy output to meet the demand, which has the same function as the diesel engine.

Figure 44 power supply unit

4.4.2 Hybrid energy storage system

The hybrid energy storage system consists of the lead-acid batteries and the supercapacitor. It operates as auxiliary energy supplier for the system. The lead-acid batteries and the supercapacitors are connected in parallel. The energy storage system is responsible for the system's energy supplying during the off-peak time. During the peak time, the energy storage system can either support the engine to supply energy or be charged with extra energy.

4.4.3 Battery

The batteries applied in this experimental test is lead-acid battery. During the off-peak time, the lead –acid batteries are responsible for most of the energy supplying. It indicates that the system need a stable and reliable energy source in the energy storage system. Lead-acid battery has been recognized as the most cost efficient of electric power storage equipment currently. For accessing the maximum energy consumption efficiency, a suitable capacity should be applied into the system. A various range of capacity have been considered during picking the battery's size such as 7, 17, 24, 38, 65,100,120,200,250AH. After calculation, the most appropriate capacity of battery 12V 38AH capacity is chosen to achieve the longest operation life.

Figure 45 Lead-acid battery

4.4.4 Supercapacitor

The Figure 46 shows the construction of the supercapacitors. The supercapacitor unit consists of 18 individual supercapacitors. They are connected each two in parallel and nine sets in series. The supercapacitors in this test are responsible for supporting the batteries to supply energy when energy demand increase unpredictably. The 12V 300F supercapacitor is selected in the study. The supercapacitor is responsible for supplying additional power for the load. In the energy storage system, it is connecting parallel with the battery. The power release can be calculated by its voltage drop based on the formula

$$P = 1/2C(U_1^2 - U_2^2) \qquad 1\ [190].$$

Figure 46 Supercapacitor

4.4.5 Load designed and integration

The load in the experimental test is a real-time simulation of a dynamic domestic load. For reaching the maximum range of domestic energy demand changing, two 5kW adjustable load are connected in parallel to simulate the fluctuations of a real-time household load. The integrated load can continuously provide energy consumption from 0-10kW including the fluctuations additionally, a resistance is also connected in series for limiting the discharging power rate of the load for safety concern.

Figure 47 The electric chopper of load

4.4.6 Data acquisition system

The data acquisition card is connected with the voltage sensors and the current sensors. It is managed by the software named KingView. The real-time data is record during the experimental test. Different from the generation, the energy storage system has two working mode which needs the DAC card to have two different status (discharging and charging). Therefore, a specially designed signal amplifier is applied which is used for adjusting circuit and obtaining the bidirectional current data.

Figure 48 The data acquisition card S3100

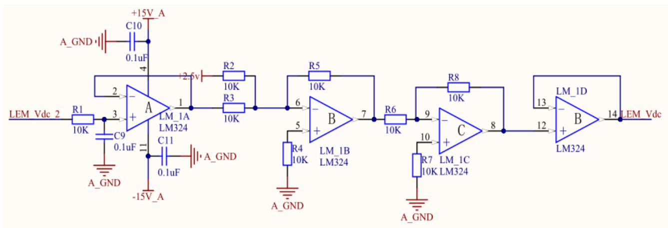

Figure 49 Designed schematic diagram of signal condition circuits

The construction of the amplifier is shown as the Figure 50. Four operational amplifiers are combined to process one signal conversion. A PCB board combined six channels as well as a LM324 chip is applied in the experimental test. A positive and negative current with 15 voltage source is applied for the panel for power supply.

Figure 50 Designed hardware of signal condition circuits

Kingview is a high-performance configuration software using for recording real-time data system. With two hours of preliminary trial test, the Kingview has been proven its ability to record test data of the experimental in stable state. The designed interface of monitoring configuration allows 4 channels of current signals and 1 channel of voltage signal. There is a database which record all of data per second. The database is also available to check the data for certain period at any time. The stored data will finally be transformed to excel format which can be further discussed and analysed.

4.5 Experimental test results

The results include the power performance of the main components. The results of the experimental is divided to two sets, which are summer load test results and winter load test results. During the experimental test, the energy required is adjusted manually which follows a basic human activity pattern. As a real-time experimental test, the energy consumption in the experimental test does not fit the raw energy demand data exactly. The details of the results and the discussion of the test are displayed in the following section.

4.5.1 Experimental result on typical summer day

The Figure 51 shows the data recorded in the experimental test. During the test, the generator supplied the domestic load for 24 hours with the help of the electric energy storage units. The four lines in the Figure 51 are load required, energy supplied by batteries, energy supplied by supercapacitors and generator's power respectively.
The adjusting of the electric load in this test follows the features of the human activities. There are a few energy demand peaks during the 24 hours which happen in the morning when people are getting up, in the afternoon when people are back home and in the evening before sleep. The two-main peak occurs at round 05:00 am and at 17:00 pm. Most of the peak energy demand last for short time.
In the Figure 51, the energy supplied by the generator and the energy storage units follow the shape of the energy demand. The generator are designed to be operating only in the peak time. In the two main peak energy demand, the generator supplied most of the energy for the load. During the rest of time, the batteries and the supercapacitor supply the energy for the load. As mentioned in the last section, the batteries in the test has larger capacity. In the experimental test, the batteries supplied twice amount of the electricity compared to the supercapacitors. Batteries take responsible to the major amount of energy demand and the supercapacitors supplied fewer energy at the same operation period. The power of batteries and supercapacitor are positive means the energy storage units are discharging the power to the load. When the value are negative, it indicates the energy storage units were in charging process. Supported by the hybrid energy storage system, the system can satisfy the electric load for during the whole test. The test also validates the function of the supercapacitors. Since the dynamic load has sudden changing of power demand, the lead-acid batteries cannot supply the energy demand instantly because of the internal chemical reaction. With the integration of the supercapacitors, the hybrid energy storage system has better response on the changing of the energy demand.

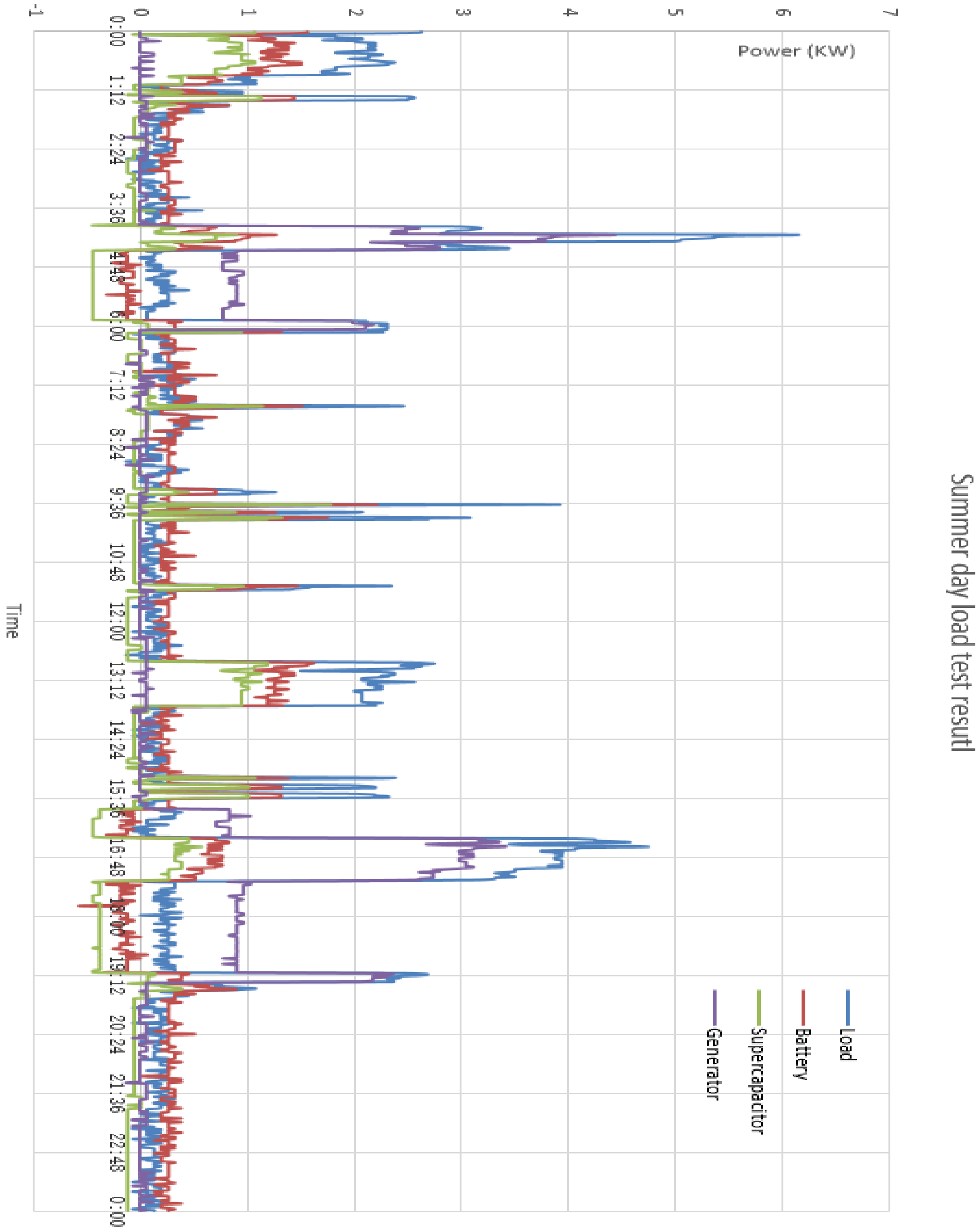

Figure 51 Summer day load test result

4.5.2 Experimental result on typical winter day

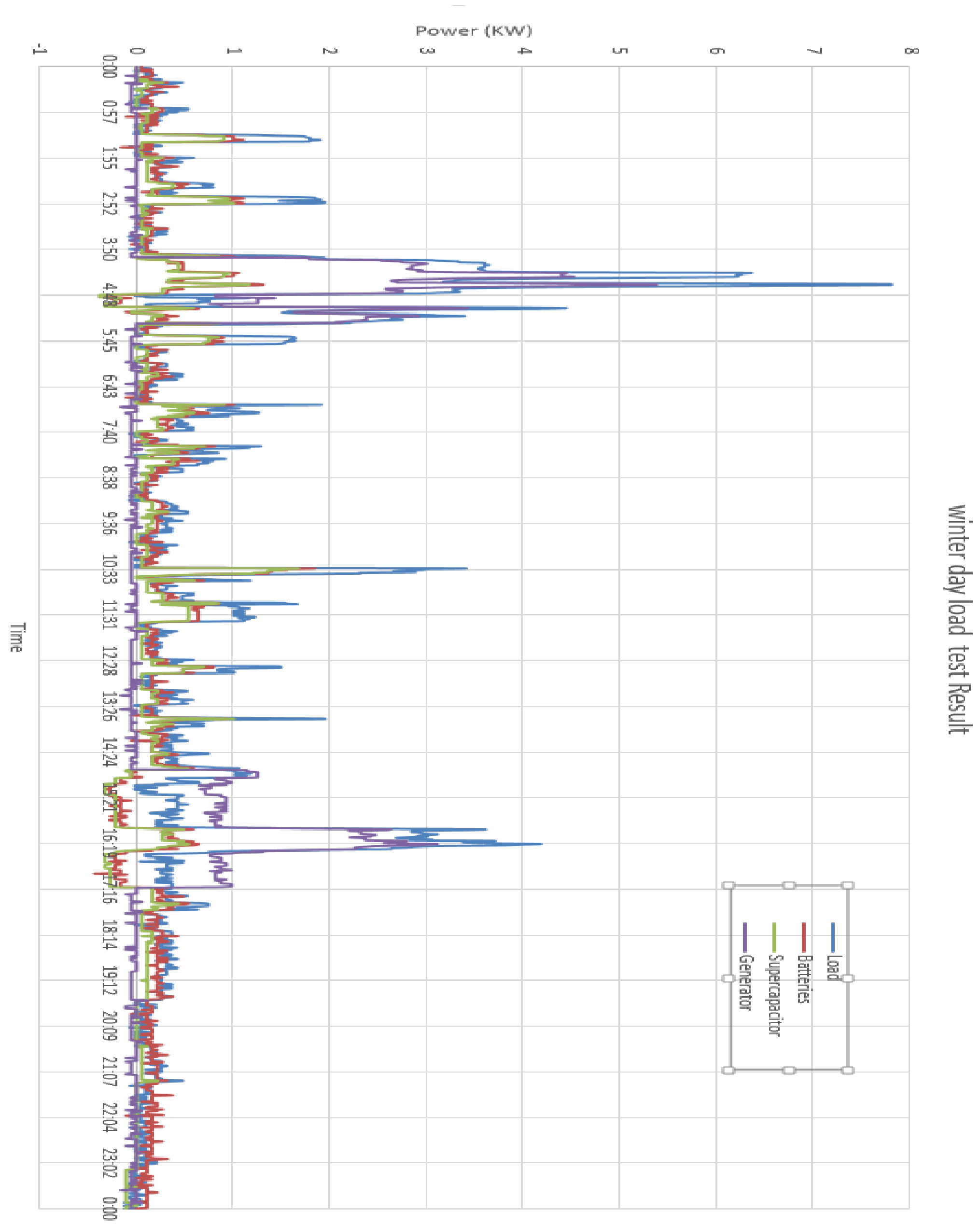

Figure 52 Winter day test results

Similar with the test on the summer load, the second set of experimental test on this system is using the system to supply the dynamic load of a winter day. In this experimental test, the energy system supplied a winter day load for 24 hours. The configuration of the energy system is same with the experiment the test of summer day load. The energy demand of the winter day is similar with the summer day, the peak energy demand last for short time. During most of the time in the 24 hours the energy demand is less than 2 kW. From the Figure 52, it shows that the two-main energy demand peak occurs in the morning and in the evening. The energy demand in the morning has the highest energy consumption rate which is up to 8 kW. There are anther two peak demand in the rest of the day reached 3.7 kW (in the noon) and 4.1 kW (in the evening). In the experimental test, the power requirement, the power rate of the generator and the power of storage units are recorded. The shape of power supplied by the system followed the power requirement in the test. As shown in the Figure 52, the generator operated only in the time of peak energy demand. When the generator's power is higher than the power demand, the extra energy is used to charge the energy storage units.

From the results of the two sets of tests carried on the system, the electric part of the system can satisfy the dynamic load on both summer day and winter day. During the peak time, when batteries' power is not enough to supply the load, the supercapacitor supplied a certain part of power in short time to make up the gap between supplier and the load. Using the following electric load control strategy makes the engine to work only at peak time. Integrating the energy storage system, the system can fulfil the load with less energy consumption compared to conventional energy system.

4.6 Summary of chapter

In this chapter, the experimental tests are introduced. There are two parts of test study. The first test focuses on the energy storage system. The second experimental study evaluates the system's performance of electricity supplying. In the beginning of the chapter, the system's configuration is introduced. Then the installation process of the test bench of the first test is introduced. Detail information about the components are explained in the installation process. The results of the first test are measurements of current and voltage of the energy storage system. From results of the test, expected operation of the energy storage system is obtained. The efficiency of the energy storage system is calculated from 90% to 99%. The capacity of the energy storage system is also measured.

The control strategy for the integrated system is designed and introduced. The control strategy is divided from two parts: strategy for the system without the ORC system and strategy for the system with the ORC system. The operation of the system is introduced in detailed with the help of the system’s configuration map.

The second experimental study evaluates the system’s performance of supplying dynamic electricity demand. The system‘s components are introduced. The results include the system’s performance on supply load on typical summer and on typical winter day. In both load scenarios, the system supplies the dynamic load successfully. The experimental tests collects key parameters for the system. The experimental results shows the system’s operation is predictable. This part of study is preparation of simulation study. Obtaining the system’s performance in tests for validation are necessary for the system’s further research.

5. System model building and simulation study domestic loads

5.1 Introduction of Modelling for the system

Modelling of the system is an important approach of investigating the performance of the system. Based on the theoretical knowledge on the system's components, the simulation models are established in Matlab Software. The model's building is based on the mathematical expression of each component. The math equations are built by mathematical blocks and the blocks constitute the components of the system. Since the experimental tests carried on the system measures the key parameters of the system. Using the measured parameters as standards, adjusting the parameters of the components in the Matlab simulation as a validation of model improves the accuracy of the simulation study.

The simulation researches the operation performance of the system such as, the energy output, the operation of the control system. These key factors are simulated to predict the system's ability of supplying dynamic load in different scenarios. The first part of this section is the model building of the system. The theory of model building and the validation of each component are described in detail. The results and discussion of the simulation study incudes the simulation study of the electric part of the system, the output of the ORC system and the performance of the integrated system. Each of the simulation system evaluates the system's performance by supplying a few sets of dynamic loads.

5.2 key components modelling

5.2.1 Engine model building

Figure 48 Picture of engine

Characteristic	value	unit
Engine model	YTG6.5S	
Engine displacement	0.638	liters
operation condition	ambient temperature not exceeding 50 °C	
cylinder bore	92	mm
cylinder stroke	96	mm
Combustion system	Direct injection	
Fuel tank capacity	11	liters
Fuel consumption	2.8	lit./h
Revolutions	2400	rpm
Max Power	8.8	kW

Table 24 Engine parameters

According to the design of the system configuration, the primary energy source is the diesel engine. The generator driven by the diesel engine produces the system's electricity. The energy source is diesel oil. The Fuel is injected in the engine and the single-phase AC generator generates the electricity. The waste gas generated by the generator is the energy source of the waste heat recovery system. The specific information about the diesel engine is shown.

The diesel engine used in this project is YANMAR YTG 6.5 S. It is the prime mover of the integrated system, which is naturally-aspirated, four-stroke single cylinder engine. The coolant fluid and the exhaust gas is also connected with a waste heat recovery system for maximum utilizing the waste energy produced by the engine. The energy transferring process in the diesel engine is closely related with the energy converter components. For accurate simulating the energy source, the mathematic model building is significant for the research in the project. The mechanical power is considered as equal to the generated electrical power.

Equation for the generator:

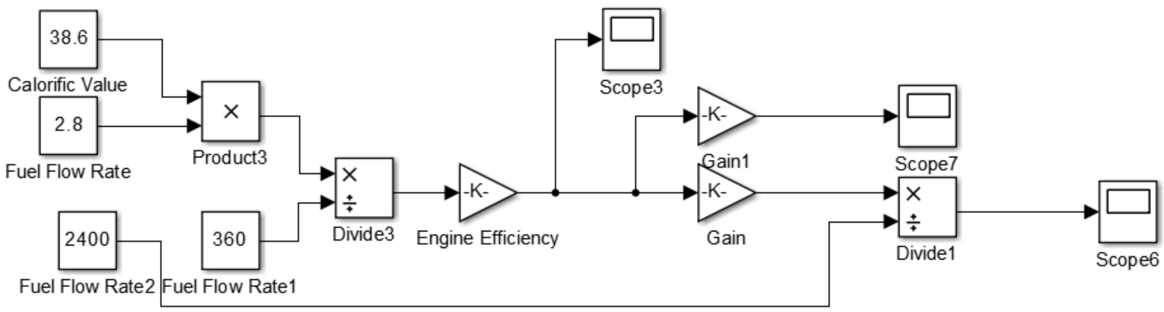

Figure 53 Model of generation

$$T_d\Omega = EI_A$$

$$E = K\varphi\Omega$$

(1) $$T_d = K\varphi$$

In the equation,

E	Generated Electromotive Force (EMF) in volts
φ	Air gap flux per pole in webers
Ω	Angular velocity in radians per second
T_d	Developed torque in newton-meters
I_A	Armature current in amperes
K	constant for the given machine

Table 25 parameters introduction

This set of equations show the static state of a generator set. The relationship between electrical parameters and mechanical parameters are reflected in these equations. The dynamic characteristics of the generator

Base on the equation listed, the model of generator is established in the Matlab software. Related data is available in the data sheet of the generator for the model building. The output of the generator is corresponded with the parameter given in the data sheet.

Load of the engine (%)	Engine efficiency (%)	Error (%)	Recovery rate simulation (%)	Error (%)
0	0	0	0	0
10	7.8	1.13	35.36	0.079
25	16.36	0.36	35.38	0.025
50	24.3	0.41	35.39	0.027
75	27.53	0.82	35.41	0.138
100	28.5	1.42	35.44	0.137

Table 26 energy output in the simulation

More detailed information is in appendix 2.

From a fixed time simulation on the engine's model, the output of the simulation is shown. The simulation results are divided by 5 sets with different load. From the comparison between the simulation results and the experimental test results. The engine's electrical power output and the recovery heat simulation have error less than 1.42%. These results indicates that the simulation of the engine can represents the operation performance of the engine applied in this project.

