# Controller Design Methodology for Sustainable Local Energy Systems

AMEER AL-KHAYKAN

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# Controller Design Methodology for Sustainable Local Energy Systems

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**AMEER AL-KHAYKAN**

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# DECLARATION

The research reported in this thesis was conducted at University of Chester, Faculty of Engineering and Technology, Department of Electronic and Electrical Engineering between October 2014 and July 2018. I hereby declare this thesis is the result of my own work and any quotation from, or description of the work of others is acknowledged herein by reference to the sources. This thesis has not been submitted for any degree at another university.

Ameer Al-khaykan

University of Chester

July 2018

# SUPERVISORS CERTIFICATION

We certify that the thesis entitled "Controller Design Methodology for Sustainable Local Energy Systems" was prepared under our supervision at the department of Electronic and Electrical Engineering, Faculty of Engineering and Technology, University of Chester as a partial of fulfilment of the requirements of University of Chester, Chester, UK for the degree of Doctor of Philosophy.

Name and Title: Professor John Mark Counsell.

Address: Department of Electronic and Electrical Engineering, Faculty of Engineering, Chester, UK.

Date: 1 / 11 / 2018

Signature: 

**Approved by Head of Department of Electronic and Electrical Engineering**

**Name and Title:** Professor John Mark Counsell

**Address:** Head of Department of Electronic and Electrical Engineering, Faculty of Engineering, Chester, UK.

**Date:** 1 / 11 / 2018

**Signature:** 

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University of Chester

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# DEDICATION

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## Previous Publications to Date

- J M Counsell, Al-Khaykan Ameer, M J Stewart. “(CHPV) control" Michael Faraday IET International Summit Kolkata, India. 2015. https://ieeexplore.ieee.org/abstract/document/7513239/.
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- M J Stewart, Al-Khaykan Ameer, J M Counsell. “$CO_2$ and Thermal Storage with Combined Heat and Power with Solar PV Technology”. World Academy of Science, Engineering and Technology, International Journal of Energy and Power Engineering, 2017.

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# ABSTRACT

Commercial Buildings and complexes are no longer just national heat and power network energy loads, but they are becoming part of a smarter grid by including their own dedicated local heat and power generation. They do this by utilising both heat and power networks/micro-grids. A building integrated approach of Combined Heat and Power (CHP) generation with photovoltaic power generation (PV) abbreviated as CHPV is emerging as a complementary energy supply solution to conventional (i.e. national grid based) gas and electricity grid supplies in the design of sustainable commercial buildings and communities. The merits for the building user/owner of this approach are: to reduce life time energy running costs; reduce carbon emissions to contribute to UK's 2020/2030 climate change targets; and provide a more flexible and controllable local energy system to act as a dynamic supply and/or load to the central grid infrastructure.

The energy efficiency and carbon dioxide ($CO_2$) reductions achievable by CHP systems are well documented. The merits claimed by these solutions are predicated on the ability of these systems being able to satisfy: perfect matching of heat and power supply and demand; ability at all times to maintain high quality power supply; and to be able to operate with these constraints in a highly dynamic and unpredictable heat and power demand situation. Any circumstance resulting in failure to

guarantee power quality or matching of supply and demand will result in a degradation of the achievable energy efficiency and $CO_2$ reduction. CHP based local energy systems cannot rely on large scale diversity of demand to create a relatively easy approach to supply and demand matching (i.e. as in the case of large centralised power grid infrastructures). The diversity of demand in a local energy system is both much greater than the centralised system and is also specific to the local system. It is therefore essential that these systems have robust and high performance control systems to ensure supply and demand matching and high power quality can be achieved at all times. Ideally this same control system should be able to make best use of local energy system energy storage to enable it to be used as a flexible, highly responsive energy supply and/or demand for the centralised infrastructure. In this thesis, a comprehensive literature survey has identified that there is no scientific and rigorous method to assess the controllability or the design of control systems for these local energy systems. Thus, the main challenge of the work described in this thesis is that of a controller design method and modelling approach for CHP based local energy systems. Specifically, the main research challenge for the controller design and modelling methodology was to provide an accurate and stable system performance to deliver a reliable tracking of power drawn/supplied to the centralised infrastructure whilst tracking the require thermal comfort in the local energy systems buildings.

In the thesis, the CHPV system has been used as a case study. A CHPV based solution provides all the benefits of CHP combined with the near zero carbon building/local network integrated PV power generation. CHPV needs to be designed to provide energy for the local buildings' heating, dynamic ventilating system and air-conditioning (HVAC) facilities as well as all electrical power demands. The thesis also presents in addition to the controller design and modelling methodology a novel CHPV system design topology for robust, reliable and high-performance control of building temperatures and energy supply from the local energy system.  The advanced control system solution aims to achieve desired building temperatures using thermostatic control whilst simultaneously tracking a specified national grid power demand profile.

The theory is innovative as it provides a stability criterion as well as guarantees to track a specified dynamic grid connection demand profile.

This research also presents: design a dynamic MATLAB simulation model for a 5-building zone commercial building to show the efficacy of the novel control strategy in terms of: delivering accurate thermal comfort and power supply; reducing the amount of $CO_2$ emissions by the entire energy system; reducing running costs verses national rid/conventional approaches. The model was developed by inspecting the functional needs of 3 local energy system case studies which are also described in the thesis.

The CHPV system is combined with supplementary gas boiler for additional heating to guarantee simultaneous tracking of all the zones thermal comfort requirements whilst simultaneously tracking a specified national grid power demand using a Photovoltaics array to supply the system with renewable energy to reduce amount of $CO_2$ emission.

The local energy system in this research can operate in any of three modes (Exporting, Importing, Island).

The emphasise of the thesis modelling method has been verified to be applicable to a wide range of case studies described in the thesis chapter 3. This modelling framework is the platform for creating a generic controlled design methodology that can be applied to all these case studies and beyond, including Local Energy System (LES) in hotter climates that require a cooling network using absorption chillers. In the thesis in chapter 4 this controller design methodology using the modelling framework is applied to just one case study of Copperas Hill.

Local energy systems face two types of challenges: technical and non-technical (such as energy economics and legislation). This thesis concentrates solely on the main technical challenges of a local energy system that has been identified as a gap in knowledge in the literature survey. The gap identified is the need for a controller design methodology to allow high performance and safe integration of the local energy system with the national grid infrastructure and locally installed renewables. This integration requires the system to be able to operate at high performance and safely in all different modes of operation and manage effectively the multi-vector energy supply system (e.g. simultaneous supply of heat and power from a single system).

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## NOMENCLATURE

*(NB * denotes n'th zone/building)*

| Symbol | Definition | Unite |
|---|---|---|
| $\dot{m}_{v.n}$ | ***Air infiltration rate **** | $(kg/s)$ |
| $\dot{m}_{w.n}$ | ***Mass flowrate of water in network**** | $(kg)$ |
| $A_{d.n}$ | ***Area of doors**** | $(m^2)$ |
| $A_{f.n}$ | ***Area of floor**** | $(m^2)$ |
| $A_{im.n}$ | ***Area of internal mass**** | $(m^2)$ |
| $A_{r.n}$ | ***Area of roof**** | $(m^2)$ |
| $A_{s.n}$ | ***Area of wall structure**** | $(m^2)$ |
| $A_{w.n}$ | ***Area of windows**** | $(m^2)$ |
| $C_a$ | ***Thermal capacity of air*** | $(\frac{W}{(m^2K)})$ |
| $C_{im.n}$ | ***Thermal capacity of internal mass**** | $(\frac{W}{(m^2K)})$ |
| $C_s$ | ***Thermal capacity of thermal store*** | $(\frac{W}{(m^2K)})$ |
| $C_w$ | ***Thermal capacity of water*** | $(\frac{W}{(m^2K)})$ |
| $C_{zone.n}$ | ***Thermal capacity of heated zone**** | $(\frac{W}{(m^2K)})$ |
| $K_{PCHP}$ | ***Engine electrical gain value*** | *% Fraction* |

| | | |
|---|---|---|
| $K_{QCHP}$ | ***Engine thermal gain value*** | *% Fraction* |
| $M_{st}$ | ***Mass of water in thermal store*** | $(kg)$ |
| $M_{w}$ | ***Mass of water in the water network*** | $(kg)$ |
| $U_{d.n}$ | ***U value of doors**** | $\frac{W}{(m^2K)}$ |
| $U_{f.n}$ | ***U value of floor**** | $\frac{W}{(m^2K)}$ |
| $U_{im.n}$ | ***U value of internal mass**** | $(\frac{W}{(m^2K)})$ |
| $U_{r.n}$ | ***U value of roof **** | $\frac{W}{(m^2K)}$ |
| $U_{st}$ | ***U value of the thermal store*** | $\frac{W}{(m^2K)}$ |
| $U_{w.n}$ | ***U value of windows**** | $\frac{W}{(m^2K)}$ |
| $d_{s.n}$ | ***Structure thickness**** | $(m)$ |
| $h_{i.n}$ | ***Heat transfer coefficient**** | $(\frac{W}{(m^2K)})$ |
| $k_{s.n}$ | ***Structure thermal conductivity **** | $\frac{W}{(mK)}$ |
| $m_{im.n}$ | ***Mass of internal furniture**** | $(kg)$ |
| $m_{se.n}$ | ***Mass of external structure**** | $(kg)$ |
| $m_{si.n}$ | ***Mass of internal structure**** | $(kg)$ |
| $m_{zone.n}$ | ***Air and furniture mass**** | $(kg)$ |

| | | |
|---|---|---|
| | | |
| $\tau_{CHP}$ | ***Time constant of the engine*** | $(s)$ |
| $\tau_{st}$ | ***Time constant of the store*** | $(s)$ |
| $\tau_{w}$ | ***Time constant of the water network*** | $(s)$ |
| *Lp* | ***Water network total length of the pipes*** | $(m)$ |
| *Up* | ***Water Network Pipe overall heat transfer coefficient*** | $(\frac{W}{(m^2K)})$ |
| Dp | ***Diameter of water network pipe*** | $m^2$ |

# Chapter One
# Introduction

## 1.1. Local Energy Systems (LES)

In the last few years there has been a significant growth in local energy systems integrated with renewable energy sources to reduce carbon emissions, energy demand and operating costs for the end user. To ultimately decelerate climate change, the UK's 2020 and 2030 climate change targets have encouraged using the use of efficient electricity generation technologies, however the challenge for the sector is to deliver low carbon solutions at a viable cost whilst meeting the thermal comfort and power for appliances requirements.

Although high voltage transmission and the distribution of electrical energy is highly efficient, conventional thermal power stations feeding this network are not. Energy conversion to electricity necessarily incurs a loss in the form of heat as a by-product. Location and large scale conventional generating plants result in low overall efficiency due to the waste of this heat. A shift to distributed generation also referred to as local energy systems can reduce emissions by utilising the by-product heat from electricity generation locally in industrial applications and buildings [17] and minimise transmission power losses by locating renewables at the point of use.

Traditionally, in colder climates including the UK, building and industrial energy systems use natural gas as fuel to provide heating and hot water services as well as electricity supplied from centralised generators via the grid. With the increasing uptake of intermittent centralised wind power generation and in particular distributed solar photovoltaic (PV) power generation, the potential for local network management problems grows. Rather than limit local zero carbon renewable capacity, an alternative solution is to create actively manage local energy systems that can also utilise any waste heat from gas powered generating systems and use energy storage technologies to help manage the local and potentially the centralised power grid systems. This solution would include a high saturation of local renewables, complemented by a Combined Heat and Power (CHP) plant at its heart.

CHP plants generate electricity for local use and makes use of the by-product heat to increase CHP efficiency to well over 80% compared to conventional generation and grid supplies of less than 30% [16]. Non-industrial local energy systems featuring CHP are suited to many different types of buildings and clusters such as hospitals, public buildings, schools, colleges and university campuses, residential complexes and private sector buildings. Regarding CHP-based Local

Energy Systems (LES), increased efficiency translates into reduced carbon emissions, increased local energy security, and greater control over local energy prices. CHP-LES is also a viable solution for remote areas and can operate in island mode (no export and no import).

This research is primarily designed for UK weather which is a cold climate, weather but the methods developed in this research especially the modelling and controller design approaches are suitable for other climatic regions even hot countries if the CHP system is extended to include tri-generation component such as an absorption chiller plant.

## 1.2. Environmental reflections

The increase in efficiency of distributed CHP over conventional generation can result in a reduction in emissions. The carbon intensity of national grid in 2013 was 0.527 kg / kWh [127] but the carbon intensity for summer 2017 was 0.35156 kg $CO_2$/ kWh. The changing in the amount of national grid carbon intensity has resulted from demand reduction (e.g. LED lightbulbs) and the increase in centralised grid renewables especially onshore and offshore wind. In this thesis, the modelling used an average of five years of carbon intensity which is 0.439 kg / kWh for the national grid in the UK. While the carbon intensity generated by burning natural gas is 0.185 kg / kWh. In practice the national grid carbon intensity is not constant, as at different times of year and the day each type of power generation is utilised to perform different functions for the grid. For example, hydro stations have the ability to store energy and generate with a, high bandwidth, i.e. fast response and are also low carbon, but are relatively expensive and usually kept in reserve for sudden changes in supply or demand or to dynamically fine-tune network frequency and power balance. Coal plants are best to have low bandwidth and thus are slower to respond. They are cheaper than hydro stations but have one of the high carbon emissions in the UK power generation mix. Traditionally, coal plants provide additional winter baseloads. Combined cycle gas turbines (CCGT) lie somewhere between, being responsive enough to follow demand under normal conditions and having lower carbon emissions than coal, but still low cost enough for bulk generation. Nuclear plants have ability to respond and cannot follow demand, so they are used world-wide for baseload generation. As a consequence: The generation is a mix of all generators performing the different functions combined. This results in:

- The fuel mix and associated carbon emissions is therefore variable throughout the day and by season.

- In the UK in 2016, DEFRA put the annual target for average carbon value attributed to electrical power supply and use of 1kWh of electricity as 0.4kgCO2e/kWh.

There are many other approaches which could be added to any LES to increase energy efficiency and reduce the amount of Greenhouse Emissions (GHE) and operational costs; for example, the reduction of energy consumption. A reduction in energy consumption is defined as using less energy to provide the same service. This results in fewer electrical losses, less $CO_2$ emissions and a reduction in costs. The Committee for Climate Change (CCC) has estimated that a reduction in energy consumption and subsequent energy demand could save 17 million Tonne of $CO_2$ per year [20].

Many non-domestic buildings can reduce up to 25% [20] of their demands on energy by following some simple steps:

- Reduce heating and cooling energy demands to the lowest levels for any building by increasing building insulation and installing high quality, double glazed windows.
- The use of efficient and low powered equipment and appliances, for example replacing traditional light bulbs

with LED lighting and using IT and ICT (information and communication technology) equipment.

- Improve ventilation and cooling systems.

Another approach is to add local renewable energy (RWE) sources including wind energy (RWE) to the LES system to further reduce CO2 emissions. RWE and LES for residential households could reduce CO2 emission by between 21-62%, depending on the type and scale of RWE [21]:

- Effective RWE is not limited to creating positive environmental impacts it also affects the economy by reducing operational costs. An addition, wind turbine or PV do not need fuel, but may require regular maintenance. There are different types of renewable energy sources of various size and energy production capacity. Regarding LES, there are two popular types which are widely used because they are easy to install and use: Wind energy (WE):

  Wind generator systems convert wind energy into electrical power. WE is one of several promising and efficient types of RWE sources especially when it is integrated with CHP technology. This combination increases its efficiency and reliability by filling an energy gap and reducing electrical energy demands, while reducing overall operational costs. Wind energy reduces total costs by up to 20% by supplying electricity using wind turbines [22].

- **Photovoltaics (PV):**

  This type of technology works to convert sunlight into electricity. PV technology is useful not only for the generation of electrical power but also solar thermal power generation for heating or cooling [26]. PV panels are found to operate up to 75-80% efficiency and supply more than 25% of the electrical power demands in addition to 55% of thermal energy leading to a reduction in operational costs by approximately 30% [23,24].

The use of RWE, however presents challenges and has limitations. They are dependent on the weather and so cannot guarantee to work all the time. Windy or cloudy weather will reduce PV efficiency by up to 50%. In addition, all RES systems require maintenance to keep them working properly. For example, the PV panels may require periodic inspection for physical damage, dirt over it or proper tightness and the wind turbine need same checking and testing plus checking the electrical connections and inverters.

Finally, one of the biggest technical challenges is integrating the (RWE) with (LES) is maintenance supply of demand matching while reducing the power curtailment especially unexpected curtailment. [25].

## 1.3. Energy storage systems (ESS)

Energy storage systems are an important element in any LES as they control and increase the efficiency and reliability of the system, at the same time minimising CO2 emissions. Many designers and companies use ESS to manage and schedule their power use. For example, a decrease in peak energy demand by using saved excess energy and supplying it when required will result reduced costs. There are two types of ESS thermal and electrical storage. In this thesis just thermal storage is explored.

### 1.3.1. Thermal Heat Storage (THS)

Thermal Heat Storage is used to store excess heat from the CHP engine. In a hot water tank, this heat is then pumped back into the system, or hot water network (HWN), when the system is short of heat energy or when the system needs more heat to meet energy demand at peak times, thus reducing the cost and CO2 emissions

[28]. The Hot Water Network (HWN) is the network, or system of pipes, full of water which distribute the heat generated by the heating system to their end use points e.g. buildings.

Adding THS to LES gives the system more flexibility in that it can operate continuously with less switching on and off the CHP engine compared with a local energy system (LES) working without a control system or working by only responding to energy demand. The CHP engine can then work for a longer time and generate more electricity and heat simultaneously, allowing the system to be more economic. There are also less CO2 emissions by reducing the amount of electricity imported from the National Grid, by burning fuel only for heating [27,29,30].

One of most important features of thermal heat storage is its size. The appropriate size of THS in a local energy system can reduce operating costs by up to 6% from the total cost [22]. Most designers do not recommend very large thermal storage for different reasons including construction costs and the cost of an insurance licence and increased heat losses. Loss of heat to the environment (about 1% every hour) makes it less beneficial and efficient.

Smaller thermal storage facilities have lower heat losses and are flexible and more effective such as the system in [29] where it was recommended that the THS be no more than 25% of total heat production in the LES. Attention must also be paid to the length and insulation levels of the hot water network (HWN) as it distributes heat energy to meet local demand; i.e. its' size and water flow rate are also important design parameters.

### 1.3.2. Electrical energy storage (EES)

This type of storage which is electrical batteries, works as a bank to store excess electrical power, returning it to the system when there is a deficit. Electrical energy storage is very effective when paired with CHP technology so that the system is operated to a schedule or is off-grid. When EES satisfies high or unexpected variations in electrical demands, this makes all local energy systems more efficient and economical [31]. for that the electrical energy storage or the electrical batteries helping the power generation to switch off during low power demand or helping to reduce very high pick of electrical demand.

Chen and Roskilly 2012 [32], demonstrated that EES can increase the total efficiency of a system up to 48% compared to conventional

CHP. They also illustrated additional advantages when integrating EES with (CHP) technology such as reduced capital costs compared to renewable energy technology.

In common with THS, one of the biggest challenges for EES is size; if the system is larger than needed, it becomes more expensive and less effective. Choosing the correct size can substantially reduce the amount of electricity which needs to be exported. EES have economic system performance advantages however, as they reduce the amount of electricity sold to the national grid at much reduced price, storing it instead until needed. At the same time, there is a technical issue which is another benefit of EES, reducing exportation and importation of power from the national grid, while there are many different types of electrical energy storage systems, all involve high capital costs. The constant charging and discharging of the battery also reduces their lifespan [33].

Finally, the Electrical energy storage (EES) is very important to maintain the power quality specially with renewable energy (wind turbine and the PV panels) which the fluctuation nature of wind power and time of generation by PV panels are effects on the power quality. For that the Electrical energy storage to keep power quality such as active and reactive power, harmonics and variation of the power voltage [126]

## 1.4. Prime movers (CHP Engines)

The prime mover is the heart of any combined heat cooling and power system providing its primary energy. There are many different types of prime mover engines, each having advantages and disadvantages making them suitable for use in different situations.

There are two categories of CHP engine; combustion-based technologies such as reciprocating engines, Stirling engines, gas turbines and Rankine cycle engines, and electromechanical based technologies for example, fuel cells [1]. This section will evaluate and compare the common prime movers currently available in the market, as summarised in table [1.1].

### 1.4.1. Reciprocating internal combustion engines (RICE)

A reciprocating engine is one of most popular technologies in use for CHP systems, also known as a piston or IC engine. This type of engine converts pressure to a rotational motion, using a piston placed in a cylinder, where chemical reactions resulting from fuel combustion take place. There are two types of internal combustion engine. The first is a spark engine which can use many different types of fuel such as natural gas, propane, gasoline and landfill gas. The second is a compression ignition engine which uses diesel fuel or heavy oil [2]. Reciprocating internal combustion engines is acknowledged as having many advantages such as ready availability in the market, low cost, a good response with variable loads, exceptional efficiency, part load flexibility and a very short start up time. RICE however, produces high emissions, excessive noise, much mechanical vibration and the need regular maintenance [4].

### 1.4.2. Gas turbines (GT)

This type of engine is a well-established technology, especially in large scale power generation because it is highly power efficient, between 70 and 90% [4]. GT's have a flexible design which works well with a wide range of local energy systems and are typically low maintenance. They have a highly efficient engine comparator which is cost effective, generating electricity and heat in parallel (36% efficiency). It has a quick response to fluctuations in electricity demand which makes it more reliable and more effective than LES. Nevertheless, limitations include the need for a high-quality fuel e.g. diesel. It can also be inefficient with a poor economic performance under part loading.

Regarding greenhouse emissions, a gas turbine can dramatically reduce CO2 and NOx emissions per kilowatt-hour.

### 1.4.3. Stirling engines (SE)

The Stirling engine is a reciprocating engine with a closed cylinder and separate combustion chamber. There are two types of Stirling engine, namely the Kinematic Stirling engine and the Free-Piston Stirling engine. These types of engine can run on almost any kind of fuel, such as gasoline and natural gas. Importantly, SEs can also be run on renewable energy e.g. solar heat radiation, meaning that SE's can have very low greenhouse emissions.

SE's however, present several challenges in operation such as low specification power output when compared with the same size IC engine. Other drawbacks include high capital costs and poor weight to power ratio [1,2,5,6,7].

### 1.4.4. Fuel cells (FCs)

Fuel cell engines convert electrochemical energy to electrical power through a chemical reaction with oxygen and oxidizing agents. FC engines usually have three primary components, the first being the reformer which extracts hydrogen from gaseous fuel. The second is the fuel cell stack which is an electrolyte material placed between oppositely charged electrodes, the last being the inverter, the function of which is to convert DC electrical power output from the stack to AC electrical power.

The engine generating power methodology is very similar to that of producing DC power by electrochemical processes. As a result of this, FC's are considered as the cleanest method to generate electricity. FC engines are also one of the more reliable engines because of fewer moving parts and constant power production.

One of the important problems with the FC engine is that although it is highly efficient, reaching approximately 55%, this target is sometimes impossible to attain because of the amount of heat produced. It also has high initial capital and ongoing costs because it is depending on the hydrogen and oxygen. On the positive side, it has low operating costs and is highly efficient over a range of loads. While FCs also have a low environmental impact with respect to greenhouse emissions, this type of technology is in need of more development [2,3,4,8,9,10,11,12].

### 1.4.5. Organic Rankine Cycles (ORC).

There are two main types of ORC systems: a steam Rankine system using water as the working fluid, and an organic Rankine system working with organic fluid. ORC engines have many advantages including high flexibility and durability, cost effectiveness and low operational temperature and pressure. Their simplicity and proven levels of safety make them highly rated. Organic Rankine cycle engines can use heat from many different sources. For example, sources of low temperature energy including waste water, biomass and solar thermal energy. In contrast, the organic Rankine system has very low efficiency with reference to electricity, having an average efficiency between 6% to 19%. On the other hand, it is highly efficient in winter. [1,3,13,14,15]

The advantages and disadvantages of each CHP technology type are summarised and compared in Table 1.1

| Prime mover | Advantages | Disadvantages | Emission rates $CO_2$ (kg/MWH) $NO_x$ (kg/MWH) |
|---|---|---|---|
| Reciprocating internal combustion engines (RICE) | Low capital cost. Rapid start. Good response with load fluctuations. High reliability. | Regular maintenance. Loud noise. Very high emission rates. | Up to 650<br>Up to 10 |
| Gas turbines (GT) | High efficiency and cost effective. Quick response to load fluctuations. Low maintenance costs. | Inefficient with part loads. Economically poor for small scale use. Needs high quality fuel. Elevated noise levels. | 580-720<br>0.1-0.5 |
| Stirling engines (SE) | Safe with low noise. Low maintenance requirements. Easy to control. | Poor weight to power ratio. Expensive materials. Long time needed to start up. | 672<br>0.23 |
| Fuel cells (FCs) | Low operation costs. Low environmental impact. Low noise levels. High efficiency levels. High reliability. | Very high capital costs. Requires hydrogen for storage. | 430-490<br>0.005-0.01 |
| Organic Rankine cycle (ORC). | High flexibility and simple design. Low operational pressure and temperature. Wide range of fuel. | Low electrical efficiency. | Depends on fuel |

Table 1.1 Prime mover comparison

## 1.5. Local energy system (LES) Technology: Reliability and Availability when paired with CHP engine and PV panels

Every local energy system must address issues around reliability and availability. There is the need to ensure that the system will operate continuously and supply energy when required while still achieving the best economic and environment results.

The following section reports on the reliability and availability for a system working with CHP technology across three different research papers:

- In [34], the researchers used the state-space method (SSM) and the Markov model to calculate the reliability and availability of a CHP system suppling power and energy to a building, comparing these results to a separation production system (SP). They found that the systems' reliability was 99.63% for electricity, 94.30% for heating and 99.97% for cooling.
- Reza and Manbachi [36] also used state-space and Markov methods to test system reliability in 3 different user-cases (Island, Standby and Parallel), the results in Table [1.2]:

| case | R electrical | R thermal |
|---|---|---|
| island | 95.6662% | 98.221% |
| standby | 99.6301% | 98.8221% |
| parallel | 99.6395% | 98.8221% |

Table 1.2: Reliability in case studies

The results above were calculated when the hot-water network reliability was assumed at 100%. However, they show the HWN reliability at 94% meaning a decrease in CHP thermal reliability of 6% in each case. The thermal reliability with HWN is 92.8928%, 92.8928% and 92.8928% for Island, Standby and Parallel, respectively.

- The UK government produced a report on CHP technology in 2015 [35]. The reliability and availability section show that CHP systems have to have 94.95% guaranteed reliability and 90.21% guaranteed availability for 8760 hours (whole year). The formulae below explain how reliability and availability were calculated:

Reliability = T – (S+U) / T – S *100%

Availability = T – (S+U) / T *100%

where:

S = maintenance schedule (hours / year).

U = unscheduled shutdown (hours / year).

T = the time planet working and suppling energy (hours / year).

The report also recommends the maximum time schedule required for maintenance is 438 hours per year while the shutdown schedule is 420 hours per year. In conclusion any technologies that can increase the hours of operation of CHP will provide a valuable contribution to efficient and low carbon LES solutions.

## 1.6. CHP based Local Energy System (LES) Challenges and Problems Addressed in This Thesis

The energy efficiency and carbon dioxide (CO2) reductions achievable by CHP and CHPV systems are well documented [20,21,27,28,29]. The merits claimed by these solutions are predicated on the ability of these systems being able to satisfy: perfect matching of heat and power supply and demand; ability at all times to maintain high quality power supply;

and to be able to operate with these constraints in a highly dynamic and unpredictable heat and power demand situation. Any circumstance resulting in failure to guarantee power quality or matching of supply and demand will result in a degradation of the achievable energy efficiency and CO2 reduction [37,42,43,44]. CHP based local energy systems cannot rely on large scale diversity of demand to create a relatively easy approach to supply and demand matching (i.e. as in the case of large centralised power grid infrastructures) [22,29,**131**]. The diversity of demand in a local energy system is both much greater than the centralised system and is also specific to the local system. It is therefore essential that these systems have robust and high performance control systems to ensure supply and demand matching and high power quality can be achieved at all times [65,**132**]. Ideally this same control system should be able to make best use of local energy system's energy storage to enable it to be used as part of a smarter grid and become a flexible, highly responsive energy supply and/or demand for the centralised infrastructure [**31,32,133]**. In this thesis a comprehensive literature survey in Chapter 2 has identified that there is no scientific and rigorous method to assess the controllability or the design of control systems for these local energy systems. Thus, the main challenge of the work described in this thesis is that of a controller design method described in Chapter 4 based on a modelling approach described in Chapter 3 for LES. In this thesis CHPV type LES systems are specifically the main research challenge for the controller design and modelling methodology was to provide an accurate and stable system performance to deliver a reliable tracking of power drawn/supplied to the centralised infrastructure whilst tracking the require thermal comfort in the LES buildings and high performance local energy system solution.

There are many challenges associated with LES. These challenges vary depending on the type of LES, its design and mode of operation. There are two types of challenges to any system (technical and non-technical).

The technical challenges are:

- How to manage large, relatively fast, out of phase fluctuations in local thermal/electrical demand by hour, day and season, which is a characteristic of non-industrial consumers. Make sure the system utilises all the energy generated by the CHP engine and the renewable source in an efficient way to meet the energy demands required to satisfy the consumer requirements (e.g. electricity supply for appliances and thermal comfort).

- How to deal with the increased uncertainty in the prediction of the magnitude of electrical power available via local renewable generation.
- How to control a local energy system containing multiple generation and storage devices such as CHP engine, gas boiler, cooling system and energy storage. How to intelligently configure and control such hybrid arrangements in a stochastic operating environment, constitute the most significant challenges.
- How to make sure the system has the resilience and the reliability to work in all operating modes (exporting, importing, island).
- The control strategy should able to deal with scalable multi-zones, multiple devices on the local energy network as well as multi-vector demand (heat, cooling & electrical power) while ensuring high efficiency, resilient to disturbances, economical, low carbon and reliability.
- There is a lack of system modelling and simulation tools/methods that can assist in the correct sizing of plant (e.g. CHP engine, Boilers, thermal stores etc) for a complex local energy system with multiple consumer requirements (e.g. thermal comfort heating and cooling and electricity supply).

The non-technical challenges are:

- Private wires required for the local energy system are expensive and can breach EU competition law.
- licensing to connect to the National Grid: Licensed supply is too expensive and onerous for a small community [129].
- The local energy system electrical tariff will need to be competitive with national grid to be attractive for the end user.
- Financial incentives for carbon reduction are currently not part of the energy policy/regulations and thus make such an energy solution less attractive [130]
- Commercial viability depends on favourable energy policies relating to CHP manufacturers and financial incentives otherwise high capital costs would make this solution less feasible.
- Currently there are no heat tariffs which need research and uptake by energy companies as well as legislation framework.