5.2.2 Modelling of the hybrid energy storage system

5.2.2.1 Batteries

The batteries are main electricity storage units in the same energy storage system. The batteries are lead acid batteries. From the literature review, the reason of the choice of this batteries is stated. In this section, the operation principle of this batteries is introduced and the simulation of this batteries is based on the knowledge of the batteries. The charging and discharging process are expressed as mathematical

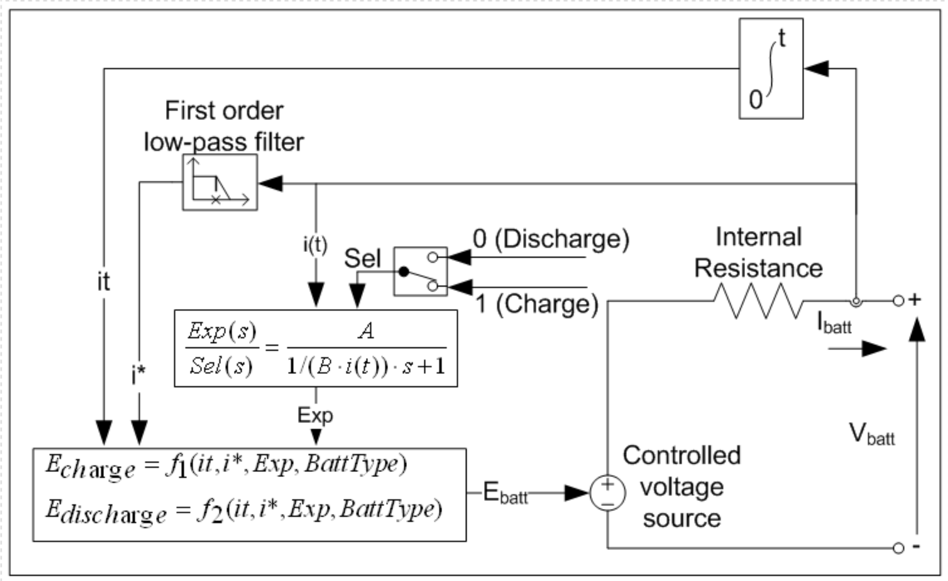

Figure 54 Theoretical battery model in Matlab[1]

expressions below. Parameters are connected in the Simulink block shown below. The Figure 54 is a battery block which simulates the generic dynamic performance of a certain model of battery. The model is parameterized to represent the most popular types of rechargeable batteries. In this project, the lead-acid batteries set is simulated with this model by regulating appropriate parameters inside the model. The input side is the DC voltage connected with the batteries. The output of the block is the performance generated by the simulations. Based on the charge of the state, the operation mode could be controlled during the simulation process of the battery. The data of performance could also be collected after simulation. The discharging and charging functions are shown,

Lead-acid batteries model

$$f_1(it, i^*, i, Exp) = E_0 - K \cdot \frac{Q}{Q-it} \cdot i^* - K \cdot \frac{Q}{Q-it} \cdot it + Laplace^{-1}\left(\frac{Exp(s)}{Sel\,(s)}\right)$$

(2) [1]

$$f_2(it, i^*, i, Exp) = E_0 - K \cdot \frac{Q}{it+0.1 \cdot Q} \cdot i^* - K \cdot \frac{Q}{Q-it} \cdot it + Laplace^{-1}\left(\frac{Exp(s)}{Sel\,(s)} \cdot \frac{1}{s}\right)$$

(3) [1]

Where:

E_0	Constant voltage (V)
$Exp(s)$	Exponential zone dynamics (V)
$Sel\ (s)$	Represents the battery mode $Sel\ (s)$ = 0 during battery discharge, $Sel\ (s)$ = 1 during battery charging.
K	Polarization constant (Ah−1) or Polarization resistance (Ohms)
i^*	Low frequency current dynamics (A)
it	Extracted capacity (Ah)
Q	Maximum battery capacity (Ah)

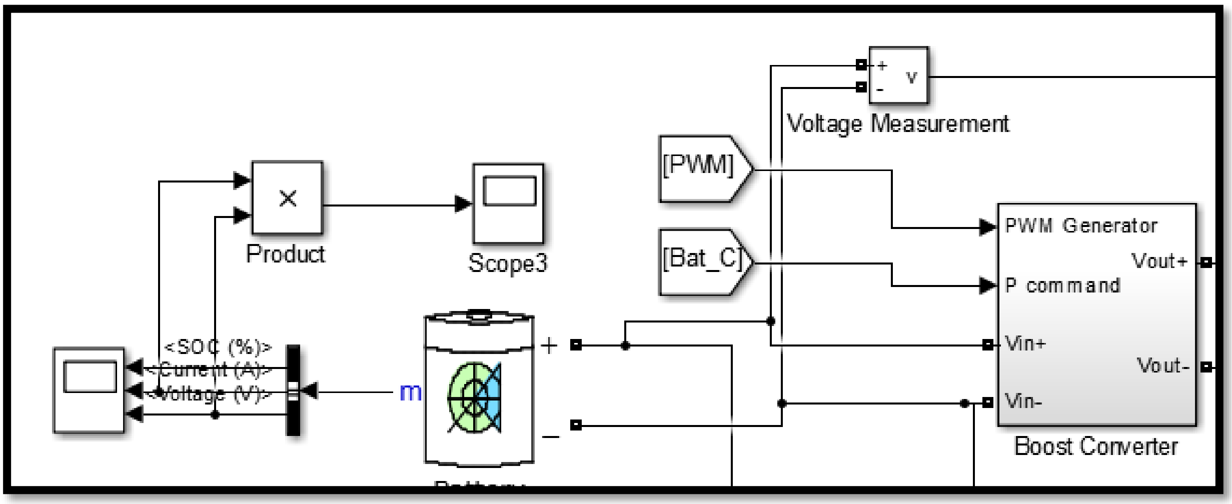

Figure 55 Battery model in the Matlab

The Figure 55 shows the batteries' model in the simulation environment Matlab. The model is connected with the boost converter for connecting the DC voltage bench. The battery is applied with a variable load for discharging. The charging of the batteries is regulated by the mathematic model sharing sources. Based on the results of the experimental tests charging characteristic is corresponded to the performance of the batteries in the lab.

5.2.2.2 Validation of the battery model

Smart energy storage units are the most important components in the electric power cycle. The smart energy storage units makes the system to be able to handle wider range of load. For accurate estimating the performance of the system, the validation of the smart energy storage is necessary in this project. The simulation results of the smart energy storage units are compared with the experimental data. The table 27 shows the numbers and the errors.

Batteries simulated in this project for now are lead acid batteries. Lead-acid batteries are one classic type of electrical energy storage units. The electrode of lead acid batteries is made of lead. The lead acid batteries transfer chemical energy to electrical energy. Because of the limitation of the chemical procession, the power rate and the efficiency of the lead acid batteries are limited. In the experimental tests, the batteries in this project are working with the Multiplus which is an equipment charging and discharging the batteries with serval stages. Based on the former research by Mashers, the multi-stage charging and discharging method could improve the efficiency of the batteries[55]. From the experimental test carried out on the batteries, the efficiency of the batteries is illustrated by the table 27,

Discharge power level Performance indicators	1kW	2kW	3kW	4kW
Energy released (Wh)	8000.3	7296.26	6887.23	6588.06
Energy consumed (Wh)	6846.71	8257.03	7849.10	7516.11
Discharge duration (hours)	7.83	3.50	2.42	1.63
Charge duration (hours)	3.88	3.48	3.32	3.18
Energy efficiency (%)	92.02	88.36	87.75	87.65
SOC at discharge end (%)	41.1	35.5	30.8	25.5
Discharge Capacity (Ah)	325	299	287	284

Table 27 experimental results used validate the simulation

The Table 27 shows the experimental test results. Data in the table is obtained from the experimental tests on the energy storage system. In the basic tests, the value of the batteries' voltage and the current are recorded by the sensors. The results are collected by the software LabView. In the test, the energy saturates units are tested with different loads which are 1 kW, 2 kW, 3kW, and 4kW. In the project, the peak power requirement of the energy storage units is 5 kW. Most of the cases, the power demand for the energy storage units are less than 3 kW. This indicates the power range of basic tests could cover the operation of the energy storage units.

The Figure 56 shows the error of the simulation. From the Figure 56 shown, with different load, the error of the batteries is different. When the batteries are supplying 1 kW and 2 kW load, the value of error varies between -0.6% and 3.7 %. And the error is larger in the beginning compared to the end of the test. When the load is more than 2 kW, the simulation has less error compared to the low load. During all the comparison, the error is controlled within the range of 3.7% which is acceptable for this project.

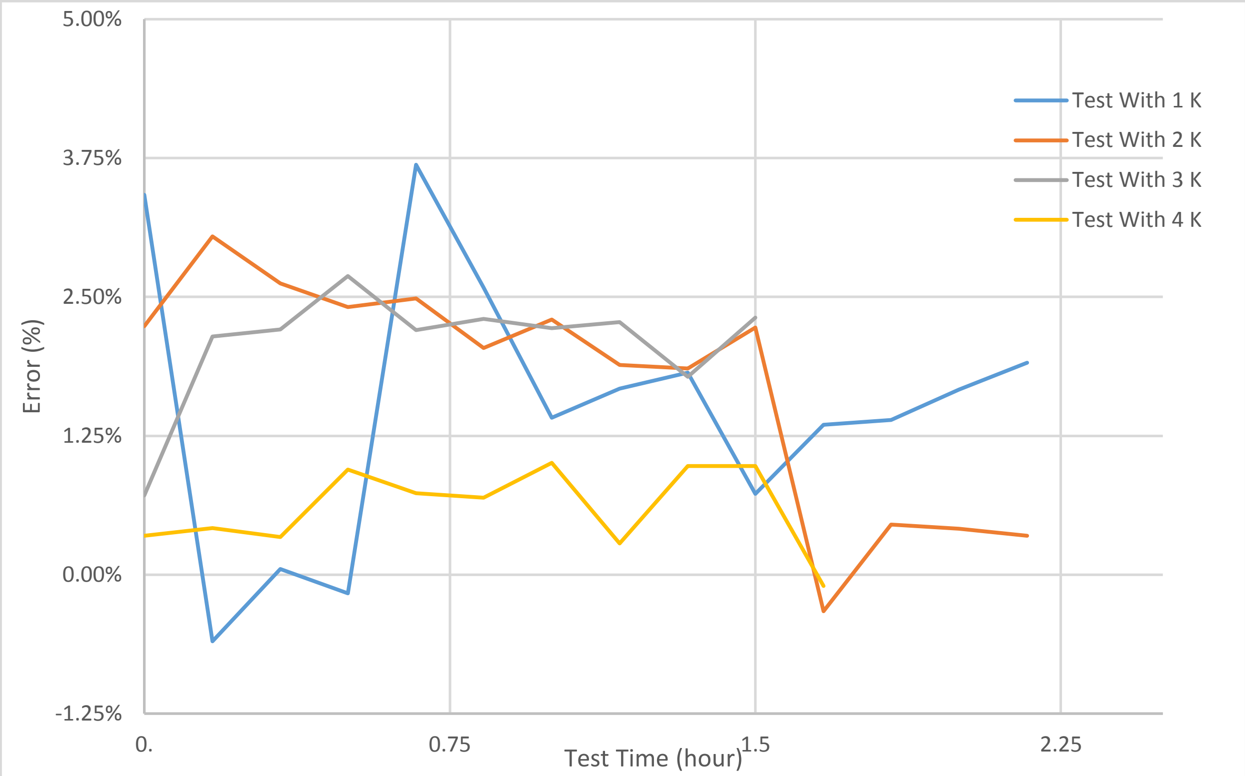

Figure 56 Errors in power during different rates' operation

5.2.3 Supercapacitor

A supercapacitor is working together with the batteries in the projects. The supercapacitor has some advanced feature which are suitable for this system. The supercapacitor has much higher efficiency than normal battery units do. Even with the high current charging and discharging, the Coulomb efficiency is still higher than 99%. Compared to traditional batteries, Supercapacitor uses much less time to charge and discharge which make it produce much less heat in its operation period. Supercapacitors also support high current operation. A Large pulse of energy demand could be satisfied since the supercapacitor could discharge the energy with the much higher current.

Supercapacitor is another one important energy storage units in this project. For meeting the dynamic energy demand for the applied loads, the supercapacitor is integrated within the energy storage unit to offer a high density of power. Based on the theory of the supercapacitors[191], the model was build following the construction of the Figure 57 and the equations displayed in Figure 57.

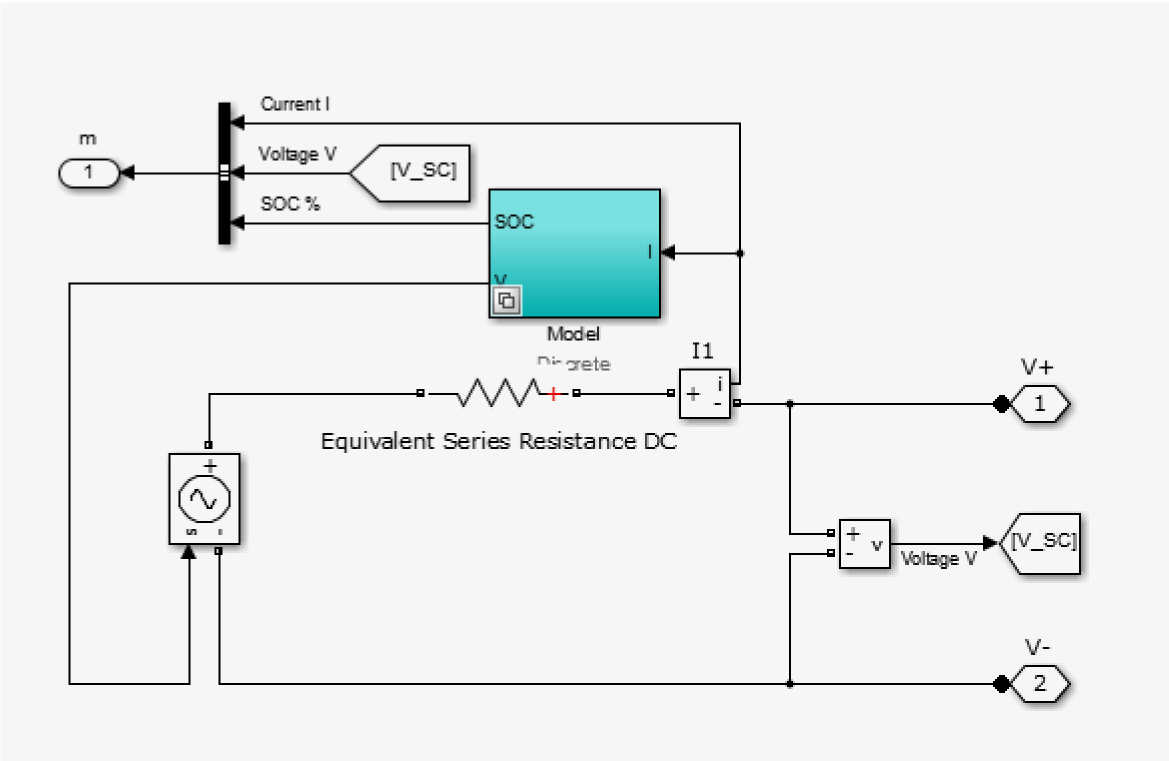

Figure 57 Simulation model in Matlab[192]

$$V = \frac{NN_8Qx_2}{N_pN^2\varepsilon\varepsilon_0A} + \frac{NN_8 2RT}{F}\, arsinh\left(\frac{Q}{N_pN^2A\sqrt{8RT\varepsilon\varepsilon_0 c}} -\right) i_c(t) = Ai_0\exp\left(\frac{aF\left(\frac{V}{N_8}-\frac{V_{max}}{N_8}-\Delta V\right)}{RT}\right)N$$

[192] (4)

Equation 1 Super-capacitor's equation

Where:

Variable	Description
A	Interfacial area between electrodes and electrolyte (m^2)
c	Molar concentration (mol m^{-3}) equal to c = 0.86/(8NAr3)
F	Faraday constant
i	Current density (Am^{-2})
i_0	Exchange current density $i_0 = i_f$/A (Am^{-2})
i_f	Leakage current (A)
N	Number of layers of electrodes
N_p	Number of parallel supercapacitors
N_s	Number of series supercapacitors
Q	Electric charge (C)
R	Ideal gas constant
r	Molecular radius equal x^2
a	Charge transfer coefficient
ΔV	Over potential
ε_0	Permittivity of free space

Table 28 Parameters in the super-capacitor's model

The equation shown is the theoretical expression about the supercapacitors. The model implements a general model of the supercapacitor model which expresses the voltage, current and SOC during the supercapacitor’s operation. By adjusting the parameters inside the model, the model’s performance could fit the present standard.

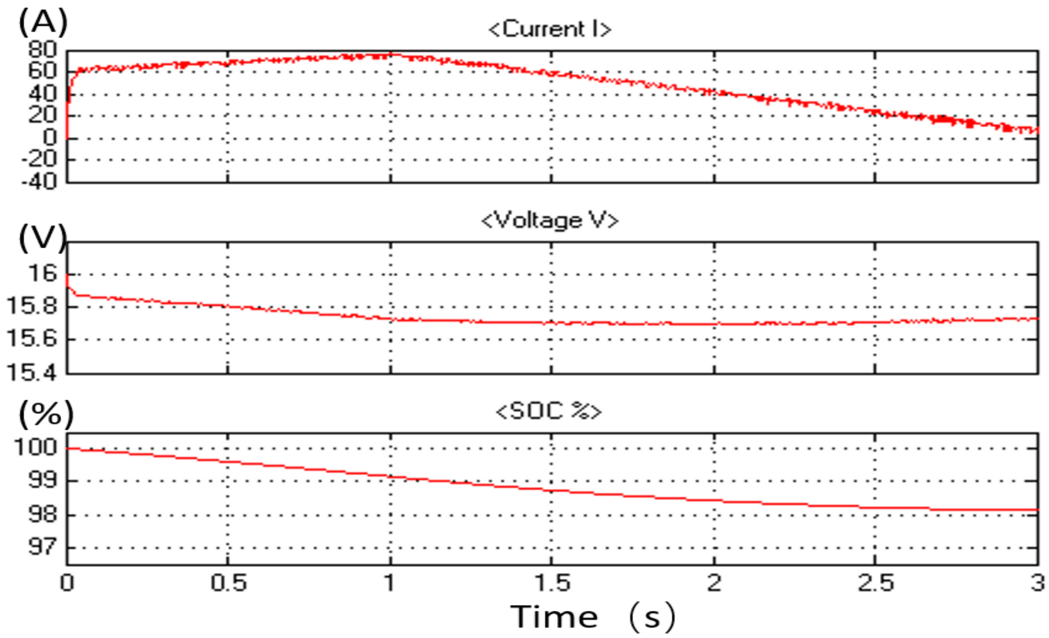

Figure 58 simulation results for the energy storage units

The main factors to adjust is the rated capacitance, the rated voltage and the equivalent dc series resistance. One of the requirements in this project is supplying 4-5 kW in a peak power demand time. The time period normally last for more than 1minutes and less than 5 minutes. (see more information in Chapter 3’s contents) Based on this requirement, the model is adjusted to having more than 3 kW power rate for emergency electricity demand. The simulation performance for the supercapacitor is shown. For supplying peak demand of electricity, the supercaptor's discharging current increased from zero to more than 70 A in less than 1 minute. From the simulation results of the model, the supercapacitor model can take and release a large density of power in short time. It indicates the supercapacitor conforms the requirement of the hybrid energy storage system.

With the combination of the batteries and the supercapacitor, the system could have a high capability of supplying the dynamic energy demand. Most power loss caused by the energy storage units occur in batteries. The supercapacitor is designed to work only for energy demand peak. Because of the supercapacitor has much higher efficiency than batteries and the working period is much shorter, in the project, the power loss on the supercapacitor are neglected in this study.

5.2.4 Waste heat recovery module building

The model of the waste heat recovery module is using the experimental results done by former swan researcher to build a simulation model. In the research of the biofuel micro-trigeneration system, Yu, et al tested the engine with 5 type of oil which are shown in the Table 29 [193]. In this study, the experimental results of gas oil is applied to build up a module to simulate the recovery heat from the engine.

Samples	Carbon (wt%)	Hydrogen (wt%)	Oxygen (wt%)
Croton oil	76.9	11.6	11.5
Jatropha oil	76.5	11.9	11.6
Rapeseed oil	76.7	11.9	11.4
Sunflower oil	76.8	11.7	11.5
Gas oil	86.3	12.8	0

Table 29 Elementary composition of the vegetable oils[193]

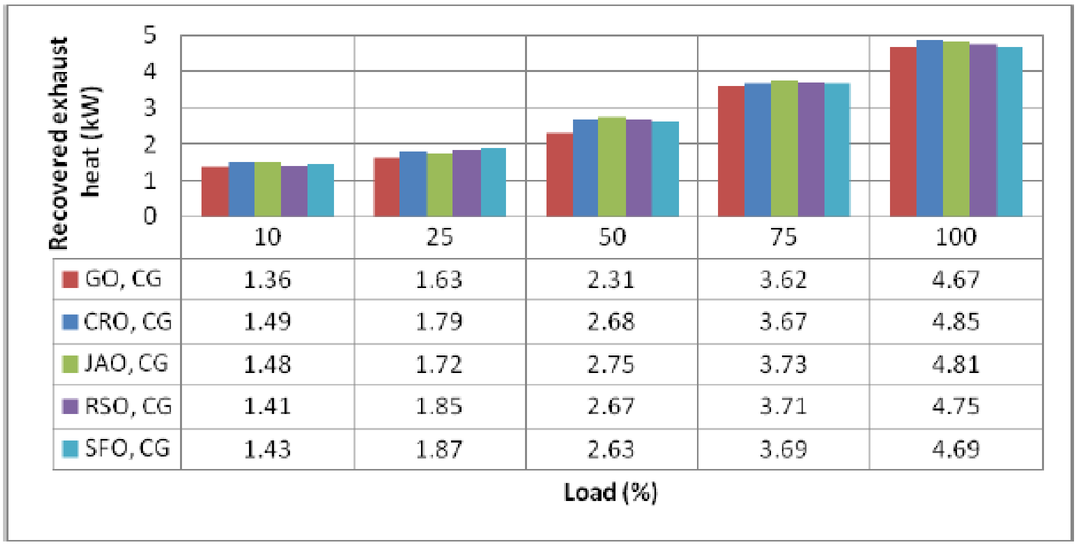

Figure 59 recovered exhaust gas heat for cogeneration[193]

The simulation of the heat recovery is based on the results from Yu, et al's experimental tests. The heat recovery system is simulated as a black box and using a performance curve to fit the experimental results. There are five operation point. At 10%, 25%, 50, 75% and 100% load, comparing the heat recovery system's actual performance with the simulation module, a block representing the heat recovery system is built.

5.2.5 Some other components in the system

5.2.5.1 DC converters

The energy output from the engine is AC power. Before receiving the power generated from the engine, the AC power needs to be transferred to DC power. The DC converters connect the batteries and supercapacitors with the DC main line. The converters in the simulation could regulate the energy transporting in the system's operation. The converters adjust the input and output power during the charging and discharging. They are important components as part of the system's controlling

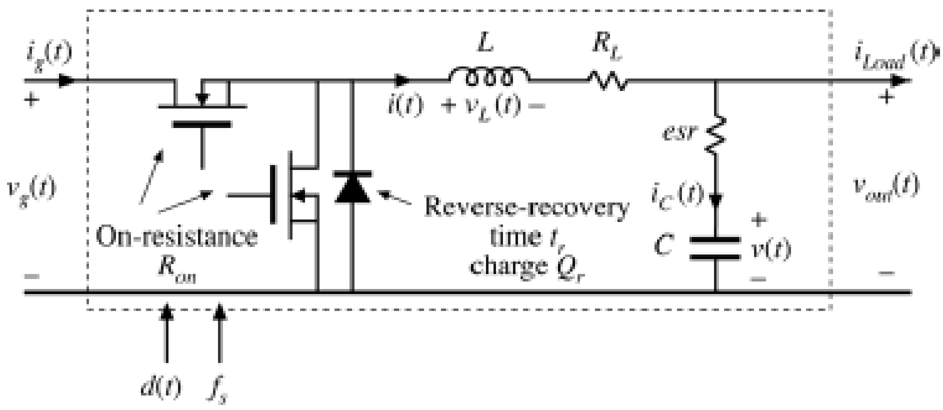

Figure 60 theoretical model of the converter[194]

One model of the DC converter is shown in the Figure 60. Under the controlling of the switch, the dc converter could operate at two states. Under the controlling of designed PWM wave, the converter could realize the function of increasing the DC voltages or decreasing the DC voltages.

The left side of this model is the input voltage. The energy is output at the right side. Certain power needs to be realized from the batteries is used to control the operation of the electrical energy storage. A PID controller is applied in this model for better dynamic operation performance. The current signal is also combined with the PID controller to regulate the energy transporting in this model.

5.2.5.2 Rectifier of the system

Simulation for the system is important for the project because the simulations provide the verifying of the system's operation. Since the electric demand will be satisfied firstly, the electric energy storage has been simulated. The configuration of system's simulation is shown in Figure 61,

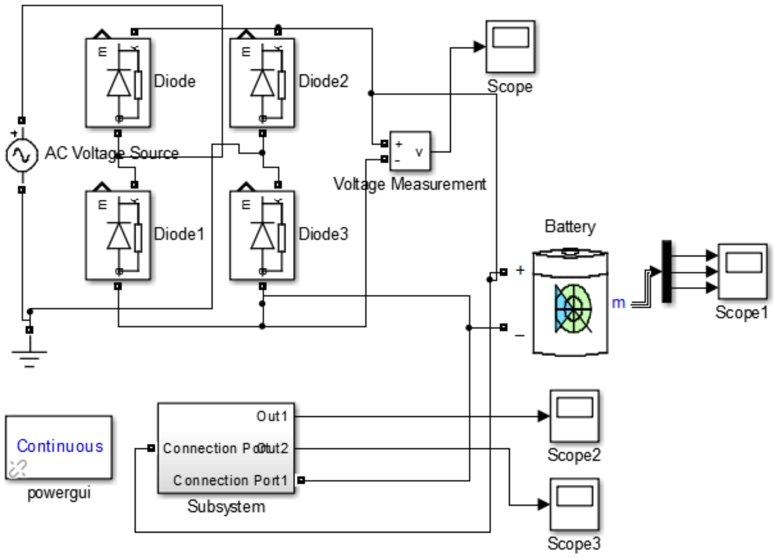

Figure 61 Energy storage simulation module in MatLab software

The primary simulation of the storage unit contains 3 parts-a super-capacitor, a battery and an energy source. The system simulates the charging of the energy storage system and the results are shown in the Figure 62,

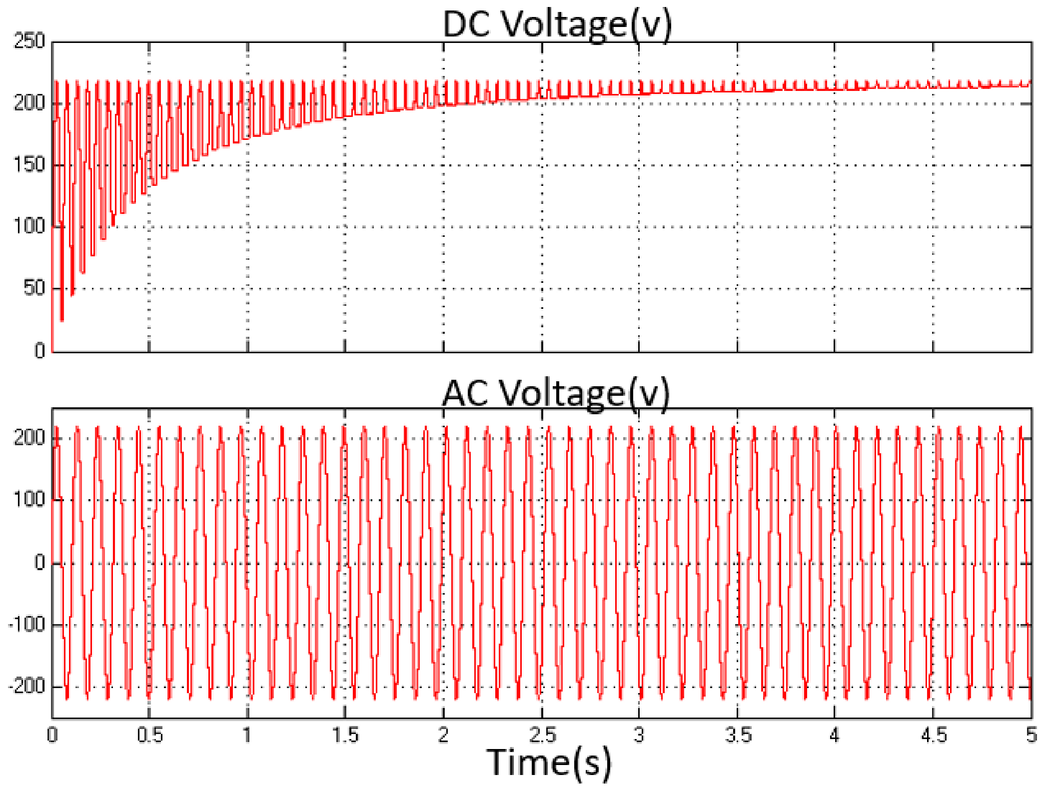

Figure 62 Simulation results of the converters in Matlab

The Figure 62 shows the charging state of the battery. The first scale on top shows the state of charging of the battery. The scale in the middle shows the current through the battery and the button scale shows the voltage of the battery. The data was displayed in the module. From the module, the data of the simulation can also be collected for researching.

5.2.5.3 Load

Load in the project is the basic components, which consumes the power. It refers to the electrical appliance, thermal power demand and cooling power demand in the research. The consumed power in a domestic household is divided by three formats. In simulation study of the integrated system, electrical load unit is used to simulate the domestic load. The unit consumes the power generated by the system. The detailed information is recorded by the Matlab software. The controlling strategy of this system is following electric load. The load in Matlab's block is shown.

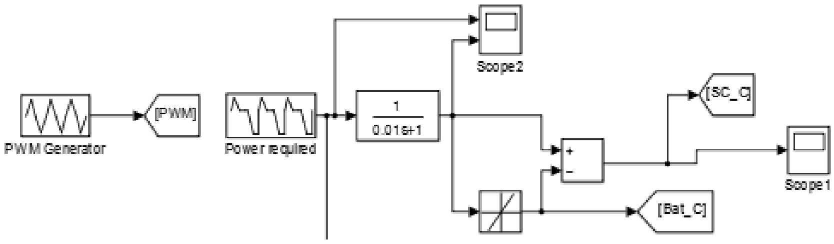

Figure 63 Loads in the simulation

The simulation model shown in the Figure 63 is used to simulate the dynamic electric loads in the simulation studies. Based on the power demand from load profile, the input side of this block control the value of the load in this simulation. Editing a continuously changing number to value the input side makes this block to be a dynamic load. From this approach, the energy consumed is controlled and recorded in this simulation. In the simulation of this project, the value of the load is flexible. The most principle rule of defining the load is following the data collected from the experimental tests.

5.2.6 ORC model building

The ORC system integrated in is designed for low-grade heat recovery to generate electricity. The system is based on a diesel engine; with a waste heat recovery unit integrated in it; as well as an ORC unit driven by the waste heat. Several key factor have the most significant on the ORC's performance which are source temperature, working medium, safety issues, problem of degradation, Ozone Depression Potential (ODP) and Global Warming Potential (GWP). R134a and R245fa are appropriate to be applied in a small-scale ORC[195]. R123a has ozone depletion potential which leads to aggravate the global warming. The R245fa has similar chemical and physical properties as a good candidate for ORC system. It also has zero-ozone depletion potential, low toxicity, none flammability and applicable critical temperature and pressure. Therefore, R245fa is selected as working fluid in the ORC system. An ORC system contains several basic components: heat source, evaporator, turbine, condenser and pump.

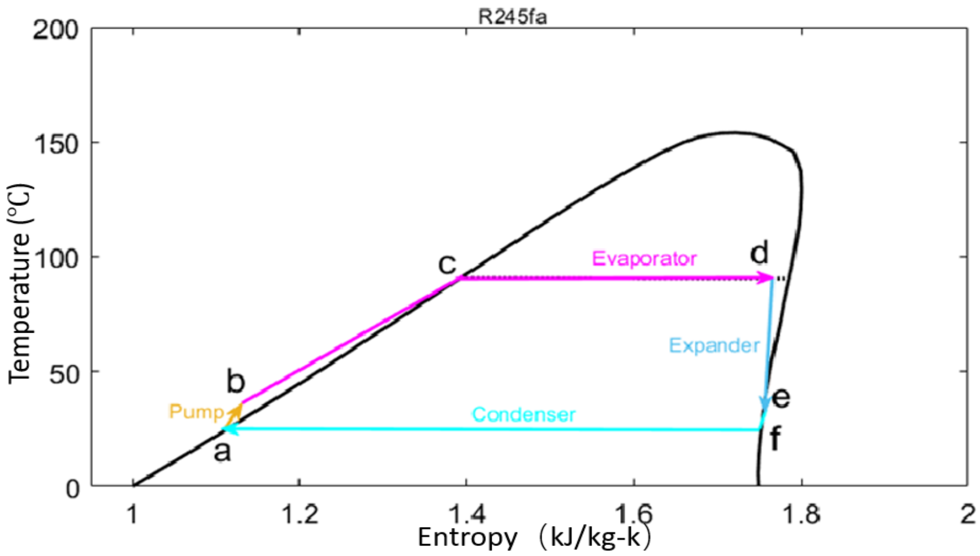

Figure 64 T-S diagram of R245fa

The design of the ORC system is shown in Figure 64. The heat source used to drive it (Q_{ro}) is from the exhaust gas and the coolant of the engine. The available energy recovered from waste heat is converted by ORC system to electricity. The ORC system consists of an evaporator, a turbine, a condenser and a pump. Heat energy from exhaust energy and engine coolant water are transported into evaporator. The working fluid used is an organic component R245fa in the ORC. It has lower ebullition temperature which has lower evaporating temperature than water. The Figure 64 shows the T-S diagram of R245fa in an ORC cycle. The R245fa is pumped to the evaporator and its entropy and temperature are slightly increased before entering the evaporator. When the working fluid is leaving the evaporator, the entropy of R245fa increase compared to its state before. After that, the R245fa goes into the turbine, and the temperature decrease with its entropy slightly increases.

Water temperature at evaporator inlet	°C	95.7
Water temperature at evaporator outlet	°C	86.8
Water temperature at condensator inlet	°C	26.8
Water temperature at condensator outlet	°C	36.3
Hot water mass flow rate	kg/s	0.288
Cold water mass flow rate	kg/s	0.248
R245fa pressure at scroll inlet	bar	9.95
R245fa temperature at scroll inlet	°C	89.7
R245fa pressure at scroll outlet	bar	2.17
R245fa temperature at scroll outlet	°C	38.4
R245fa pressure at scroll outlet	bar	9.99
R245fa temperature at pump outlet	°C	35.8
R245fa pressure at pump inlet	bar	2.02

Table 30 ORC parameters

The Table 30 shows some measured parameters from experiments done by E.Galloni et al[195]. Because of the ORC system in Swan's laboratory is unavailable, during the building of this ORC simulation model, these measured results are applied as reference. Details of the model structure is shown in appendix 3.The Figure 65 and the Table 31 express a simple working cycle of a ORC system.

Pumping process	1-2
Heating process	2-3
Expansion process	3-4
Heat rejection process	4-1

Table 31 Operation process of the ORC system

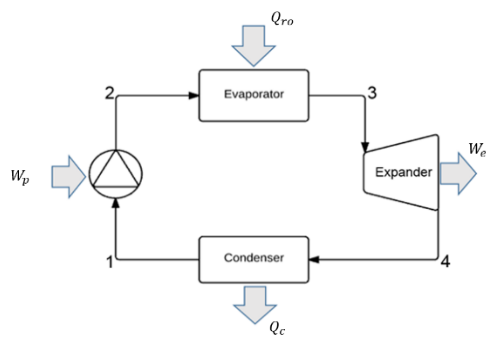

Figure 65 Working Cycles of ORC system

5.2.6.1 ORC Modelling equations

A Simulink model is set up in Matlab. The engine/trigeneration and the ORC system is assumed working in the steady state.

The first operation step of the ORC is the pumping process, the power output is related to the entropic efficiency which is expressed as equation shown:

$$W_p = m_{\text{ORC}}(h_2 - h_1) = \frac{m_{\text{ORC}}(h_{2s-}h_1)}{\eta_p}$$

(5)

$$\eta_p = \frac{h_{2s-}h_1}{h_{2-}h_1}$$

(6)

Where, W_p is power of pump; m_{ORC} is the organic fluid mass flow rate; η_p is efficiency of pump; h_2, h_1 are the enthalpies of organic fluid at inlet and outlet of pump respectively, s represents enthalpy in isentropic case.

The key parameters which have influence on the power output of the ORC are the enthalpies of working fluid and the fluid mass flow rate. The mechanical efficiency of the pump is the second factor. The pump's efficiency is calculated by the energy exported and the energy injected in.

The energy source of the ORC system is the waste heat recovered by the recovery system. The thermal energy is used to heat the working fluid in the evaporator. The energy transferring process is expressed in the equation 7,

$$Q_{ep} = Q_{ro} \cdot \xi = m_{orc}(h_3 - h_2) \tag{7}$$

Where, Q_{ep} is the heat obtained by evaporator; Q_{ro} is the recovered thermal energy; ξ is the evaporator effectiveness; h_2 are the enthalpies of working fluid at outlet of the evaporator.

The energy obtained in the evaporator is related with the evaporator effectiveness and the enthalpies of the working fluid in this process.

The operation process of the condenser is shown in the equation

$$Q_{cd} = m_{orc}(h_1 - h_4) \tag{8}$$

Where, Q_{cd} is heat energy in the condenser; h_4 is the enthalpy of working fluid at the outlet of turbine.

The thermal energy exchanged in condenser is related with the efficiency of ORC and the enthalpy of the working fluid.

The power out of turbine is expressed in the equation. The key parameters in the equation is the entropic efficiency and the enthalpy of the working fluid at outlet of the turbine.

$$W_t = m_{orc}(h_3 - h_4) = m_{orc}(h_3 - h_2)\eta_t \tag{9}$$

$$\eta_t = \frac{h_3 - h_4}{h_3 - h_{4s}} \tag{10}$$

Where, W_t is turbine output power; η_t is the isentropic efficiency of turbine.

The equation shows the overall efficiency of the ORC system.

$$\eta_{\text{ORC}} = \frac{W_t - W_p}{Q_{ep}} = \frac{(h_3 - h_{4s})\eta_t - (h_{2s} - h_1)\eta_p^{-1}}{h_3 - h_2} \tag{11}$$

$$W_t = Q_{ro}\eta_{ORC}\eta_{gen} \tag{12}$$

Where, η_{ORC} is the efficiency of the ORC cycle

5.3 results and discussions

5.3.1 ORC system simulation results

For investigating the operation characteristics and testing the performance of the ORC system. A Matlab simulation model is built. Based on the designed operation conditions of engine and the ORC system, the electricity output of the ORC system is directly related to the waste heat available from the engine. The Heat recovery system and the ORC system are set to operate in steady state. When the R245fa is applied as the working fluid, Figure 66 shows the ORC electricity output under different mass flow rate. In the Figure 66, keeping the other variable as constant, the influence on the output power caused by mass flow is simulated. When the output of the ORC system accesses the maximum power, the operation speed of diesel engine is 2400 rpm and the mass flow rate is 0.18 kg/s. When the ORC system is designed to operate in a

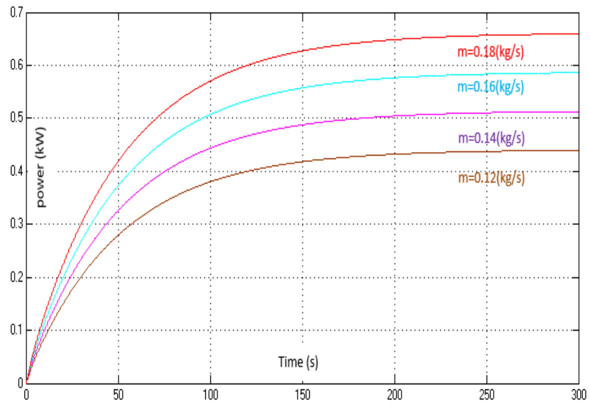

Figure 66 ORC output

steady state, the mass flow has a positive linear relationship with the output power. The Figure 66 shows a higher mass flow rate leads to a higher electricity output. When the operation condition is set as steady state and the maximum power out is simulated as 0.737 kW. The efficiency of the ORC system reached the maximum point 9.25% at rated operation.

5.3.2 Simulation of electric part

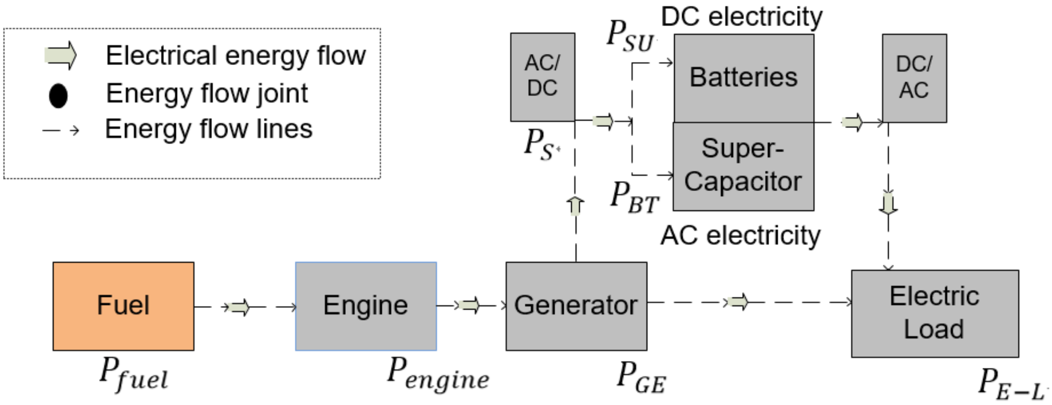

Figure 67 Electric part of the system

The simulation model is built in the Matlab software. All the components have the identical parameters with those in the experimental test. Same as the test, the simulation using the hybrid energy system to supply the dynamic domestic load for 24 hours. The system's structure is shown on the figure. The generator and the energy storage units are connected in parallel to supply the dynamic load. The energy storage system consists of the batteries and the supercapacitors.

There are plenty of simulations on the energy system supplying the domestic load. [196] [197] [198, 199] However, since few system has applied the hybrid energy storage system (conventional batteries combined with supercapacitors), this simulation model can validate the experimental test of this system. The control strategy of the system in the simulation uses the same algorithm in the experimental test. The ideal simulation results is the identical results of the experimental test. Based on the test results, a successful validation of the system supports the system's further investigation.

In the following section, the of the simulation results of the electric part of the system are shown a discussed. The simulation results are displayed by two sets in the following section (summer load and winter load). The model records the performance of each components in the system during the simulation. The model is designed to simulate the 24 hours test with same conditions. With the two different energy requirement of a summer day and winter day, a validation of the experimental test is expected.