In this thesis, only the technical challenges are addressed. In Chapter 2 a comprehensive literature survey is described that addresses all the aforementioned technical challenges. This survey concluded that there was a gap in the knowhow and the methods to model a complex local energy system with multiple objectives in a manner that can be also utilised to design a control system and its control algorithms. To create this modelling framework and the resulting controller design methodology was the main mission of this PhD study.

## 1.7. Research aims and objectives

The main aim of this research is to create a modelling and control system and control algorithm design methodology to enable the control a complex local energy system with multiple objectives. The study has utilised a specific case of local energy system based on CHP technology, thermal storage technology and renewable power generations using Photovoltaics for a cluster of buildings using a heat network and private wire power network.

The energy dilemma to meet both building or buildings temperature set point and the electrical power demand.

A cascade controller will control the CHP engine and hot water network. At the same time, it will control the temperature inside the zone(s) to keep it convenient to residential units though out the year.

The proposed control system will be able to:

- Address electrical demand and use the CHP waste heat for heating.
- Control the CHP engine, or any prime mover, by controlling the amount of gas injected into inside the engine.
- Control a single zone system or any number of multi-zone systems.
- Set and control the temperature thus maintaining comfort levels.
- Control the electrical cooling system in summer.
- Control the temperature of the hot water network and heat storage.
- Consider other renewable energy sources.
- Control heat storage by storing excess heat, re-pumping it into the system when required or inhibiting the amount of heat produced by the engine.
- Give the LES high operational flexibility with regard to exporting, importing and island mode. And ability to Communicate with the National Grid.

The controller in this research will be the best solution for all local energy system working with CHP technology because it allows for control and tracking the electrical and temperature setpoint of the whole system automatically. Therefore, the user will not have to individually:

1. schedule heat and electrical demand, or

   Approximate the amount of energy consumption or amount of heat energy store in heat storage,
2. predict or guess the amount of energy from renewable sources and avoid any unexpectable load or disturbance because this controller will handle and correct itself.

Setpoint Tracking control (STC) of systems mostly depends on scheduling energy demands which if poorly implemented, could lead to one of two scenarios:

- If the energy produced is more than the energy demand (heat and electrical energy), the system will work at full capacity and waste heat and electrical power. This will, in turn, make running costs very high, create pollution and may eventually lead to system failure.
- The system can experience an unexpected load or overload of energy meaning that it will need to import energy from the national grid in order to avoid failing to meet the demand.

The main research task and development of this research are summarised as follows:

1- Build and calibrate a MATLAB simulation model of a CHP-driven, local energy system for multiple zones situated in the UK, to analyse both thermal and electrical demand, system efficiency, amount of CO2 emissions and to use it as a platform to test the new control system.

2- Design a new multi-vector control system which controls and optimises the whole local energy system to reduce running costs and CO2 emissions.

3- Analyse the performance of the MATLAB system model with reference to electrical and heat demand in the local energy system.

4- Investigate the possibility of integration of renewable energy sources such as PV with the local energy system working with a CHP engine.

5- Investigate the possibility of integrating energy storage such as heat storage and electrical storage.

6- Design a cascade controller to control the temperature inside the building to stay within a comfortable range all year round.

7- Include an electrical cooling system for the LES during summer.

8- Investigate the possibility of an LES system integrated with the national grid for exporting or importing energy.

9- Investigate and test LES with and without external sources of heat i.e. gas boiler.

The conceptual LES design with CHP engine and renewable sources is shown in figure 1.1.

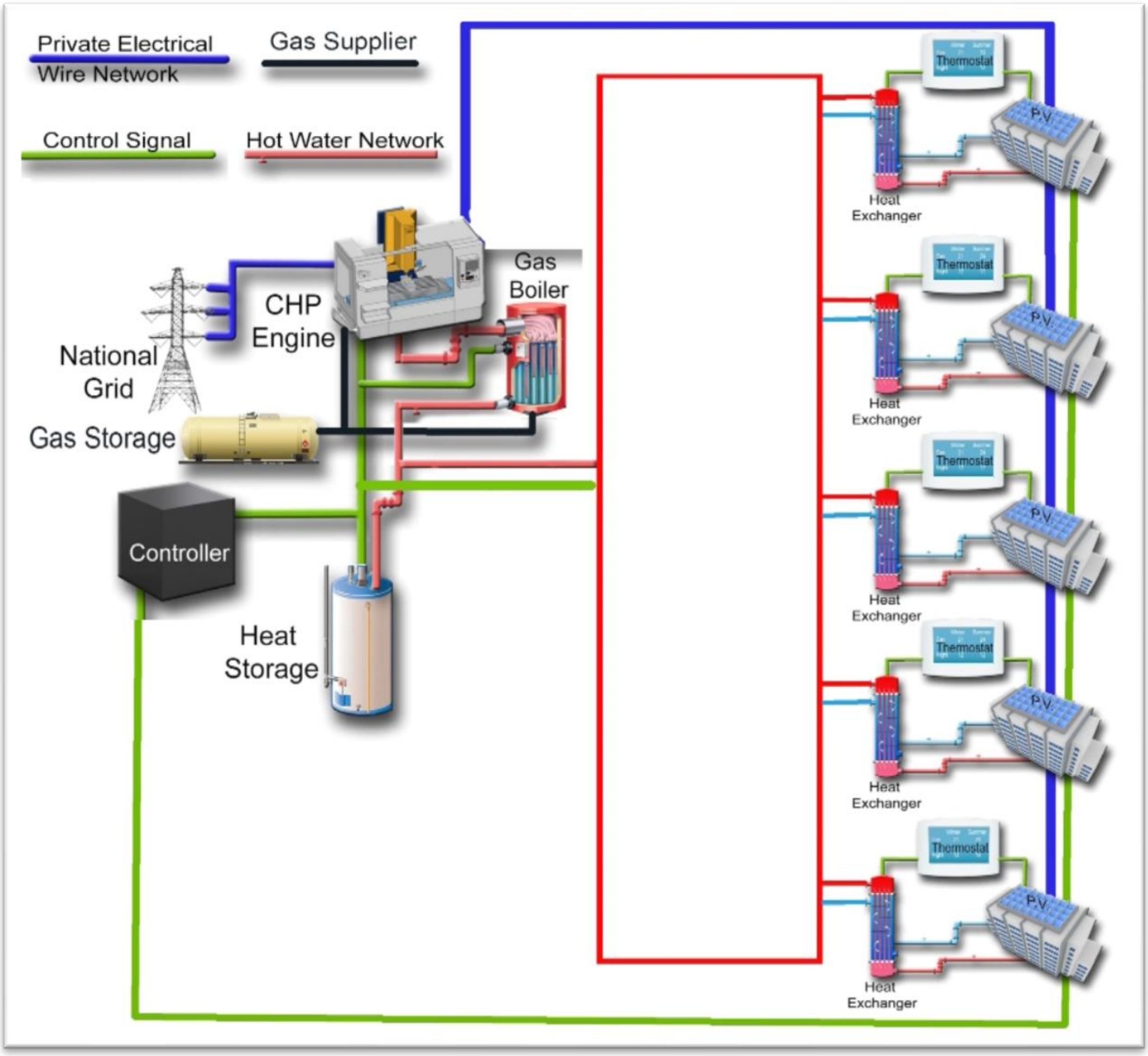



Figure 1.1 Local energy design with CHP engine and renewable sources

## 1.8. Contribution of this research to the field of study

- Calibration of a dynamic MATLAB model comprising multi-zones local energy with an electrical, heating system and electrical cooling system depending on in the UK standard, including use of a CHP engine, renewable energy source and energy storage.
- Dynamic model of CHP engine response to the new smart controller following the dynamic electrical and heat demand.
- Proposed new cascade heating system integrated with heat storage to control the hot water network temperature and follow a set point temperature inside each single zone, individually, all year round.
- Proposed electrical cooling system response to the controller to meet the set point temperature inside each zone which will work automatically when the temperature gets higher than the set point in summer.
- Proposed model which involves a CHP engine coupled to the heating and electrical systems of a local energy system. It is fully dynamic all year round, working second by second to deal with a fully dynamic load demand (heat and electrical demand) able to interact with the energy storage system.

- An innovative Controller Design Methodology for CHP based, multi-vector LES, with second by second feedback. The method is used in a specific case study to design a controller that will control the CHP engine to follow dynamic electrical demand and control the cascade heating system (including heat storage) according to zone set points by using inverse dynamics and method to demand it. At the same time, it will control the electrical cooling system to keep the local energy zones following the set points in summer.

## 1.9. Over View of The Thesis

This thesis consists of seven chapters:

**First chapter:** giving background of the local energy system and what they are consist of like (renewable energy, electrical storage, heat storage, …) and what the local energy system reflecting on the environment. It is also show type of CHP engines and the options. Finally, the reliability and availability of local energy system.

**Chapter Two:** this chapter reviews the background literature, identifying the latest technology available to provide a rationale for the current research: the control and operation of local energy systems (LES) using CHP technology.

**Chapter Three:** show’s three cases studies, first one used for modelling and design while the other two cases studies used for calibration and validation for the use of the modelling approach for a wide range of LES configurations. Each case study has characteristics different than of each other. All of them designed by MATLAB program. Also, this chapter has methodology of system design.

**Chapter Four**: this chapter details the Inverse Dynamics controller design methodology for the controller design of multi-vector local energy systems**.**

**Chapter Five:** this chapter shows the results of the local energy system in one case study application. Results are shown for the multi-vector components of the system: the electrical side and the heat energy system side minute by minute and second by second. The model parametric data in the case study are for the Copperas Hill Building Project (Liverpool John Moores University, Liverpool) and these parametric values were used in a MATLAB/Simulink embodiment of the model to generate the results in this chapter.

**Chapter Six:** this chapter discusses the results obtained by the local energy system case study in MATLAB to draw the final conclusion for this research study.

**Chapter Seven:** it is the last chapter in this thesis and shows the future work required for the local energy system which can improve the all the system performance and the system reliability.

# Chapter Two

# Literature Review

## 2.1. Introduction

This chapter will review the background literature, identifying the latest technology available to provide a rationale for the current research: the control and operation of local energy systems (LES) using CHP technology.

## 2.2 Operation strategies for a local energy system using CHP technology

Operation strategies are defined as the way of operating a local energy system, or a building, with CHP technology, controlling the flow of thermal and electrical energy from the CHP engine and inside the LES. The main aim of controlling a LES with a CHP engine is to achieve a specific beneficial target such as minimal operational costs, a reduction in carbon emissions, minimising the amount of energy imported from the national grid or an increase in efficiency. Many, however CHP and micro-CHP systems are limited due the prime mover and balance of the LES [31]. Operation strategies can be divided into two main categories: conventional and non-conventional.

## 2.3. Conventional Operation Strategies (COS):

Conventional operation strategies for LES or CHP systems are relatively straight forward and easily implemented, controlled through conventional techniques. This type of COS focuses on a specific benefit for either electricity or heat or both [37,38]. There are many different types of COS as detailed below.

### 2.3.1. Heat Lead Operation Strategy (HLOS):

The main aim of this strategy is operating the CHP engine to meet the heat demands of a system or a building. If there is any deficit, it will be met by other sources of heat, e.g. a gas boiler [39,40]. The amount of electricity generated will supply the system or be exported to the national grid [41], but it is not guaranteed that the national grid will be able to absorb a cumulative amount of excess electricity. This means that some amount will have to be wasted to keep the control system operational [42,43,44]. This system operation is not effective in summer because there is not enough demand for heat from the system. HLOS usually use Stirling engines based on CHP technology because of its high heat to electrical power ratio [45,41,37].

### 2.3.2. Electricity-Led Operation Strategy (ELOS):

This type of operation strategy aims to meet the maximum demand for electricity by the local energy system or consumers [46,41]. If there is a shortage in the supply, this will be fulfilled be another power supplier [47]. The ELOS needs to be integrated with a form of energy storage, thermal energy storage or electrical storage, to store heat energy or electricity generated by CHP engine when there is no heat demand, re-pumping it back into the system when the CHP engine does not meet the heat demand [39]. This strategy is optimised with a fuel-cell CHP engine because the heat percentage is lower than the electricity percentage [31].

### 2.3.3. Reducing Emission Operation Strategy (REOS):

This is a new strategy which has been developed because of international concerns regarding climate change and emissions [50]. The CHP system operates to minimize emissions regardless of operational costs or other conditions. The decision to operate the CHP system or import electricity from the national grid to meet the scheduled amount of heat and electrical energy required by the local energy system is dependent on estimated CO2 emissions. Gas emissions are estimated according to the emission factor when burning fuel to its output. The ratio for the emission is:

ER = EP1/EP2

Where, EP1 represents the pollution emitted by the building when using an external energy source, EP2 the amount of pollution from the same building or system when using CHP technology. If ER is equal or greater than **1,** the CHP system should keep operating otherwise the system will shut down and use another source of energy or import energy from the national grid [37].

## 2.4. Non-conventional Operation Strategy:

The main aim of this type of operating strategy is to search for the optimal, or near optimal, strategy for the system at different periods which could be in terms of carbon emissions, operating costs or efficiency of energy use [51]. Non-conventional operational strategies for energy systems are classified into two types:

### 2.4.1 Operational strategy based on optimisation:

System operation optimisation techniques use a fixed demand profile so that a global optimal solution can be determined [52]. This type of optimisation works to find the best solution available. There are various ways to apply optimisation techniques including dynamic programming (DP), linear programming (LP) and non-linear programming (NLP). DP is a very effective method for offline system operational strategies, but not as suitable for micro combined heat and power systems. LP working with linearization of relationship is more suitable for this. NLP works with more complicated maths e.g. non-linear equations, but is slower [54, 55, 37, 56]. There are also many popular optimisation technique methods for example, like Genetic Algorithm, Evolutionary Programming, Particle Swarm Optimisation, Grey Wolf optimisation, Fuzzy optimisation and Gradient Techniques [53, 54, 57, 58, 58, 59, 60, 61, 62]. Some researchers have tried new methods and algorithms to optimize schedules for example, Wang [64] used the Kuhn-Tucker Algorithm while Maruichi [65] used the logic Token-Ring model to reduce operation costs. Regardless of method, the optimum solution will be guaranteed if the optimisation curve is convex. In convex optimisation problems, the choice of optimisation method will be influenced by computation time, case of implementation and possibly aim constraints. That said, solving non-convex optimisation problems is more complex. The poetization method is very important because it needs a specific type of optimizer to match the problem and find the best results for it [54]. Choice of an optimizer or an algorithm may affect the results and quality of the solution, for instance Wang et al. [66] proved the optimal solution using a Particle Swarm technique, getting better results by about 1% in comparison to using a genetic algorithm.

### 2.4.2 A specific control system:

Very few researchers have tried to find a specific control strategy to control a local energy system based on CHP technology. Such a method of control could manage and optimize the system without demand scheduling or guessing the amount of energy produced by renewable energy and could deal with any unexpected disturbance load or amount of energy generated. This controller should follow the set points or instructions it has been given to achieve the best results from the CHP system and local energy system.

Brinkmann and Viedenz [67] designed a practical control box for a hybrid system consisting of a PV-plant linked to a steam engine for combined heat and power, as a self-sufficient energy supply for domestic buildings which allows the best possible use of renewable energy. The control box works with a µ-Controller. Karmacharya [31] used a Fuzzy logic control method for a micro-combined heat and power system to manage the energy generated by the engine and supplied to the distribution network. Zhang [68] developed a multivariable control system for a waste heat recovery system, operating on an Organic Rankine Cycle (ORC), using a generalized predictive control strategy (GPC). This type of control is suitable for a micro CHP system working with an Organic Rankine Cycle (ORC). Allison and Counsell [69] used a multi-input multi-output (MIMO) feedback control strategy to control a CHP system with renewable energy sources and energy storage. They used a multi-input multi-output (MIMO) based inverse dynamics control strategy, with CHP technology, to minimize imports from the national grid to the building. Finally, [70] used a robust non-linear control strategy with micro-CHP and electrical storage to minimise interaction with the local electrical network and maximise the utilisation of renewable energy.

## 2.5. Modelling of CHP systems with local energy demand, energy thermal storage and renewable energy:

Modelling CHP systems have received much attention but mainly with reference to proton exchanger membrane fuel cells [71,72,73], solid oxide fuel cells [74] and reciprocating Joule-cycle engines [75].

Some models however, used different CHP and micro-CHP technology to examine CO2 emissions and cost [76,77,41,82]. Lombardi for example, presented details of a semi-empirical dynamic model for a domestic scale micro-CHP Stirling engine [78]. Some researchers have modelled CHP systems with heat storage to show how much this impacts on system efficiency and emissions [79, 80, 81, 83, 85]. At the same time, there has been a reasonable amount of attention paid to renewable energy with micro-CHP technology, specifically with Photovoltaics, because it is suitable for use in residential areas. Renewable energy sources help the system to reduce fuel consumption leading to a reduction in CO2 emissions and cost [26, 21, 24, 84, 23]. Very few researchers have worked on dynamic simulation models, specifically focusing on the detailed dynamic response to local heating and electricity demand, to consider environmental conditions and controlling the temperature inside plants or zones. Drer and Weber designed simulation models to compare two types of fuel cells [86]. Onovwiona, Ugursal and Fung used a simulation program called TRNSYS to simulate an internal combustion engine and Stirling engine based on micro-CHP systems to demotic scale [87]. The majority however, of models are designed to examine micro-CHP for dwellings and residential houses. There is not enough attention given to CHP design with multi-zones which can respond to many zones or building energy demands simultaneously. Furthermore, no attention has been paid to system energy balance modelling components and sub-systems. There are also very few models that can predict export or import from/to the with national grid at a set point or when the system requires energy in an emergency.

Most simulations models collect data at time intervals of less than 15 minutes [31] which is enough to capture daily and seasonal energy demands and the system performance. These however, fail to capture smaller effects such as the dynamic relationship between local energy deman4d and the local electrical grid.

## 2.6. Review Murphy G.B., Counsell J.M., Allison J. [69]:

In this paper the authors used the multi-input multi-output (MIMO) inverse dynamics control strategy to minimise the using the national grid as much as possible for one building only (single zone) and in same time they are trying to match the heat demand of the same building. The results got out of this research is maximising the utilisation of the available energy from the CHP engine and reduce amount of energy importing from the National Grid. This system is electrical led, but in same time the system trying to match the building temperature set point.

This research work concluded the following:

- The multi-vector energy system requires to by electrical demand led.
- The proposed controller design method assumes the system has only one zone/building.
- A controller is capable of minimising the utilisation of national grid power generation and maximising the utilisation of the local power generated by the CHP engine.
- The building temperature is controlled only by using the surplus heat generated by CHP engine and the heat stored in the heat storage.

The main disadvantages of this controller design approach are:

- The system operation and control strategy does not work for more than one zone/building.
- There is no stability and no set pint tracking analysis in the controller design method.

## 2.7. Summary

As the Literature Review has described, the proposed control approaches of the local energy system utilise optimisation methods by time scheduling CHP plant and energy storage.

Research work has been proposed for a controller design method, but it is for a single zone/building and is not rigorous enough to prove reliable system's performance. So, in conclusion there is no specific controller design method to control the supply of heat and power in an any local energy system with multiple zones/ buildings that can guarantee system stability and set point tracking. (e.g. tracking of all required buildings' temperatures and the national grid power demand/export). In particular, there is no controller design method for when the local energy system consists of fully integrated use of CHP technology and local renewable power generation with energy storage such PV power generation. Thus, the Literature Review has shown gap in knowledge and scientific methods for the controller design of multi-vector LES. IT IS THE CONTRIBUTION OF THIS THESIS TO FILL THIS GAP AND THE SOLUTION IS DESCRIBED IN SUBSEQUENT CHAPTERS.

# Chapter Three
# Cases Studies Modelling and Calibration

## 3.1. Introduction

In the search for solutions to reduce emissions at an affordable cost while 'keeping the lights on', locally managed integrated buildings and district energy systems, featuring combined heat and power as part of an overall energy strategy, are increasingly attractive. With millions of pounds of capital investment at stake, accurate representation of these systems is essential to correctly inform decision making and assess performance in design and operation. This is especially the case in the UK which has implemented a carbon emissions policy for buildings to European Performance of Buildings Directive (EPBD) Standards through mandated energy performance benchmarks and certification [88]. Statutory requirements for buildings are given by UK's Building Regulations, providing materials, construction and energy performance expectations to demonstrate compliance [89]. Compliance with these regulations and EPBD is achieved through the use of certification using quasi-steady, state benchmark energy assessment methods; SAP and SBEM [90] [91].

Dynamic simulation software is also valuable to industry by providing a mechanism to rapidly simulate a building or zone to determine and assess its thermal and electrical responses to demands and disturbances

[92]. The IDEAS (Inverse Dynamics based Energy Assessment and Simulation) framework is a dynamic modelling and numerical calculation environment developed using Robust Inverse Dynamics Estimation (RIDE) and small perturbation theory to accurately simulate energy utilisation and control of complex energy flows in buildings served by one or more low or zero carbon energy sources such as CHP and photovoltaics [69] [93]. This framework has previously been applied to domestic dwellings and calibrated with reference to empirical data derived from the UK's Standard Assessment Procedure (SAP) for domestic buildings [94]. The IDEAS framework is used in this chapter, extended to host:

1- Complex multi-domain zones buildings.
2- A CHP engine to supply simultaneous thermal and electrical power to the system.
3- Photovoltaics power to help the CHP engine.
4- Thermal store to store excess heat.
5- A gas boiler to supply the system with heat energy when the CHP and thermal store do not have enough heat energy required to meet a desired zonal set point temperature.
6- A hot water network to supply zones with required heat.

7- A multi cascade control system to control the CHP engine heat, thermal store and the temperature inside the zones.

The simulation model was run at a 1-minute sampling rate for one year and 1-second sampling rate for 7 days to assess how accurate the control system was when following electrical and thermal set points. This chapter details three cases studies, each with different characteristics and control options to assess the control system under a variety of conditions and circumstances. The cases studies are:

- Copperas Hill Building in Liverpool city which is a single university building.
- Green Bank Student Village, Sefton Park, Liverpool, a residential cluster comprising 5 buildings.
- Media City in Salford, Manchester which is a ten zone, mixed commercial and residential cluster.

The first case study is used for modelling and the case studies two and three are used for calibration.

For all cases studies, an optimum start algorithm is implemented as near ideal heating system control as a reference performance metric. This demonstrates how accurate the control system is and how well it follows the set point. The use of an optimum start on building temperature control enables better utilisation of heat generated by the CHP and the thermal store minimising the need for gas boiler supplementary heating. Building modelling methods and energy assessment procedures are adopted as given by the National Calculation Methodology (NCM) and complementary reference datasets [95], and by CIBSE environmental performance benchmarks [96] [97].

## 3.2. Case studies

All three cases studies were built on real project data.

### 3.2.1. Modelling case study: Copperas Hill Building in Liverpool city

The first case is the proposed refurbishment of a single university campus building to BREEAM standards, featuring building integrated CHP and PV supplies. The total area of the university building is 35,000 $m^2$ containing a CHP engine with PV panels and electrical cooler as illustrate in Table 3-1 below.

| Primary Activity | University Building |
|---|---|
| Building Gross Internal Area (GIA) | 35,000 $m^2$ |
| CHP Engine | 131kW |
| Solar PV | 350 $m^2$ Roof Mounted |
| Electric Cooling | 4x600 kW DX VRF plus passive |
| Ventilation | Mechanical with 70% heat recovery |

*Table 3-1 Copperas Hill Building Configuration*


Figure 3.1 Copperas Hill Building in Liverpool city [98]

A proportional breakdown of NCM defined areas as given in Figure 3.2 shows the active areas inside the building and the amount of electrical and heat energy required. 50-60% of the building serves its primary function with the remainder split between circulation areas and secondary services.

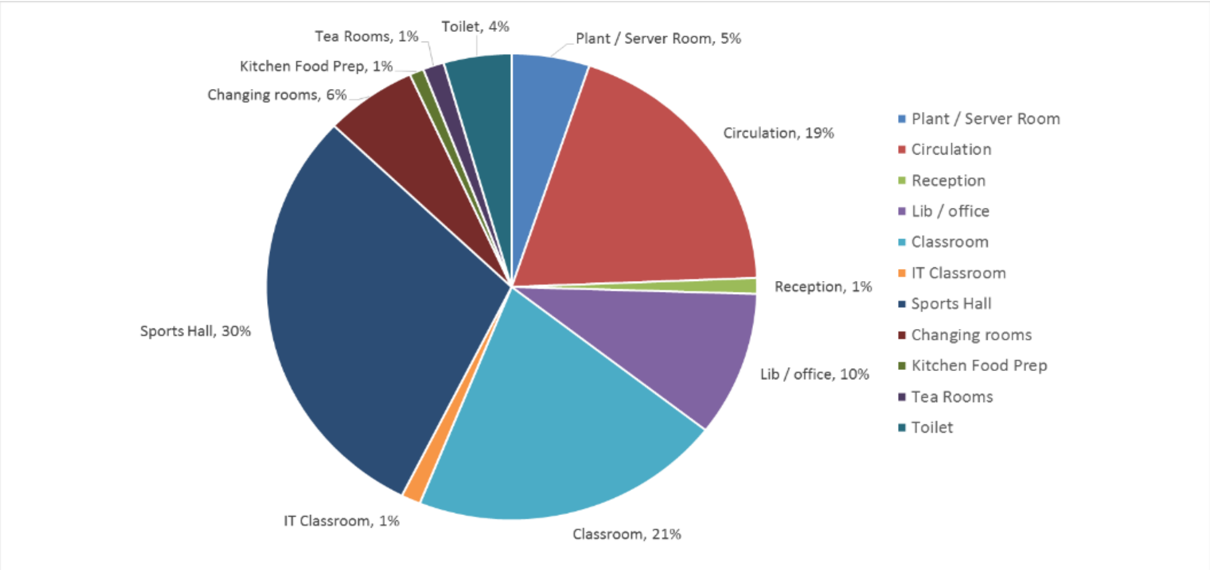



Figure 3.2 Proportional breakdown of activities within Copperas Hill University

The data in Table 3.2 details the parameter values for design and test the Case study for heating and cooling setpoints, heating setback temperature, ventilation, domestic hot water, occupant density, occupancy gains, and equipment and lighting electricity as given by NCM. These values are used to calculate an overall weighted average dataset for the building zone.

| | Heat SetPoint | Heat SetBack | Cool SetPoint | Vent | DHW | occupancy | Occupancy gain | Equip | Light |
|---|---|---|---|---|---|---|---|---|---|
| | Celsius | Celsius | Celsius | L/s/m2 | L/h/p | m2/p | W/p | W/m2 | W/m2 |
| Plant / Server | - | - | - | 1.100 | 0.000 | 9.09 | 90.0 | 54.41 | 7.5 |
| Circulation | 20 | 12 | 23 | 1.065 | 0.000 | 9.39 | 70.0 | 1.83 | 5.2 |
| Reception | 20 | 12 | 23 | 1.122 | 0.107 | 8.91 | 85.4 | 4.63 | 9.0 |
| Library / Office | 21 | 12 | 24 | 1.030 | 0.364 | 9.71 | 73.0 | 14.50 | 12.0 |
| Classrooms | 20 | 12 | 23 | 1.107 | 0.082 | 2.50 | 70.0 | 4.74 | 11.3 |
| IT Classrooms | 22 | 12 | 24 | 2.313 | 0.324 | 4.32 | 73.2 | 27.81 | 11.3 |
| Sports Hall | 16 | 12 | 25 | 0.536 | 0.000 | 18.65 | 102.0 | 1.89 | 12.0 |
| Changing Rm | 22 | 12 | 25 | 1.339 | 112.050 | 7.47 | 70.0 | 4.79 | 5.2 |
| Food Prep | 17 | 12 | 21 | 2.390 | 0.431 | 10.46 | 63.0 | 23.13 | 12.0 |
| Tea Rooms | 20 | 12 | 23 | 1.122 | 0.000 | 8.91 | 70.0 | 8.01 | 10.4 |
| Toilets | 20 | 12 | 25 | 1.278 | 0.000 | 9.39 | 70.0 | 4.57 | 10.4 |
| Av for Building | 19 | 12 | 24 | 1.030 | 5.696 | 11.17 | 81.3 | 9.05 | 9.8 |

Table 3.2 NCM parameter matrix for defined University Building activities

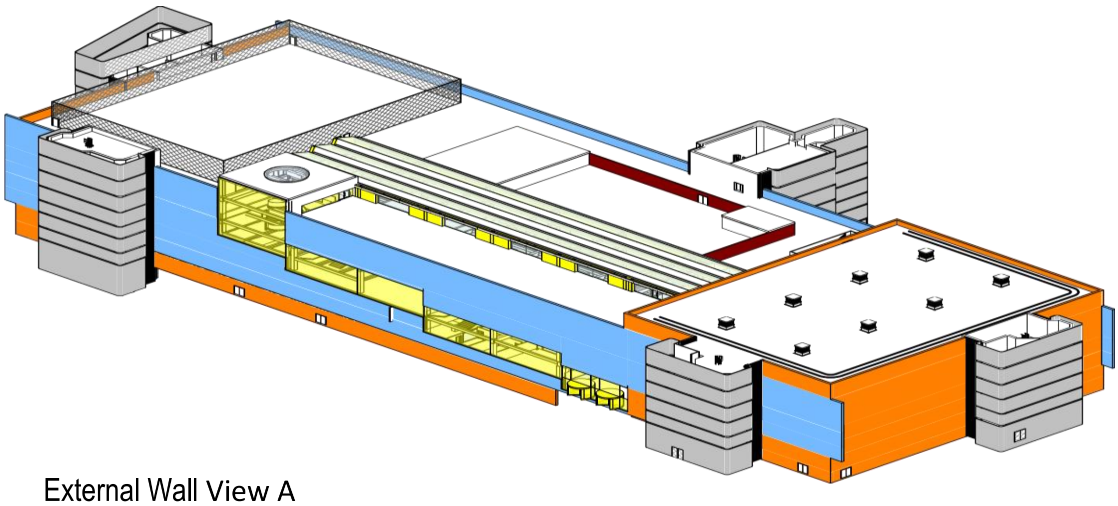
Further known design information includes fabric u-values and assumed control regimes for heating, ventilation, cooling and lighting as given in Tables 3.3 and 3.4.

| | Floor | Roof | Wall | Glazing | Doors |
|---|---|---|---|---|---|
| U-value | 0.18 | 0.14 | 0.6 | 1.44 | 1.7 |