5.3.2.1 Summer day load

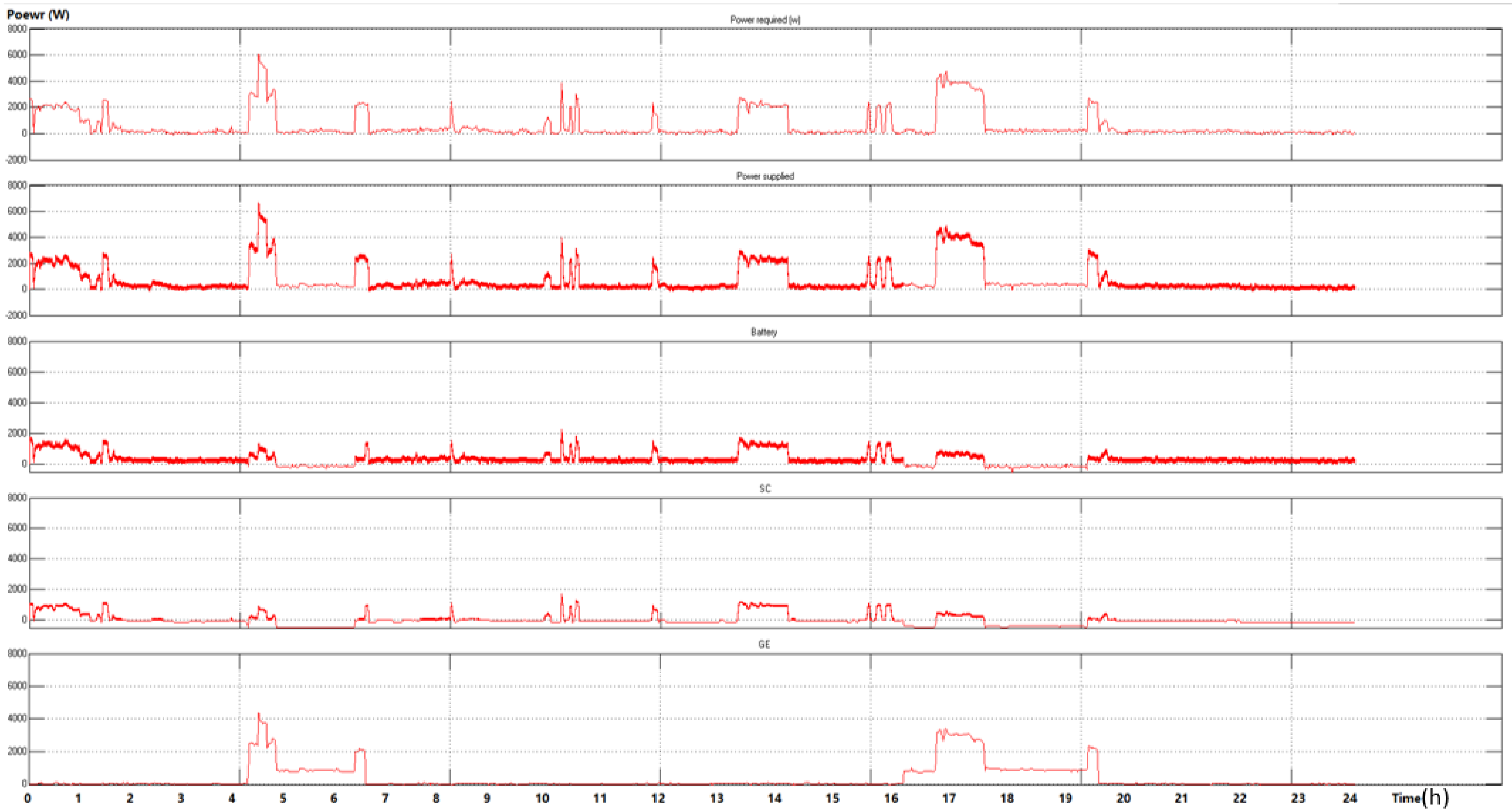

Figure 68 Summer day simulation results

The Figure 68 shows the simulation results of the system's operation on a summer day. The required power is identical with the load in the experimental test. 24 hours power supplying is simulated in this model. In the simulation, the generator is designed to operate in the same period. Therefore the generator and the electrical energy storage units supply the power demand. From the waveform of power required and the wave of power supplied, the conclusion is that the power demand is satisfied by the system in this simulation. The amount of power supplied has 2.69% error compared to the experimental results which is acceptable in this simulation. Same with the experimental test, the generator only worked during the peak hours. In the two main peak power demand period, the generator supplied the power to the load with the power storage units. In the other several peak power demand period, the load is satisfied by the energy storage units only. From the Figure 68, the batteries supplied larger amount of power because of large capacity. The power supplied by the supercapacitor has the same trend of power supplying. The supercapacitor supplied fewer power compared to the batteries. In the simulation, the batteries' power rate is governed by a power regulator. A PWM wave is the control single of the batteries' power which makes the power of batteries has ripples. Most of the error comes from the ripples of batteries' power rate. During the 24 hours simulation period, most of the time the power supplying waves of generator and the energy storage units were similar except when the generator was operating. When the generator was operating, it can either supply the load or charge the energy storage units. The operation condition is based on whether the load can be satisfied by the engine individually.

5.3.2.2 Winter day load

Figure 69 Winter day simulation results

The Figure 69 includes the simulation results of the domestic load on winter day. Same with the simulation of summer day load, the target of the simulation is to satisfy the power demand with the system. In the simulation, the target load varies during the simulation hours. The first and the second waveforms in the Figure 69 shows the required power demand in the simulation and the power supplied during the simulation. From the comparison of the two waves, the conclusion is that the load was fully supplied by the plenty of power from the system. Based on the calculation, the error of the simulation was under 2.35%. The third and the fourth waves are the power supplied by the batteries and the supercapacitors (labelled Battery and SC). The specifications of the equipment's are set same as the energy storage units in the experimental test. During most of the simulation process, the power supplied by the batteries and the supercapacitors follows the load. The batteries supplied roughly 2 times power of the supercapacitors supplied. The fifth waveform was the power supplied by the engine. When the engine was working. A large amount of power is used to supply the peak power demand. The extra power is used to charge the energy storage units to keep the batteries' SOC (state of charge) in designed range.

	Summer load	Winter load
energy required (kWh)	9.76	7.28
energy supplied (kWh)	9.81	7.36
Energy supplied by the generator (kWh)	7.38	4.33
Energy supplied by the storage units (kWh)	2.43	3.03
maximum battery power (kW)	2.113	1.96
maximum supercapacitor power (kW)	1.078	1.76
Maximum simulation error (%)	2.69	2.35
Average simulation error (%)	1.86	1.79

Table 32 simulation results

The Table 32 summaries the two simulation studies. The energy demand from the load and the energy supplied by the system are listed in the Table 32. From the table, the system operates as designed. The batteries supplies a larger amount of the energy. The supercapacitors are responsible for supplying the load with the batteries during the peak time. The error of the simulation is controlled within 2%. These simulation studies are fundament to further system simulation and optimisation.

5.3.3 Integrated system performance on an autumn day

The integrated system's evaluation requires the target load has a variety of energy demand. The load targets selected in the last section is an autumn day and a winter day. Because of domestic load has little heating demand on neither spring day nor on summer day, in this section, the autumn day load and winter day load are selected as energy demand to evaluate the integrated system.

For the integrated system, the electricity is generated by the generator. The thermal energy is recovered heat form the engine's operation. Part of the recovery heat supplies the heating load. The left recovered waste heat is used to drive the adsorption chiller and supplies the cooling load.

In both simulations, the control strategy applies FEL. Electricity demand gets the first priority. The system focus on satisfy the electrical demand at the first time. The recovery heat are regarded as available thermal energy generated by the system and fully consumed by the load. Part of the revered heat are utilised to supplying cooling load. For household domestic cooling load, in the majority situation, the load is a refrigerator in the kitchen. The part of load is simulated as ordinary pulse shape energy demand.

The first simulation is supplying energy for a residential load in an autumn day. The operation results are shown in Figure 70. Five key parameters' value are recorded during the operation period of trigeneration system with label a, b, c, d, e which are electrical energy demand, engine operation, batteries operation, supercapacitors operation and batteries' state of charge respectively.

The electrical efficiency expressed the operation of the electric cycle. For the electric part of this system, the generator is driven by the engine and it provides most of the electricity. The generator could supply the electric load directly. In the distributed system, the system's energy supply capacity is limited by the generator's rated power. The system in this project combines the trigeneration system with the hybrid electrical energy storage system. When the energy storage system is working, some losses are generated inevitably. However, with the assistance of the energy storage units, the system's supply capacity is expanded. Based on the simulation results, with the energy storage system, the capacity of the electric cycle expanded by 47%. At the same time, the losses make the electrical efficiency drop by 3.58%.

At the same time, the combination of supercapacitor and the batteries increase the system's stability. The supercapacitors supply a large amount of energy in short time. Due to chemical reaction, the batteries need a certain time to prepare the energy's supplying. Applying this combination of energy storage units makes the system can provide a high quality of electricity. Part of the waste heat is utilized by the ORC. Part of the thermal energy transmitted to the ORC during the operation time is converted to electricity which increases the energy utilisation efficiency. The ORC contributes 8.91% electricity which make a 2.45% enhancement on the system's electrical efficiency.

Equation 2 heating demand equation

$$Q_h = \int_0^{24} P_h \cdot d(t)$$

Besides the electricity supplying, another energy demand for this system is thermal energy. The system using the recovery waste heat to supply the thermal demand. For the heating energy demand, the high-resolution data is difficult to obtain. The energy consumption is estimated based on government's data and the household's energy consumption pattern. The thermal energy generated is 4.6 kWh and regarded as fully consumed. A large part of the waste heat is transferred to thermal energy. The thermal energy could be either stored or consumed. The system is flexible to deal with the thermal energy. Part of it is supplied to the ORC to generate electricity. The thermal efficiency is another key parameter for examining the trigeneration system. Based on the results, the ratio of recovery heat is 41%.

Equation 3 Cooling demand equation

$$Q_c = \int_0^{24} P_c \cdot d(t)$$

The cooling demand of the load a pulse shape energy demand. Cooling energy demand in the household comes from some certain electrical appliance. Part of the waste heat is used by the absorption chiller to produce cooling energy. During the 24 hours scale, the cooling energy demand for the selected household is 0.37 kWh which could be satisfied with 9.36% recovered heating energy.

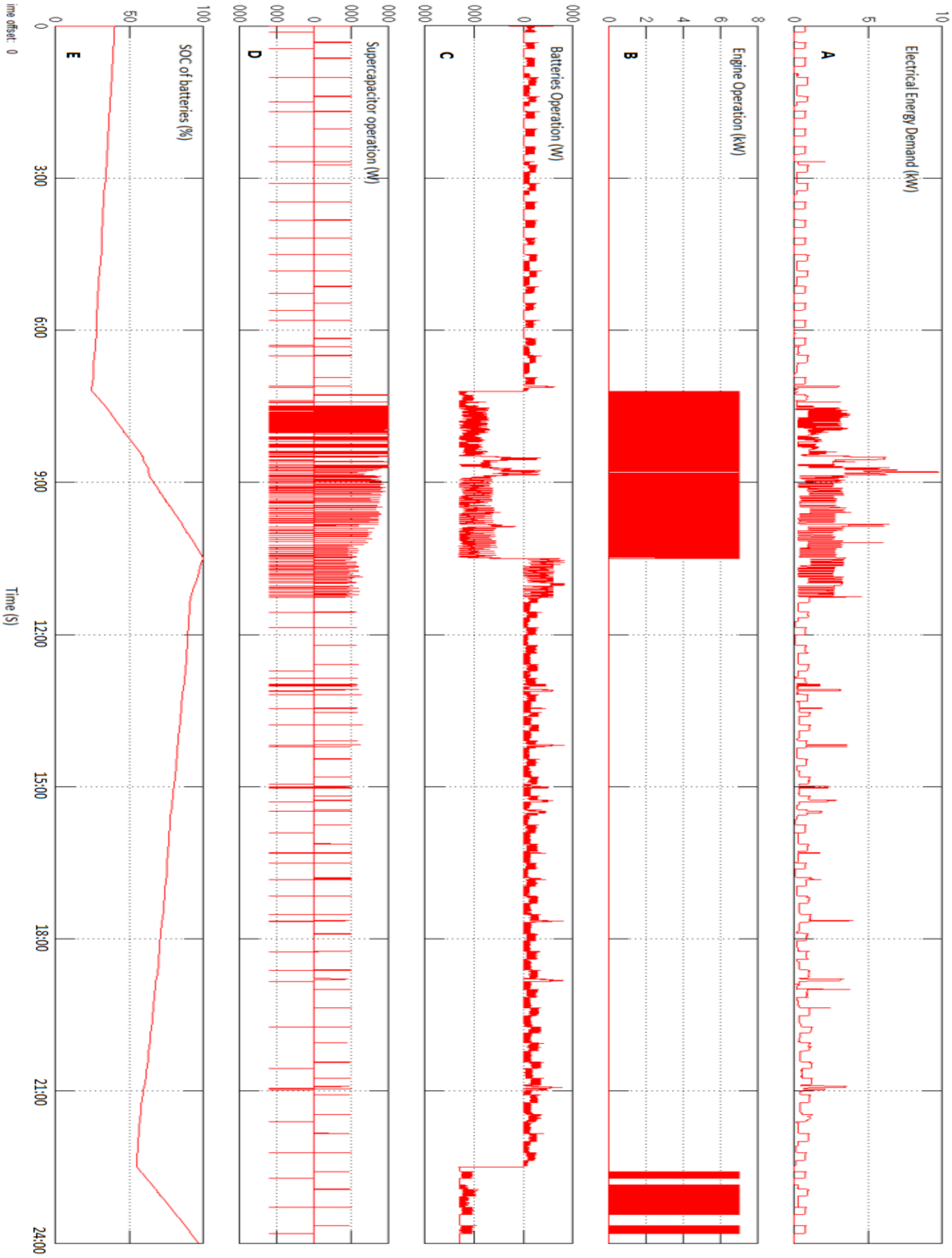

Figure 70 High resolution simulation of the electrical energy supplying. (a) Electrical energy demand, (b) engine operation period, (c) batteries charging/discharging, (d) supercapacitor charging/discharging, (e) the tracking of batteries' SOC.

5.3.4 Integrated system performance on a winter day

Similar with the previous results, the key parameters are displayed in the Figure 71. The energy demand in the winter is slightly larger than load of an autumn day. In this simulation, the engine operates in two time zones which cover the peak energy demand during the one day time. Part of the electrical energy demand is satisfied by the generator directly. The function of the energy storage units expanded the system's energy supplying capacity. As the Figure 71 shown, batteries supplied most of the electrical energy demand when engine was not working. The supercapacitors were only responsible for energy demand peaks. The engine has 6.5 kW rate power output. The energy storage units enhances the system's energy supplying capacity from 6.5 kW to 7.3 kW (12.3%)

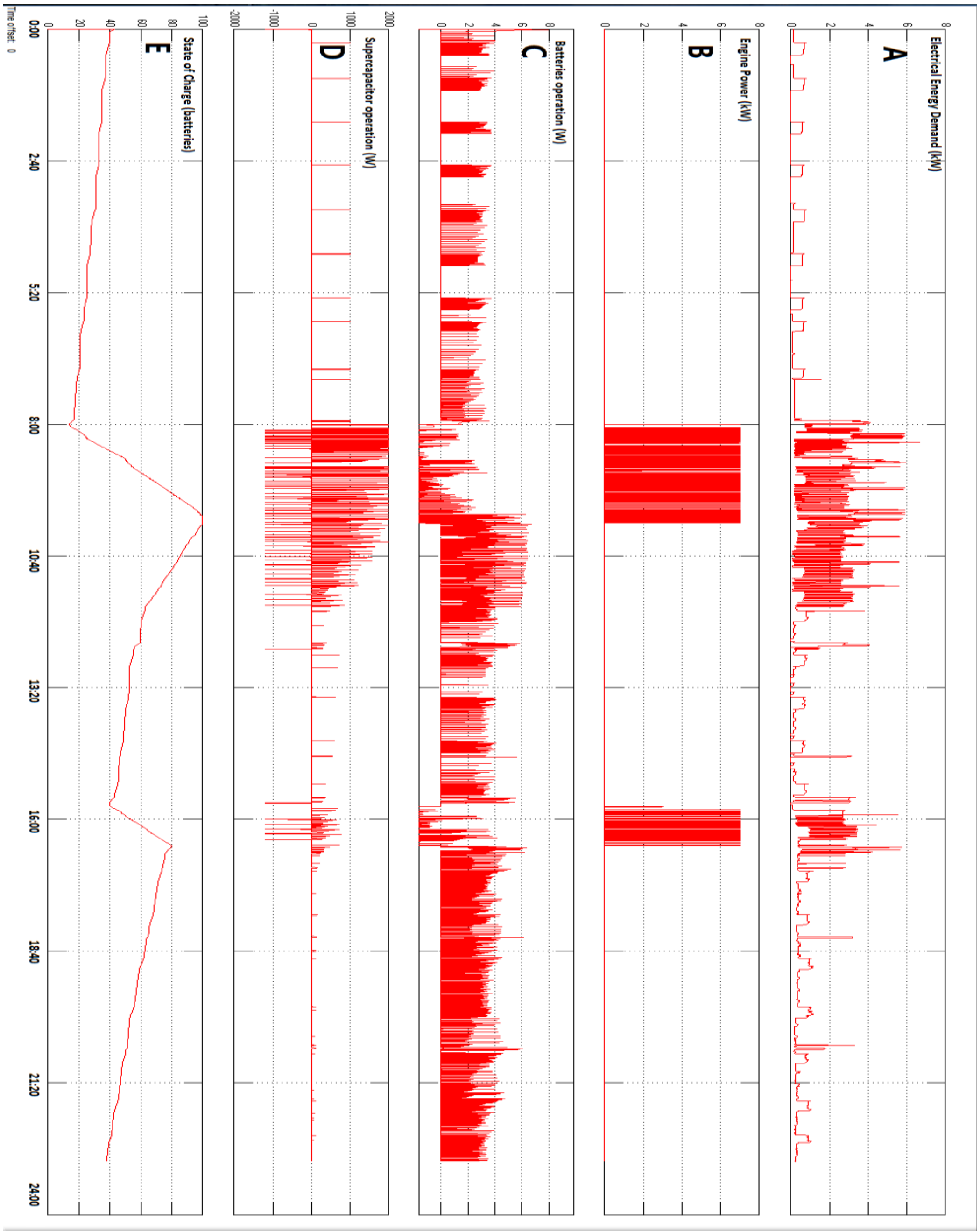

Figure 71 High resolution simulation of the electrical energy supplying. (a) Electrical energy demand, (b) engine operation period, (c) batteries charging/discharging, (d) supercapacitor charging/discharging, (e) the tracking of batteries' SOC.

Same as the last simulation target on an autumn day load, the combination of the supercapacitor and the batteries increase the system's capacity and stability. The engine in the system has 6.5 kW rate power which was not enough for supplying the dynamic load. In the second simulation, energy storage units supplement the energy gap when the peak energy demand is larger than the rate power of engine. From the C and D chart in the Figure 71, large amount of electrical energy was supplied by the batteries. The supercapacitors offered certain amount of energy in short time to fulfil the dynamic energy demand. Batteries' state of charge started from 40 % and ends at 40% when the simulation ends.

ORC system in this simulation uses the waste heat to generate electrical energy. In the second simulation, it produces 0.42 kWh during the 24 hours system operation. The ORC system has same working period with the engine. Electricity produced by the ORC system used the heat sources from waste heat. The operation of the ORC system make the trigeneration to have higher conversion rate on the waste heat energy. The electrical energy supplied by the ORC system took up 2.8% of the total dynamic energy demand.

Obviously, when the recovery heat is used to generate the electricity, the supplying of the heating demand will be affected. Since the efficiency of the recovery heat is higher than that of ORC system, using large amount of the recovery heat for electricity generation may cause the heat demand being sufficient supplied.

The heat demand is fulfilled by the recovered waste heat. The energy consumption is estimated based on government's date and the household's energy consumption pattern. The thermal load is calculated around 5.1 kWh on a winter day in this case study. A large part of the waste heat is transferred to thermal energy. The thermal energy could be either stored or to be transferred to the thermal load. Part of the thermal energy is supplied to the ORC to generate heat energy and electricity. The thermal efficiency is another key parameter for examining the trigeneration system.

5.3.5 Integrated simulations discussion

	Autumn Day	Winter day
Electrical energy demand	15.53 *kWh*	16.34 *kWh*
Energy supplied by engine	10.74 *kWh*	11.3 *kWh*
Energy supplied by batteries	4.88 kWh	5.64 *kWh*
Cooling energy demand	0.37 kWh	0.24 *kWh*
Heating demand *	4.6 kWh	5.7 kWh
Energy supplied by ORC system	0.37 *kWh*	0.42 *kWh*
System capacity enhancement	47%	12.30%
Energy consumed by trigeneration system	32.15 kWh	31.18 *kWh*
Energy consumed by normal system	51.70%	53.92 *kWh*
Overall system efficiency	48.30%	52.20%
Efficiency enhancement	18.30%	21.70%

* part of thermal demand is supplied by electrical energy, that is why the thermal demand is smaller than normal residential cases

Table 33 key parameters displaying in the two set of simulations

Information of the simulation results is displayed in the Table 33. In the two simulations, the energy demand are similar which are 15.53 kWh and 16.24 kWh respectively. The energy demand of the target residential household has larger energy demand on a winter day than an autumn day. The engine is designed to operate at a shortest time to save energy. The trigeneration system satisfies the energy demand of the load in both cases when the engine only works at peak times. During the long off-peak time, the energy storage units supplies the energy demand to the load. The ORC system transferred part of the waste heat energy to electricity. Limited by the heat source, the ORC system only generates a small amount of energy in these two cases. Although the ORC system could enhance the system energy conversion ratio based on the results of the simulations, stable heat sources is necessary to have high economic efficiency. The electrical energy storage units is important in the simulation. It expanded the system's capacity and enhanced the system's stability. With the energy storage units, the trigeneration system has ability to supply load larger than engine's rate power.

The two simulations finished the validation of the experimental tests. Both in the summer load and winter load simulations, the electric load are satisfied fully by the system. Same as in the test, during the simulation process, most of the energy is supplied by the engine. The amount of power supplied by the engine was 7.38 kWh in summer 4.33 kWh in winter. As the same time, the energy storage system only supplied 2.33 kWh in summer and 3.03 kWh in winter. It indicates that the energy storage system operates as auxiliary supplied in the electric part of trigeneration system. Combined with the energy storage system, the energy supplying has little waste. The calculation results from the generator output and energy consumption, the efficiency of the system is quite high. In the energy storage system, the lead batteries has high-energy capacity compared to the supercapacitors. In the test and simulation, the batteries supply a larger amount of energy to the load. The supercapacitor supplies fewer energy. It plays an important role to make the energy gap when energy demand peak came. As a conclusion, the maximum error of the two set of simulations are 2.69% and 2.35%. The average simulation error were 1.85% and 1.79%. These results states the simulations validated the model.

5.4 Chapter Summary

This chapter consists of the model building and the simulation results. In the beginning of the chapter, the methodology of the simulation study is introduced. The first half of this chapter express the model building process. The theories of key components of the system are introduced. The model for each components are displayed with its validation. The simulation results validated by a coordinate experimental tests are displayed with explanation in the end of each model building part.

The results and discussion part shows the simulation results of the system's operation. The ORC's simulation results shows the ORC's output power under different conditions. The simulation results of the electric part of the system indicates the system has ability to supply dynamic electricity demand. After a summer load and a winter load simulations, the error is controlled within the range of 2%. The integrate system simulation results also includes two parts. In both two sets of simulations, the energy produced by the system satisfy the energy demand. Energy generated by each components are recorded in detail in the simulation for analysing the system's performance.

The simulation study on the system's electric part shows that the system's model has high accuracy. From the simulation results, the conclusion is obtained that the model is built successfully and the error of the model is controlled in reasonable range. With the help of the ORC system and the hybrid energy storage system, the integrated system has high efficiency performance in the simulations. The discussion of the model building and the preliminary simulation study is finished in this chapter. Combined with the experimental tests, the system is further investigated in the next chapter.

6. Performance analysis and optimisation of the integrated system

6.1 Introduction

After the simulation and experimental tests on the electric part of the system, the system's performance is predicted with high accuracy. Using the validated model to simulate the system's performance and the optimisation process for the system are the main contents of the chapter. An overall efficiency calculation for the system's operation is the first part of this chapter. It express the system's basic operation efficiency. The second part of this chapter is the optimisation of operation logic of the electric part of the system. It shows the basic logical methodology of system optimisation. The final optimisation process is carried on the integrated system. Before the optimisation, different scenarios of load are picked to test the system's performance. Considering both the electrical demand and the heat demand, an optimisation method is introduced. The results of the simulation of the system and the optimisation of the system's operation are also displayed in this section. Comparing the simulation results of before and after the optimizations shows the enhancement of the system's performance.

The previous simulations, experimental tests and validations proved the model's accuracy in previous chapters. The simulation of the system's operation is considered as the actual performance of the integrated system. The optimisation of the system in this chapter is built on this hypothesis. In this project, the integrated system is designed to supply a dynamic load. The energy demand depends on the characteristics of the specific applications. Aiming at satisfying the load with the lowest primary energy consumption, the optimisation on the system is a adjusting of the system's operation for higher efficiency. Before the optimisation on the system are designed to reflect the features of the applications under different conditions. Before using the system to supply several sets of load, a preliminary discussion about the system's efficiency introduces some key components of the system and gives a basic evaluation on the system's efficiency. The following simulation on the system uses the trigeneration system to supplying the designed load. The system's efficiency results are compared with and without the energy storage units. An optimisation on the trigeneration is the key part in this chapter. Based on the purpose of the system and the regulations of the system's operation, a better operation is designed to save the primary energy consumption. The results are displayed and discussed as an evaluation of the enhanced system.

6.2 Preliminary calculation on the system's efficiency

6.2.1 System capacity evaluation

The energy system in this project is a multi-energy products supplying system. The system is capable to produce electricity, heat and cooling energy simultaneously. it is meaningful to evaluate the capacity of this system for a more precise energy supplying. As mentioned in the previous chapter, the energy source of this system chemical energy from diesel oils. The engine transfer the energy from chemical energy in the fuel to electricity. The heat recovery system recovers also the unutilised waste heat to useful heat energy. The cooling energy is obtained from the transferred waste heat. This system is integrated with prime mover (diesel engine), energy storage units (electrical energy storage and heat storage), and energy transferring components-electrical heater, absorption chiller, electrical chiller and ORC system. This design make this multi-functional trigeneration system to be flexible for energy supplying. It is meaningful to evaluate the energy supply capacity of this system to make batter allocation of energy transmission. In the simulation, the trigenereation system will be set to three different mode to generate one single format of energy, which is electricity, heat and cooling respectively.

6.2.2 Electricity generation mode

The trigeneration system is set to generate electricity only. The waste heat produced by the engine is recovered and transmitted to ORC system, the ORC system transfer the waste heat to electricity.

Electrical	
	Unit (kW)
Primary fuel consumption	17.5
generator power	6.5
waste heat	11
heat recovery system rate	4.4
Power of ORC	0.4
Power of Electrical heater	0
Power of Electrical chiller	0
Power of absorption Chiller	0
Efficiency （%）	39.42

Table 34 Waste heat to electricity

6.2.3 Combined heat and power mode

In this simulation mode, when the heat and the electricity is generated simultaneously, the integrated system is operating as cogeneration mode. The power flow and efficiency is shown in the Table 35.

	Electricity	**Heating**
	Unit (kW)	Unit (kW)
Primary fuel consumption	17.5	17.5
generator power(kW)	6.5	6.5
waste heat(kW)	11	11
heat recovery system rate(kW)	4.4	4.4
Power of ORC(kW)	0.4	0
Power of Electrical heater(kW)	0	6.175
Power of Electrical chiller(kW)	0	0
Power of absorption Chiller(kW)	0	0
Efficiency （%）	39.42	60.4
Overall efficiency	39.42%-60.4%	

Table 35 System's overall efficiency when the electricity and heating generation are all applied

6.2.4 Trigeneration mode

In this simulation mode, when the heat, cooling and the electricity is generated simultaneously, the integrated system is operating as trigeneration mode. The power flow and efficiency is shown in the Table 36.

	Electricity	Heating	Cooling
Primary fuel consumption in power(kW)	17.5	17.5	17.5
generator power(kW)	6.5	6.5	6.5
waste heat(kW)	11	11	11
heat recovery system rate(kW)	4.4	4.4	4.4
Power of ORC(kW)	0.4	0	0
Power of Electrical heater(kW)	0	6.175	0
Power of Electrical chiller(kW)	0	0	2.6
Power of absorption Chiller(kW)	0	0	2.2
Efficiency （%）	39.42	60.4	27.4
Overall efficiency	27.4-60.4%		

Table 36 System's overall efficiency in trigeneration mode

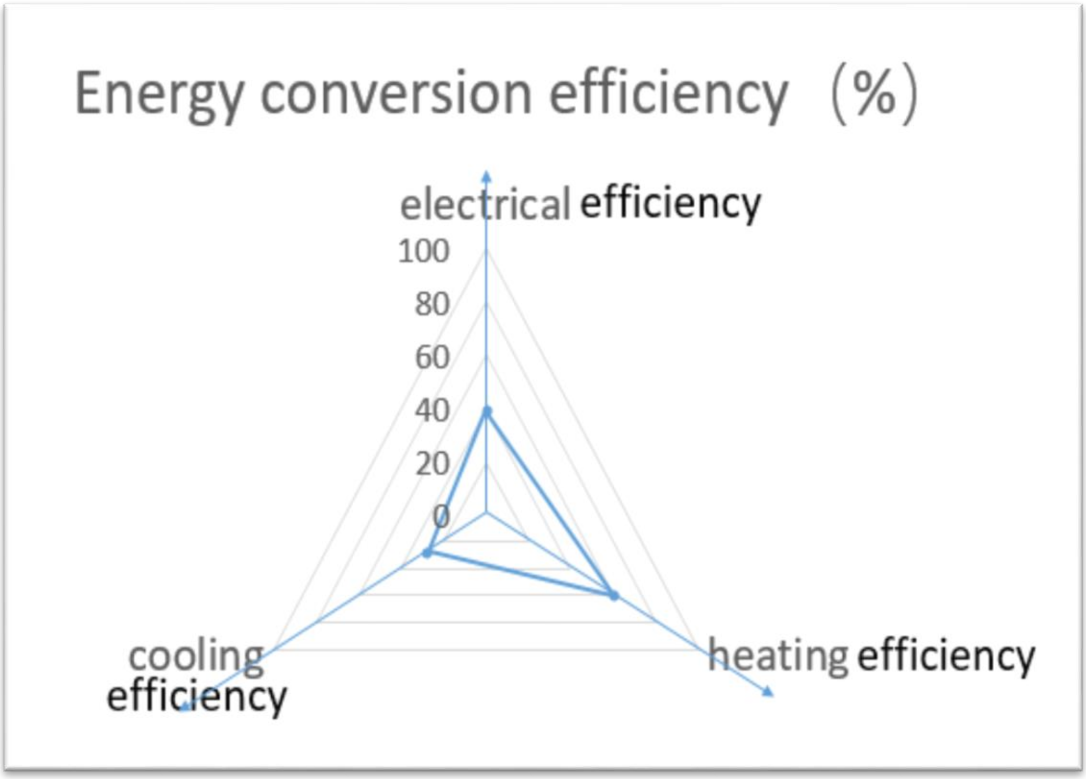

Figure 72 efficiency chart

The Figure 72 shows the energy amount transferred from the fuel and the maximum conversion efficiency of the system respectively. The amount of available energy transferred from the primary energy consumption decides the maximum capacity of the system. From the figure, the available energy conversed by the system has positive linear-relationship with the system's efficiency. From the figure, the cooling production has the lowest efficiency. Cooling generation depends on the waste heat recovery in the system. This makes the electricity generated by the system is wasted when there is no other load demand. The electricity generation takes the second high efficiency in the system's operation. With the help of ORC system, part of the waste heat is transferred to electricity which improves the electricity generation efficiency. The thermal energy generation has the highest efficiency. Besides the thermal recovered from the waste heat, the electricity generated is also available for thermal energy generation. This is the reason why the thermal energy generation has the highest efficiency. This calculation shows the system's efficiency boundary in theory.

From the calculation results of the system's efficiency, generation of thermal energy in this system has the highest primary energy utilization efficiency.

6.3 electric part optimisation process

The previous experimental tests and simulations, the operation strategy of the system is using engine only during the energy peak time. Although the load was fully satisfied, the efficiency of the system is not maximized. During the system's operation, the engine's power rated adjusted based on the power requirement of the load. The preliminary test on the engine indicates that the engine's performance reaches the maximum efficiency only at rated power. As shown in the chapter 4 and chapter 5, the engine's operation fluctuated from 20% to 95%. In the most of time, the engine's operation was not in rate condition which indicates more electrical energy could be transformed from the fuel.

6.3.1 System optimisation design

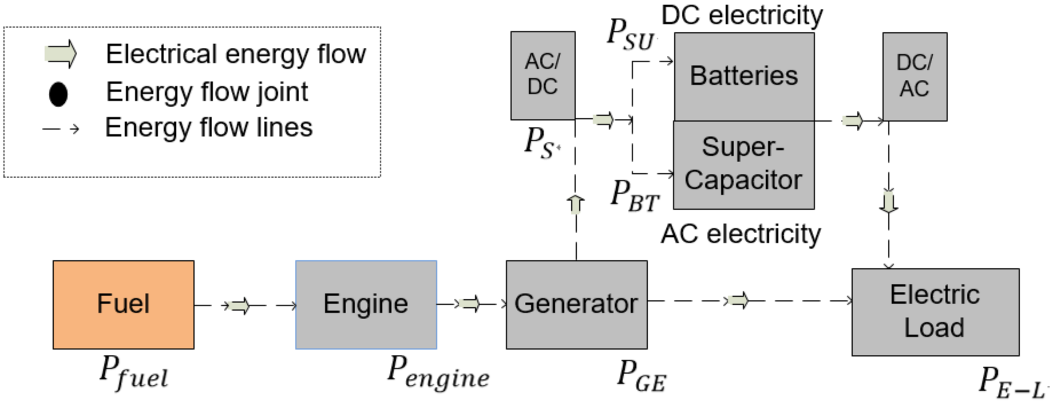

Figure 73 system configuration map with labels

Nomenclature	
P_{fuel}	Power the primary energy can release
η_{engine}	Efficiency of engine
P_{engine}	Power of engine
P_s	Power of energy storage system
P_{SU}	Power of supercapacitor
P_{BT}	Power of batteries
P_{LOAD}	Energy demand of load
SOC	Batteries' state of charge
te	At the end of operation time
C_S	Batteries' capacity
DG-ES	distributed power generation with energy storage system

Table 37 Nomenclature for system's electrical part

The system's operation method and the optimisation strategy is shown in the equation.

$P_{fuel}.\eta_{engine} = P_{engine}$ (13)

In this system, the energy source is from the engine. The primary energy is converted to the system by engine as certain efficiency. The number of efficiency was validated from previous tests on the engine.

$P_s = P_{SU} + P_{BT}$ (14)

In the energy storage system, the output power is always equal to the sum of the batteries' power and the supercapacitors' power.

The operation of the system can be simply divided to two modes based the engine's operation condition.

When generator is operating

$P_{LOAD} = P_{GE} + P_S$ (15)

The electric energy demand is satisfied by the power of engine and energy storage units.

When generator is not operating

$P_{LOAD} = P_S = P_{SU} + P_{BT}$ (16)

When the engine is not working, the electric load is supplied by the energy storage system which consists of the supercapacitor and the batteries.

Limiting conditions:

$40\% < SOC(t) < 100\%$ (17)

$P_{engine} + P_s \geq P_{Load}$(18)

$\int_0^{te}(P_{GE} - P_{LOAD})dt \geq \int_0^{te} P_{BT}(t)dt + C_S \cdot [SOC(t_e) - SOC(t_0)]$(19)

For the system's operation, the energy demand of the electric load must be satisfied. In case of over discharging and energy wasting, the state of charge of batteries is control within the rage from 40% to 100%. The system also is configured to prepare enough energy for the energy peak demand.

Saved energy

$Energy_{Saved} = \int_{t_1}^{t1e} \frac{P_{engine}(t)}{\eta_{engine}} dt + \int_{t_2}^{t2e} \frac{P_{engine}(t)}{\eta_{engine}} dt - P_{engine}(max)t_{op}$(20)

The energy saved by the optimisation process is calculated by the original energy consumption amount and optimized energy consumption amount. Since the engine has the highest efficiency at the rated power, the energy saved can be theoretically calculated based on the efficiency of engine at different conditions. The data of energy efficiency came from previous test.

6.3.2 Optimisation results

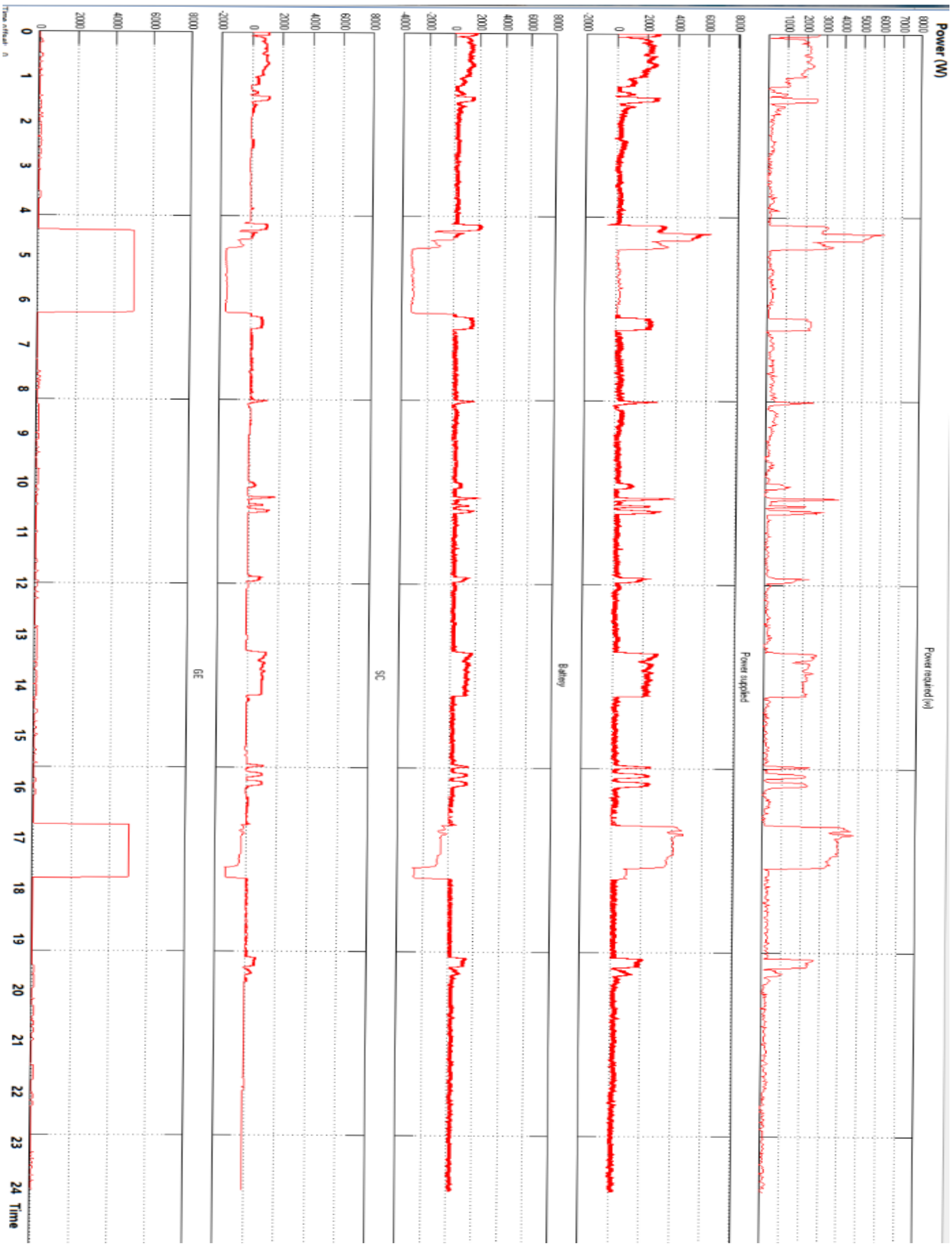

Figure 74 optimisation results of summer load

Similar with the operation in the previous section, the engine only operated at the peak times. The control of the system was enhanced based on the theoretical calculation, which reduced the operation time of the engine. The first wave and the second wave in the Figure 74 are the energy required and the energy supplied by the system. Comparing these two waves, they are almost identical. It proves that in the optimised operation, the electric load was still satisfied fully by this system. The wave of batteries, supercapacitor and engine are different between the waves before. Because of the engine worked at rate power during the two periods, the energy storage units began to charge during the same period. The engine operated in similar time zones but lasted for fewer time.

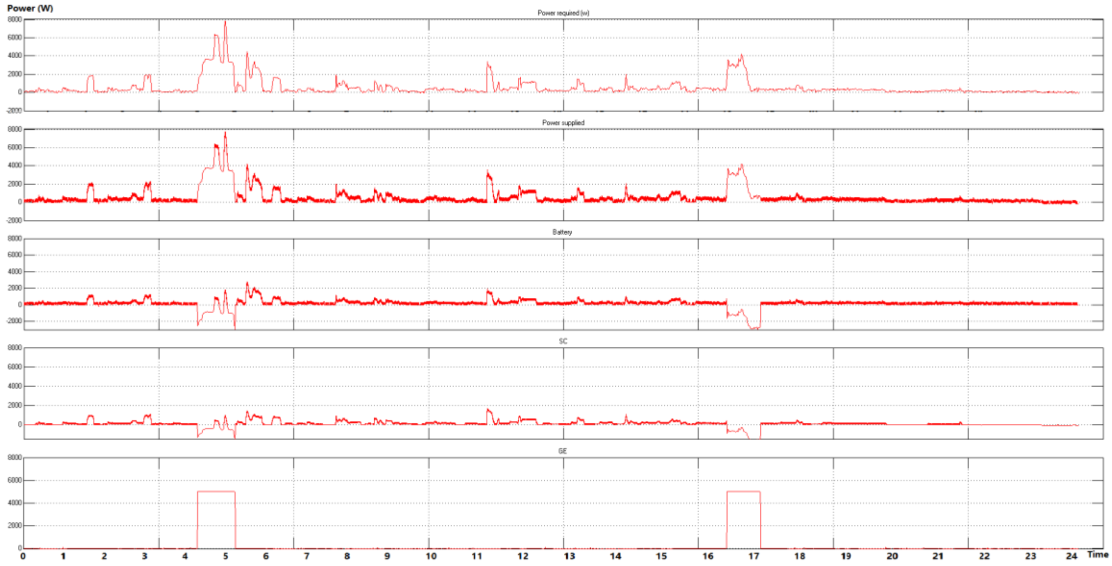

Figure 75 Optimisation results of winter load

The optimisation results of the engine's operation for the winter load are shown respectively in the Figure 75. As discussed in the system optimisation design in the last section, the primary energy consumption can be save by reducing the engine's operation time. For the winter load simulation, the energy demand is fewer compared to the summer load. From the fifth wave, the operation time of the engine is lower than that of summer load. In the original operation of the system, the engine worked in the peak time. After the optimisation process, the engine's power was adjusted based on the peak power. When the engine's maximum electrical efficiency was reach when the engine is working in full load, the reduction of the engine's operation time makes a certain part of primary energy to be saved. Comparing to optimized simulation results, in the previous simulation results, the operation time of the engine was longer.

	Summer load	Winter load
Energy required (kWh)	9.76	7.28
Energy supplied (kWh)	9.81	7.36
Energy supplied by the engine (kWh)	7.38	4.33
Energy supplied by the storage units (kWh)	2.43	3.03
Maximum battery power (kW)	2.113	1.96
Maximum supercapacitor power (kW)	1.078	1.76
Simulation error (%)	2.69	2.35
Previous engine working time (h)	4	3.83
Improved engine working time (h)	1.47	0.86
Energy saved by the optimisation process（kWh）	3.61	1.86

Table 38 optimisation results summary

The Table 38 shows the optimisation results of the system's operation. For both the two sets of simulations, the engine supplied most of the energy and the energy storage units supplied the rest of energy demand. The energy supplied is slightly larger than the energy required, which express that the system has a high overall efficiency. In the previous tests and simulation, the engine worked for 4 hours in each scenarios. After optimisation process of the system, the operation time of engine has a significant reduction. The energy saved by the process were 3.61 kWh (for summer load) and 1.86 kWh (for winter load) which shows a remarkable enhancement.