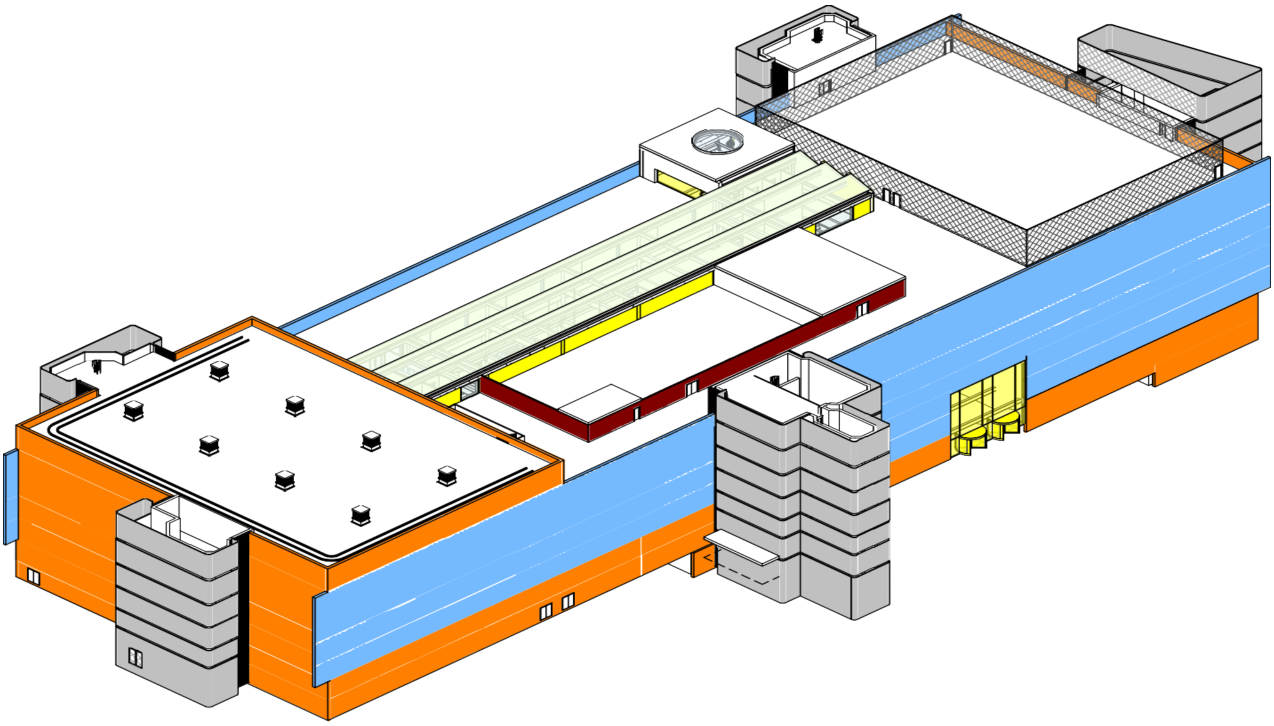
Table 3.3 Copperas Hill Building fabric u-values

| | Control Regime |
|---|---|
| Heating | Auto |
| Ventilation (MVHR) | Continuous |
| Electric Cooling | Auto during occupancy |
| Domestic Hot Water | Auto during occupancy |
| Lighting | Auto on / off |

Table 3.4 Copperas Hill Building Service controls



External Wall View A



External Wall View B

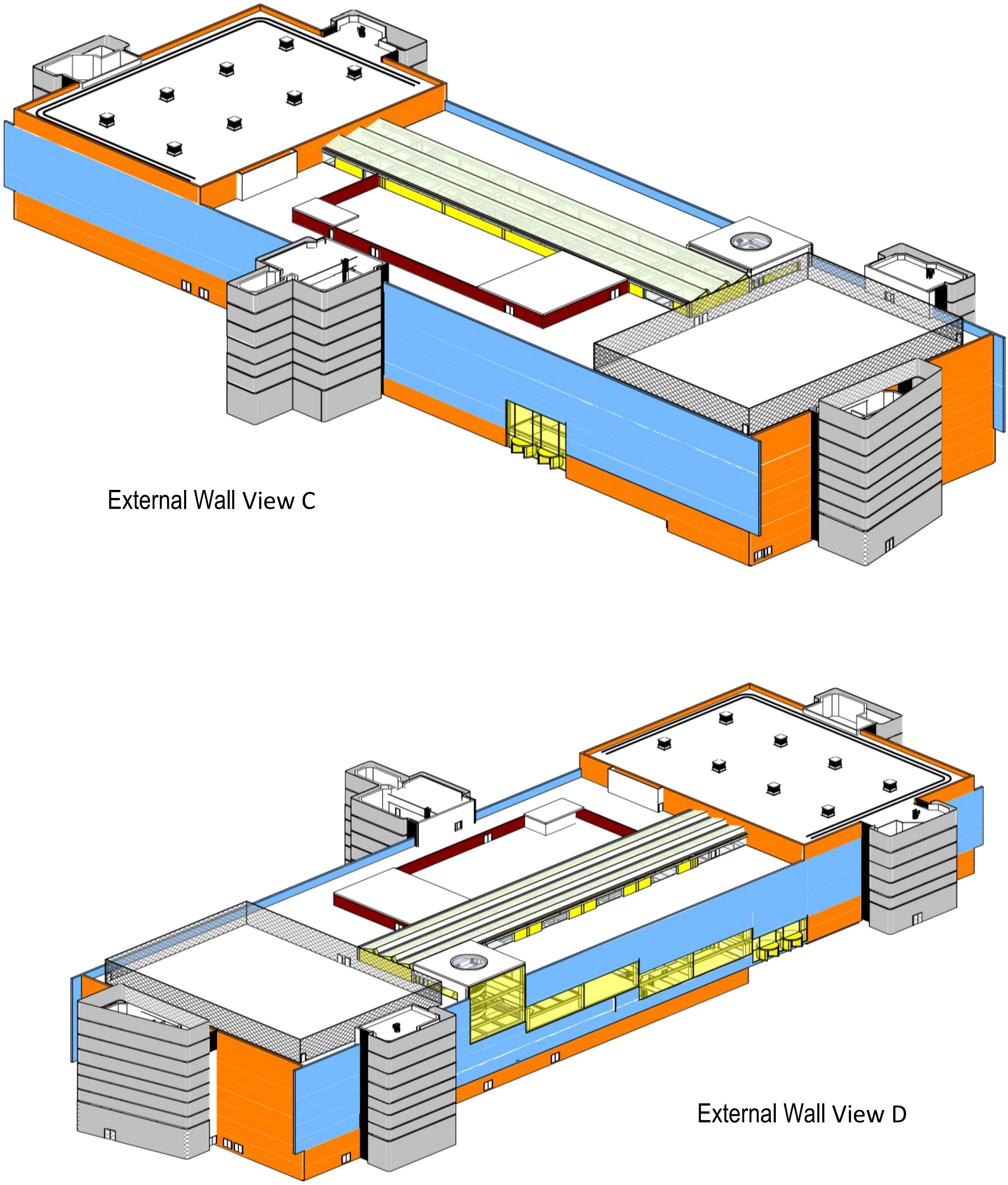



Figure 3.3 Copperas Hill Building External Wall 3D Views

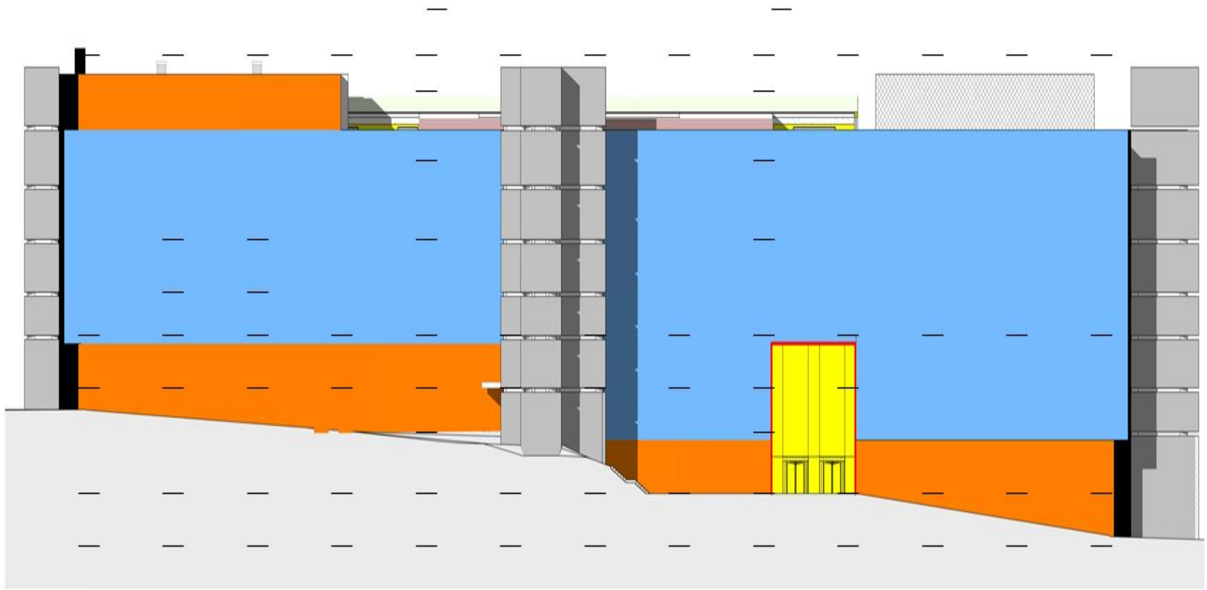


Figure A Copperas Hill Building External Wall - North Elevation

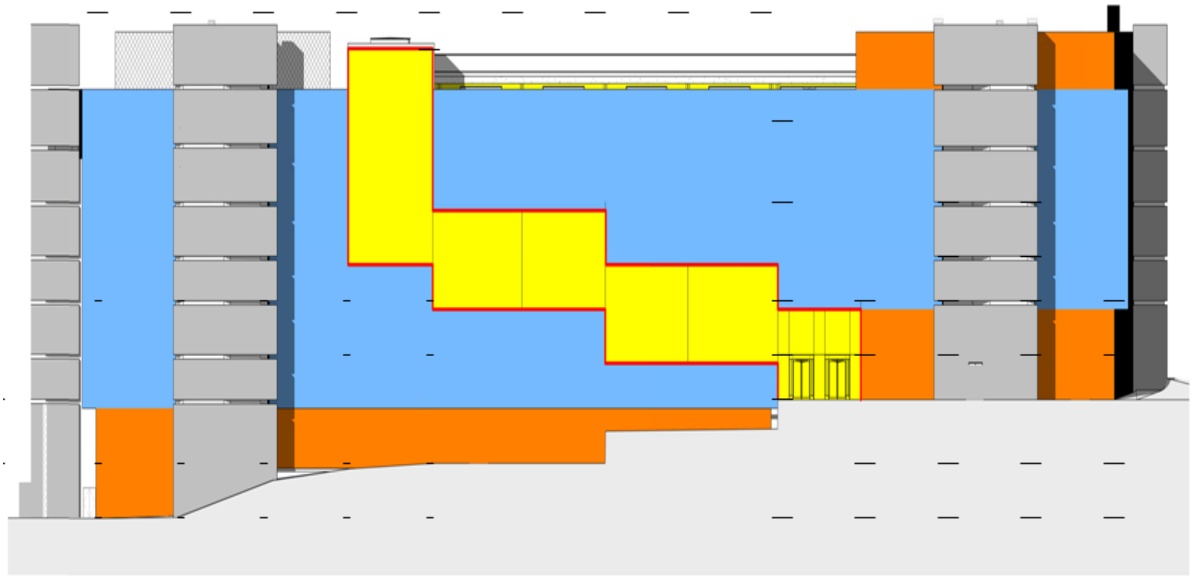


Figure B Copperas Hill Building External Wall - South Elevation

Figure 3.4 Copperas Hill Building External Wall

Figures 3.3 and 3.4 show: **'Textured' facades**

A unitised façade system consisting of anodised aluminium-framed glazed flat panels and projecting glazed units with integral natural-ventilation acoustic attenuation (manual and actuated opening) and service risers.

**Plinth, gables and sports hall**

A unitised façade system consisting of anodized aluminium-framed glazed flat panels with opening windows (manual and actuated), anodised aluminium flat panels with integral natural-ventilation acoustic attenuation (manual and actuated opening), tern-coated steel flat panels at the lower levels (for durability) and anodised aluminium plant louvers.

**Learning terraces, entrances and roof-light**

A stick system façade consisting of anodized aluminium-framed glazed flat panels with opening windows (manual and actuated) and anodised aluminium flat panels. Glazed areas to have integral, motorised, rol-formed stainless steel solar control blinds. System to include anodised aluminium protruding 'frame' to leaning terraces.

**Existing cores**

Anodised perforated aluminium 'wrap' on galvanised steel substructure. Cores to be clad in insulated composite panel fixed directly to the existing brickwork.

**Shadow gaps**

A unitised façade system consisting of anodized aluminium flat panels and tern-coated steel flat panels at the lower levels (for durability).

**Rooftop plant**

Anodised aluminium plant louvers.

VENTILATION STRATEGY

Mechanical Ventilation

Natural Ventilation – Attenuate

Natural Ventilation - Via Wind Catchers

Natural Ventilation – Unattenuated

## 3.2.2. calibration case study: Green Bank Student Village

The second case is Green Bank Student Village, Sefton Park in Liverpool, UK and is a proposed BREEAM compliant, residential cluster of buildings. The total internal area of the campus is 39,520$\boldsymbol{m^2}$, this campus featuring two CHP engines and a DHN (domestic hot-water network) with a central thermal store capacity. The campus comprises 5 individual building zones as shown in Table 3.5.

Figure 3.5 Green Bank Student Village in Liverpool city [99]

Figure 3.6 Green Bank Student Village in Liverpool city [100]

| University Residential Campus | |
|---|---|
| Gross Internal Area (GIA) | 39,520$m^2$<br>Five building |
| CHP Engines | 150kWe + 220kWe |
| DHN | 1500m |
| Electric Cooling | Sports Hall Only. Passive elsewhere |
| Ventilation | Mechanical with 70% heat recovery |

Table 3.5 Green Bank Student Village Base Configuration

Table 3.6 shows the parameter values for design and test the Case study for heating and cooling set points, heating setback temperature, ventilation, domestic hot water, occupant density, occupancy gains, and equipment and lighting electricity as directly given by NCM. These values are used to calculate the overall weighted average dataset for the building zone.

| | Heat Set Point | Heat Set Back | Cool Set Point | Vent | DHW | Occupancy | Gains | Equip | Light |
|---|---|---|---|---|---|---|---|---|---|
| | Celsius | Celsius | Celsius | L/s/p | L/day/m2 | m2/p | W/p | W/m2 | W/m2 |
| Plant / Server | - | - | 25 | 10 | 0.00 | 9.09 | 90 | 54.41 | 4.21 |
| Circulation | 20 | 12 | 23 | 10 | 0.00 | 9.39 | 70 | 1.83 | 2.15 |
| Bathrooms | 22 | 12 | 27 | 12 | 0.00 | 4.32 | 152.5 | 1.56 | 2.63 |
| Bedrooms | 20 | 10 | 25 | 10 | 8.00 | 10.41 | 50 | 4.32 | 2.63 |
| Changing Rm | 22 | 12 | 25 | 10 | 30.00 | 7.09 | 130 | 4.85 | 2.15 |
| Communal Area | 22 | 12 | 24 | 10 | 0.30 | 8.77 | 40 | 5.27 | 3.15 |
| Food Prep | 17 | 12 | 21 | 25 | 0.33 | 10.41 | 63 | 40 | 10.65 |
| Sports Hall | 16 | 12 | 25 | 10 | 0.00 | 18.65 | 100 | 1.89 | 6.45 |

Table 3.6 NCM parameter matrix for defined Green Bank Student Village

For more information about the buildings, U-values are specified in the given design, reproduced in Table 3.7, while Table 3.8 gives details about the control regime for the site.

| U-value | Floor | Roof | Wall | Glazing | Doors |
|---|---|---|---|---|---|
| New buildings | 0.18 | 0.14 | 0.6 | 1.44 | 1.7 |
| Refurbish building | 0.25 | 0.25 | 0.27 | 2.20 | 2.18 |

Table 3.7 Green Bank Student Village U-values from the TAS Design

The campus consists of five individual building zones; four of these are new build developments, the fifth a refurbishment of an existing building.

| | Control Regime |
|---|---|
| Heating | Auto |
| Ventilation | Continuous |
| Cooling | Auto during occupancy |
| Domestic Hot Water | Auto during occupancy |
| Lighting | Auto on / off |

Table 3.8 Green Bank Student Village Service Control Regimes

A goal of 5 air changes per hour is assumed for the site as per CIBSE TM46 recommendations. The heat network is assumed to be 1500m long with an average pipe diameter of 0.2m. The energy centre for this group of buildings comprises models of CHP plant, back-up gas boilers and a central thermal store.

### 3.2.3. Case study 3 for Calibration: Media City in Salford, Manchester.

The last case study is Media City in Salford, Manchester, UK. A cluster of 8 buildings represented by 10 distinct residential and non-residential zonal configurations. Energy for this fully operational site is supplied via a tri-gen CHP and absorption chiller cooling system as described in Table 3.9.

Figure 3.7 Media City in Salford, Manchester, UK city [101]

Figure 3.8 Media City in Salford, Manchester, UK. [102]

| MIXED 10 zone & TRI-GEN supply | Value |
|---|---|
| site Gross Internal Area (GIA) | 167,520m2 |
| CHP Engine | 2MWe |
| DHN | 2200m |
| Absorption chiller | 1.5MWe |
| Ventilation | MVHR |

Table 3.9 Media City Base Configuration

The real operation and control of the site includes zones where a third-party supplies one or more services or where a different cooling technology is employed. The zonal variations in scale and services are highlighted below in Table 3.10.

| | Activity | Footprint ($m^2$) | Floors | Elecric | Heat | DHW | ABO | Chill |
|---|---|---|---|---|---|---|---|---|
| Zone 1 | Office | 2640 | 12 | X | X | X | | X |
| Zone 2 | Garage | 5525 | 10 | X | | | | |
| Zone 3 | Retail | 485 | 2 | X | X | X | | X |
| Zone 4 | Office | 1690 | 6 | | X | | | |
| Zone 5 | Residential | 650 | 18 | | | X | | |
| Zone 6 | Residential | 650 | 18 | | | X | | |
| Zone 7 | Commercial | 5222 | 4 | X | X | X | X | |
| Zone 8 | Office | 652 | 20 | X | X | X | X | |
| Zone 9 | Office | 675 | 9 | X | X | X | X | |
| Zone 10 | Hotel | 675 | 9 | X | X | X | X | |

Table 3.10 Media City Base Configuration

The model was configured for each zone's particular requirements and set of services with each service in each zone tailored to the operational characteristics where known and estimated from comparable test cases where not known. U-values for the zones were assumed using these previous tests and using BREEAM as a guide. Glazing and door areas were estimated from site visits and photographs. Summary estimated u-values are given in Table 3.11.

| u-values: W/m²K | Floor | roof | wall | Glazing | door | door area | % Glazing |
|---|---|---|---|---|---|---|---|
| Zone 1 | 0.5 | 0.3 | 0.4 | 1.7 | 2.2 | 24 | 15 |
| Zone 2 | 0.5 | 0.3 | 0.4 | 1.7 | 2.2 | 24 | 00 |
| Zone 3 | 0.5 | 0.3 | 0.4 | 2.2 | 2.2 | 6 | 80 |
| Zone 4 | 0.5 | 0.3 | 0.4 | 1.7 | 2.2 | 12 | 00 |
| Zone 5 | 0.5 | 0.3 | 0.4 | 1.7 | 2.2 | 12 | 20 |
| Zone 6 | 0.5 | 0.3 | 0.4 | 1.7 | 2.2 | 12 | 20 |
| Zone 7 | 0.5 | 0.3 | 0.4 | 2.2 | 2.2 | 18 | 76 |
| Zone 8 | 0.5 | 0.3 | 0.4 | 2.2 | 2.2 | 12 | 21 |
| Zone 9 | 0.5 | 0.3 | 0.4 | 2.2 | 2.2 | 12 | 20 |
| Zone 10 | 0.5 | 0.3 | 0.4 | 2.2 | 2.2 | 12 | 20 |

Table 3.11 Media City Assumed U-Values, glazing and door areas

Finally, the cases studies two and three are used for calibration of the IDEAS MATLAB model and testing the control systems ability to work in deferent situation, different criteria and the scalability to large building. As first case study is educational building with 5 zones used for modelling and design, while second case study is residential with 5 zones and the last case study is mixture between commercial and residential case study with 10 zones. Which both of them used for calibration.

The methodology of control system and design proved can work under all conditions.

## 3.8. METHODOLOGY

The building model is based on IDEAS (Inverse Dynamics based Energy Assessment and Simulation) which is a dynamic calculation method developed to analyse the energy used in a building's complex indoor environment [94] and as described in the work of Gavin Bruce Murphy [103]. In this chapter, the building model represents the transfer of heat across a defined building boundary. It is represented by a non-linear nodes analysis of four defined building temperature nodes and two system temperature nodes. External and internal structural temperature nodes capture the dynamics of heat transfer through exterior walls; an internal structural mass temperature node represents immovable masses such as load bearing beams and joists; a zone temperature node represents both air volume and furniture within a building envelope in a single node; a hot water network temperature node and a thermal store temperature node are also included. A detailed examination of this thermal resistance approach is given in [94] this including the description of differential equations derived from fundamental building physics. State space representation of these equations then allows implementation and analysis in numerical simulation software such as MATLAB/Simulink. The building model assumes uniformly distributed air volume and zone temperature with fabric u-values assumed in the steady state. This bandwidth modelling approach simplifies mathematical representations while retaining sufficient detail for energy assessment and control.

## 3.9. System Thermal Model

The main heat storage inside the buildings are walls and the heat transfer between the wall temperature and internal temperature. Heat from outside air is also stored in the wall structure. When the temperature inside the zone drops, the heat is transferred from the wall to the zone. When the wall temperature drops lower than the temperature inside the zone, the heat is transferred to the wall as show in figure 3.9.

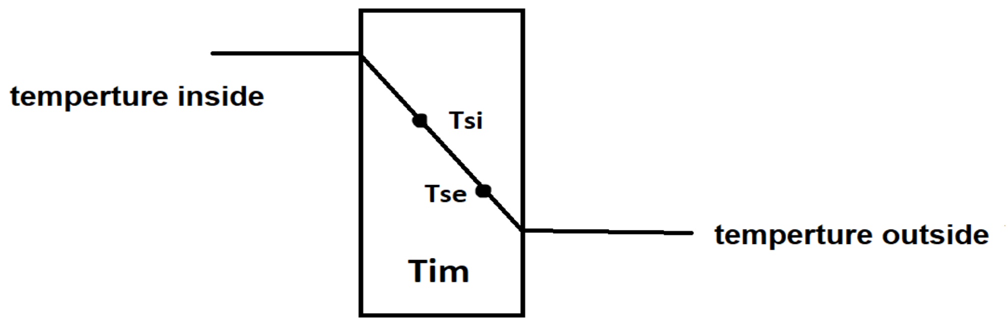



Figure 3.9 Relationship between the outside temperature and the outside solid wall of a zone [103]

There however, are many different elements and parameters which can dramatically affect the temperature inside each zone. It is very important to calculate the best comfortable temperate inside the zone for residential units such as the amount of free heat produce by appliances, human bodies, lighting and through solar gain. At the same time, there are many ways of losing heat from zones such as windows and glazing (single or double glazing), doors, floors and ventilation systems as shown in figure 3.10.

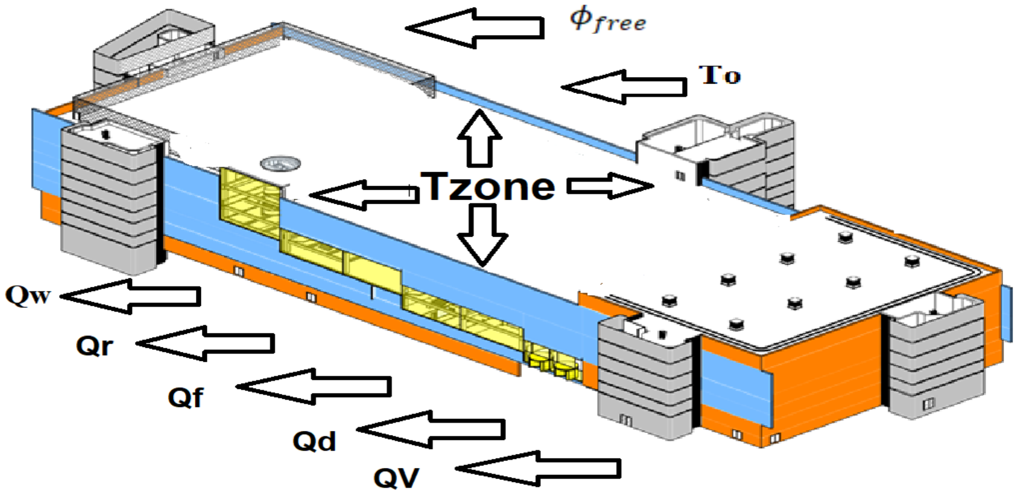



Figure 3.10 Relationship between different parameters which can affect the temperature inside a zone

Where:

$T_{zone}(t)$ is the temperature inside the zone $(K)$

$T_o(t)$ is the mean external dry bulb temperature $(K)$

$T_{se}(t)$ is the mean external temperature of the n'th structure $(K)$

$T_{im}(t)$ is the mean internal mass temperature of the structure $(K)$

$T_{si}(t)$ is the mean internal temperature of the structure $(K)$

$Qw(t)$ is energy loss by windows $(W)$

$Qr(t)$ is energy loss by the roof $(W)$

$Qf(t)$ is energy loss by floors $(W)$

$Qd(t)$ is energy loss by doors $(W)$

$Qv(t)$ is energy loss by ventilation $(W)$

There are many heat loss points including windows, floor, roof, doors and ventilation for each building/zone denoted by "n" for each zone/building such that:

Heat loss by windows for the n'th zone is given by:

$$\dot{Q}w.n(t) = U_{w.n}A_{w.n}(\bar{T}zone.n(t) - T_o(t))$$

Heat loss by floors

$$\dot{Q}f.n(t) = U_{f.n}A_{f.n}(\bar{T}zone.n(t0 - T_o(t))$$

Heat loss by roof

$$\dot{Q}r.n(t) = U_{r.n}A_{r.n}(\bar{T}zone.n(t) - T_o(t))$$

Heat loss by doors

$$\dot{Q}d.n(t) = U_{d.n}A_{d.n}(\bar{T}zone.n(t) - T_o(t))$$

Heat loss by ventilation

$$\dot{Q}v.n(t) = \dot{m}_{v.n}C_a(\bar{T}zone.n(t) - T_o(t))$$

where $\phi_{free.n}(t)$ is free heat gain for the n'th zone in watts (W) from heat given to the zone space by:

- Appliances
- People
- Lighting
- Solar Gain

So, the final linear differential equations for each modelled building temperature zone 'n' $\bar{T}_{zone.n}(t)$ in kelvin (K), taking into account the thermal capacitances of the zone air, internal and external structures [103] are given by:

$$\frac{d\bar{T}_{zone.n}}{dt} = \frac{1}{m_{zone.n}C_{zone.n}}\Bigg(U_{w.n}A_{w.n} + U_{f.n}A_f + U_{r.n}A_{r.n} + U_{d.n}A_{d.n} + \dot{m}_{v.n}C_a + \frac{4h_{i.n}k_{s.n}A_{s.n}}{4k_{s.n} + h_{i.n}d_{s.n}} + U_{im.n}A_{im.n}\Bigg)\bar{T}_{zone.n}(t)$$

$$+ \frac{4h_{i.n}k_{s.n}A_{s.n}}{m_{zone.n}C_{zone.n}(4k_{s.n}+h_{i.n}d_{w.n})+h_{i.n}d_{s.n}}\overline{T_{s\iota.n}}(t) + \frac{U_{im.n}A_{im.n}}{m_{zone.n}C_{zone.n}}T_{im.n}(t) + \frac{1}{m_{zone.n}C_{zone.n}}\dot{Q}z_{zone.n}(t) + \frac{1}{m_{zone.n}C_{zone.m}}\phi_{free}(t) + \frac{1}{m_{zone.n}C_{zone.n}}\big(U_{w.n}A_{w.n} + U_{f.n}A_{f.n} + U_{r.n}A_{r.n} + U_{d.n}A_{d.n} + \dot{m}_{v.n}C_a\big)T_o(t) \qquad (1)$$

The internal structure temperature [103] for the n'th zone $\overline{T_{s\iota.n}}(t)$ in kelvin (K) is given by:

$$\frac{d\overline{T_{si.n}}(t)}{dt} = \frac{4h_{i.n}k_{s.n}A_{s.n}}{4k_{s.n} + h_{i.n}d_{s.n}}\bar{T}_{zone.n}(t) - \frac{(4h_{i.n}k_{s.n}A_{s.n}d_{s.n} + 2k_{s.n}A_{s.n})}{m_{si.n}C_{s.n}(4k_{s.n} + h_{i.n}d_{s.n})d_{s.n}}\overline{T_{si.n}}(t) + \frac{2k_{s.n}A_{s.n}}{m_{si.n}C_{s.n}d_{s.n}}\overline{T_{se.n}}(t)$$

(2)

The external structure temperature [103] for the n'th zone $\overline{T_{se.n}}(t)$ in kelvin (K) is given by:

$$\frac{d\overline{T_{se.n}}(t)}{dt} = \frac{2k_{s.n}A_s}{m_{se.n}C_{s.n}d_{s.n}}\overline{T_{si.n}}(t) - \frac{k_{s.n}A_{s.n}(8k_{s.n} + 6h_{e.n}d_{s.n})}{m_{se.n}C_{s.n}d_{.ns}(4k_{s.n} + h_{.ne}d_{.n})}\overline{T_{se.n}}(t) + \frac{4h_{e.n}k_{s.n}A_{s.n}}{m_{se.n}C_{s.n}(4k_{s.n} + h_{e.n}d_{s.n})}T_o(t)$$

(3)

The internal mass average temperature [103] for the n'th zone $\bar{T}_{im.n}(t)$ in kelvin (K) is given by:

$$\frac{\mathrm{d}\bar{T}_{im.n}(t)}{dt} = \frac{U_{im.n}A_{im.n}}{m_{im.n}C_{im.n}}(t)\bar{T}_{zone.n} - \frac{U_{im.n}\mathrm{A}_{im.n}}{m_{im.n}C_{im.n}}\bar{T}_{im.n}(t)$$

(4)

The hot water network is modelled by a single node to estimate the average temperature of the water in the network given by $\overline{T_w}(t)$ in kelvin (K). This temperature node is represented by the equation (5) while the thermal store's single node average temperature $\overline{T_w}(t)$ in kelvin (K) is described by equation (6):

$$\frac{d\overline{T_w}(t)}{dt} = \frac{\dot{Q}_{chp}(t)(1-U_{st}(t))}{m_w C_w} + \frac{\dot{m}_w C_w}{m_w C_w}\left(T_{st}(t) - \overline{T_w}(t)(t)\right)U_{st}(t) - \frac{U_p A_p(\overline{T_w}(t) - T_{ground}(t))}{m_w C_w} - \frac{(\dot{Q}_{LOAD}(t) + \dot{Q}_{dump}(t) - \dot{Q}_{boiler}(t))}{m_w C_w} \quad (5)$$

where $\dot{Q}_{LOAD}(t)$ is the total heat load imposed on the hot water in the water network in watts (W), $\dot{Q}_{dump}(t)$ is the heat that has to be dumped to the atmosphere to prevent the water network over-heating in watts (W), $T_{st}(t)$ is the average temperature of a thermal hot water store that can supply or take hot water from the heat network in kelvin (K), $\dot{Q}_{boiler}(t)$ is the boiler supplementary heating in watts (W) to keep the water network at its required temperature when the CHP and heat store cannot supply enough heat and $T_{ground}(t)$ is the ground temperature where the heat network pipes are laid in kelvin (K).

$$\frac{d\overline{T_{st}}(t)}{dt} = \frac{\dot{Q}_{chp}(t)U_{st}(t)}{m_{st} C_w} - \frac{\dot{m}_w C_w}{m_{st} C_w}\left(\overline{T_{st}}(t) - \overline{T_w}(t)\right)U_{st}(t) - \frac{U_s A_s\left(T_{st}(t) - T_{extstore}(t)\right)}{m_{st} C_w} \quad (6)$$

where $T_{extstore}(t)$ is the external temperature of the store where it is installed in kelvin (K) and $U_{st}(t)$ is the control input, a manual or automatically controlled signal ranging in value from -1 to 1.