6.3.3 Summary of the optimisation of the electric part

In this section, the investigation of the system contains the experimental tests of the system, simulation of the system and the optimisation of the system. In the experimental part of the system, using the same scale equipment, the data of the system's performance was recorded. They are imported for analysing. The results of the experimental tests show this structure of system can fulfil the electric energy demand of domestic household in different seasons. The simulation on the experimental tests showed similar results. The error analysing on the system' simulation indicates the simulation has high accuracy on the prediction of system's performance. The optimisation of the system contains two parts of work. After optimisation of the system's operation, energy is saved during the supplying of summer load and winter load. In the optimisation, the engine's operation time is cut to minimum value for excessing the highest efficiency.

6.4 Simulation results of different scenarios

Aiming at a comprehensive evaluation on the system's performance, a various scenarios are applied for the system's simulation. The power demand is designed based on data from Yang's research. Yang's paper shows the characteristics of commercial load, industry load and domestic load in two seasons [200]. These power demand in 6 scenarios is calculated to power demand fitted to the system size of this integration system for research in this section. The cooling, heating and electricity loads on typical summer and winter days under different conditions are given in the Figure 76-Figure 87. In the simulation, the loads are designed to two groups. The first groups are loads for applications on typical summer days. The second groups are loads designed for applications on typical winter days. Unlike in Spring and Autumn, people has general requirements for the heating, cooling and electricity, during summer days and winter days, the energy consumption shows a significant difference under the influence of outside climate. the energy consumption in the scenarios come from the cooling, heating and electricity loads profiles for industrial, commercial and residential areas. The system simulated in this research has a fixed power. The capacity of the system limited its applications within the range from small-scale domestic application to micro commercial application. However, using the system to supplying a wide range of loads give a comprehensive evaluation on the system's performance. The load design in this chapter is using a certain load under specific application and transferring the load same scale of the system. The details introduction and the simulation results of the system are displayed in the next section.

6.4.1 Typical summer day loads

Case 1:

The loads consumption Figure 76 presents a typical energy consumption in the 24 hours of a summer day. From the Figure 76, it shows that the heat demand is much less than the cooling demand. The largest cooling demand has energy peak which starts from 12:00. There is a peak demand time zone last for roughly 11 hours. The cooling demand keeps more than 6 kW during the peak time. The electricity demand is larger than heat and less than cooling demand. There is a small ripple during peak time for electricity demand. The general electricity demand is 1.5-2 kW and the peak time demand is around 3 kW. The heat demand demands the least energy which only cost less than 1 kW during the 24 hours. Supplying energy for this load should consider the cooling load first and then the electricity. The extra energy after supplying the main two energy demand can fulfil the heat demand.

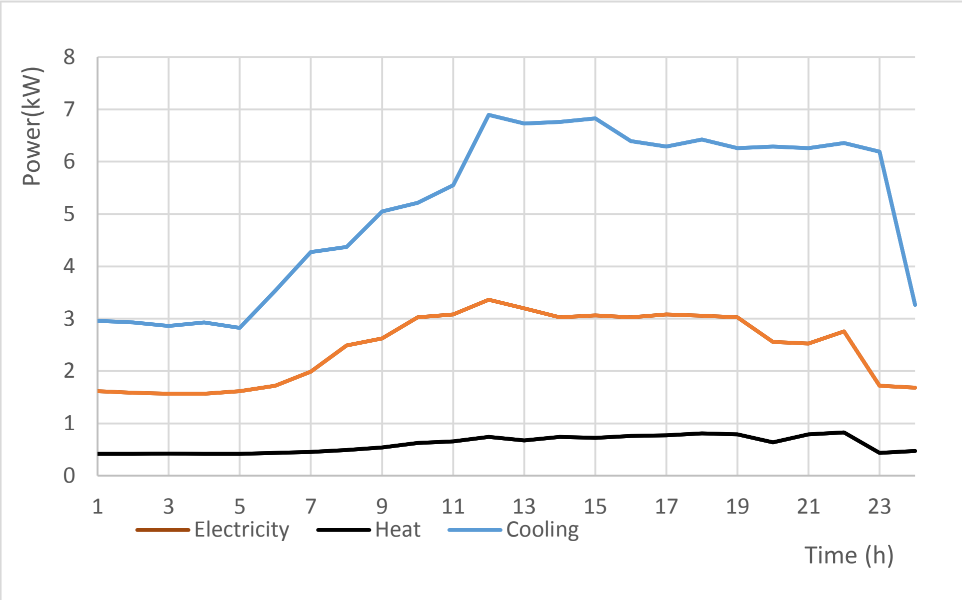

Figure 76 Power demand of Case 1

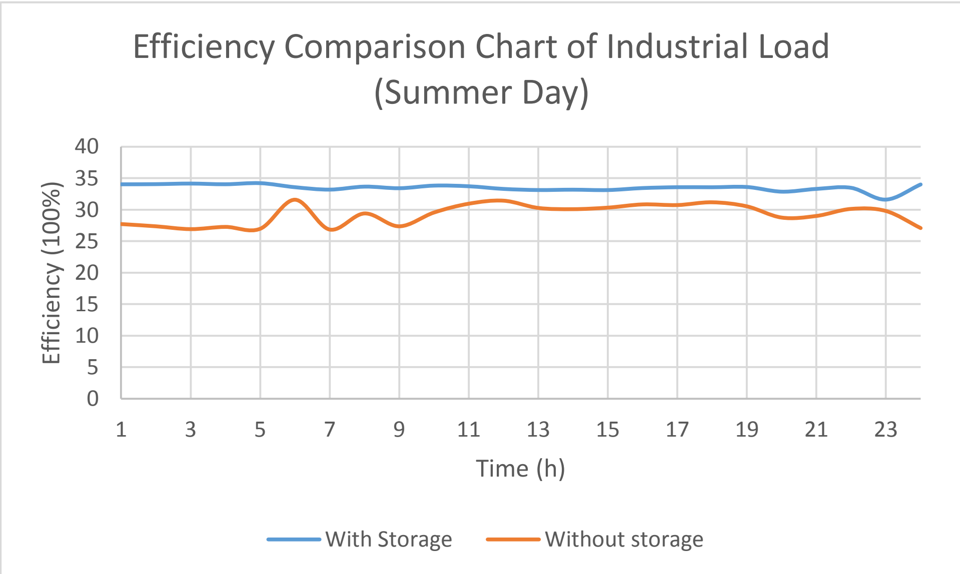

Figure 77 System performance comparison of case 1

Based on the efficiency study of this system, the cooling energy is transferred from the waste heat. Cooling energy product has the lowest efficiency during the system's operation. Since most of the load is cooling demand, the over efficiency is changing around 35% during the 24 hours simulation. The Figure 77shows the efficiency comparison of the system with and without the energy storage units. Because of the energy storage, system expands the whole system's energy capacity which make the energy can be controlled more flexibly. The efficiency with energy storage units is slightly better than the system without storage units. Especially when the system's energy demand change, the energy storage units discharge the energy when peak time comes and charge the energy for storing excess energy. There is roughly 5% enhancement when the system is integrated with the energy storage units.

Case 2:

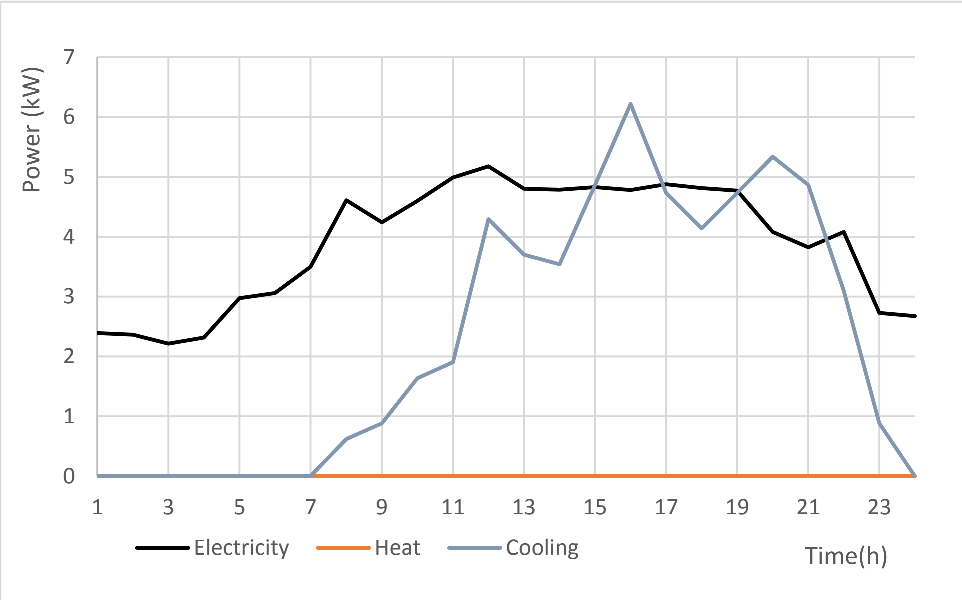

Figure 78 Power demand of Case 2

The second case study focus on other kind of load on a summer day. From the load profile, the energy demand during the simulation time consists of electricity and cooling. For the electricity, there is a rising trend in the first 12 hours and downtrend in the last 7 hours. The electricity demand risen from 2 kW in the start to the peak value in the mid of the day. From 9:00 to 19:30, the electricity demand keeps at a high value which ranged from 4.5 kW to 5.2 kW. There is an obvious drop for the electricity demand after 19:00. The cooling demand is diffrerent from the electricity demand. the rapid increasing cooling load begins at 7:00 in the morning and reaches to peak (6.24 kW) at 15:30. From 15:00 to 21:00, the cooling load keeps at the peak demand around 5kW to 6 kW. The rapid fall occurs after 21:00, it indicates the refrigeration demand becomes secondary need at that period.

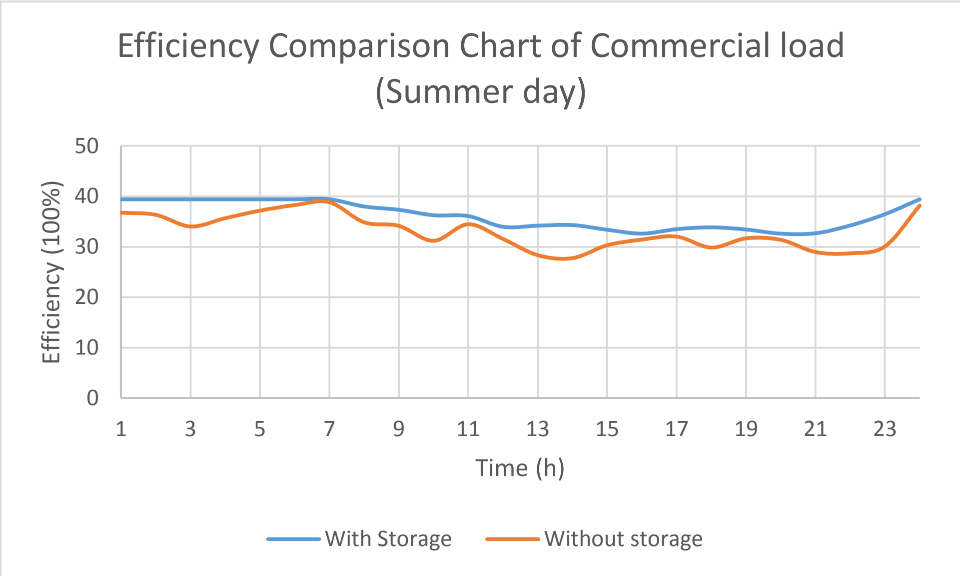

Figure 79 System performance comparison of case 2

The Figure 79 shows the comparison of the efficiency of the system. The blue line represents the system's efficiency with the energy storage system. With the energy storage system, the system's efficiency fluctuated in the range of 33.4 to 40. When the energy demand is small, the system operated at a high efficiency. System's efficiency dropped at the peak time and raised up to 40% at the end of the simulation. Without the energy storage units, the system's efficiency has an average 5% drop compared to the system with energy storage units. At 10:00, 14:00 and 21:00, the efficiency difference values are the largest. It indicates the energy storage units keep the system operating at a stable condition when the load is changing. The energy storage units helps the system accessing high efficiency when the load is dynamic changing.

Case 3:

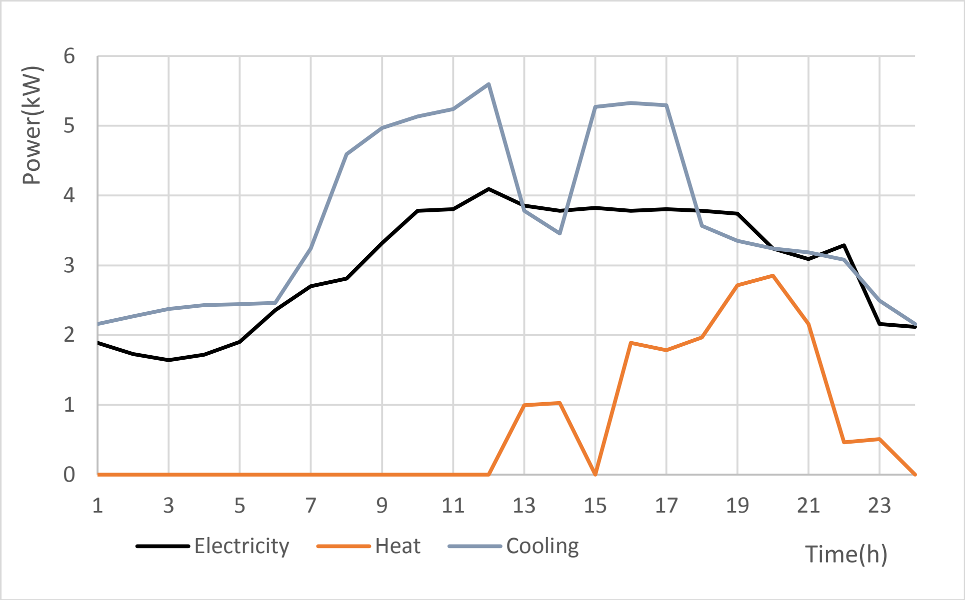

Figure 80 Power demand of Case 3

The third case express another summer day load in this simulation. This load has high cooling demand and electricity demand at day time. During peak time, the largest energy demand is cooling. There are two cooling demand peak occurs at around 11:30 and 16:30. The maximum of cooling loads reaches to5.5 kW at 11:30. During off peak times, the cooing loads changes from 2 kW to 3.5 kW. The electricity demand is the second largest energy demand for this load. It increase smooth and steady from the beginning of the day to peak times. From 11:00 to 19:00, relative large electricity demand is required. After 19:00, the reduction tendency is obvious. For the heating demand, during half of the time the heating demand is required. Compared to the cooling and electricity demand, the heating demand is much less. At 20:00, heating demand reaches the peak point, which is 2.8 kW. After that, the heating demand decreases dramatically.

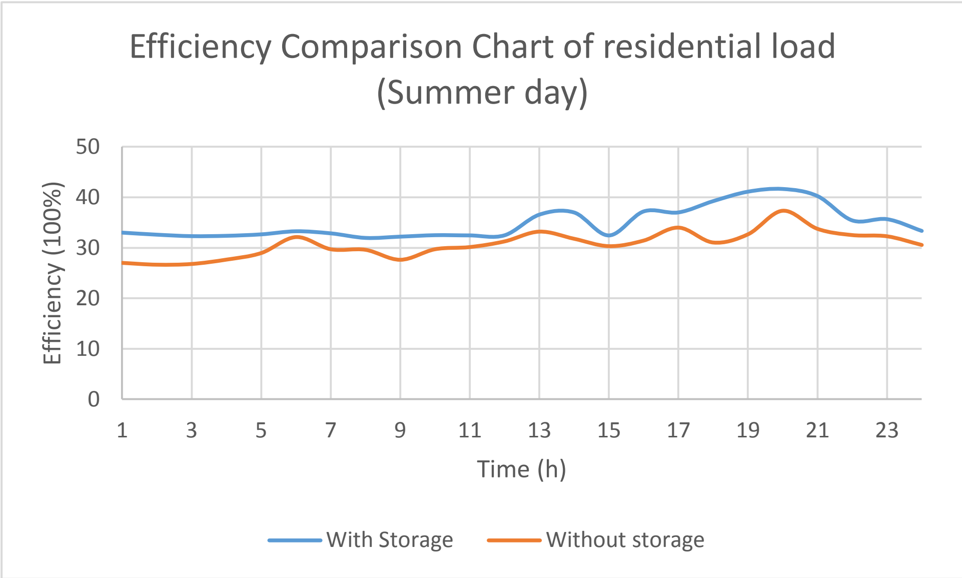

Figure 81 System performance comparison of case 3

The system's efficiency in this case is similar with the two previous cases. In most of the time, the system's efficiency kept above 28% (without energy storage units) and 35% (with energy storage units). Basically, the two efficiency curves followed same tendency. The efficiency increases slowly from the begging and reached the peak at 20:00. From the previous efficiency study on the system, the heating energy conversion efficiency is higher than the other two products, which is the reason the system, had highest efficiency when the heating demand was the maximum value.

6.4.2 Typical winter day loads

Case 4

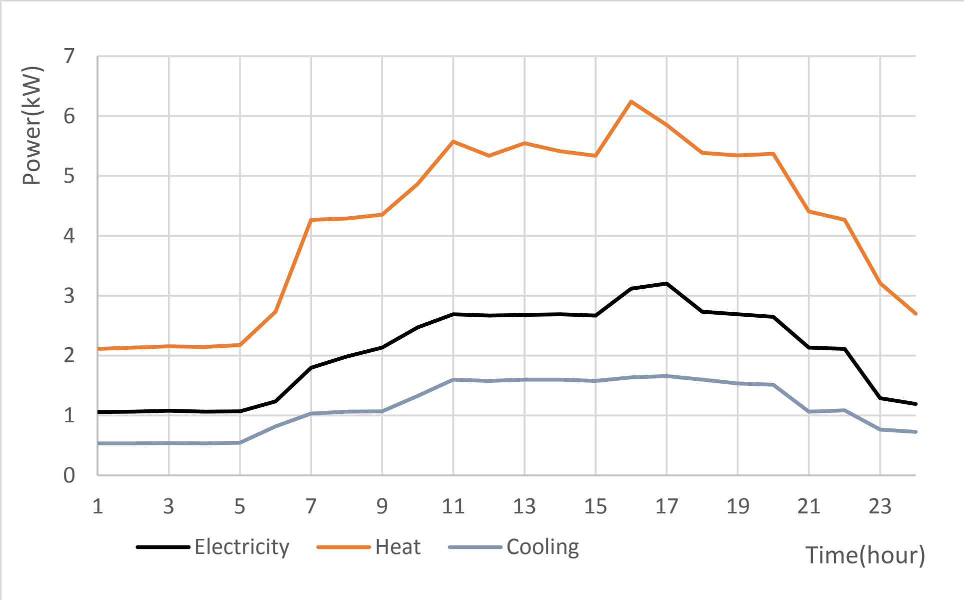

Figure 82 Power demand of Case 4

The Figure 82expresses a load scenario on a typical winter day. From the curves on the Figure 82, the three energy products demand have similar tendency but different value. Heating, the highest energy demand in this case has an upward tendency from the starting of the day. It reaches 6.2 the maximum point at 16:00 and drops to less than 3 kW in the next 9 hours. The electricity demand has similar curve Sharpe with the hating demand. The maximum value of electricity demand is much less than heating, which is 3 kW at 16:00. The cooling demand is the smallest energy requirement in this case. It changes from 0.5kW to 1.5 kW during the 24 hours.

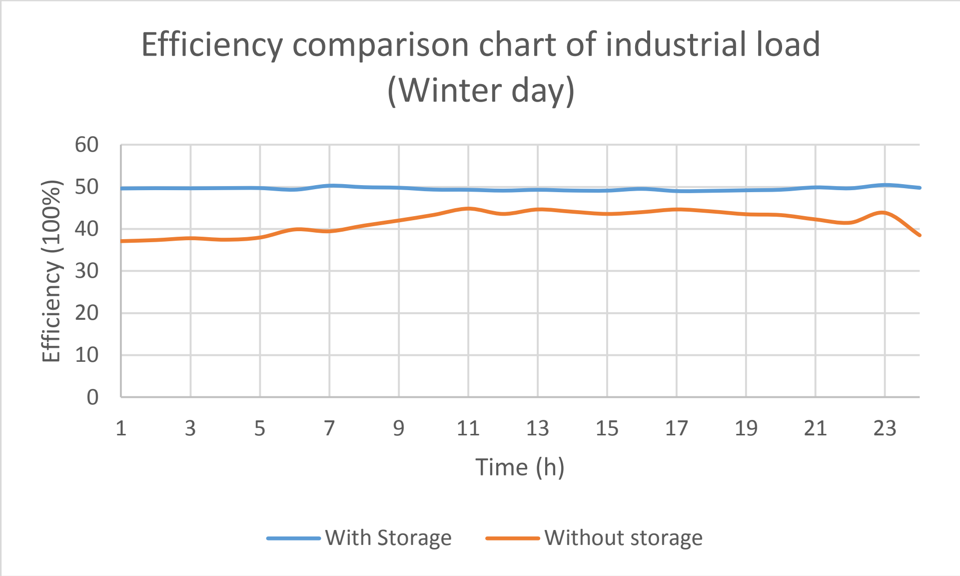

Figure 83 System performance comparison of case 4

The efficiency of the system with and without energy storage are displayed in the Figure 83. The orange curves represents the system's efficiency without the energy storage units. It had an increasing tendency during the first simulation time and decreasing tendency in the last half simulation time. The blue curve represent the system's efficiency with energy storage units. During the simulation, the system's efficiency kept at 50%. The smooth changing of the load caused this phenomenon. Compared to the previous cases, the efficiency in this case is higher because of a large demand of heating.