Each heated building/zone uses proportional thermostatic control of each heating zone. In this case the total heat load on the water heat network for “N” number of heated buildings/zones is given by:

$$\dot{Q}_{LOAD}(t) = \sum_{1}^{N} \dot{Q}_{Zone.n}(t) \quad (7)$$

Where the thermostatic control law in response to a set point comfort temperature in kelvin (K) $Tz_{setpoint.n}(t)$ for each heated zone “n” is given by the proportional controller equation:

$$\dot{Q}_{Zone.n}(t) = K_{T.n}\,(Tz_{setpoint.n}(t) - T_{zone.n}(t)) \quad (8)$$

The heat generated in watts (W) by the CHP engine $\dot{Q}_{chp}(\mathrm{t})$ is given by

$$\dot{Q}_{chp}(\mathrm{t}) = K_{QCHP}\,U_{CHP}(t) \quad (9)$$

Where $K_{QCHP}$ is the fractional amount amount valued 0 to 1 that the CHP engine converts the input gas power in watts (W) $U_{CHP}(t)$ in to heat.

## 3.10. System Electrical Model

A simplified resistive electrical model represents real power flow within and across the boundary of the system, describing primary nodes in a private or local electricity network such that the power flow $P_{GRID}(t)$ in watts (W) at the junction of the national grid and private wire network of the LES is given by:

$$P_{GRID}(t) = P_{Load}(t) - P_{GCHP}(t) - P_{GPV}(t) \qquad (10)$$

where $P_{GPV}(t)$ is the total amount of electrical power generated by M zones with Photovoltaics arrays of the local energy system given by:

$$P_{GPV}(t) = \sum_1^M PV_{Zone.n}(t) \qquad (11\text{ a})$$

*where* $PV_{Zone.n}(t)$ is the n'th building/zone PV power generated in watts (W) which is given by a function look up table generated using time t and the outside temperature $T_o$ that approximates the PV power generated per unit area in W/m$^2$ such that:

$$PV_{Zone.n}(t) = A_{PV.n}\ f_{Pv.n}\left(t, T_o(t), \dot{T_o}(t)\right) \qquad (11\text{ b})$$

where $f_{Pv.n}\left(t, T_o(t), \dot{T_o}(t)\right)$ is a function derived from the watts per unit area of PV for the geographic and physical location of the PV array of panels. The total electricity demand $P_{Load}(t)$ for B buildings/zones requiring an electricity supply is given by:

$$P_{Load}(t) = \sum_1^B P_{ZoneLoad.n}(t) \qquad (12)$$

where$P_{ZoneLoad.n}(t)$ the n'th building/zone's electricity demand in watts (W). These are defined by the load profile datasets [103].

Power generated by the CHP engine $P_{GCHP}$(t) in watts (W) is given by:

$$P_{GCHP}(\mathrm{t}) = K_{PCHP}\, U_{CHP}(t) \tag{13}$$

where $K_{PCHP}$ is the fraction of gas power converted to electricity valued (0 to 1). The CHP engine response dynamics are approximated by a first order linear, time-invariant, differential equation to represent reaction time with a time constant $\tau_{CHP}$ in seconds (s) to a change in controlled gas power flow input $U_{Gas}(t)$ in watts (W) such that:

$$\tau_{CHP}\, \dot{U}_{CHP}(t) = U_{Gas}(t) - U_{CHP}(t) \tag{14}$$

## 3.11. State Space

The set of differential equations (1-14), together with design input signals, are solved in a state space as vector x(t) functions of time as given by Eqs. 15 and 16 (Bradshaw and Counsell, 1992) [104].

$$\dot{\boldsymbol{x}}(t) = \boldsymbol{Ax}(t) + \boldsymbol{Bu}(t) + \boldsymbol{Ed}(t) \tag{15}$$

$$\boldsymbol{y}(t) = \boldsymbol{Cx}(t) + \boldsymbol{Du}(t) + \boldsymbol{Fd}(t) \tag{16}$$

where Eq. 15 is the state equation, **x(t)** is the State Vector, **A** is the State Matrix, **B** is the Input Matrix and **E** is the Disturbance Matrix. Eq. 16 is the output equation for output **y(t)**, **C** is the Output State Matrix, **D** is the Disturbances Matrix, **D** is the Feedforward Matrix and **F** is Output Disturbance Matrix.

Assuming a high gain thermostatic control can isolate the temperature control in each zone, the resulting state vector for heat and power networks simplified to 17:

$$\boldsymbol{x}(t) = [\overline{T_w}(t)\ \overline{T_{st}}(t)\ U_{CHP}(t)]^T \tag{17}$$

The control input vector u(t) is defined as:

$$u(t) = [U_{st}(t)\ \ U_{Gas}(t)]^T \tag{18}$$

The disturbance vector d(t) resulting from (Eqs. 1-14) is defined as:

$$\boldsymbol{d}(t) = \left[\, T_g(t)\ \dot{Q}_{dump}(t)\ \dot{Q}_{LOAD}\,(t)\ \dot{Q}_{boiler}\,(t)\ T_o(t)\ \ P_{GPV}(t)\ P_{Load}(t)\right]^T \tag{19}$$

The output vector (y(t)) i.e. the system outputs/feedback measurements to be controlled in the CHP feedback control system and is defined as:

$$y(t) = [\,\overline{T_w}(t)\quad P_{GRID}(t)\,]^T \tag{20}$$

By using linearized representations of the state equations, the resulting state space A, B, C, D, E and F matrices shown in 15 and 16, using vectors 17, 18, 19 and 20 are derived as:

$$A = \begin{bmatrix} \dfrac{-\dot{m}_w c_w\, Uo -\ U_p A_p}{\tau_w} & \dfrac{\dot{m}_w c_w\, Uo}{\tau_w} & \dfrac{K_{QCHP}(1 -\ Uo)}{\tau_w} \\ \dfrac{\dot{m}_w c_w\, Uo}{\tau_{st}} & \dfrac{-\dot{m}_w c_w\, Uo - U_s A_s}{\tau_{st}} & \dfrac{K_{QCHP}\, Uo}{\tau_{st}} \\ 0 & 0 & \dfrac{-1}{\tau_{CHP}} \end{bmatrix}$$

$$B = \begin{bmatrix} \frac{-\dot{Q}_{CHPO} + \dot{m}_w c_w \Delta TO}{\tau_w} & 0 \\ \frac{\dot{Q}_{CHPO} - \dot{m}_w c_w \Delta TO}{\tau_{st}} & 0 \\ 0 & \frac{1}{\tau_E} \end{bmatrix}$$

$$E = \begin{bmatrix} U_p A_p/\tau_w & -1/\tau_w & -1/\tau_w & 1/\tau_w & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & U_s A_s/\tau_{st} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$C = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & -K_{PCHP} \end{bmatrix}$$

$$D = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}$$

and

$$F = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1 & 1 \end{bmatrix}$$

where $\tau_{st} = m_{st} c_w \;\; and \; \tau_w = m_w c_w$ (21)

## 3.12. MATLAB Modelling, Design and Calibration

The main case study in this thesis is the Copperas Hill Building in Liverpool, a university building. This section details the MATLAB design for Copperas Hill Building. The building itself is very big serving many different purposes. It is divided into five zones, each zone controlled independently. The system model mainly consists of:

- Five independent zones (each zone can be a building or part of a building). Each zone on the roof contain photovoltaics arrays and an electrical cooling system.
- Five heat exchangers, one for each zone.
- A hot water network to supply heat energy to each zone.
- An energy centre which include a CHP engine and a gas boiler.
- Thermal storage.
- An engine controller.
- A local electrical grid.
- An electrical set point.
- as shown in figure 3.11. and all details of MATLAB Simulink design and programming in the Appendix [A, B, C, D, E, F]

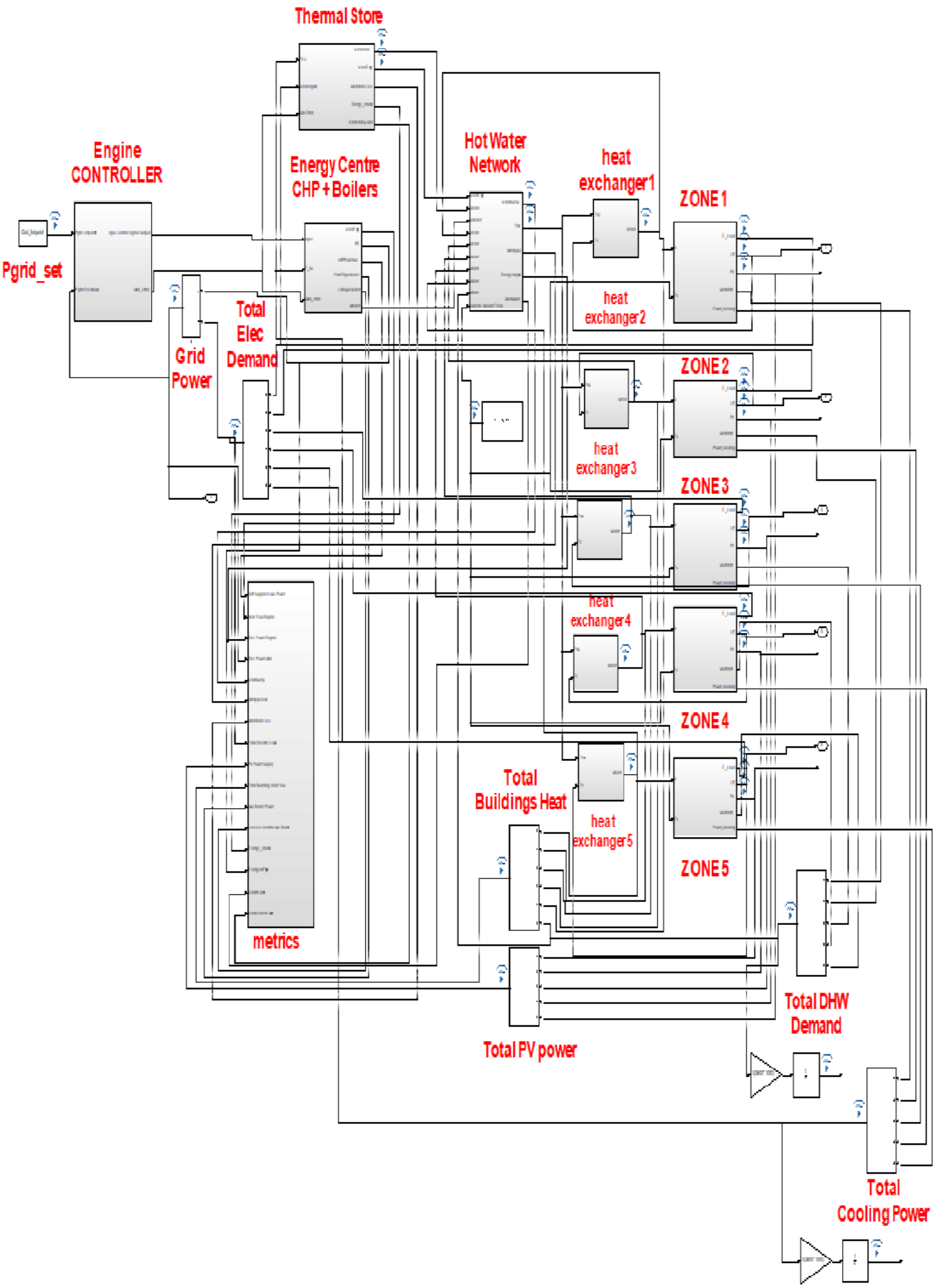



Figure 3.11 Copperas Hill MATLAB Simulink five zones design

### 3.12.1. MATLAB Calibration

Transparency in the modelling and calibration process and a clear understanding of how results compare with benchmarks is essential to provide confidence in any proposed modelling method or application. The general process shown in Figure [11] is the procedural basis for sequentially calibrating the model using available reference data as input. The process iteratively converges primary electrical then thermal behaviour before fine tuning in both domains through assuming control of sub-systems such as cooling and ventilation. Reference data and modelling benchmarks can be output derived from another trusted simulation package or estimation tool, or against industry standard datasets or can use real data in the model configuration. Aspects from all of these sources are employed to demonstrate calibration of the model in three test cases. The configuration of a model incorporates reference data with system topology characteristics and feedback from previous iterations to converge the model parameters and simulation towards chosen performance metrics. The energy supply model in this thesis simulates a parallel configuration of PV-enabled zones connected by a heat network to a central energy centre featuring a CHP engine and thermal store with boiler backup. Scope of the building models includes both domestic and non-domestic configurations and appropriate services controls.

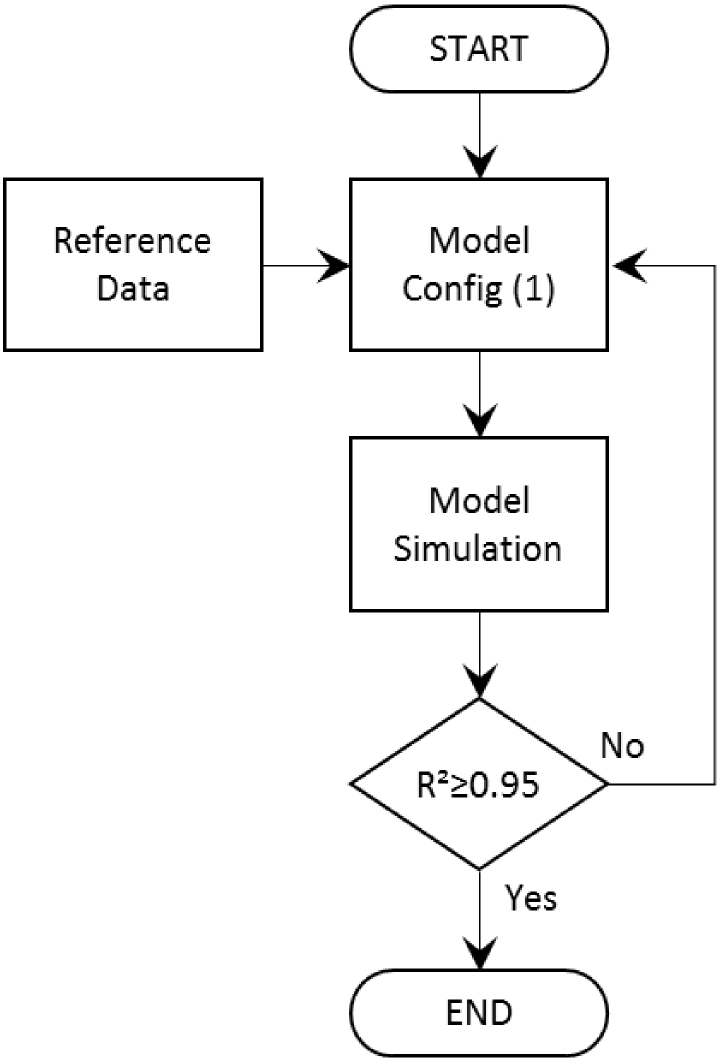



Figure 3.12 Model Calibration Process Flowchart

An accuracy target for simulation performance outputs against reference of 95% is chosen and is deemed more than sufficient to capture sufficient dynamic behaviour for purposes of energy estimation and test case validation.

### 3.7.2. Model calibration with NCM

In the UK, the primary data source for benchmark building fabric, construction, appliance and lighting energy values, activity and occupancy profiles is the National Calculation Methodology (NCM) and associated databases. The publicly and freely available NCM databases collate calibrated data from decades of empirical testing by standards bodies and are maintained by BRE for the UK government. These databases provide core reference data used by many dynamic simulation and energy estimation software products certified as compliant with Part L requirements of the UK Building Regulations. For the CHPV building models, the NCM databases provides sufficient data to enable generation of a calibrated notional baseline building from which an actual building can be developed, simulated and assessed. For example, an NCM derived non-domestic space is potentially made up of several sub-activities from; car parks, changing areas, circulation and connecting spaces, eating and drinking areas, food preparation areas, gym’s, office spaces, plant rooms, reception areas, storerooms, toilets and workshops. Each of these activities is defined by a calibrated dataset giving values for occupant density, electrical loads, lighting requirements, heating and cooling setpoints, hot water demand, and ventilation parameters typically at hourly intervals. A notional building model is generated by aggregating and proportionally scaling the NCM dataset for each of its defined activity areas by a conditioned gross internal floor area (GIA).

### 3.7.3. Steady State Calibration

The key metric for calibration of the model is energy transfer across the building envelope through a mass and energy balance. The model in this thesis, two primary parameters must match with given or reference data to demonstrate calibration; the system electrical energy transfer and the system thermal energy transfer. An actual building model differs from an NCM generated notional building model primarily by subsequent inclusion of dynamic and highly cross coupled effects of weather, heating, cooling and ventilation combined with their controls, on electrical and thermal demands. For this study, calibration with NCM assumes a linear scalar between an NCM notional and actual building electrical energy demands.

# Chapter Four
# Control Theory

## 4.1. Introduction

As chapter 1 and 2 explored, most of previous research in local energy system (LES) and CHP technology has focused on the feasibility and performance of CHP engine in given different scenario or on comparisons between different CHP technologies with respect carbon emissions and commercial benefits.

This chapter telling the story of developing a control system for control and operation a local energy system with CHP technology with renewable energy sources. This control system follows the electrical demand and allows the CHP system with renewable energy sources to operate continuously with the aim to utilise the energy generated in an effective way to fulfil the energy demands. The second aim of the controller is control the zones temperature independently and keep it all the time within the set point during all the year. The third aim of this control system is manage and control a (heat storage, gas boiler and electrical cooler) to reduce the gas emission to minimum, increased the commercial advantage to the maximum and gives the system best performance. Finally, the control system increases the resilience and reliability by connecting all the system with electrical national grid for emergency issues, so the local energy system can be used.

The story of design controller for local energy system started with first attempt was control the air temperature inside of a building by pumping the heat energy direct to the building and control the temperature by the thermostat set point but the results show very bad controllability specially more than one zone for full year. And this method is published in “CHPV Control” [93]. The second idea is using a cascade control system for a hot water network (HWN) and heat storage (HS) with thermostat to control the temperature inside the building. This method based on the RIDE controller design methodology [111] which use to solves the inverse dynamic problem of a multi-input multi-output control system. This method applied for a local energy system consist of a single building single zone for a full year time to test it. Finally, to ensure the system follow the setpoint in both sides (electrical and heat) the controller should be fast enough to follow the setpoints. There is no controller can reach the Ideal System Response, but it should be fast enough to give accurate and stable tracking for high power quality performance and good thermal comfort in all heated buildings/zones.

## 4.2. Ideal System Response (ISR)

What is the ideal response of a system?

The ideal system response is the system has no time delay in responding to the step change in set-point i.e. the set-point is followed exactly at all times [106]. Theoretically is possible but in reality, this is not possible because the systems do not have infinite bandwidth i.e. in terms of buildings having infinite cooling and heating. Which mean the Ideal System Response achievable in practice is the first order response. For example, a first order temperature response to step change in temperature set-point is given in the figure (4.1) below.

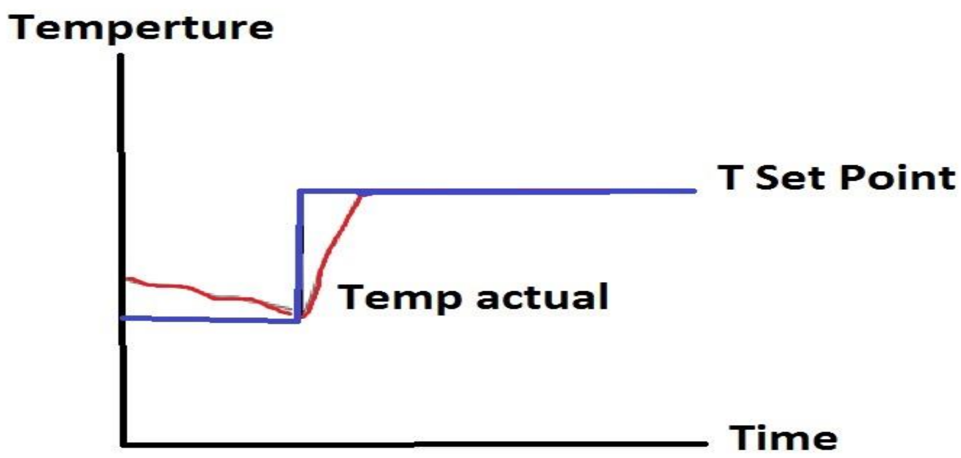



Figure 4.1 first order temperature response to step change in temperature [106]

If the Stable First order system act well the system will be easy to control. But in same time, the real-world response is higher order and difficult to control because there are many difficulty problems like oscillations, overshoots etc. in the response. However, there are some higher order systems are dominantly as first order which is mean easiest to control in the real world.

Recently, buildings are such types of systems that are known as multiple inputs multiple outputs (MIMO) systems just like MIMO systems in other industries. That is mean, there are several control channels like temperature, lighting, humidity, CO2 etc. that can operate in parallel and each channel will have its own actuator (Plant) system and all are coupled together in terms of building physics [106].

In practice a simple system (or first order system) is easier to control. Unlikely most of the systems are not simple (higher order). So, Inverse dynamics input $\mathbf{U}_{eq}$ (equivalent control) makes a complex system act like a simple building which can then be controlled accurately by a proper controller.

## 4.3. Robust Inverse Dynamic Estimation (RIDE) control theory

The RIDE control law for controlling a first order system is the PDF algorithm. And this algorithm uses the response of the system which is completely controllable using the gains of the system. Counsell [111] produced a new control law by combining PDF system with the equivalent control input $(\mathrm{U}_{eq})$. For that Counsell was able to prove that the Robust Inverse Dynamic Estimation (RIDE) control law for a complex multivariable system nonlinear (MIMO):

**Robust Inverse Dynamic Estimation (RIDE) CONTROL ALGORITHM = PDF controller + Inverse Dynamics Input ($\mathbf{U}_{eq}$)**

**In this thesis not using PDF part of theory, using high gain proportional error actuated control only**

Which the $\mathrm{U}_{eq}$ is able to decouple the multivariable system and reduces each control channel to a perfect integrator while the PDF controller is able to completely control its response which is a function of its gains the block diagram (4.2) shows the story and the back ground of the RIDE

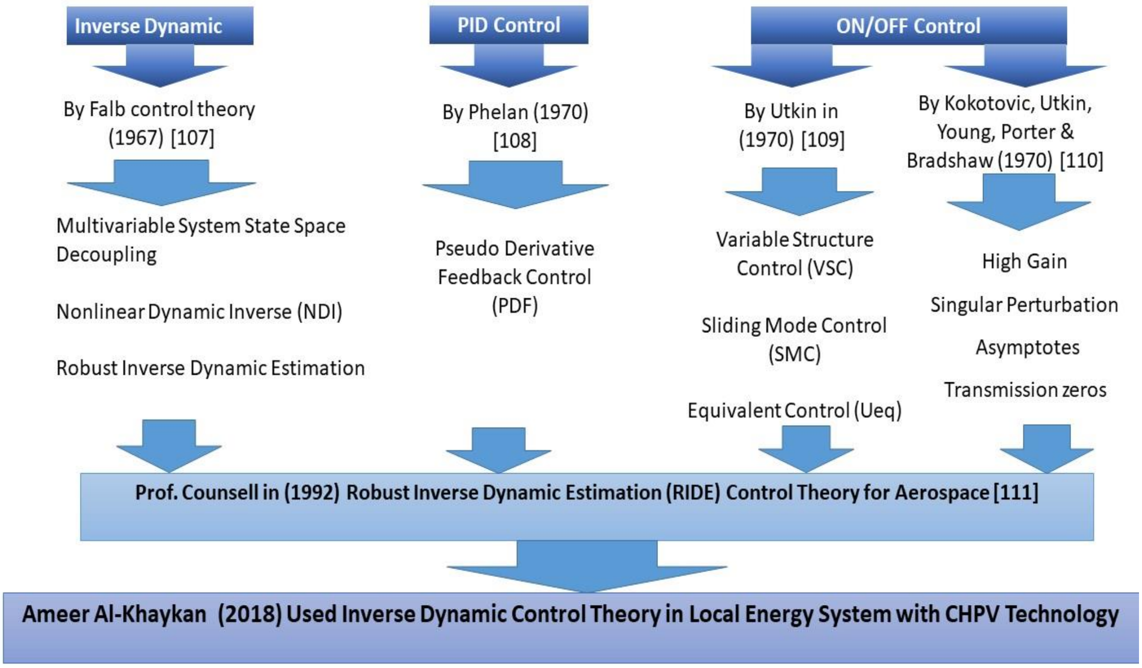



Figure 4.2 Block diagram of the Inverse Dynamic Control Philosophy

## 4.4. Inverse Dynamics Controller Design Method

### 4.4.1. State-Space Representation

The coupled set of linear and nonlinear ordinary differential equations (1-11) in chapter 3 for the purposes of controller design are linearized to create a controller-design state-space representation (CDSSR) [106] to enable stability analysis and the design of an inverse dynamics controller.

Assuming a small perturbation $\delta$ on all state variables from a steady condition at t = 0, such that $\dot{Q}_{chp}(0) = \dot{Q}_{chpo}$ , $U_{st}(0) = Uo$ & $(T_{st}(0) - T_w(0)) = \Delta TO$ , equations (1 – 11) in chapter 3 were linearized and combined to create a CDSSR of the system's dynamics with a small perturbation linearized (SPL) controller input vector u(t), x(t) the system's SPL state variable vector and d(t) the SPL disturbance vector. The resulting CDSSR is as follows:

$$\dot{\boldsymbol{x}}(t) = \boldsymbol{A}\boldsymbol{x}(t) + \boldsymbol{B}\boldsymbol{u}(t) + \boldsymbol{E}\boldsymbol{d} \quad (1)$$

$$\boldsymbol{y}(t) = \boldsymbol{C}\boldsymbol{x}(t) + \boldsymbol{D}\boldsymbol{u}(t) + \boldsymbol{F}\boldsymbol{d}(t) \quad (2)$$

where:

The state variable vector is defined as

$$\boldsymbol{x}(t) = [\overline{T_w}(t)\ \overline{T_{st}}(t)\ U_{CHP}(t)]^T \quad (3)$$

the control input vector u(t) is defined as

$$\boldsymbol{u}(t) = [U_{st}(t) \;\; U_{Gas}(t)]^T \tag{4}$$

the disturbance vector d(t) is defined as

$$\boldsymbol{d}(t) = \left[ T_g(t)\, \dot{Q}_{dump}(t)\, \dot{Q}_{LOAD}(t)\, \dot{Q}_{boiler}(t)\, T_o(t) \;\; P_{GPV}(t)\, P_{Load}(t) \right]^T \tag{5}$$

and where the matrices A, B, C, D, E and F are:

$$A = \begin{bmatrix} \dfrac{-\dot{m}_w c_w\, Uo - U_p A_p}{\tau_w} & \dfrac{\dot{m}_w c_w\, Uo}{\tau_w} & \dfrac{K_{QCHP}(1 - Uo)}{\tau_w} \\ \dfrac{\dot{m}_w c_w\, Uo}{\tau_{st}} & \dfrac{-\dot{m}_w c_w\, Uo - U_s A_s}{\tau_{st}} & \dfrac{K_{QCHP}\, Uo}{\tau_{st}} \\ 0 & 0 & \dfrac{-1}{\tau_{CHP}} \end{bmatrix}$$

$$B = \begin{bmatrix} \dfrac{-\dot{Q}_{CHPO} + \dot{m}_w c_w \Delta TO}{\tau_w} & 0 \\ \dfrac{\dot{Q}_{CHPO} - \dot{m}_w c_w \Delta TO}{\tau_{st}} & 0 \\ 0 & \dfrac{1}{\tau_E} \end{bmatrix}$$

$$E = \begin{bmatrix} U_p A_p/\tau_w & -1/\tau_w & -1/\tau_w & 1/\tau_w & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & U_s A_s/\tau_{st} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$C = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & -K_{PCHP} \end{bmatrix}$$

$$D = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}$$

and

$$F = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1 & 1 \end{bmatrix} \tag{6}$$

The choice of state vector x(t) has been simplified by isolating the temperature control of each zone from the CDSSR by assuming that high bandwidth (i.e. fast response) thermostatic control is achievable in each building/zone as per equation (8) in chapter 3. Providing this is achieved, then it can be assumed that the desired heat flow needed for each zone can always be delivered by the heat network via the building/zone's heat exchanger. Hence, the importance of the supplementary heating to help maintain the efficacy of the heat exchangers. In which case each building zone can be considered to be a time varying heat load on the hot water heat network giving a total heat load given by equation (5) in previous chapter. and thus, the building's thermodynamic response can be assumed to be decoupled from the dynamics of the local energy system's heat delivery and power generation networks.

The output vector for the local energy system controller was chosen to be the hot water network temperature and the power imported from the national grid. By maintaining the set point temperature in a highly insulated hot water network the system can always ensure that there is efficiently enough heat for the buildings/zones. By tracking the set point for power imported from the national grid, the controller provides a solution to islanding the PWN from the national grid with a set point of zero kW, or it can be driven as a national grid resource for demand side response and/or generation. This output vector is defined in the CDSSR as y(t) (i.e. the system outputs/ feedback measurements to be controlled) and it is given by:

$$\boldsymbol{y}(t) = [\,\overline{T_w}(t) \quad P_{GRID}(t)\,]^T \tag{7}$$

The CHPV control system is required to track simultaneously a desired imported grid power demand normally set to zero and a desired water network temperature normally fixed between 70 and 90°C. In this case it was set constant 24 hours a day at 85°C (i.e. 358.15K). These set points can be described mathematically for controller design in a set point vector v(t) which is given by

$$v(t) = [\mathrm{Twnset\ (t)} \quad \mathrm{Pgridset\ (t)}]^T \tag{8}$$

And in this case, which the hot water network setpoint is $358.15\mathrm{K}$ and the electrical setpoint is zero as (Island mode). The equation will be

$$v(t) = [358.15 \quad 0]^T \tag{9}$$

The general form of the Inverse Dynamic controller design method [106] is shown in Figure [4.3].

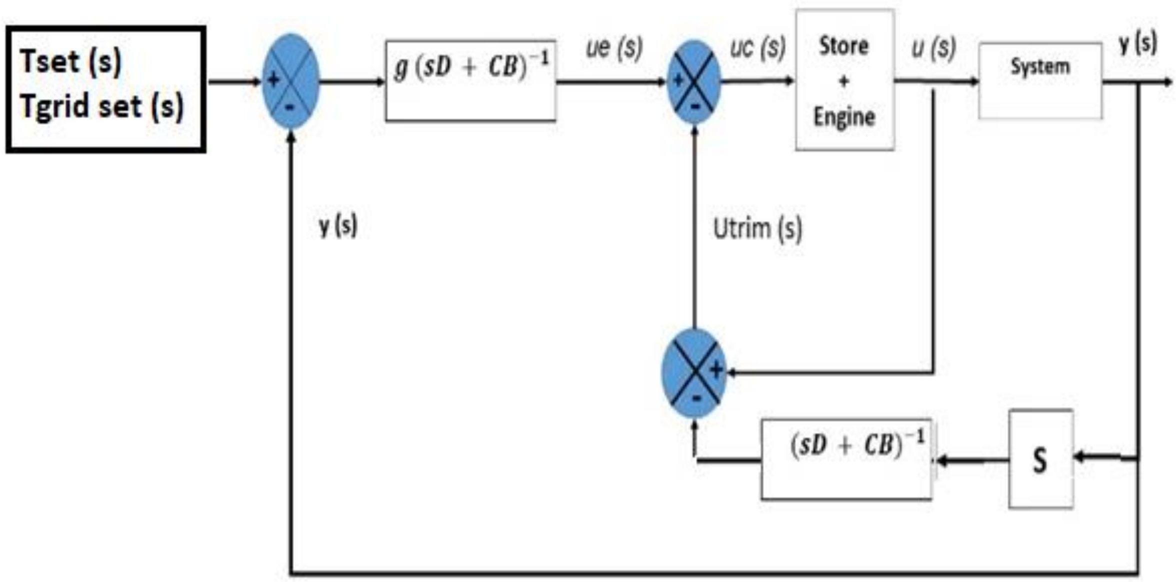



Figure 4.3: Basic Dynamic Controller Control Structure

The inverse dynamics controller design methodology [18] solves the inverse dynamic problem of a multi-input multi-output control system to guarantee closed-loop stability, set point tracking and robustness in the presence of model and disturbance uncertainties. Given a desired set point vector v(t) to track, the control input vector $u_c$(t) must equate to the inverse dynamics law to give a set of decoupled linear first order responses. This control law is given by:

$$u_e(t) = g(sD + CB)^{-1}\Sigma\big(v(t) - y(t)\big) \tag{10}$$

$$u_{trim}(t) = u(t) - (\boldsymbol{CB})^{-1}\dot{y}(t) \tag{11}$$

such that:

$$u_c(t) = u_e(t) + u_{trim}(t) \tag{12}$$

and where $\Sigma = diag\{\sigma_1, \sigma_2, \ldots .\sigma_m\}$ (13)

The response of the closed-loop system for the output vector y(t) in equation (1) is two first order closed-loop system responses given by:

$for\ i = 1\ to\ m$

$$y_i(t) = (1 - e^{-g\sigma_i t})v_i(t) \tag{14}$$

Under these conditions and as $t \to \infty$ then $y_i(t) \to v_i(t)$. The resulting response tracks with zero steady state error, thus the RIDE method allows implementation of an ideal control and hence generates a benchmark against which realistic controls can be designed and tested. In many instances as was proven in this case, a high enough gain value g can be achieved such that $u_e(t) \gg u_{trim}(t)$, and is such a case then the control law for inverse dynamics can be approximated by equation (10) only! This equation only requires knowledge of the C and B matrices, not any other matrix values. It however, must be invertible and also the system transmission zeros must also be in stable locations (i.e. have negative real parts) [106]. The Transmission Zeros are given by:

$$TZ: \quad \begin{vmatrix} sI_n - A & -B \\ C & D \end{vmatrix} = 0 \tag{15}$$

By substituting the matrices from (6) into equation (15) it is shown that there is one transmission zero (TZ). By simple row and column elimination it can be shown that this TZ is given by:

$$\begin{vmatrix} sI_n - \begin{bmatrix} \frac{-\dot{m}_w c_w\, Uo - U_p A_p}{\tau_w} & \frac{\dot{m}_w c_w\, Uo}{\tau_w} & \frac{K_{QCHP}(1 - Uo)}{\tau_w} \\ \frac{\dot{m}_w c_w\, Uo}{\tau_{st}} & \frac{-\dot{m}_w c_w\, Uo - U_s A_s}{\tau_{st}} & \frac{K_{QCHP}\, Uo}{\tau_{st}} \\ 0 & 0 & \frac{-1}{\tau_{CHP}} \end{bmatrix} & - \begin{bmatrix} \frac{-\dot{Q}_{CHPO} + \dot{m}_w c_w \Delta TO}{\tau_w} & 0 \\ \frac{\dot{Q}_{CHPO} - \dot{m}_w c_w \Delta TO}{\tau_{st}} & 0 \\ 0 & \frac{1}{\tau_E} \end{bmatrix} \\ \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & -K_{PCHP} \end{bmatrix} & \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix} \end{vmatrix} = 0 \quad (16)$$

$$\text{TZ: } s = 0 \quad (17)$$

The transmission zero is at the origin, which is marginally stable and also can prevent perfect tracking of the desired set point v(t). It is impossible to remove this zero as it is an inherent dynamic characteristic of the system as a whole.

### 4.4.2. Inverse Dynamics Controller with Stable Transmission Zero (TZ)

The transmission zero at the origin will prevent perfect tracking of the required output v(t) by the real system output y(t), it may also affect the stability of the system. The TZ of the closed-loop system at the origin ideally must be removed to enable tracking of the required imported national grid power. The chosen control vector u(t) is practical and desired, i.e. to control the CHP engine gas input and the net water flow to and from the thermal store as CB is invertible. The desired outputs y(t) of water network temperature and grid power demand or export are also ideal control variables for an energy efficient heating solution and a smart grid system topology. Thus, the control system would be the same, but a different approach to the controller design is required to prevent a TZ occurring at the origin. By inspecting the transient behaviour of the different modes of the system, it is observed that the CHP engine transient response can be considered to be fast when compared with the dynamics of the water network and thermal store. By invoking a model order reduction algorithm [18] which reduces the number of the states of the system by assuming that the engine is stable and relatively fast then the state variable $U_{CHP}(t)$ can be assumed to have reached its quasi-steady state value such that:

$$U_{CHP}(t) \equiv \ U_{Gas}(t) \tag{18}$$

To give a reduced set of linear time-invariant state-space and output equations:

$$\dot{x}_R(t) = A_R x_R(t) + \ B_R\, u_R(t) \ + E_R d_R(t) \tag{19}$$

$$y(t) = \ \ C_R\, x_R(t) + \ D_R\, u_R(t) \ + \ \ F_R\, d_R(t) \tag{20}$$

and the corresponding reduced order model matrices are

$$A_R = \begin{bmatrix} \dfrac{-\dot{m}_w c_w\, Uo - \ U_p A_p}{\tau_w} & \dfrac{\dot{m}_w c_w\, Uo}{\tau_w} \\ \dfrac{\dot{m}_w c_w\, Uo}{\tau_{st}} & \dfrac{-\dot{m}_w c_w\, Uo - U_s A_s}{\tau_{st}} \end{bmatrix}$$

$$B_R = \begin{bmatrix} \frac{-\dot{Q}_{CHPO} + \dot{m}_w c_w \Delta TO}{\tau_w} & \frac{K_{QCHP}(1 - Uo)}{\tau_w} \\ \frac{\dot{Q}_{CHPO} - \dot{m}_w c_w \Delta TO}{\tau_{st}} & \frac{K_{QCHP}\, Uo}{\tau_{st}} \end{bmatrix}$$

$$E_R = \begin{bmatrix} U_p A_p/\tau_w & -1/\tau_w & 1/\tau_w & 0 & 0 & 0 \\ 0 & 0 & 0 & U_s A_s/\tau_{st} & 0 & 0 \end{bmatrix}$$

$$C_R = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}$$

$$D_R = \begin{bmatrix} 0 & 0 \\ 0 & -K_{PCHP} \end{bmatrix}$$

and $$F_R = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & 1 \end{bmatrix} \tag{21}$$

Thus, for this new reduced order model the inverse dynamics control law given by equation (26) where in this new case $C = C_R$ , $B = B_R$ $and$ $D = D_R$ is

$$u_c(t) = g \begin{bmatrix} \frac{-\dot{Q}_{CHPO} + \dot{m}_w c_w \Delta TO}{\tau_w} & \frac{K_{QCHP}(1 - Uo)}{\tau_w} \\ 0 & -sK_{PCHP} \end{bmatrix}^{-1} \big(v(t) - y(t)\big) \tag{22}$$

In the new reduced order model case the TZ are derived using (23) such that:

$$\left| \begin{matrix} sI_n - \begin{bmatrix} \frac{-\dot{m}_w c_w\, Uo - U_p A_p}{\tau_w} & \frac{\dot{m}_w c_w\, Uo}{\tau_w} \\ \frac{\dot{m}_w c_w\, Uo}{\tau_{st}} & \frac{-\dot{m}_w c_w\, Uo - U_s A_s}{\tau_{st}} \end{bmatrix} & - \begin{bmatrix} \frac{-\dot{Q}_{CHPO} + \dot{m}_w c_w \Delta TO}{\tau_w} & \frac{K_{QCHP}(1 - Uo)}{\tau_w} \\ \frac{\dot{Q}_{CHPO} - \dot{m}_w c_w \Delta TO}{\tau_{st}} & \frac{K_{QCHP}\, Uo}{\tau_{st}} \end{bmatrix} \\ \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} & \begin{bmatrix} 0 & 0 \\ 0 & -K_{PCHP} \end{bmatrix} \end{matrix} \right| = 0$$

(23)

and the resulting transmission zero when $Uo \equiv 0$, is therefore given by

$$TZ: s = -\frac{U_S A_S}{m_{st} c_w} \tag{24}$$

Thus, since all the physical parameters contained in 24 are positive and real values, the transmission zero will have negative real parts and therefore a stable inverse of the system exists that will also guarantee tracking as $g \to \infty$. [111] The tuning of g depends on the speed of the neglected dynamics. In this case the speed of the engine. Ideally the closed-loop time constant given by 1/g should be at least 3 times slower than the neglected dynamics [106]. Thus,

$$g\Sigma < \frac{3}{\tau_E} I_m \tag{25}$$

There is a compromise between tight tracking control which requires a large g value and stability where can be assumed the engine is fast. In this case study a large enough g was attainable to prevent the need for robust control solutions such as Inverse Dynamic control as used in the full method [106]

## 4.5. CHPV System Operation Method

The control algorithm for the controllers in the CHPV system was designed using the Inverse Dynamic methodology [118] to create a robust independent controller for the CHPV system as shown in figure

(4.3). This controller tracks a desired power demand from the national grid (e.g. set to zero watts in this case) and a target heat network temperature set to 85ºC. In this case study simulations showed the CB matrix should be diagonal and invertible. For that it could be assumed that:

$$\begin{bmatrix} \frac{-\dot{Q}_{CHPO}+\dot{m}_w c_w \Delta TO}{\tau_w} & \frac{K_{QCHP}(1-Uo)}{\tau_w} \\ 0 & -sK_{PCHP} \end{bmatrix}^{-1} \approx \begin{bmatrix} \frac{-\dot{Q}_{CHPO}+\dot{m}_w c_w \Delta TO}{\tau_w} & 0 \\ 0 & -sK_{PCHP} \end{bmatrix}^{-1} \quad (26)$$

By assuming $\Delta TO = 10$ And $Uo = 0$ equation (26) gives:

$$\begin{bmatrix} \frac{-0.42*1800000+92}{300} & \frac{0.42*1}{300} \\ 0 & -s\,0.42 \end{bmatrix}^{-1} \approx \begin{bmatrix} \frac{-\dot{Q}_{CHPO}+\dot{m}_w c_w \Delta TO}{\tau_w} & 0 \\ 0 & -sK_{PCHP} \end{bmatrix}^{-1} \quad (27)$$

As equation (27) is dominantly diagonal then consequently, two primary single input single output (SISO) control systems can be robustly created to decouple heat and power feedback control loops in the CHPV system. These SISO tracking control systems were specified as follows:

a) A feedback control system that tracks desired national grid demand by regulating the gas power supplied to the CHP engine.
b) A feedback control system that tracks a set point of the average temperature of the heat network (e.g. 85°C) by regulating the target average temperature of the hot water tank thermal store.

c) A thermostat control for each building/zone to track the desired building temperature by regulating the heat delivered by the heat network to building/zone via its heat exchanger.

A secondary supplementary control operates the back-up gas boiler only when CHP heat output is at its maximum and the average water network temperature is below a set point of 80ºC. Whilst the controllers are non-interacting systems, they were designed using a multi-input multi-output controller Inverse Dynamic [118] [119]. The novel system controller topology has created a remarkable and simple solution to decouple the interaction between heat and power that exists with all CHP based solutions. The control also allows tracking of target set points in the presence of multiple heat [121] and power disturbances such as the power generated by on-site renewables such as PV. A MATLAB/Simulink model was developed to incorporated models of the three SISO control systems and supplementary boiler control to test this new electrically led CHP engine and the heat network control strategy. This strategy in addition to models mentioned also modelled the thermostatic control of the buildings by controlling the heat flow from the heat exchanger in the heat network to maintain the required thermal comfort temperature 21°C (including an optimum start and at night time set point of 12°C) and a chiller compressor for electrical cooling of the building when the building temperature exceeds 24°C. The controller of CHP engine follows the electrical demand of the building and at same time pumps the heat generated into the heat network. When the building has enough heat to maintain the thermal comfort requirements and the CHP has surplus heat, the controller directs the surplus of heat to the heat storage. In the case the CHP does not have enough heat and the building requires more heat to maintain comfort then the heat storage will pump heat back into the heat network. If the combined CHP and thermal store heat supplies still cannot provide enough heat, the gas boiler control operates to top up any heat supply deficit.

# Chapter Five
# Results

## 5.1. Introduction

This chapter shows how the local energy system works and how the controller can control both sides of the system: the electrical side and the heat energy system side minute by minute and second by second. However, the results of the data in this chapter belong to the **Copperas Hill Building Project (Liverpool John Moores University, Liverpool)** and the results obtained using MATLAB/Simulink modelling and simulation software. The other two cases studies (Green Bank student village and Media city in Manchester) are used for calibration and validation the MATLAB model and to be sure the control methodology can work in different criteria, conditions and any number of zones. The results however, in this chapter are divided into two scenarios to show the benefit and the advantages of using Local energy with CHPV system rather than using the ordinary method (using the national grid for electricity and the Gas boiler for heating) as show in the second scenario and how much the new system can save CO2 emission and running cost.

The two scenarios are:

**First scenario**: the local energy system is run by a CHP engine with photovoltaic arrays, heat storage, a gas boiler and electrical cooling system. This local energy system is controlled by the new control system. However, the results will show:

1- the controllability of the control system on the temperatures inside each zone independently. Which consists of three stages:
   - Control the zones temperatures without a gas boiler but with an electrical cooling system (published in [112]).
   - Control the zones temperatures with a gas boiler but without an electrical cooling system (published in [113]).
   - Control the zones temperatures with a gas boiler and with an electrical cooling system. This system is the subject of this thesis.

2- the controllability of the control system on electrical demand and how it responds second by second to variations in electrical demand.

3- The controllability of the control system on the CHP engine and amount of fuel injected inside it (depending on the electrical load), hot water network, heat storage, photovoltaics and gas boiler.

4- Show the amount of CO2 emissions within the local energy system and compare it to the national grid in terms of reduced emissions and economic benefits.

5- Finally, the efficiency of the local energy system over a full year- adapting to the four seasons.

**The second scenario:** the CHP engine and the heat storage turns off and runs the system solely by the national grid for electrical demand and a gas boiler for heat demand. This is achieved by the same system and the same controller which controls the temperature in the five zones, to give the same ambient temperature.

In other words, the same results are achieved with the same controller but in two different scenarios from two different sources of energy supply. Thereby, the use of the CHPV system yields economic benefits and reduced CO2 emissions.

Finally, the system increases reliability, as it uses the national grid as a secondary temporary source of energy in emergency scenarios or in any situation where the electrical demand is higher than the CHPV engine size.

For example, if the CHPV engine and heat storage turned off for any reason (maintenance, faults, fuel running out or natural disasters etc.) the controller will send a signal to import electrical energy from the national grid.

## 5.2. System Results with the First Scenario.

### 5.2.1. Zonal temperature and cascading control system.

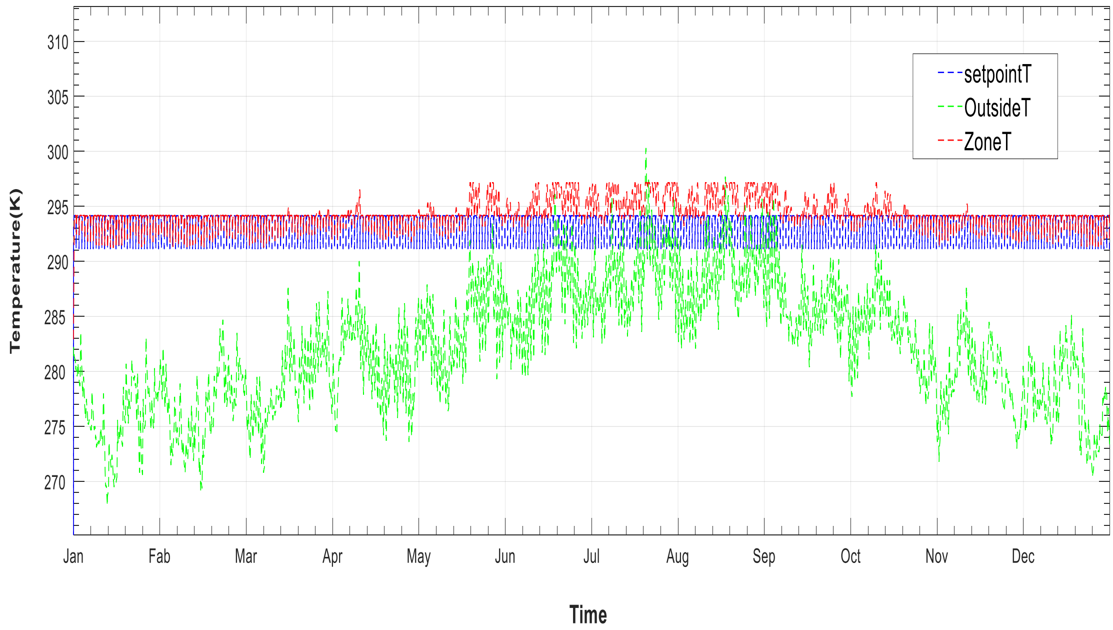
This section shows the temperatures inside each zone of the five zones and each figure has 3 colours. The Red Line is the temperature inside the zone, the Green Line is the temperature outside the zone during whole year (the weather temperature) and the Blue Line is the set point temperature of the zone. The temperature set points of the zones are:

- Heating set point 21°C in daytime and 18°C at night.
- Cooling set point is 24°C.

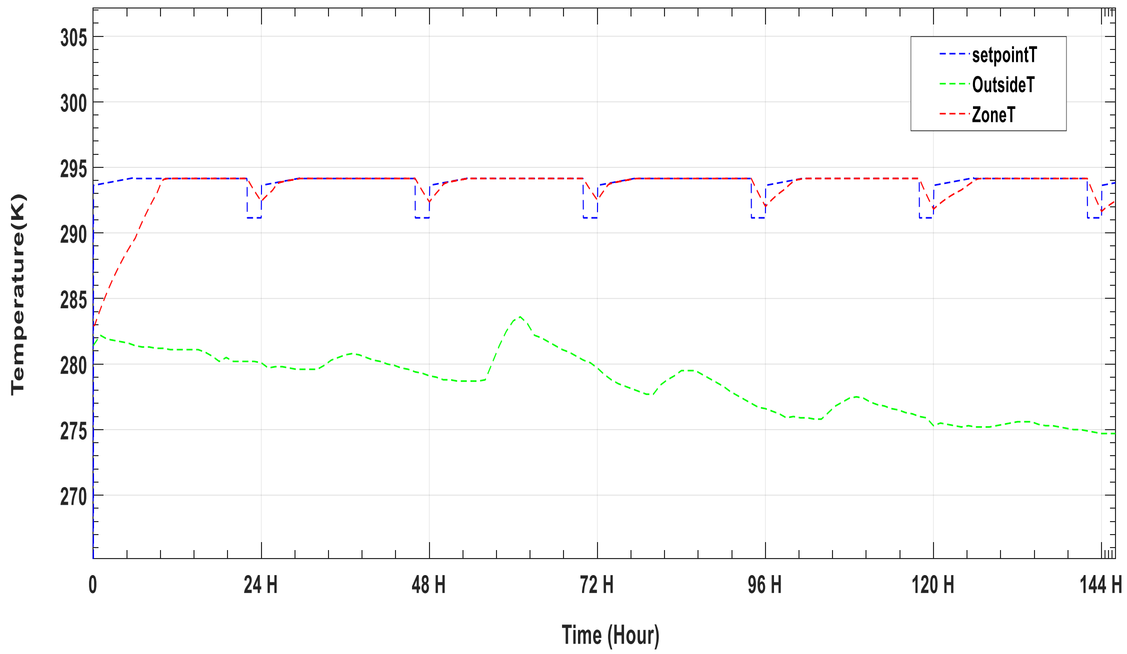
Figure [5.1] shows five zones and zooming of each zone for first 6 days of January of each zone to show how the controller can response to the load and the setpoint in very high accuracy way and also Figure [5.1] shows how the CHPV engine controller control the hot water network and the thermal storage control contributes to the temperature of each zone during the whole year. In the winter at the start of the simulation period (1 January) and end of period (31 December) each zone temperature shows some shortfall due to insufficient heat from the CHP engine and store. During these times, the zones require supplementary heating from the gas condensing boiler to achieve setpoint tracking. During spring autumn and summer months, Figure [5.1] shows the building temperatures follow the set point very accurately both in heating and cooling modes of operation. The second Figure of each zone shows the accuracy of the temperature (red) control tracking in the zone for 6 consecutive days in January. The set point (blue) moves up from 18°C to 21°C in the mornings using and pre-heat ramp in set point temperature. This ramp in desired temperatures is important for two reasons:

- To reduce the peak heat demand at the start of an occupancy period. This minimises the need for supplementary heating from the gas boiler.
- To create a useful and efficient use of heat during the un-occupied period to allow the CHP engine to generate electricity at a low electricity demand period whilst efficiently utilise the generated heat without the need for thermal storage.

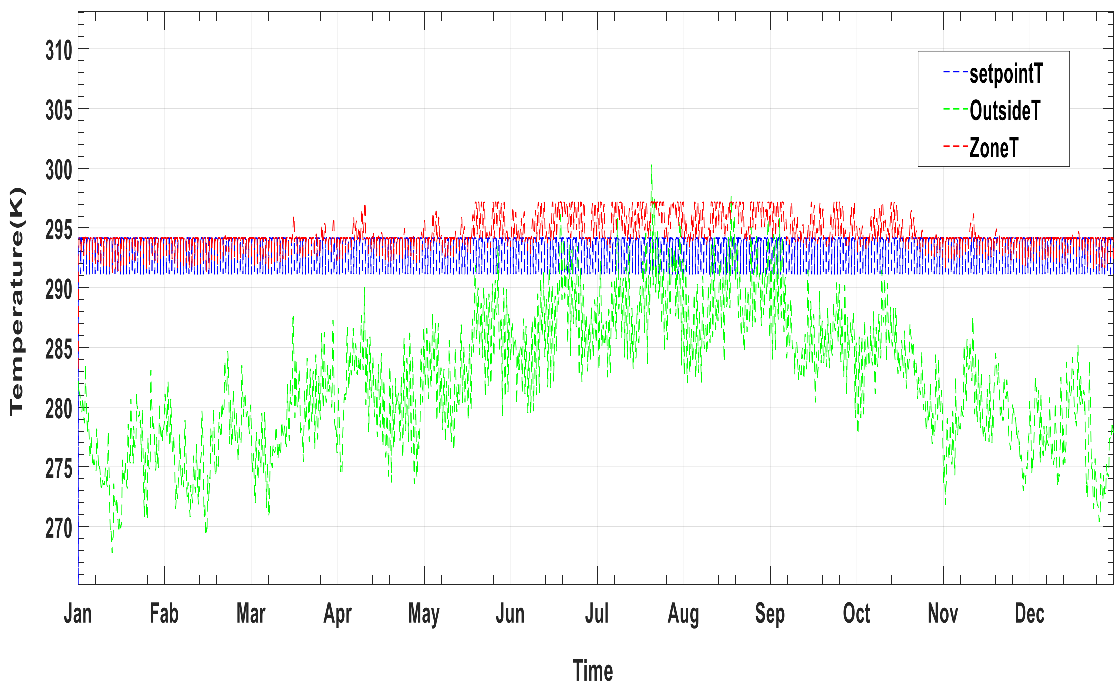
In order to achieve such accurate temperature control, the heat network temperature must also be accurately controlled despite many sources of heat disturbance and the dynamic nature of building heat demand. The heat network comprising CHP and gas supplies is thermostatically controlled by using the thermal store as an active load. For example, when the heat network temperature is too high, the boiler would be switched off first. If the network temperature is still high, the CHP engine heat is directed to the store. When it is too low, it is taken form the store (if there is available heat). If it is still too low, the gas boiler would supplement the supply. These conditions prevent gas boiler heat ever being stored. The minimum temperature in the heat storage has been set it as 50°C.