Case 5

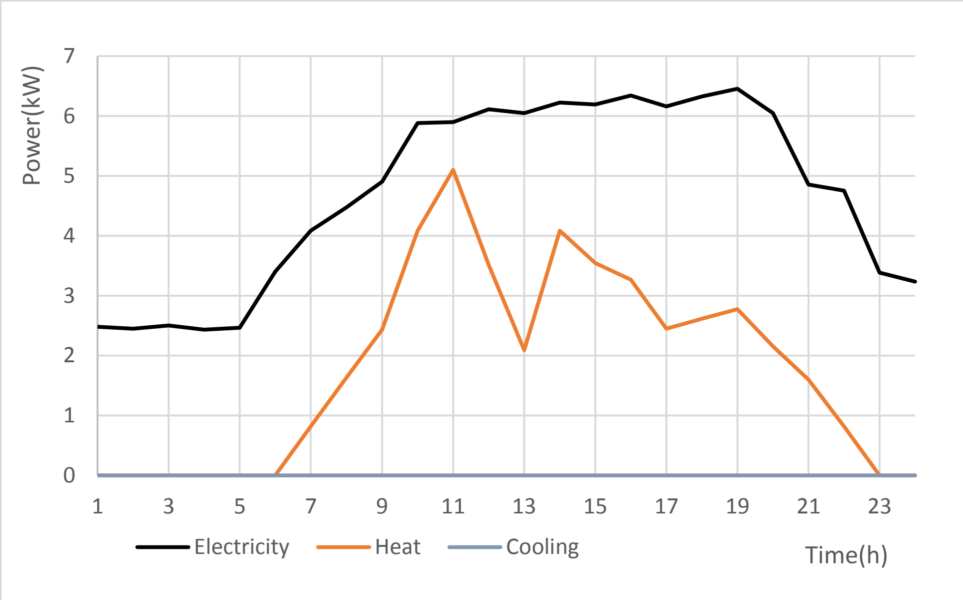

Figure 84 Power demand of Case 5

In this case, there are only heating demand and electricity demand. The electricity demand is larger than the heating demand. It started from 2.5 kW at the beginning. The 2.5 kW electricity demand last for 3 hours than it increases to 6 kW from 5:30 to 9:30. From 11:00 to 19:00, it has a slow rising rate until reaching 6.5 kW peak point at 19:00. After that, the electricity demand drops to 3.2 kW at the end of the day. The heating demand starts from 6 am in the morning. During the whole day, it fluctuates within a large range. It increased to 5 kW at 11:00, which is the peak point during the day. After that, the heating demand has a general reduction tendency until 23:00 when it decrease to 0 kW.

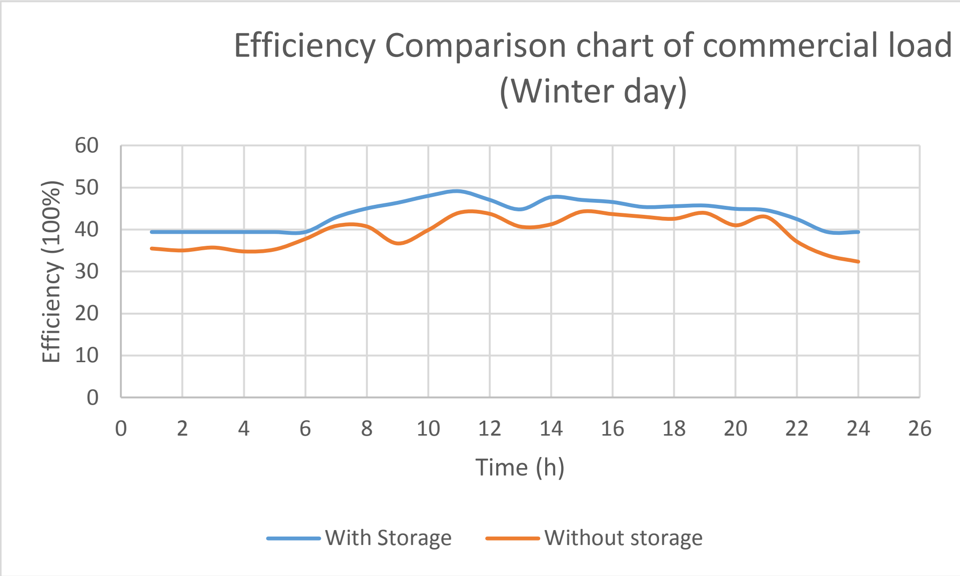

Figure 85 System performance comparison of case 5

The two curves on the Figure 85 shows the system's efficiency during the simulation under different conditions. System's efficiency without energy storage units is a bit lower than system with energy storage units. There is a 3-5 % difference between these two sets of system efficiency. In the beginning and the end of the simulation, the system's efficiency was lower than the peak time. At 11:00, the system's efficiency reached to the peak and decreased smoothly in the rest of time.

Case 6

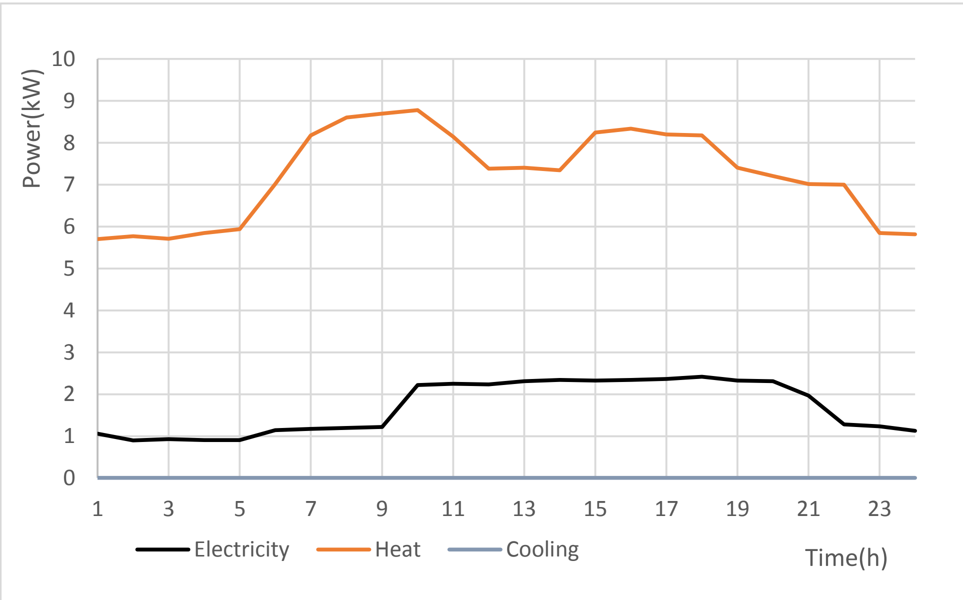

Figure 86 Power demand of Case 6

In this case, the load requires a large demand of heating. The other energy demand for this load is electricity. The heating demand varies between 6kw to 8.8 kW during the 24 hours. There are two peak demands locating at 9:00 and 16:00. In the rest of time, the heating demand keeps in the range of 6 kW to 7.5 kW. The electricity demand for the load is much less compared to the heating load. it consists of two phases. In the first phase, the demand is 1 kW last for 9 hours until 9:00. Then the electricity demand increases to over 2 kW from 10:00 until 21:00. There is a small reduction at the end of the day.

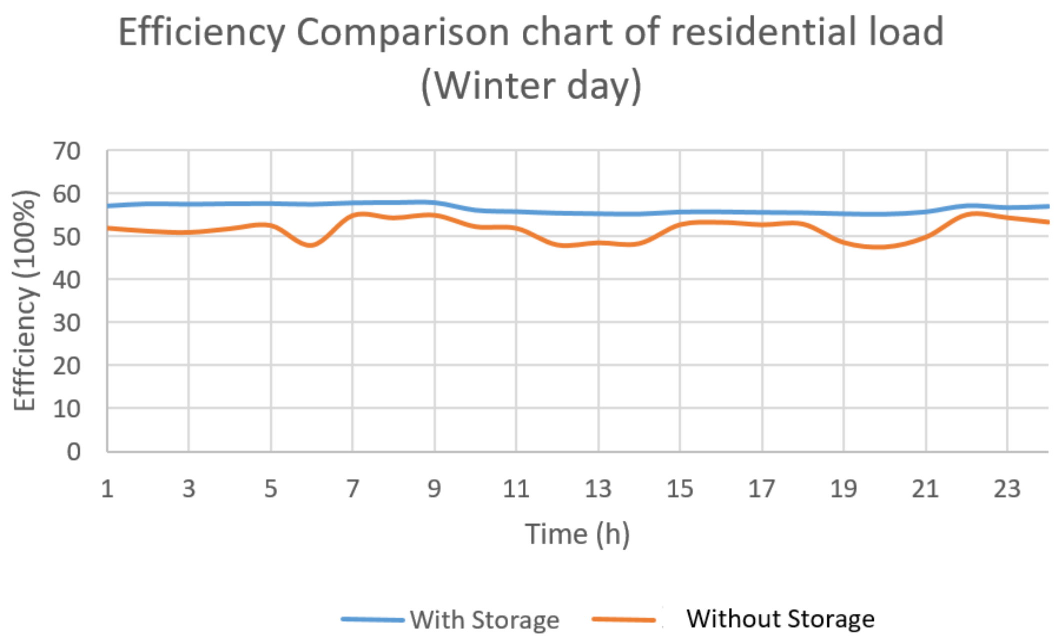

Figure 87 System performance comparison of case 6

Different from the system's efficacy with energy storage units, the system efficiency without energy storage units had been changing during the simulation time. It varied from 49% to 55% in the 24 hours. The efficiency curve shape was similar to the heating load shape since the heating demand has a large influent on the system' over efficiency. The other set of simulation had a steady system efficiency with the help the energy storage units. It keeps above 55% during the whole simulation.

6.5 Optimisation methodology for the integrated trigeneration system

The Figure 88 shows the system's map. This trigeneration system in this research consists of three energy cycles which are represented by different colours. This configuration map shows how the energy is transferred to the loads by the system. In this section, the optimisation process for this system is presented as the format of equations and explanations.

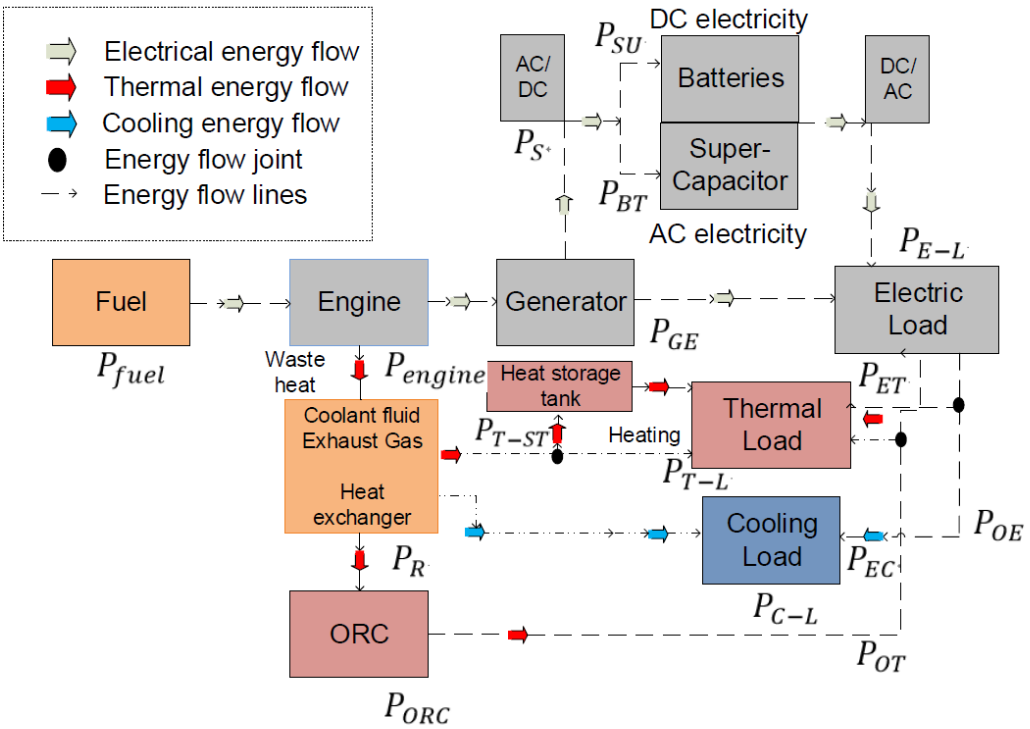

Figure 88 integrated system

Nomenclature	
P_{fuel}	Fuel consumption (primary energy consumption) of the trigeneration system
η_{engine}	Efficiency of engine
P_{engine}	Power output of engine generator
P_s	Power output of energy storage system
P_{SU}	Power output of supercapacitor
P_{BT}	Power output of batteries
P_{LOAD}	Electrical power demand (load)
soc	Batteries' state of charge
te	At the end of operation time
C_S	Batteries' capacity
DG-ES	Distributed power generation with energy storage system
P_R	Power output of the recovery system
P_{T-ST}	Power output of the thermal storage system
P_{ET}	Power consumption of transferring from electricity to thermal energy
P_{EC}	Power consumption of cooling generated by electricity
P_{OE}	Power generated from ORC system
P_{OT}	Rate of low level heat from ORC
P_{ORC}	Power output of the ORC system
P_{C-L}	Cooling load

Table 39 Nomenclature table for the optimisation of trigeneration system

6.5.1 Trigeneration optimisation system

During the simulation of the system, the primary task for the system is to satisfy the energy demand of the load. All the operations of the system follows the basic goal. The optimisation processes shown in this section aims at maximum the system's efficiency

The engine in the system is the prime mover. It transfer the energy in the fuel into the system with certain efficiency.

$$P_{fuel}.\eta_{engine} = P_{engine}(21)$$

The energy storage units contains the supercapacitors and the batteries. The power of the energy storage equals the summation of the two components' power rate.

$P_s = P_{SU} + P_{BT}(22)$

The equation expresses the recovery energy amount from the engine.

$$P_R = P_{fuel} \cdot \eta_{recovery} (23)$$

Part of the recovery energy is used to support the operation of the ORC.

$P_{ORC} = P_R(1 - \alpha - \beta)(24)$

When generator is operating, the energy using to supply the load consists of the power of generator, energy storage system and the electric power output from the ORC. During the system's operation, the recovery energy is used to satisfy the heat demand. The thermal storage unit reserves part of the excessive energy.

$P_{LOAD} = P_{GE} + P_S + P_{OE}(25)$

$P_R \cdot \alpha + P_{T-SL} = P_{T-L}(26)$

$P_R \cdot \beta = P_{C-L}(27)$

When generator is not operating, the energy storage units supports the electric loads. Because of lacking recovery energy, the heating load and the cooling load are supplied by the energy stored in the storage units.

$P_{LOAD} = P_S(28)$

$P_{ET} + P_{T-SL} = P_{T-L}(29)$

$P_R \cdot \beta = P_{EC}(30)$

Suppose the system's operation follows the electric load (FEL), the optimisation of the system aims at minimizing the engine's operation time. From calculating difference between the minimum engine operation time and the compensational engine operation time, the optimized results for the engine's operation can be obtained.

$t'_{min} = \frac{\int_0^{te} P_{engine}(t)dt}{P_{engine}(max)}$(2931

$t' = t'_{min} - t_{min}(32)$

$\int_0^{t'} P_{OE}(t)dt = P_{engine}(max) \cdot t'(33)$

6.5.2 Limiting conditions

There is a few limit condition when the system is operating. For insuring the batteries' lifespan, the state of charge of the batteries is limited within the rage from 40% to 60. At the same time, the power supplied by the system must be equal or higher than the load's energy demand. The thermal energy stored in the storage units is required to fulfil the thermal load and the cooling load. The recovery thermal energy is allocated to three parts which are responsible for the thermal storage, heating demand and cooling demand respectively.

$40\% < SOC(t) < 100\%$ (34)

$P_{GE} + P_S + P_{OE} \geq P_{LOAD}$(35)

$P_R \cdot \alpha + P_{T-SL} \geq P_{T-L}$(36)

$P_R \cdot \beta \geq P_{C-L}$(37)

The saved energy is expressed by the equation.

The energy save $= \int_0^{te} \frac{P_{engine}(t)}{\eta_{engine}} dt - P_{engine}(max) t_{min}$(38)

6.5.3 Optimisation results

Scenarios	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Electrical energy demand (kWh)	58.92905	93.47788	72.21316	49.49	113.14	40.461
heat demand (kWh)	14.44465	0	16.35953	101.22	43	173.77
cooling demand (kWh)	123.422	55.46018	87.13556	27.56	0	0
Electrical energy generated by the engine (kWh)	68.87	52	61.49	62.4	58.73	74.95
energy supplied by electrical energy storage (kWh)	20.04	24.3	37.48	27.04	46.8	12.61
energy supplied by heating storage unit (kWh)	38.52	10.6	0.99	47.31	9.46	0
energy supplied by ORC system (kWh)	4.48	3.37	4	4.06	3.56	4.88
System capacity enhancement (%)	63%	47.01%	64.61%	55.10%	41.50%	64.15%
engine operation time (h)	10.55	8	9.46	9.6	8.41	11.53
energy consumption amount (kWh)	196.7957	148.93	175.7	178.28	156.13	214.23
Overall efficiency (%)	33.49	36.13	34.92	49.51	43.7	56.53
Efficiency enhancement (%)	3	3.18	2.85	17.11	8.98	22.35

Table 40 Optimisation results summary Table

The Table 40 shows the simulation results and the optimisation results. Simulations results from the 6 cases give a comprehensive evaluation on the system' performance. The case one, case two and case three simulated the system's performance on a summer day and the last three cases investigated the system's performance on a winter day. During the system's simulation, the ORC system supplied about 10% of the electric energy demand. In the different cases, the energy storage units improves system's capacity significantly. The minimum value was in case 5(41.5%) and the maximum value was in case 6 64.15%. after the optimisation process, the system's engine operated with less time and the system's overall efficiency was improved in each case. Based on the optimisation results, the engine was controlled to operate with full power rate with minimum time to satisfy the load. Different from the previous simulation of the trigeneration system, short time of engine's operation with full power rate improves the electric efficiency of the system. The optimisation process converts more energy to electricity from the fuel, the higher electricity efficiency contributes to the system overall efficiency. In the first three cases, the overall efficiency were lower than the last three cases. The load on a typical summer day needs more cooing energy, which is the weak part of the system. The cooing energy in this system is transferred from the recovery heat. It limited the cooling energy conversion efficiency, which is the fundamental reason why the system's efficiency was low in the first three cases. In the last three cases, the system generated more heating and electricity which make the overall efficiency to be higher.

6.6 Chapter summary

In this chapter, the system's efficiency is firstly calculated based on the details of the components. The theoretical efficiency show the system has highest amount of thermal energy generation with consuming certain amount of primary energy. The optimisation of the electric part of the system follows the theoretical calculation of the system's efficiency. Based on the optimisation process, the results shows less time of engine operation can satisfy the dynamic load successfully. In the next parts, a various cases of load are simulated to evaluate the system's performance. The simulation results suggests the trigeneration system can satisfy a dynamic load with a high efficiency with the help of the ORC and the heat recovery system. The energy storage system in the system enhances the system's energy capacity. It also has a buffering function when the energy demand peak comes. The optimisation process calculated the maximum engine operation time and control the engine' operation. With less time of operation, the system has higher electrical efficiency. The optimized engine working time are displayed in the last section. After the optimisation process, the system's efficiency has a remarkable improvement.

This chapter shows the optimisation on the system's operations. The integrated system consumes less primary energy to satisfy the dynamic load after the optimisation process. The results of this project is finished by this chapter.

7 Conclusions

This study describes a detailed study on the Trigeneration with energy storage and ORC system integrated. The system is designed and built to meet small-scale energy demand. The details of the findings are summarized at the end of each chapter. An overall summary is displayed in this chapter as the conclusion of the study.

7.1 Summary of the results

The aim of this study is designing an integrated energy system to supply changing small-scale load with high efficiency. This system is meant to combine the advantages of the trigeneration system, ORC system and hybrid energy storage unit. In chapter 2, a series of trigeneration system including the systems integrated with ORC system are discussed. From the investigation on the similar systems, this system design has never been posted. The energy storage equipment is also discussed. The combination of conventional batteries and supercapacitor is a good choice for satisfying dynamic power demand. After researching the ORC technologies, energy storage equipment's and recent developed trigeneration, the new design which combines all these technologies engages the advantages of high efficiency energy supplying and flexible operation. It has potential to be an alternative approach to solve the energy crisis.

The system's design is displayed Chapter 3. For the investigation of this new design, the methodology of the study is discussed. Because of this integrated system is designed for small scale load, an energy consumption background investigation and the domestic household energy demand analysis are carried to discuss the possible loads for the system. Based on the specific calculated results of the small scale load, the system size is introduced in chapter 3. The discussion shows a 6.5 kW diesel engine is capable to drive the system to supply a dynamic load. However, the size discussion only shows an estimated value of the small scale load. Analysing of the obtained data from previous researcher's measurement on a household's energy consumption is used to display the speciation of the target load. The methods of investigation of the system are also introduced in chapter 3 which are experimental tests and computer modelling. The optimisation is also included in the methodology. After deciding the direction of the system's research, the experimental tests on the system's key components are carried at the first step. The experimental test includes two parts. The first part is the charging and discharging test. The second part is supplying energy using the electric part of the integrated system. The results from the first part of tests are used to get accurate parameters of system's key components. The second part of the tests shows the system's performance on supplying dynamic load. With the help of hybrid energy storage units, the changing load is fully supplied during the whole test period. The control strategy in chapter 4 shows the logic state of system's switches in the mode of individual system and system with ORC system respectively.