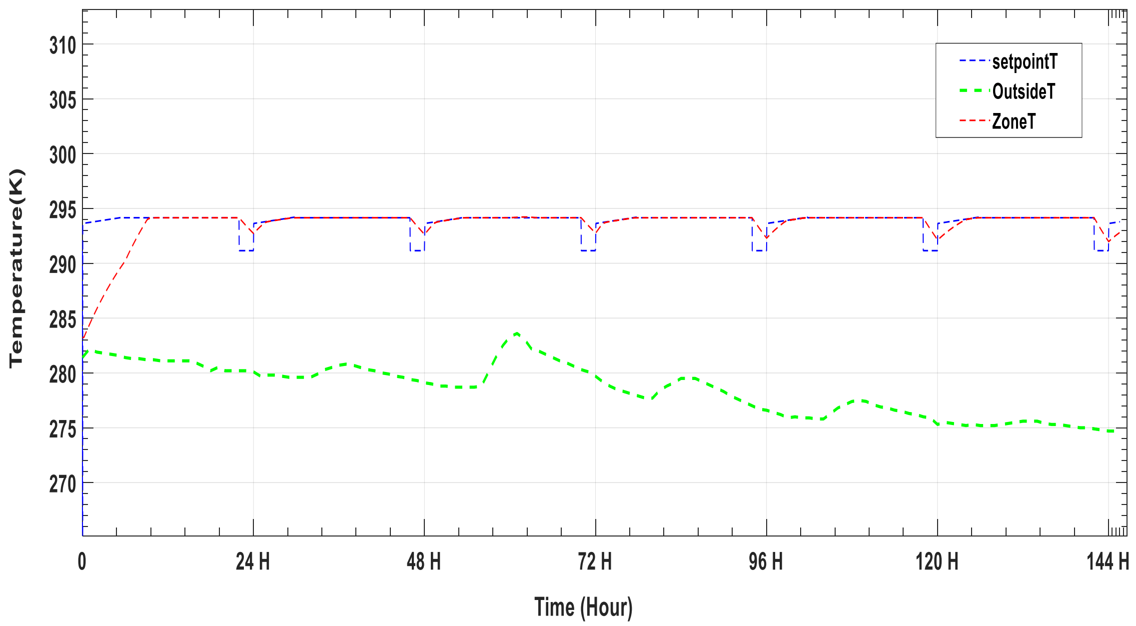

5.1.1A Zone 1 temperature for a full year



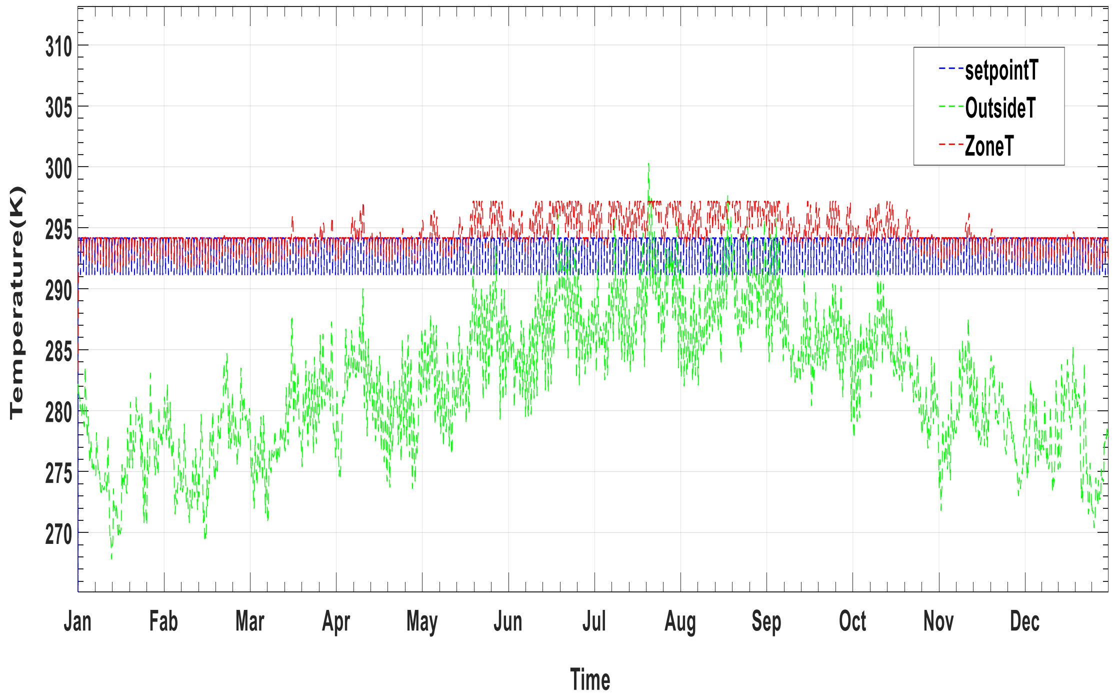

5.1.1B Zoom in Zone 1 temperature for first 6 days of January



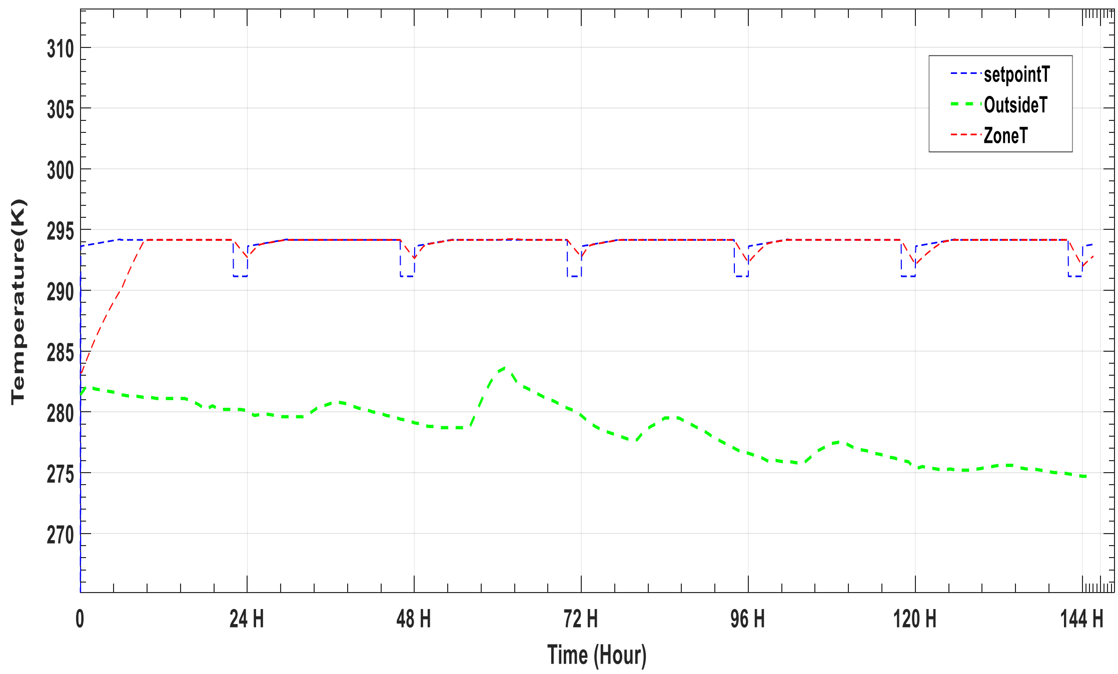

5.1.2A Zone 2 temperature for a full year



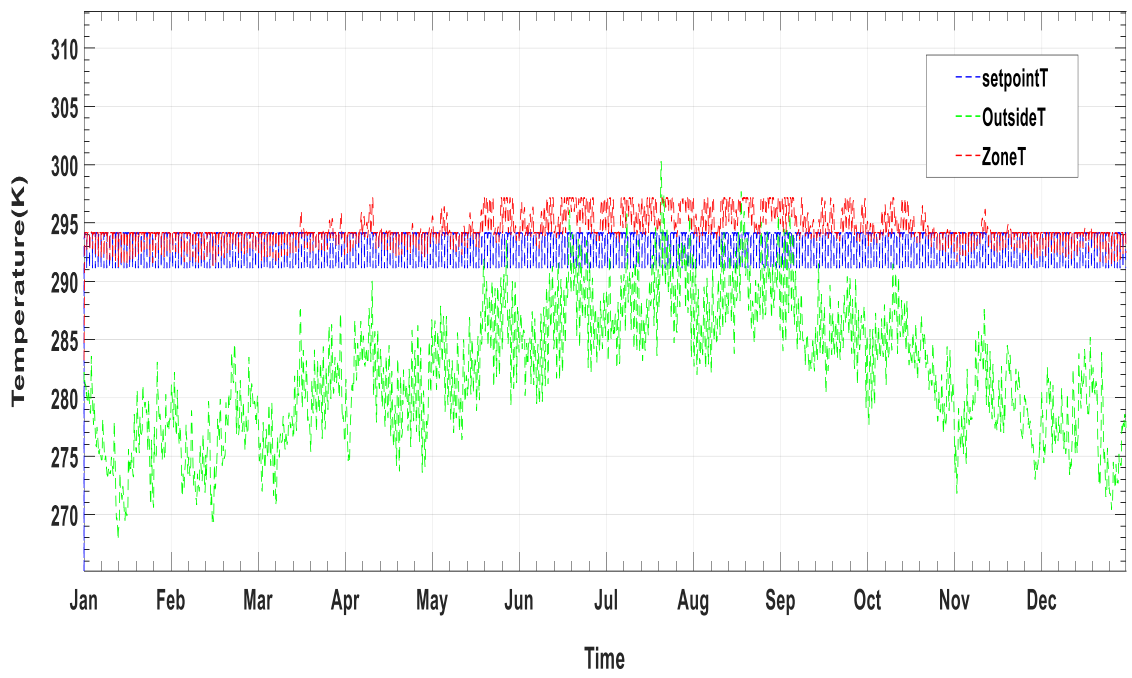

5.1.2B Zoom in Zone 2 temperature for first 6 days of January



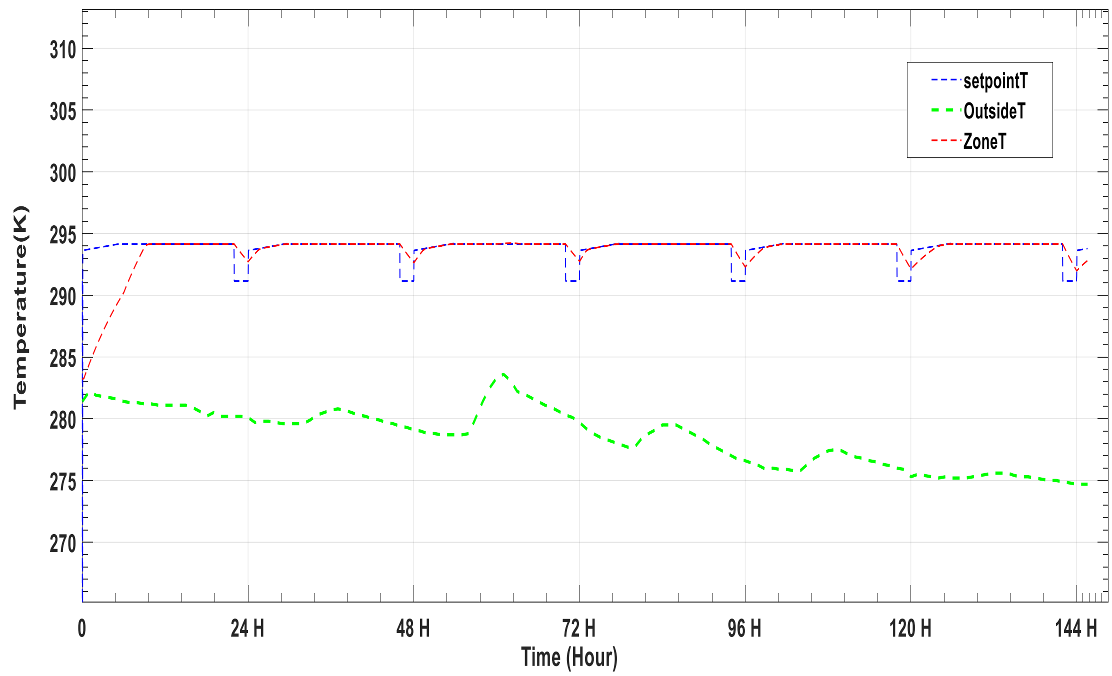

5.1.3A Zone 3 temperature for a full year



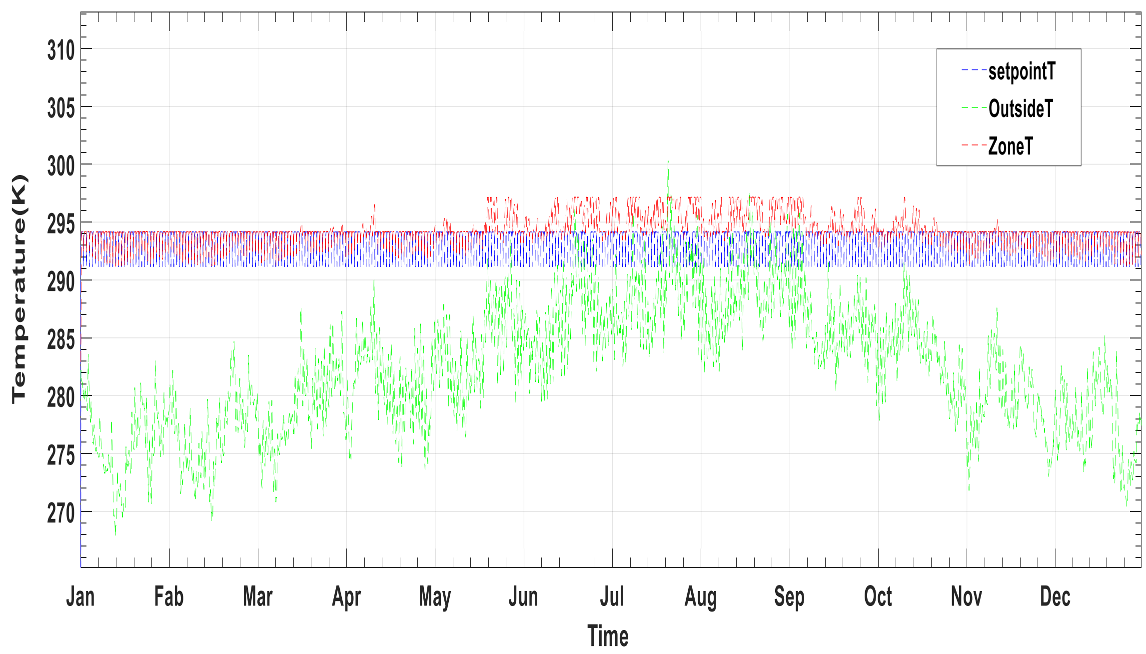

5.1.3B Zoom in Zone 3 temperature for first 6 days of January



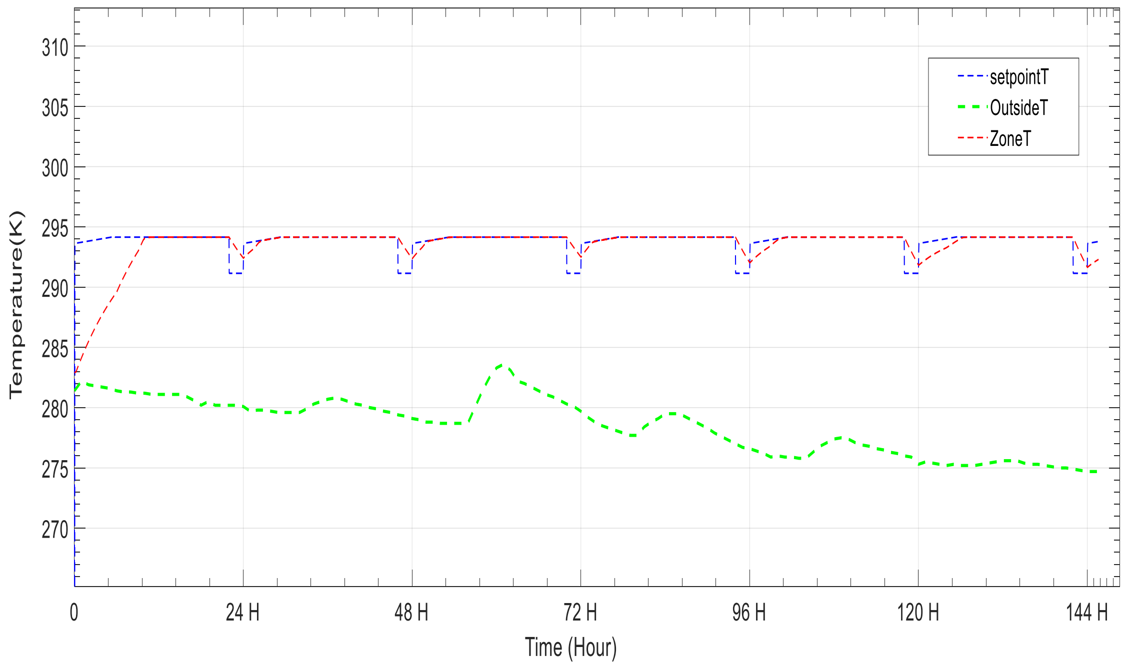

5.1.4A Zone 4 temperature for a full year




5.1.4B Zoom in Zone 4 temperature for first 6 days of January




5.1.5A Zone 5 temperature for a full year




5.1.5B Zoom in Zone 5 temperature for first 6 days of January

Figure 5.1 Five Zones Temperature for a full Year and zoomed in for the first 6 Days of January

## 5.2.2. Heating System

The heating system include amount of heat generated by the CHP engine, thermal store to save excess heat from the heat generated by the CHP engine, gas boiler to supply heat energy to the hot water network when the CHP engine shortage and there is no heat in heat storage. and the hot water network to join the system zones to the heating system.

The controller follows the electrical demand for that the capacity of CHP engine depending on the electrical load but in same time the controller controls the heat flow from CHP engine. However, the heat generated by the CHP engine pump to the hot water network till reach the hot water network reach the set point (90°C) as figures [5.6 & 5.7] are showing. While if the heat generated by CHP engine is not enough the control will send signal to the heat storage to pump heat to the hot water network if their available heat. If not, the control will send a signal to the gas boiler to turn on and supply heat energy to the hot water network till reach the set point. The figure [5.2] is shows amount the heat energy generated by the CHP engine during the year and its show amount the heat during the weekend reduced to less than half because there are no students in the university during the weekend and amount the electrical load decreased which lead to reduce amount the heat energy.

The Figure [5.3] shows the temperature inside the thermal store during full year and it is shows there is no CHP supplied heat in heat storage in cold time of year, whilst at the warmer periods it stores the surplus heat as seen by rise in the average temperature of the store. By summer time if the CHP engine is required to run to supply electricity, the store reaches its maximum temperature of 90°C. In Figure [5.4 & 5.5] the control signal (Red) for the heat storage system is shown for 6 days in January while the control signal [Blue] is shown for full year since 1st of January till 31st of December. The range of the storage control signal is between (-100% to 100%), the positive signal mean storing the heat inside the storage while the negative signal mean pumping the heat outside the storage to the hot water network. However, they are show the control of the heat store modulating during the day to keep a steady heat network temperature and the store being drained of heat during the night when the CHP engine heat generated is very low. In same time, Figures [5.8 & 5.9] are showing amount the heat energy generated by gas boiler to full the shortage of heat during the time of no enough heat in the system specially during the cold time and week days.

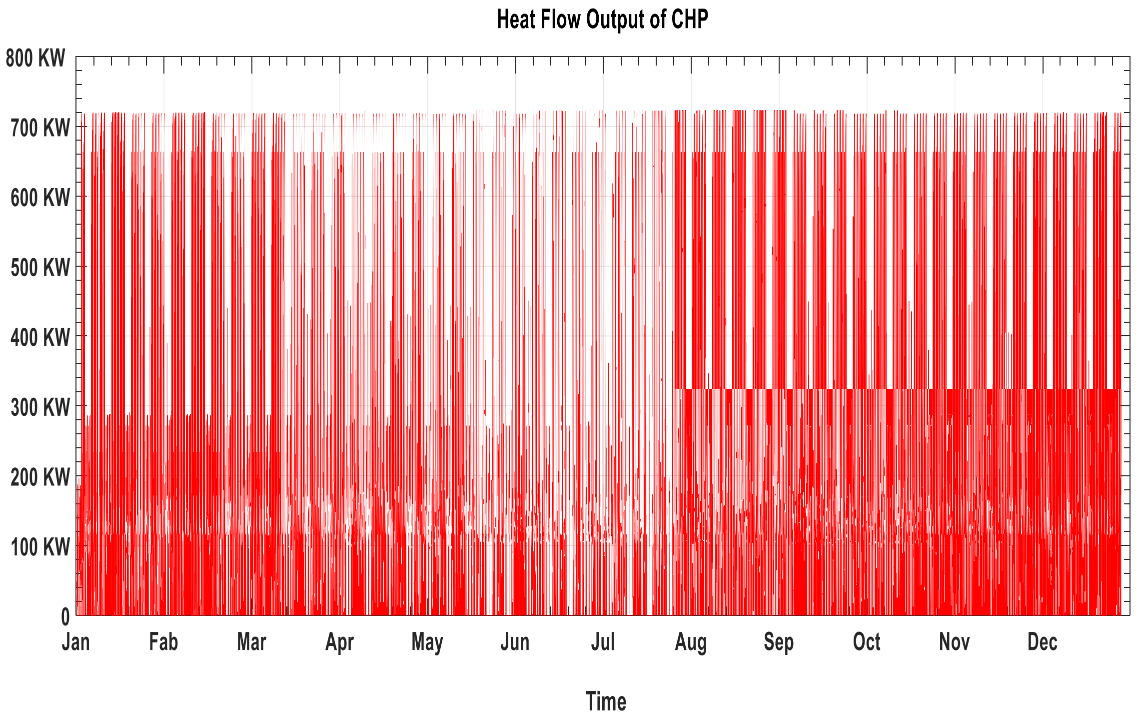



Figure 5.2 Amount of Heat Generated by the CHP Engine During the year

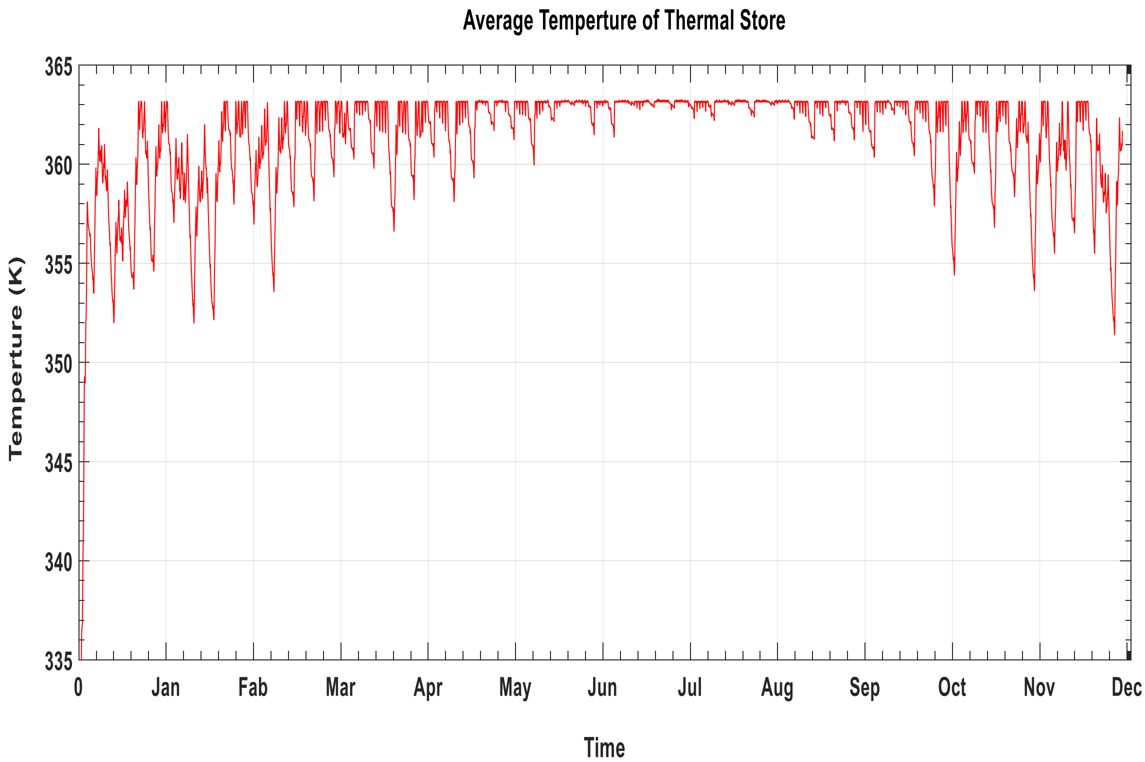



Figure 5.3 Average Temperature of thermal store During the year

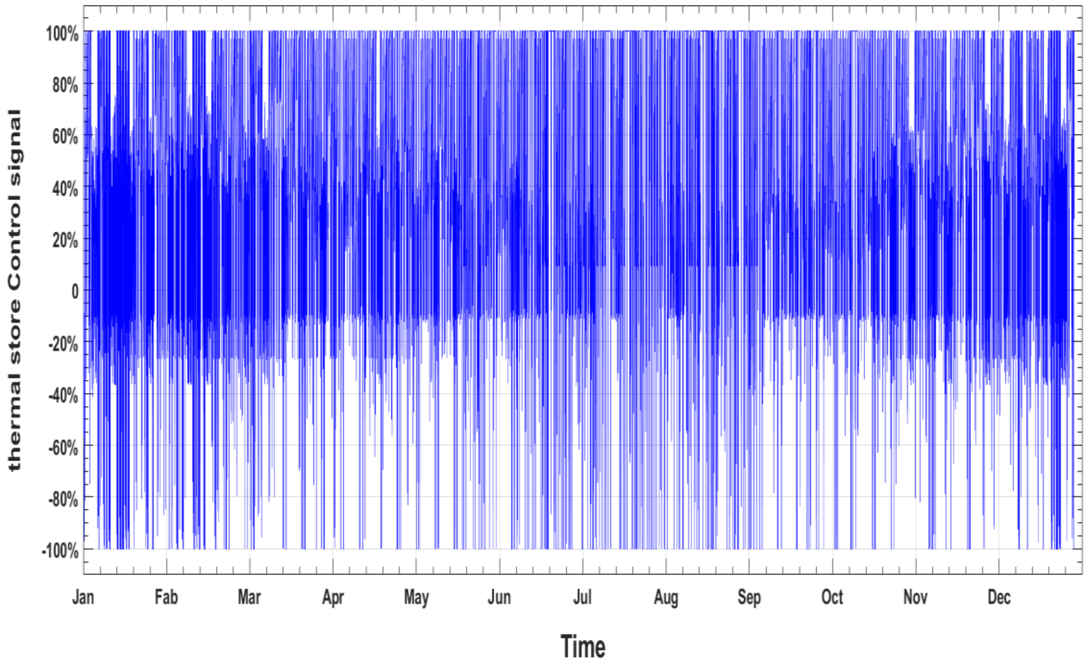



Figure 5.4 control signal of thermal store during the year

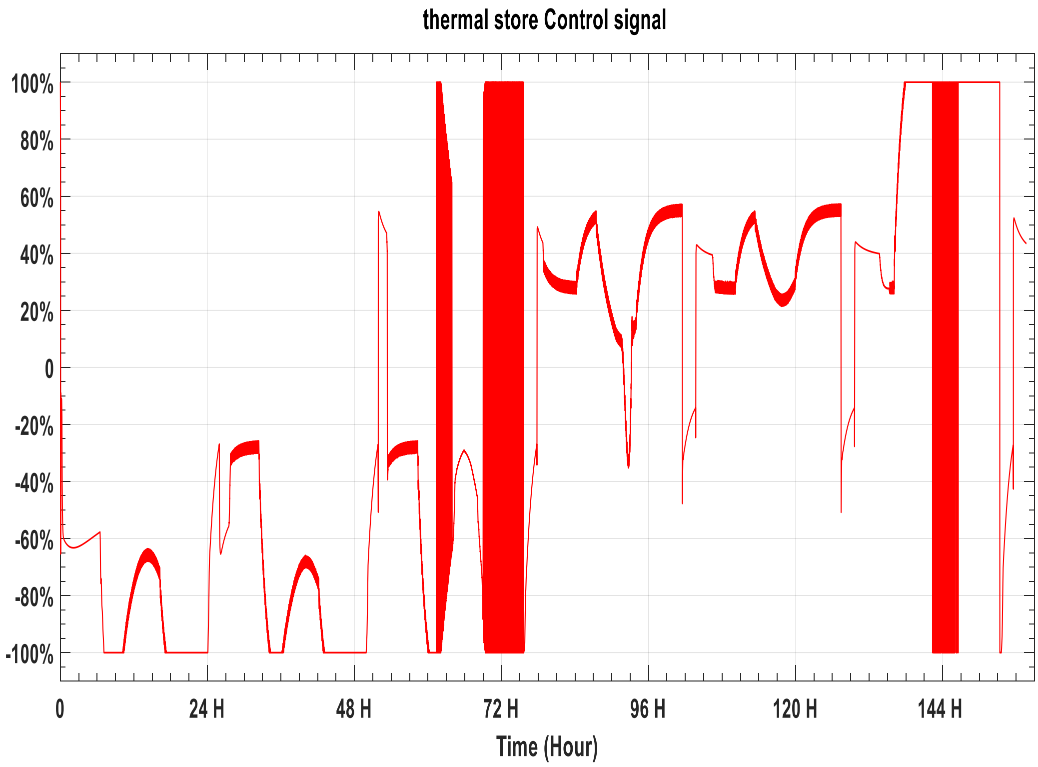



Figure 5.5 Zoom in control signal of thermal store for first 6 Days of January

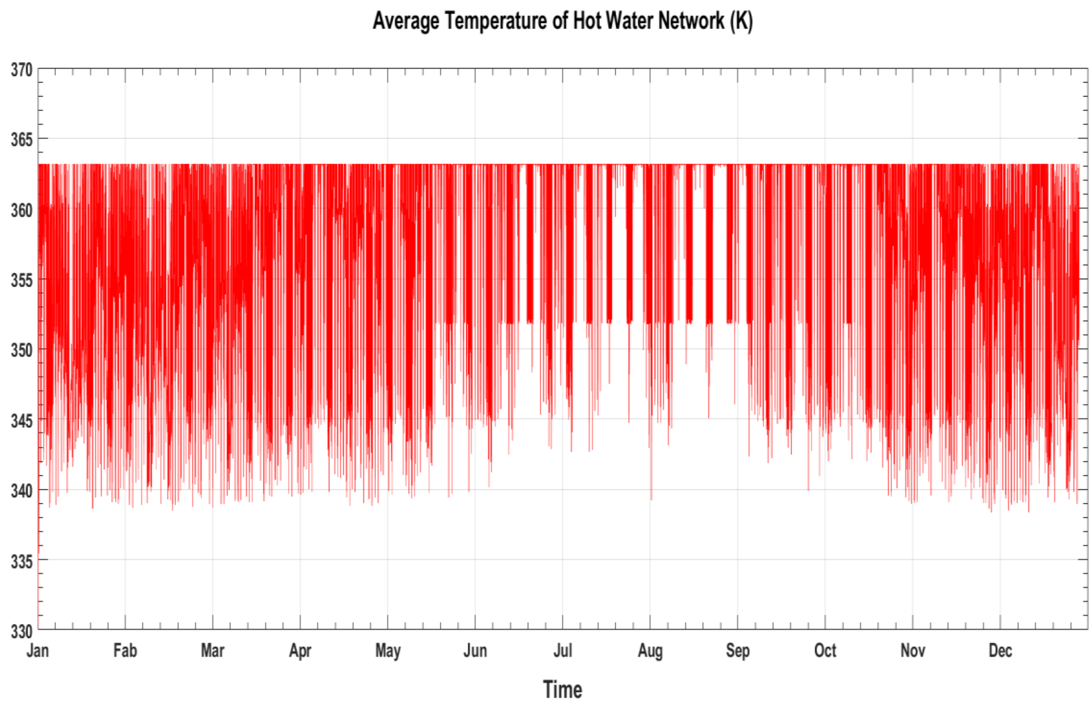



Figure 5.6 Average Temperature of Hot Water Network during the year

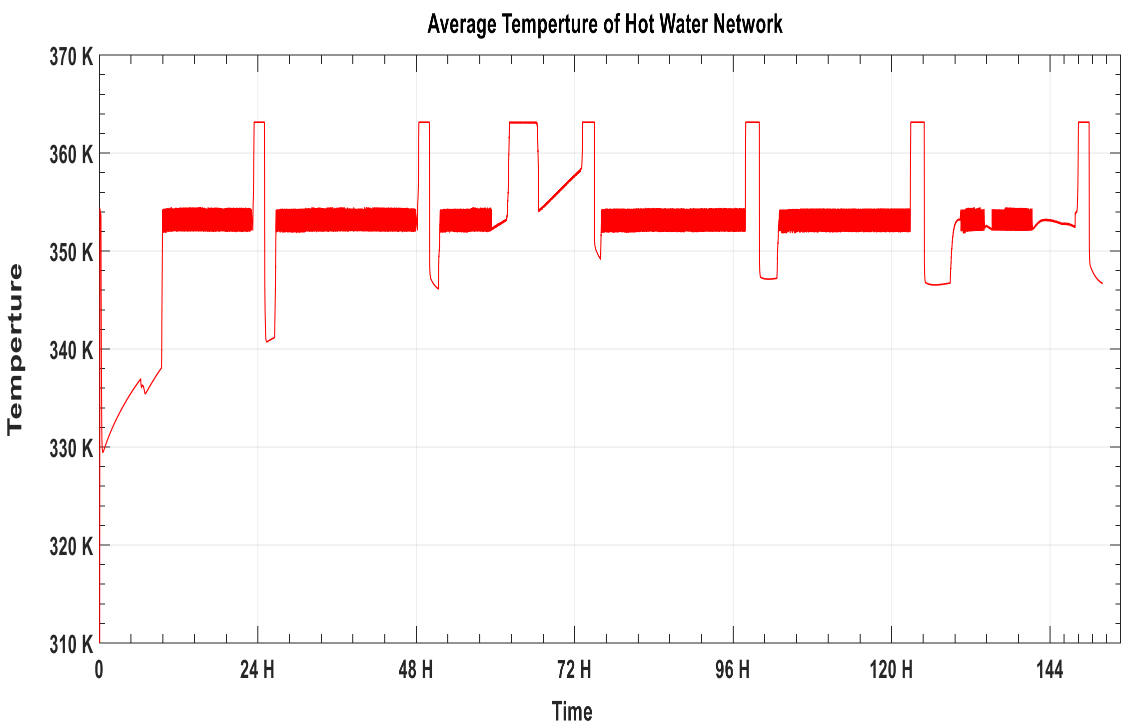



Figure 5.7 Zoom in the Average Temperature of Hot Water Network for first 6 Days of January

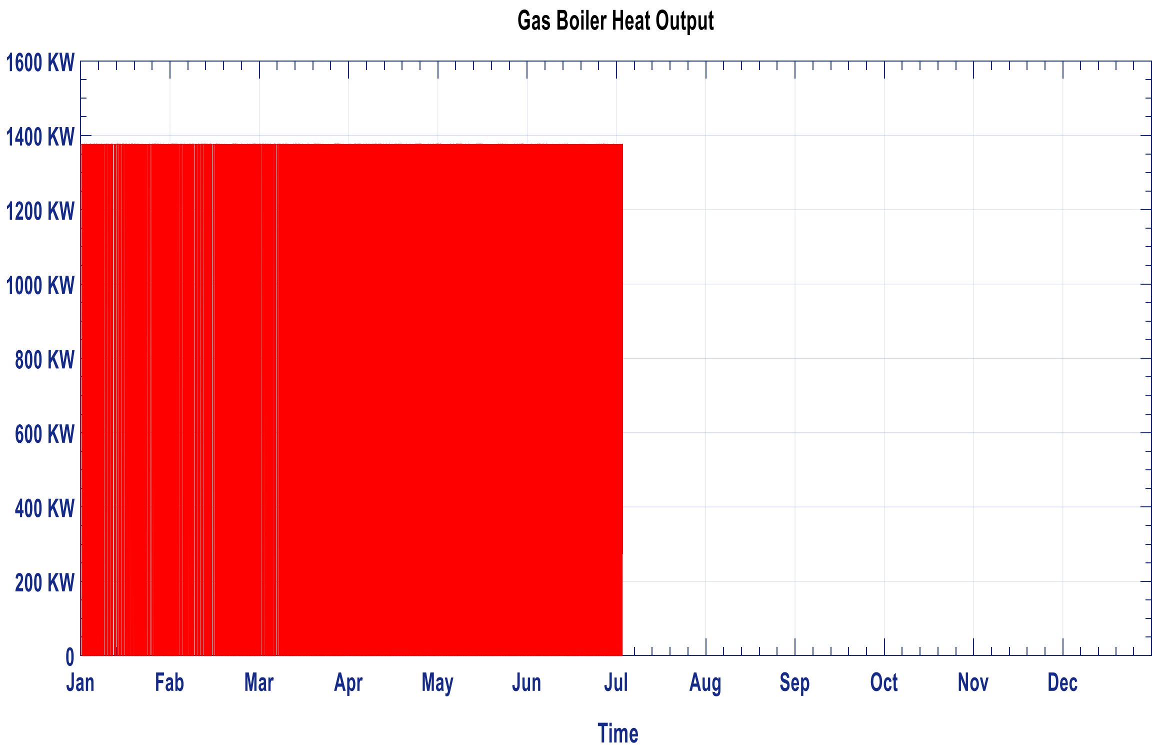



Figure 5.8 Amount of Heat Energy produced by the Gas Boiler during the year

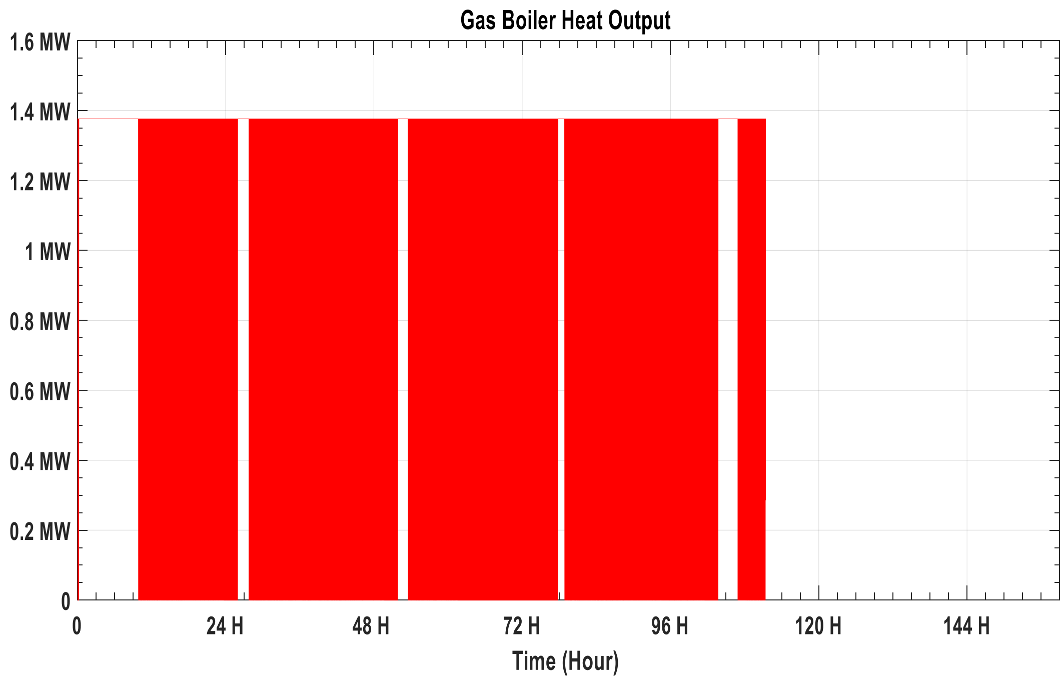



Figure 5.9 Zoom in Amount of Heat Energy produced for first 6 Days of January

## 5.2.3. Local Electrical Grid (LEG):

It is wires network connecting all the local system between each other and with the electrical sources. The local electrical grid has three electrical sources:

- Electricity generated by Photovoltaics arrays.
- Electricity generated by CHP engine.
- The National Gird as emergency electrical source.

Within its operational range, the CHP engine is controlled to drive the local grid power demand to be equal to zero at all times (as the set point) and it is tracking the electrical demand second by second which is mean no exporting and no importing. This means the CHP generated power must follow the system electrical (LEG) demand as figure [5.10] show.

But also figure [5.10] shows in the (blue) signal of actual local grid power there are some small spike varying between (-15 & +15) KW for few second before the signal get stable to the zero. This problem caused by the CHP engine because there is no CHP engine fast enough to response to the controller signal. which the controller is responding to the demands second by second.

Initially, all amount of electrical power generated by PV supply to the system firstly and the remain of electrical demand supply by the CHP engine (i.e. system electrical demand minus any demand side generation e.g. from PV) second by second.

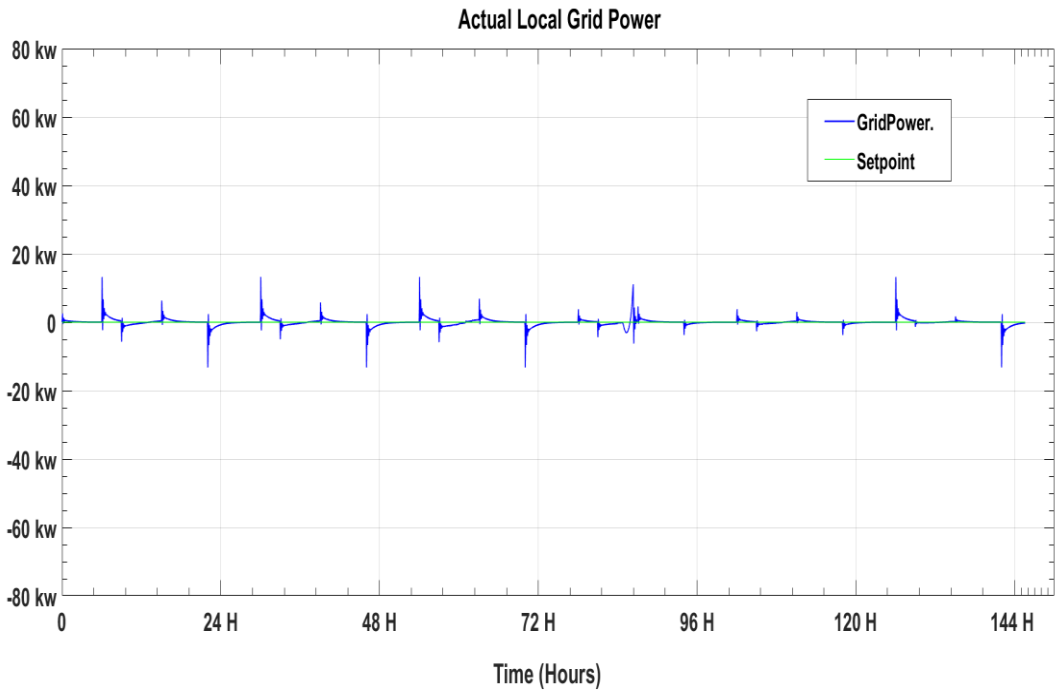



Figure 5.10 Local Electrical Grid Demand for first 6 days in January

The figure [5.11] shows the Photovoltaic generation during a full year since 1st of January till 31st of December and it is also show the highest electrical power generation and the most befit of PV arrays during summer season. Which can reach 1200 KW per day and this amount of enough to supply all the system electricity demand and led to turn off the CHP engine for few hours.

The total PV arrays area used in the system is 9750 $m^2$ and the total cumulative PV energy generated during the year is 1072800 KWH per year as figure [5.12] shows.

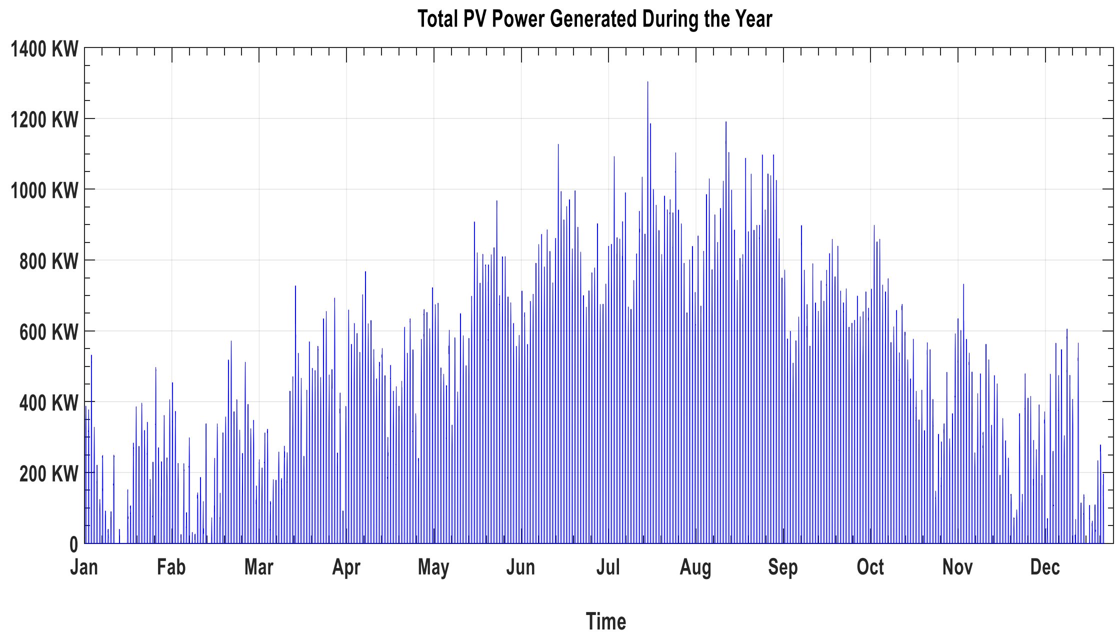



Figure 5.11 PV power generated During the Year

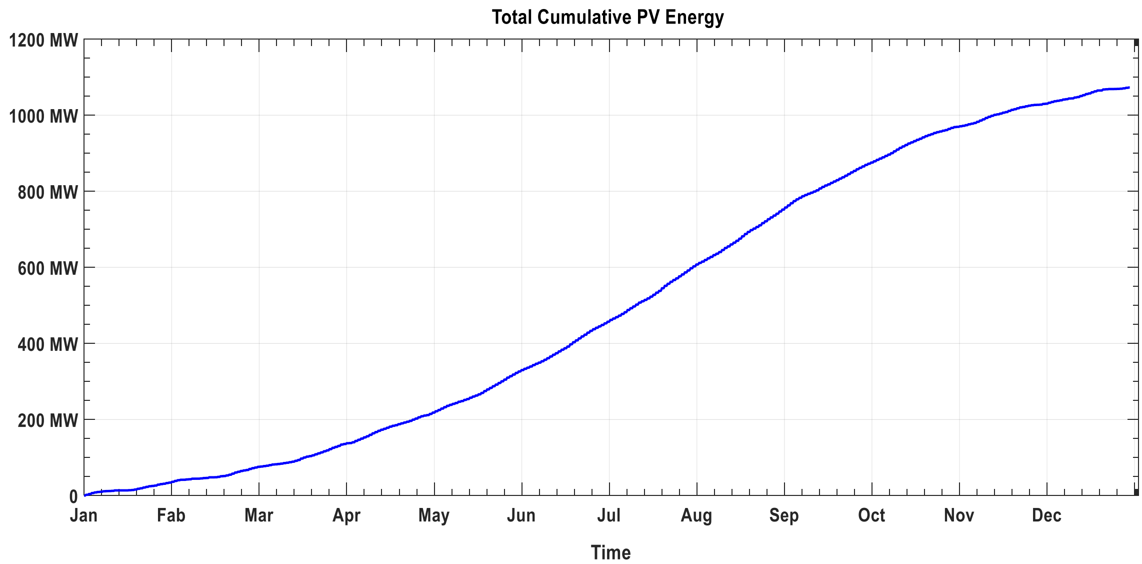



Figure 5.12 Cumulative Total PV Energy generated During the Year

The figures [5.13 & 5.14] show the CHP control signal for a year and it is zoom in for first 6 day of January. They are shows the control signal (blue) of the CHP engine to follow the local electric grid system demand after cutting out the demand supplied by the PV generation. As same as for the 6-day period in January figure [5.14], highlighting the control system reacting to the injection of PV power generation with the dips in control action during the occupied periods both on weekdays and weekends. And also, it is shows the CHP engine turned off about two hours during the day time of weekend as no much electrical demand (no students attending) and the amount of electrical energy generated by the PV arrays meet the electrical demand but the CHP engine turn on again when the system required more electrical energy.

however, the capacity of CHP engine changing depending on electrical local grid load.

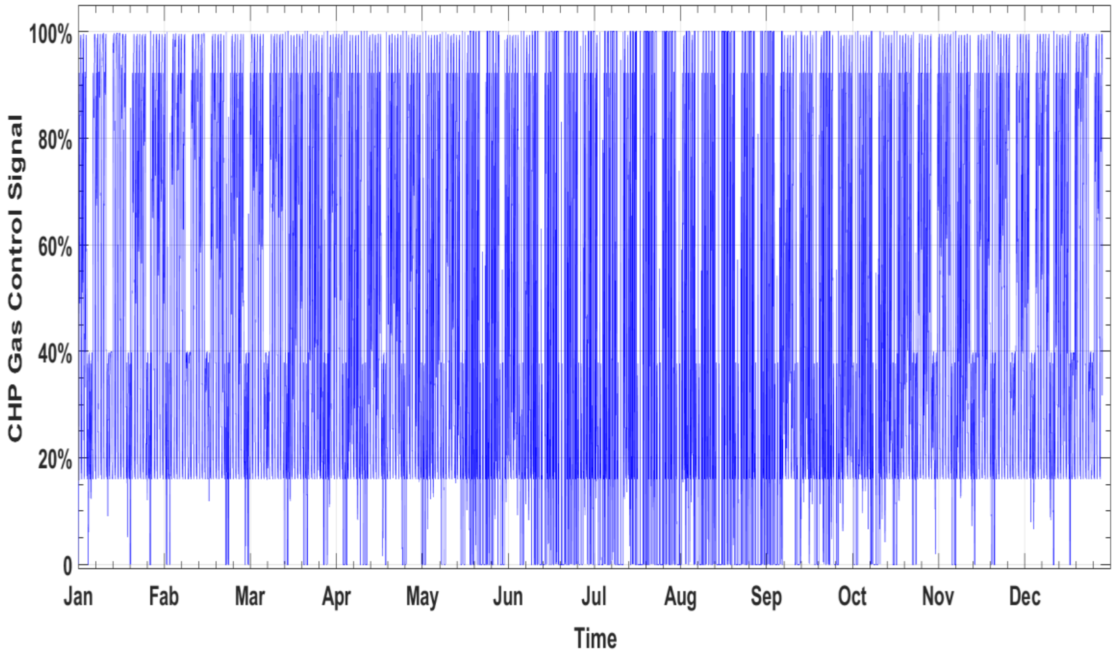



Figure 5.13 control signal of CHP Gas during the year

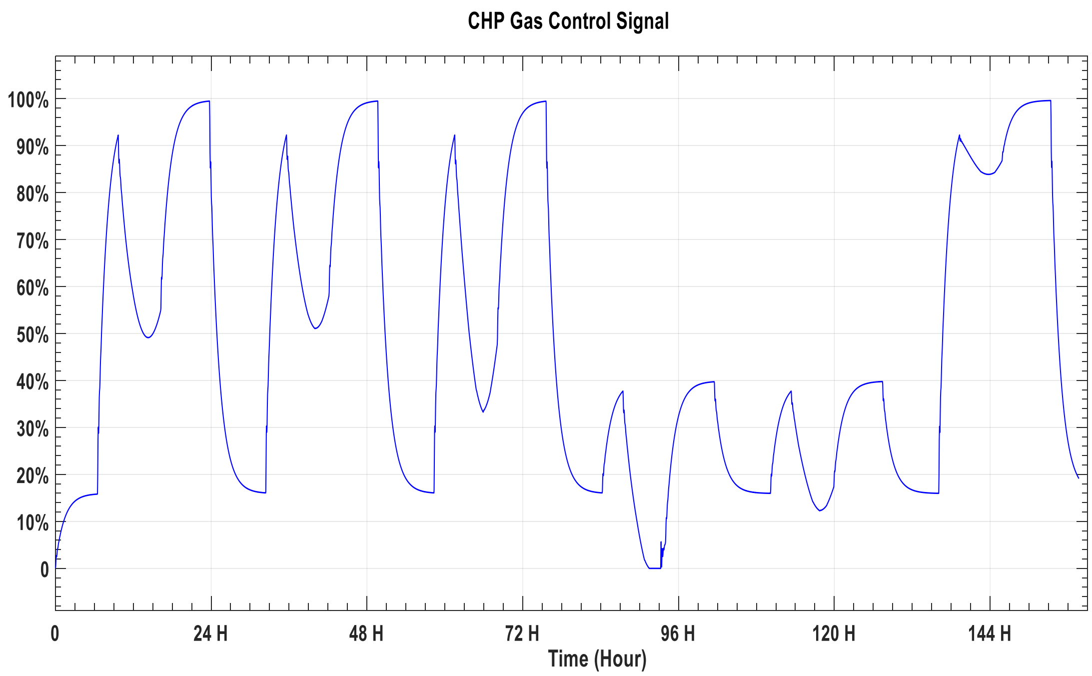



Figure 5.14 Zoom in control signal of CHP Gas for first 6 Days of January

Finally, the Local Electrical Grid (LEG) connecting with national grid for emergency issue as the fault in the CHP engine or for CHP engine maintenance or in case the system electrical demand increased more than the CHP engine capacity for any reason, in that cases the controller will import electrical energy from the national grid the second scenario will show.

### 5.2.4. CO2 Emissions and the Total System Efficiency:

System efficiency is one of very important side of any local energy system because efficiency is mean reduce amount of the gas used, energy losses, CO2 emissions and economic costs. The figure [5.15] shows the cumulative efficiency of the total efficiency for the local energy system as it varies throughout the year, in deep winter the efficiency reaches to the highest level at 78% when almost all of the generated CHP heat is utilised to heat the five zones. While the efficiency droop in summer season to 68% because most of heat dumped as not required after the heat storage filled with the heat. while the efficiency increased again in October when the cold weather starts again. However, the resulting end-of-year efficiency taking into account the warmer months reduces to 70.51%.

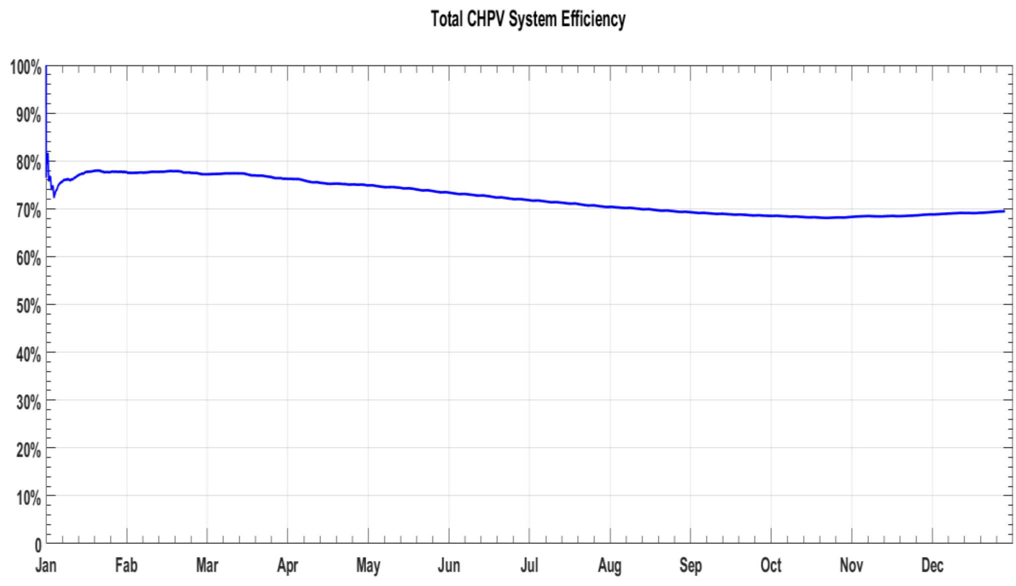



Figure 5.15 Total Efficiency of Local Energy System

CO2 emission is one of the mean reason for globule Green House problem. For that the main goal for UK government is reduce the emission to the lowest level by 2020.

The accumulation local energy system CO2 emissions during the year is 1873.600 Tonne during a full year as figure [5.16] shows. And amount of gas energy used during the year for CHP engine and gas boiler is 10.128*$10^6$ KWH per year.

When comparing the total Local Energy System emission with national grid emission for same amount of energy consumption as figure [5.17] shows the Local system reducing about 28% during the cold weather (when the gas boiler turns on) and about 38% during the hot weather (the gas boiler off and usage maximum amount of PV energy).

**NOTE:** figure [5.17] compare the local energy system emission of CO2 per kwh for gas used for both CHP engine and gas boiler all together VS same amount of electrical energy should supply to the same local energy for **electrical demand only per** year without calculating amount of CO2 emission generated for heating the same local energy system as the second scenario will show.

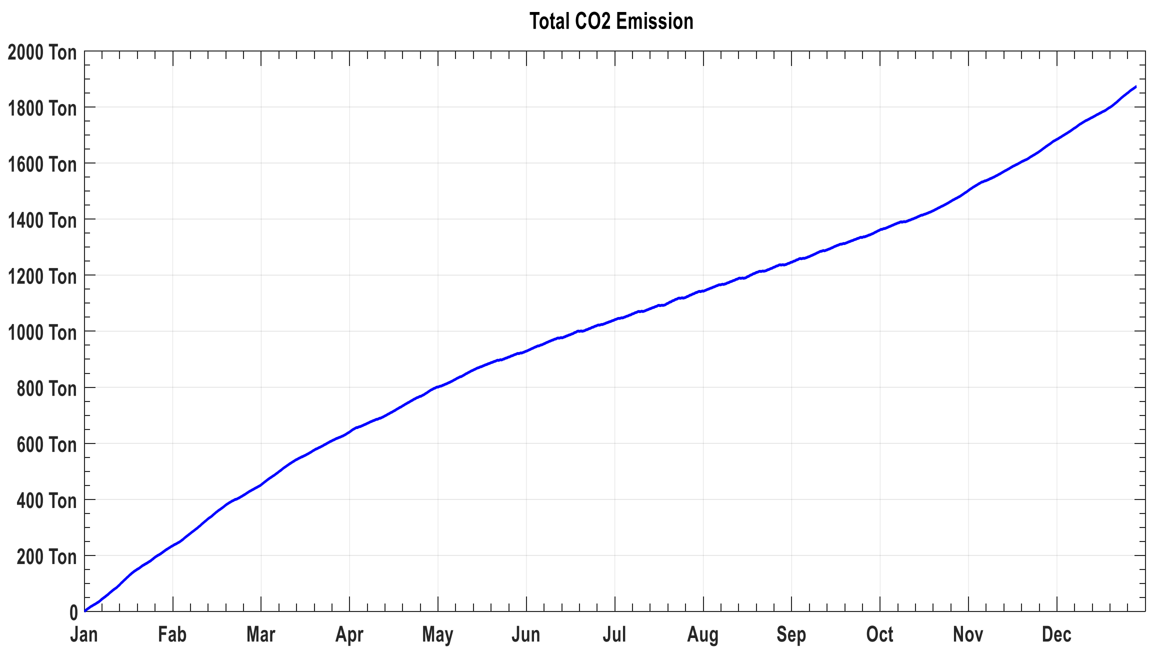



Figure 5.16 Total System CO2 Emission

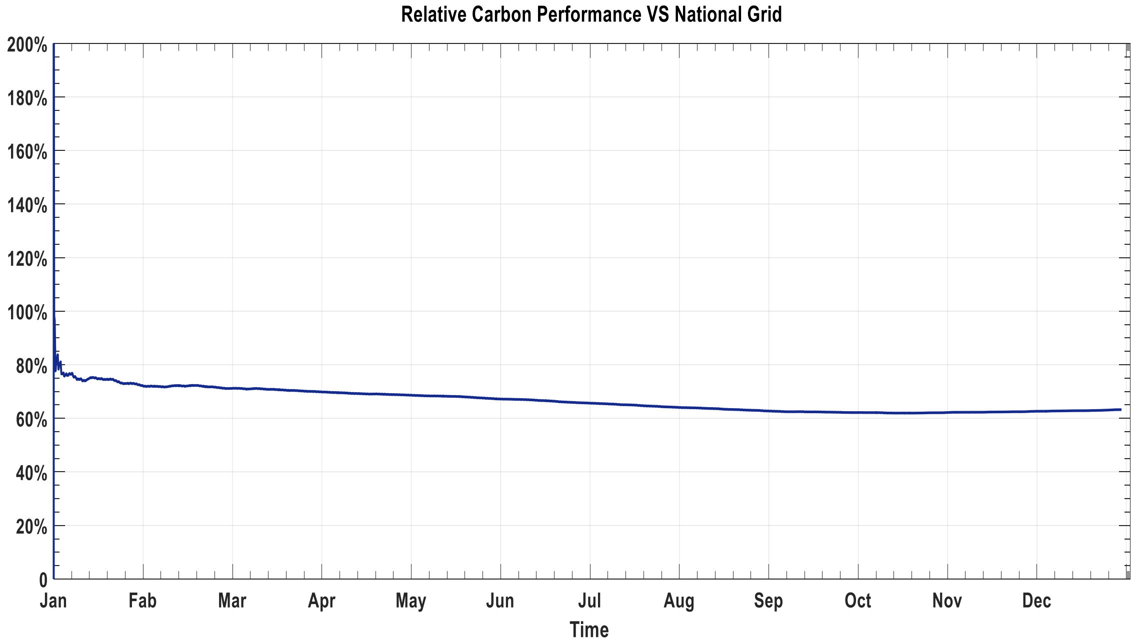



Figure 5.17 CHPV Carbon Emission Performance VS national grid

## 5.3. local energy System Results with second Scenario:

In this scenario, the CHP engine and heat storage are turn off. As assuming they are turn off for any reason (maintenance, CHP engine Fault, …. etc) to show how the system and the controller will react.

this scenario aiming to show two important points

- The reliability of the Local Energy System when the CHP engine shutting down.
- Amount of CO2 emission when the Local Energy System running by the national grid and a gas boiler to give same results of the CHPV system.

However, when the CHPV system and heat storage shutting down the controller have allowed to import the electricity from the national grid immediately to keep supply the electrical demand while the controller will use all the heat energy by gas boiler to supply the heat demand but the gas boiler should be big enough to meet the heat demand to keep the zones comfortable to residences.

### 5.3.1. Zones temperatures:

In this section, the figure [5.18] illustrate the temperatures inside each zone of the five zones and each figure has 3 colours just exactly like figure [5.1] but in this time the suppliers are the gas boiler only to meet heat demands and the national grid for electrical cooler. The Red Line is the temperature inside the zone, Green Line is the temperature outside the zone during whole year (the weather temperature) and the Blue Line is the set point temperature of the zone. The temperature set points of the zones are:

- Heating set point 21°C in daytime and 18°C at night.
- Cooling set point is 24°C.