Because of the limitation of the equipment, using experimental tests to build an accurate model can help the investigation on the system's performance to a further step. In Chapter 5, the system's modelling building which refers to the computer modelling building in the Matlab software environment is displayed. The validation process which compares the simulation results and the results obtained from the experimental tests shows the accuracy of the system is ±2.7%. A simulation study on a domestic load supplying shows the energy demand of the selected domestic load is fulfilled by the integrated system. The system obtained high efficiency in the two loads simulation (48.30%) and 52.20%. After analysing the simulation results, it is found that the power source (diesel engine) in simulation has potential efficiency to be developed which indicates there is a better operation for the system. An optimisation process on the system's operation is needed for discovering the potential of the system.

The key point of optimisation on the integrated system is the regulation of engine's operation. Theoretical discussion shows the idea of optimisation on system's operation. After simulations on the system to supplying selected load with different operation, the results shows the optimisation process saves 3.61 kWh and 1.86 kWh in the two cases from former simulations. Furthermore simulations are carried on random selected scenarios. The random loads are selected based on energy consumption in on typical summer days and on typical winter days. By supplying the designed load and processing the optimisation on the system, the system's energy performance is evaluated. The optimisation process is proved to enhance the system's efficiency from 4% to 22.35% in different cases. These results shows the optimisation process is useful.

7.2 **Further work of the system's investigation**

This project shows a successful design of an integrated energy system for small-scale load. Using the integrated system, the waste heat from the energy source is capable to be transferred to useful electricity, heat or cooling. The hybrid energy storage units make the system flexible to operate. The ORC system helps the integrated system use low temperature heat source for additional electricity generation. Although there are obvious advantages using the designed integrated system to supply the small-scale load. There are spaces for potential improvement in the further work on this system. According to the results of the simulation, the efficiency improvement brought by the ORC system is around 2%. With the integration of ORC system, part of the recovered heat is occupied for electricity generation, the heat supply and cooling supply are affected in the system's operation. The reason of this problem is the energy source is this integrated system. Only a diesel engine generated limited waste heat. The ORCs system is more suitable for applications with more available waste heat. This does not indicate the design of the integrated system is a failure. Since this design is a distributed system, there is potential that other energy source could be engaged with this system. For applications of distributed energy system, a wide range of heat source could be the energy source of ORC system other than the diesel engine.

Because of applying the conventional batteries in the hybrid energy storage system the overall performance of the energy storage unit is not satisfactory. The lead acid batteries suffer from the aging problem, which makes the state of health to be one key factor to affect the system’s overall energy performance. Aiming at sustainable energy supplying wit high efficiency, the energy storage system could be a research point for further work. Considering the lifespan of the batteries, recovery the state of health of the batteries and safe control strategy to the energy storage system can improve the system’s performance to next level.

As discussed that additional energy sources are encouraged to be integrated within the system. The renewable energy source is an interest choice to be combined in. For example, the photovoltaic and wind turbine are both compatible in the small-scale system. The geothermal energy is a clean energy source for ORC system to generate more electricity. With a simple correction, the control strategy for the system can achieve an integration of the renewable energy sources. Further experimental tests are necessary to evaluate the overall performance of this design of structure. Tests are always take priorities of simulations. For a more accurate evaluation of the system’ performance, tests on thermal and cooling part are recommended. The experimental work for the system to fulfil three kinds of energy products are also a feasible research direction for this complicated system. The evaluation of the system’s performance is based on the simulations. More experimental work will be more convincing in the further evaluation.

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Appendices

Appendix 1: summary of recent similar system

	construction	power	application	System's performance and research results

xi chen	CCHP based on PEMFC and PTSC	13.2 kW	Residential load	Efficiency ≥80.5% density reach 7.19kw AT 900 MaCM-2
zhe tian	CCHP	23000 kW	office building	Verified detailed model has more accurate economical performance
Riccardo Amirante	CCHP	280 kW	commercial building (airport)	Two different typologies tested. One plant can ensure a emission reduction
Simin anvari	CCHP	72 MW	industrial load	New definition for exergy economic factor reduces the cost rates
J, Y, Wu	Micro-CCHP	40.2 kW	Residential load	Appropriate load ratio is reached for satisfying the load
Yq, W, Yix, S	Micro CCHP based on fuel cells	30 kW	Domestic load	High efficiency, reaches over 90%
xiling z	CCHP station	20 MW	Hybrid load	High comprehensive energy efficiency (94.94% in winter 84.33 in summer) Primary energy saving 32.2% in winter and 4.9 % in summer
wang, j ,l , j. y .wu. C.y cheng	CCHP system with exhaust gas recovery system	16 kW	Domestic load	high efficiency 94.4% energy saving ratio 0.304 cost saving ratio 0.417
bracco stefano	Polygeneration microgrids with trigeneration system	132 kW	Commercial loads	Carbon emission reduction. Cost 9 € to reduce the CO2 of about 0.02 tCO2
GE. Y	CCHP	80 kW	Commercial loads	The CCHP system could satisfy more than 90 % of energy demand.
	construction	power	application	System's performance and research results
xi chen	CCHP based on PEMFC and PTSC	13.2 kW	Residential load	Efficiency ≥80.5% density reach 7.19kw AT 900 MaCM-2
bracco stefano	Polygeneration microgrids with trigeneration system	132 kW	Commercial loads	Carbon emission reduction. Cost 9 € to reduce the CO2 of about 0.02 tCO2
wang, j ,l , j. y .wu. C.y cheng	CCHP system with exhaust gas recovery system	16 kW	Domestic load	high efficiency 94.4% energy saving ratio 0.304 cost saving ratio 0.417

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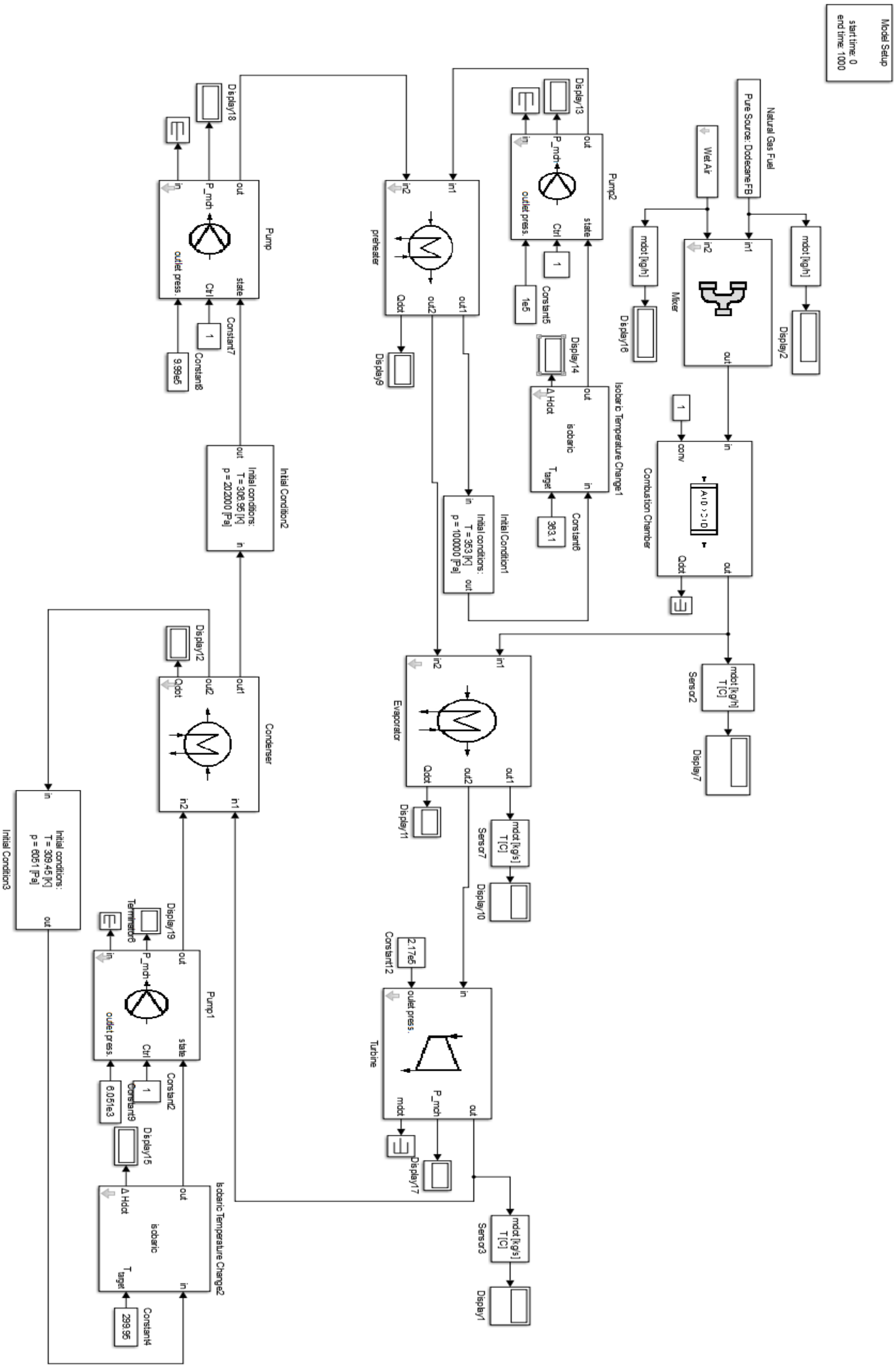
xiling z	CCHP station	20 MW	Hybrid load	High comprehensive energy efficiency (94.94% in winter 84.33 in summer) Primary energy saving 32.2% in winter and 4.9 % in summer
zhe tian	CCHP	23 MW	office building	Verified detailed model has more accurate economic performance
Simin anvari	CCHP	72 MW	industrial load	New definition for exergy economic factor reduces the cost rates
Information of the system listed by system's construction				
	construction	power	application	System's performance and research results
	CCHP based on PEMFC and PTSC	13.2 kW	Residential load	Efficiency ≥80.5% density reach 7.19kw AT 900 MaCM-2
	CCHP	23000 kW	office building	Verified detailed model has more accurate economic performance
	CCHP	280 kW	commercial building (airport)	Two different typologies tested. One plant can ensure a emission reduction
	CCHP	72 MW	industrial load	New definition for exergyoeconomic factor reduces the cost rates
	Micro-CCHP	40.2 kW	Residential load	Appropriate load ratio is reached for satisfying the load
	Micro CCHP based on fuel cells	30 kW	Domestic load	High efficiency, reaches over 90%

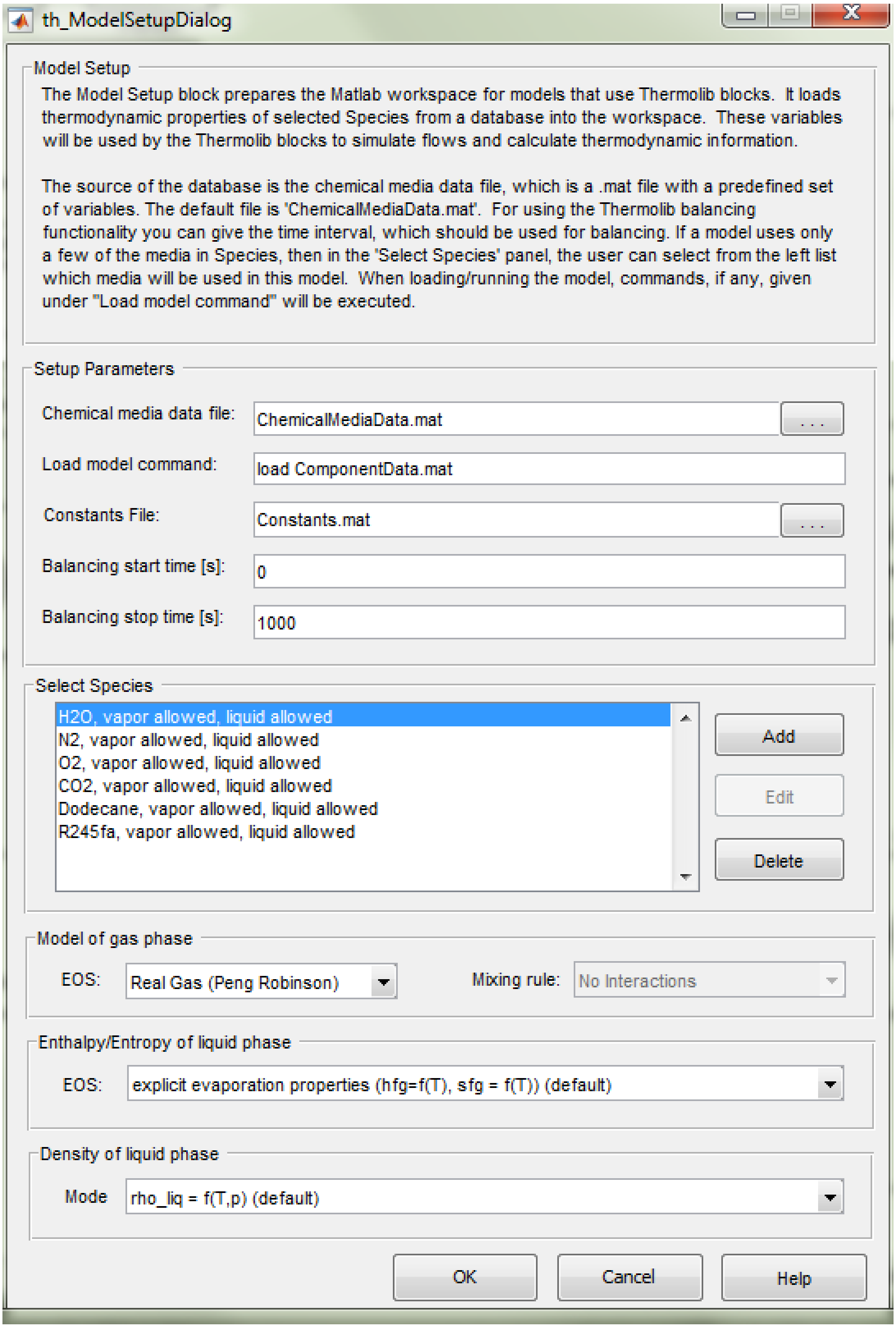
	CCHP station	20 MW	Hybrid load	High comprehensive energy efficiency (94.94% in winter 84.33 in summer) Primary energy saving 32.2% in winter and 4.9 % in summer
	CCHP system with exhaust gas recovery system	16 kW	Domestic load	high efficiency 94.4% energy saving ratio 0.304 cost saving ratio 0.417
	Polygeneration microgrids with trigeneration system	132 kW	Commercial loads	Carbon emission reduction. Cost 9 € to reduce the CO2 of about 0.02 tCO2
	CCHP	80 kW	Commercial loads	The CCHP system could satisfy more than 90 % of energy demand.

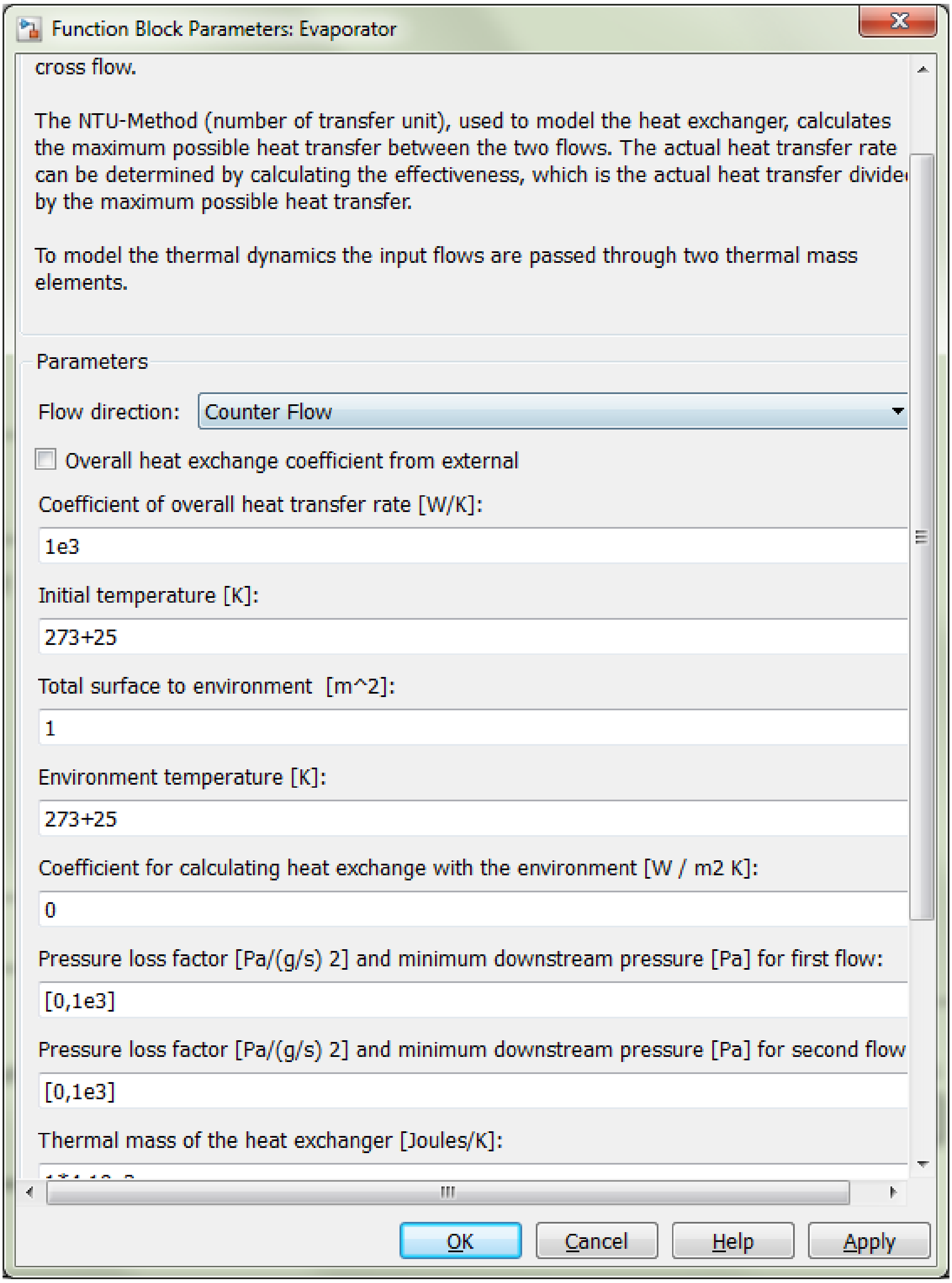
Appendix 2: Comparison of the test results and the simulation results on the engine

Load of the engine (%)	**Efficiency (%)**		**Error calculation (%)**	**recovery efficiency**		**error of simulation**
		simulation results			simulation results	
0		-0.006	0		0	0
10		7.8	1.13869E-14		35.363	0.0790885
25		16.3599375	0.367714724		35.38378	0.0256167
50		24.3	0.41322314		35.38635	0.0278476
75		27.525	0.824175824		35.40957	0.1384534
100		28.5	1.423487544		35.44343	0.1376295

Appendix 3: ORC simulation model




th_ModelSetupDialog
Model Setup
The Model Setup block prepares the Matlab workspace for models that use Thermolib blocks. It loads thermodynamic properties of selected Species from a database into the workspace. These variables will be used by the Thermolib blocks to simulate flows and calculate thermodynamic information.
The source of the database is the chemical media data file, which is a .mat file with a predefined set of variables. The default file is 'ChemicalMediaData.mat'. For using the Thermolib balancing functionality you can give the time interval, which should be used for balancing. If a model uses only a few of the media in Species, then in the 'Select Species' panel, the user can select from the left list which media will be used in this model. When loading/running the model, commands, if any, given under "Load model command" will be executed.
Setup Parameters
Chemical media data file:
ChemicalMediaData.mat
Load model command:
load ComponentData.mat
Constants File:
Constants.mat
Balancing start time [s]:
0
Balancing stop time [s]:
1000
Select Species
H2O, vapor allowed, liquid allowed
N2, vapor allowed, liquid allowed
O2, vapor allowed, liquid allowed
CO2, vapor allowed, liquid allowed
Dodecane, vapor allowed, liquid allowed
R245fa, vapor allowed, liquid allowed
Add
Edit
Delete
Model of gas phase
EOS:
Real Gas (Peng Robinson)
Mixing rule:
No Interactions
Enthalpy/Entropy of liquid phase
EOS:
explicit evaporation properties (hfg=f(T), sfg = f(T)) (default)
Density of liquid phase
Mode
rho_liq = f(T,p) (default)
OK
Cancel
Help


Function Block Parameters: Evaporator
cross flow.
The NTU-Method (number of transfer unit), used to model the heat exchanger, calculates the maximum possible heat transfer between the two flows. The actual heat transfer rate can be determined by calculating the effectiveness, which is the actual heat transfer divide
by the maximum possible heat transfer.
To model the thermal dynamics the input flows are passed through two thermal mass elements.
Parameters
Flow direction:
Counter Flow
Overall heat exchange coefficient from external
Coefficient of overall heat transfer rate [W/K]:
1e3
Initial temperature [K]:
273+25
Total surface to environment [m^2]:
1
Environment temperature [K]:
273+25
Coefficient for calculating heat exchange with the environment [W / m2 K]:
0
Pressure loss factor [Pa/(g/s) 2] and minimum downstream pressure [Pa] for first flow:
[0,1e3]
Pressure loss factor [Pa/(g/s) 2] and minimum downstream pressure [Pa] for second flow
[0,1e3]
Thermal mass of the heat exchanger [Joules/K]:
OK
Cancel
Help
Apply