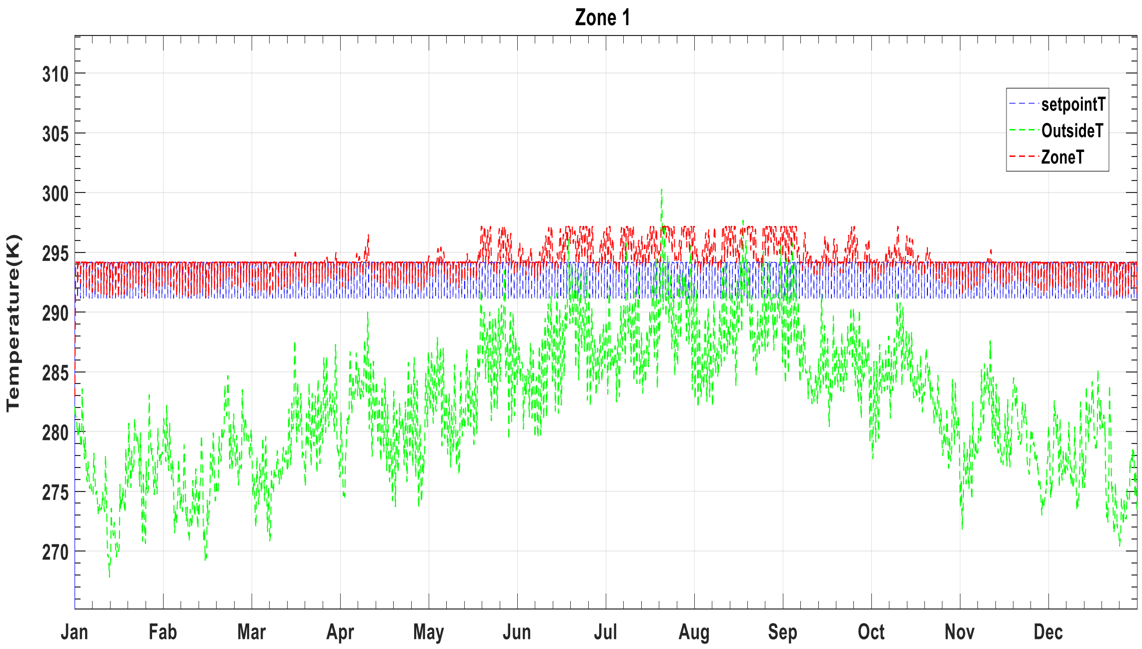



Figure 5.18.1A Zone 1 temperature for a full year

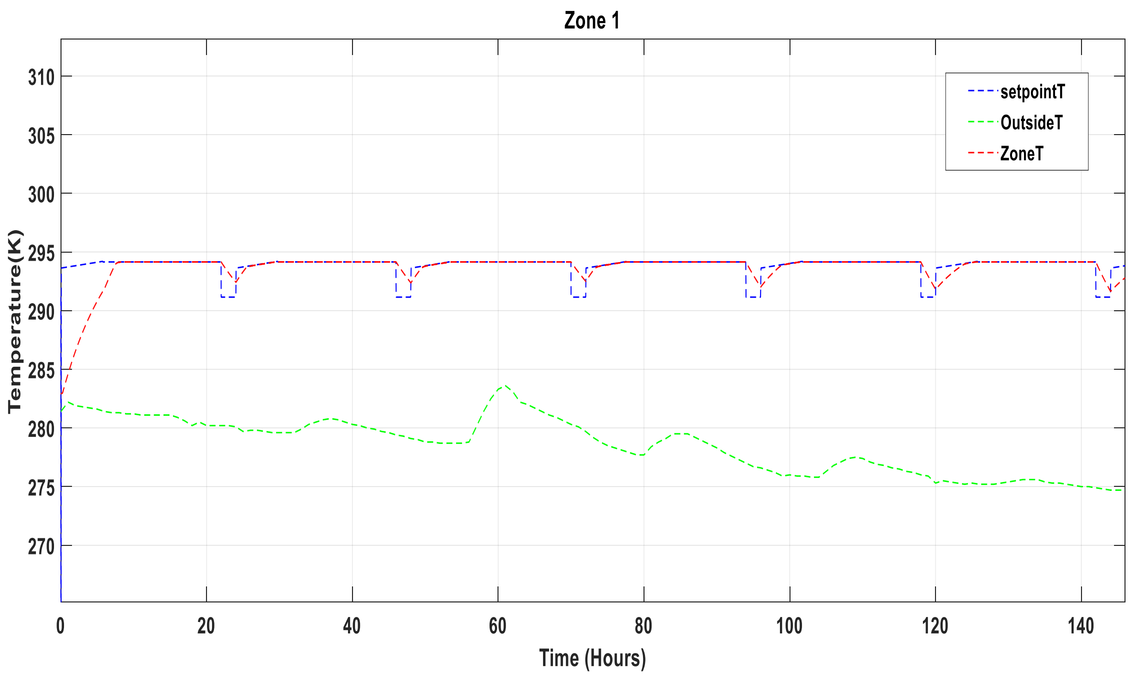



Figure 5.18.1B Zoom in Zone 1 temperature for first 6 days of January

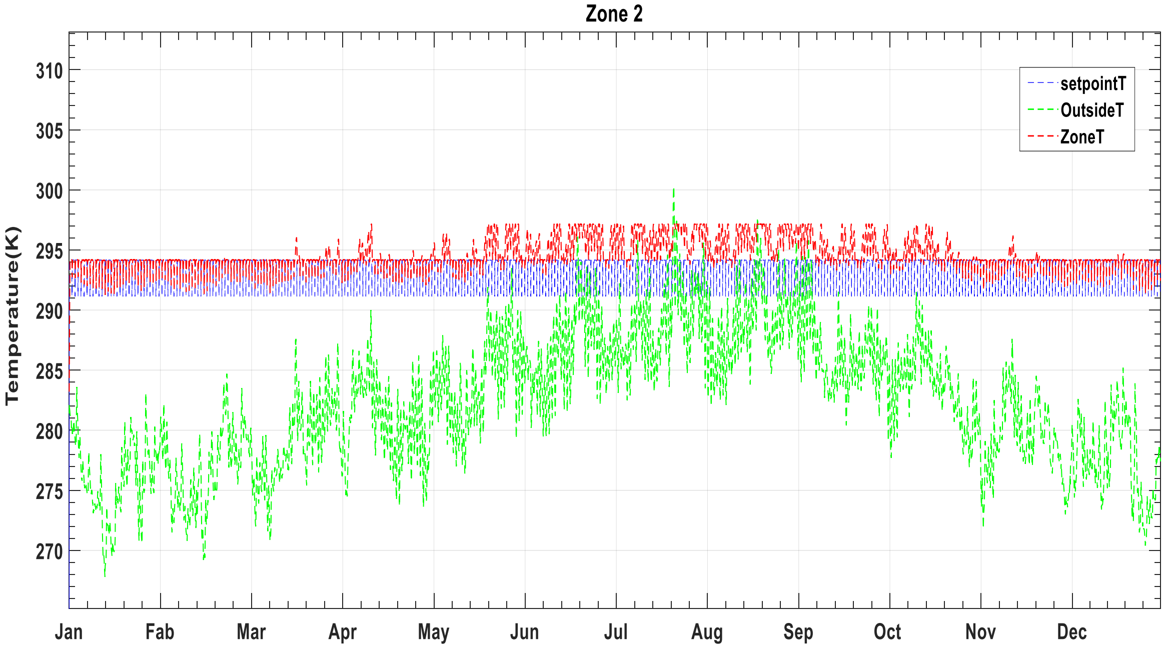



Figure 5.18.2A Zone 2 temperature for a full year

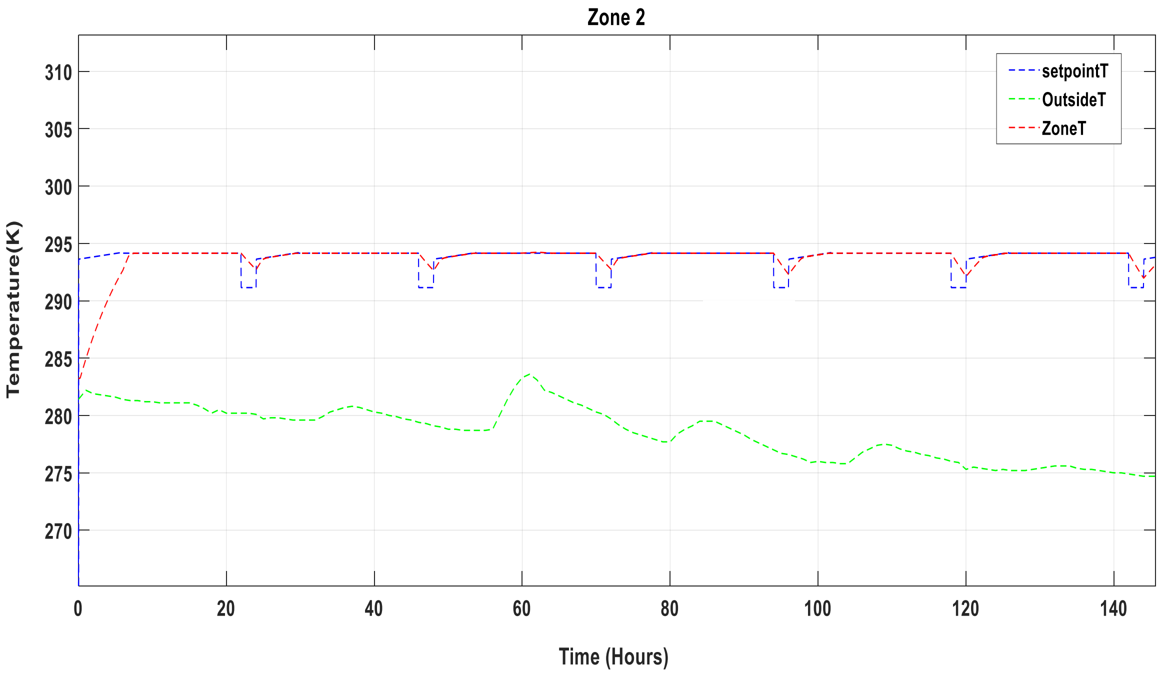



Figure 5.18.2B Zoom in Zone 2 temperature for first 6 days of January

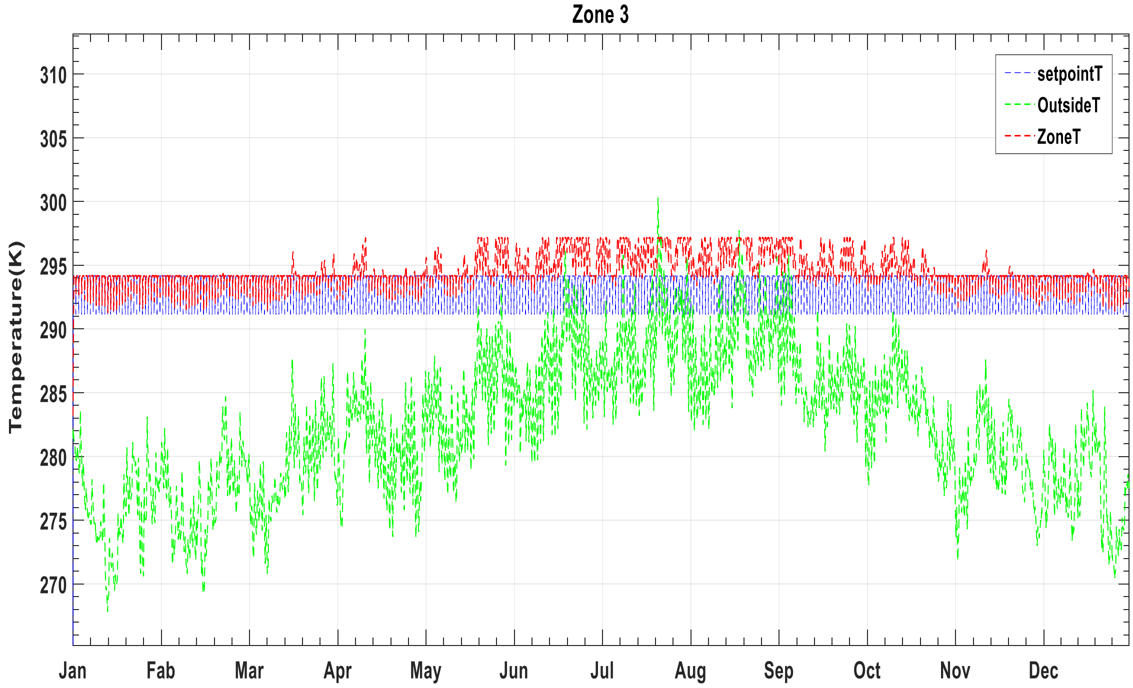



Figure 5.18.3A Zone 3 temperature for a full year

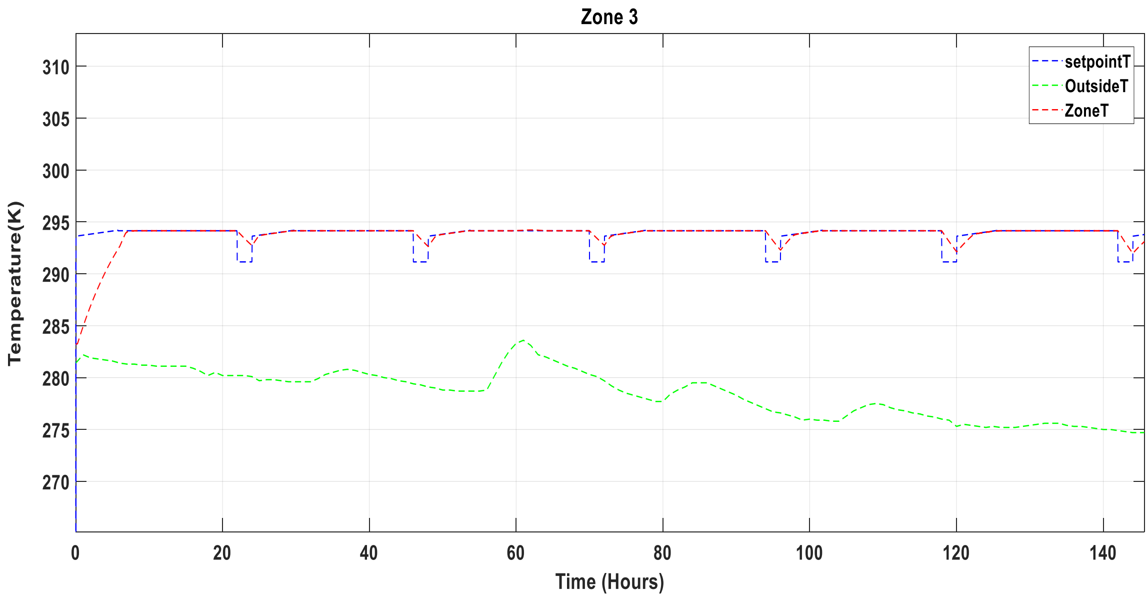



Figure 5.18.3B Zoom in Zone 3 temperature for first 6 days of January

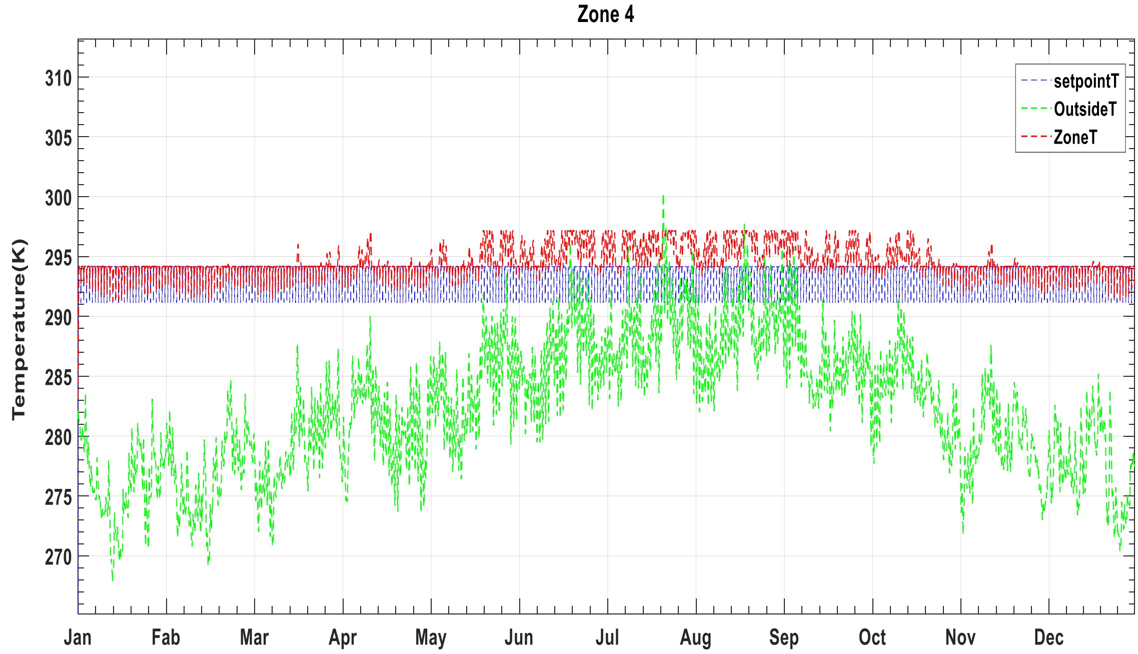



Figure 5.18.4A Zone 4 temperature for a full year

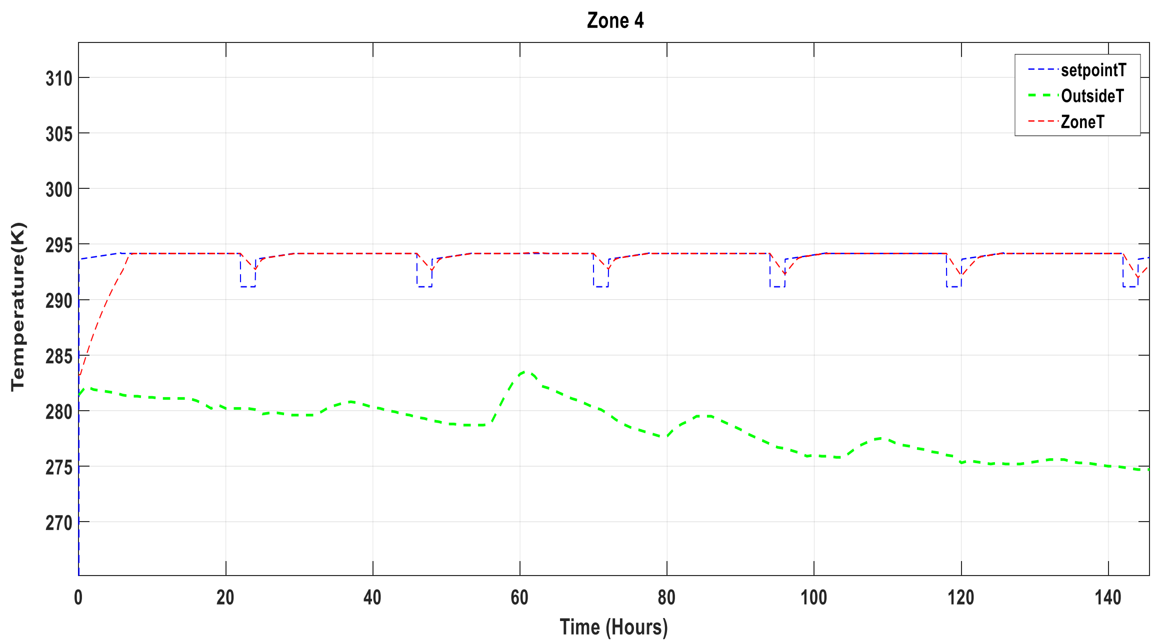



Figure 5.18.4B Zoom in Zone 4 temperature for first 6 days of January

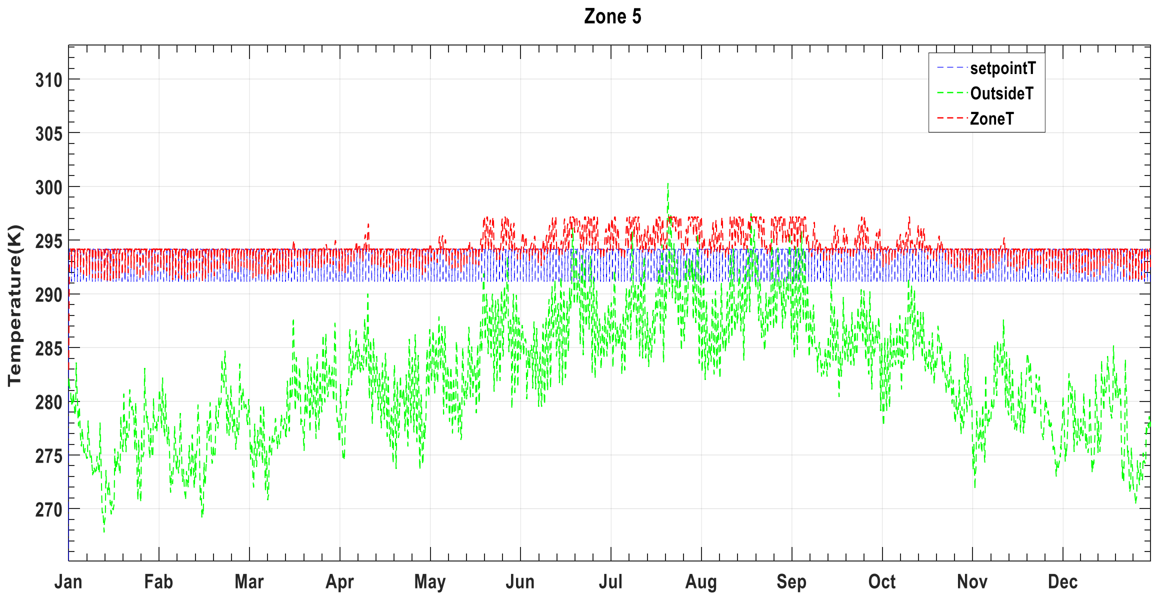



Figure 5.18.5A Zone 5 temperature for a full year

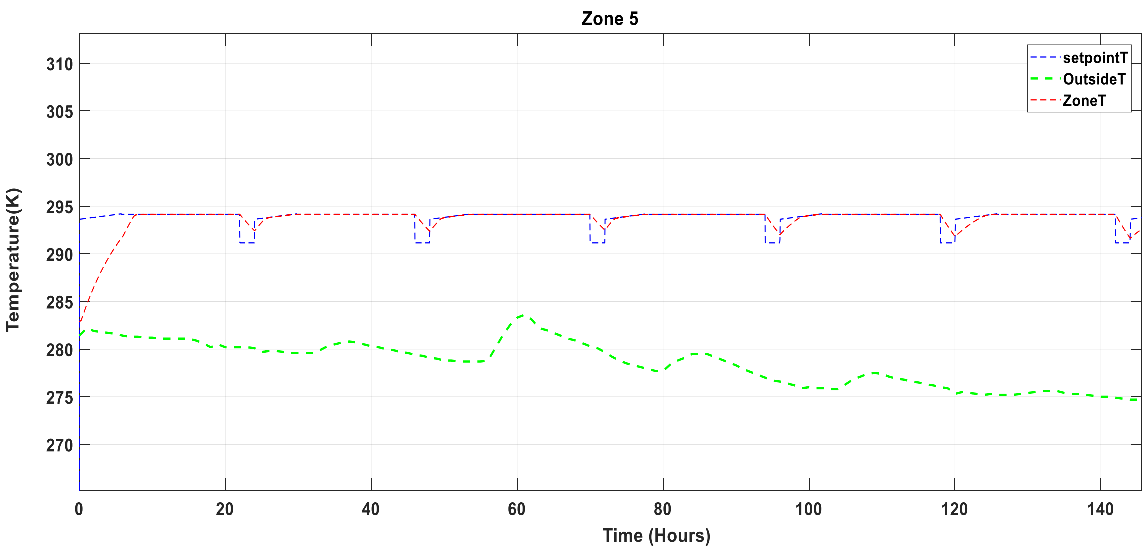



Figure 5.18.5B Zoom in Zone 5 temperature for first 6 days of January

Figure 5.18 Five Zones Temperature for a full Year Supplied by the national grid and Gas Boiler Only

## 5.3.2. Local Electrical Grid (LEG):

The local electrical grid in this case is the grid of wires connecting the local energy system electrical demand to the national grid by the controller. The figure [5.19] shows amount the electrical demand during the year and it is also showing it is spiky during the summer season because the electrical cooler. The figure [5.20] shows how the controller importing the electrical energy from the national grid while the set point is zero (the Green Line). It is mean the controller will make the decision to import the electricity by the national grid or any additional supplier when the CHP engine cannot supply enough electricity or if the CHP engine shortage at any time the controller will use the national grid to meet the local energy demand. And It is also shows the reliability of system in both side (electrical side and heating energy side) is at the maximum level.

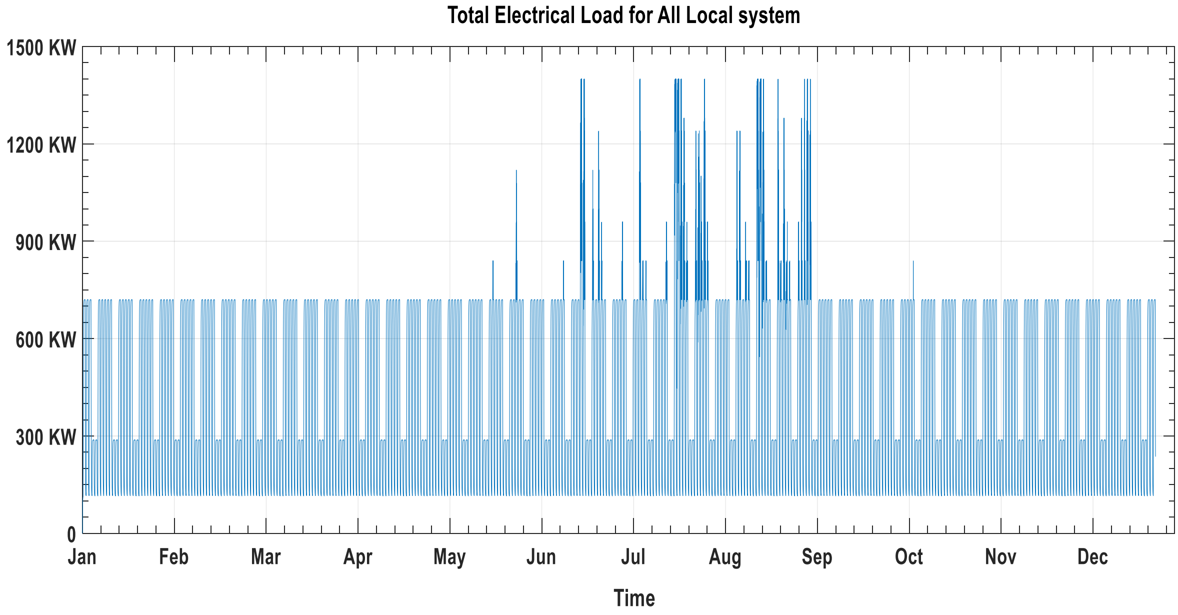



Figure 5.19 total Electrical Demands for All Local Energy System

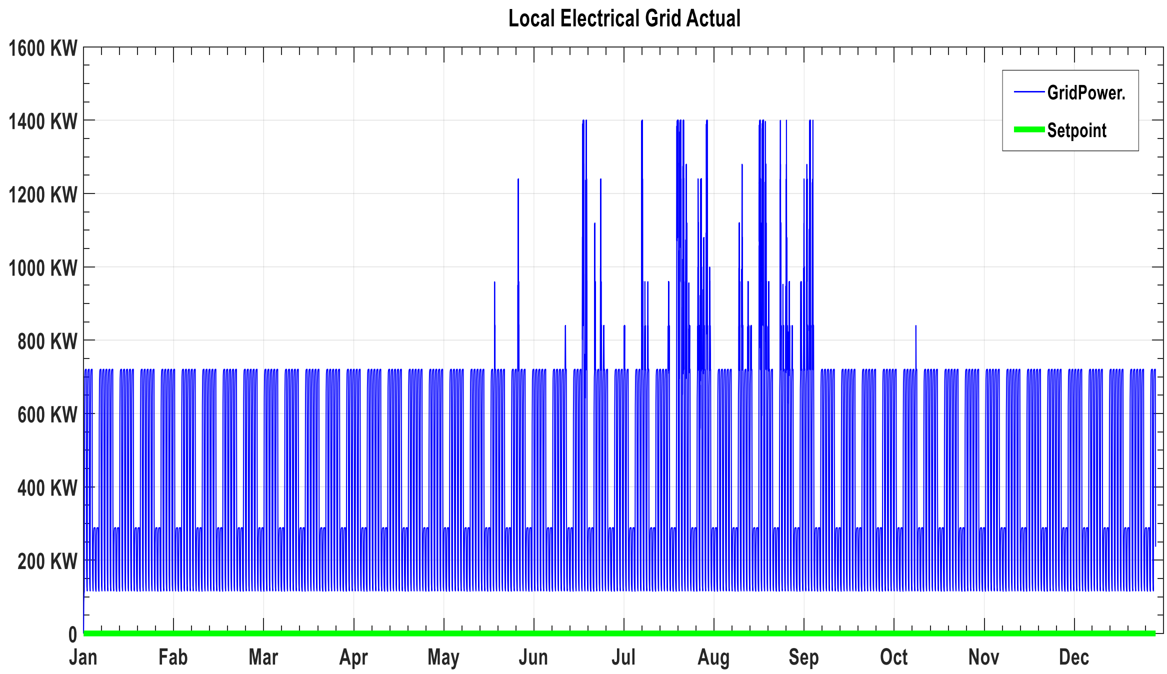



Figure 5.20 Total Amount of Electricity importing by the national grid

## 5.3.3. CO2 Emissions:

In this scenario, all amount of CO2 emission caused by the national grid and the gas boiler only. The figure [5.21] shows the cumulative amount of CO2 emission during the full year is 3575.3 Tonne while in the first scenario is 1873.600 Tonne. which it is mean using the national grid for electricity and a gas boiler for heating (the ordinary method) causing more than double CO2 emission and almost double cost if calculating the cost of gas used and importing of electricity price. Amount of gas used in first scenario is 10.128*$10^6$ KWH per year for electricity and heating energy while the Gas Used in the second scenario for heating only is 9.9168 *$10^6$ KWH wish is mean almost same amount.

CO2 Efficiency = $\frac{1873.600}{3575.3} * 100\% = 52.391\%$

In other word, the new local energy system design can save more than half of CO2 emission than the ordinary methods plus almost double cost.

As the figure [5.22] shows the local energy system CO2 performance VS national grid in second scenario. Which show 100% CO2 emission by using of electricity of the national grid **plus** amount of CO2 emission by the gas boiler for heating demands.

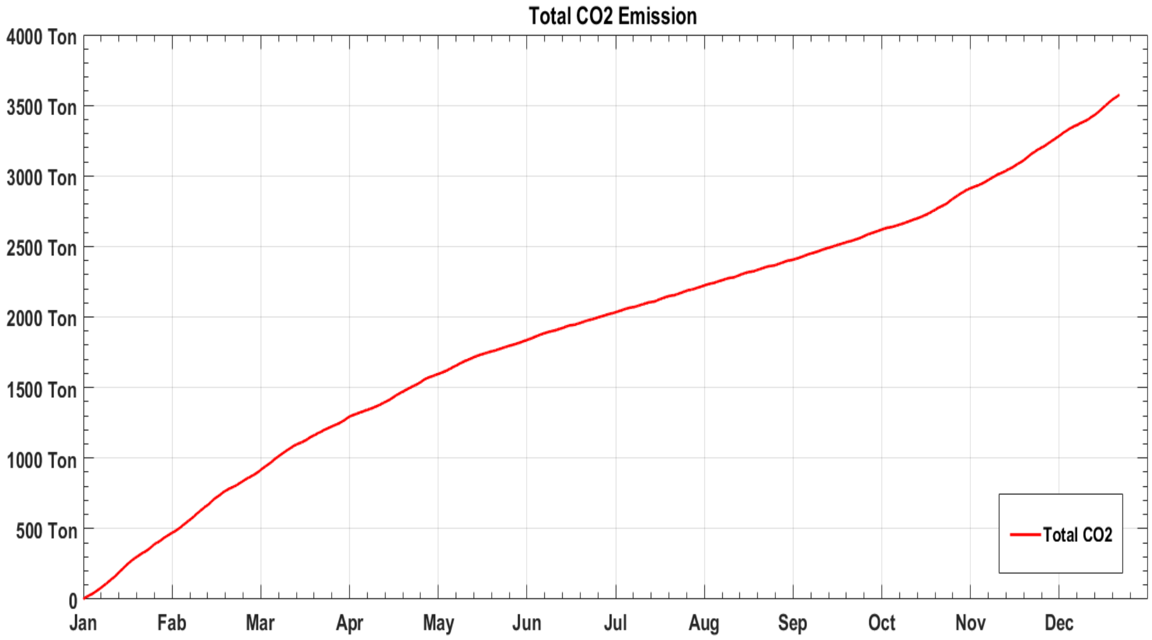



Figure 5.21 Total Cumulative Amount of CO2 emission during the Year When national grid and Gas Boiler suppliers only

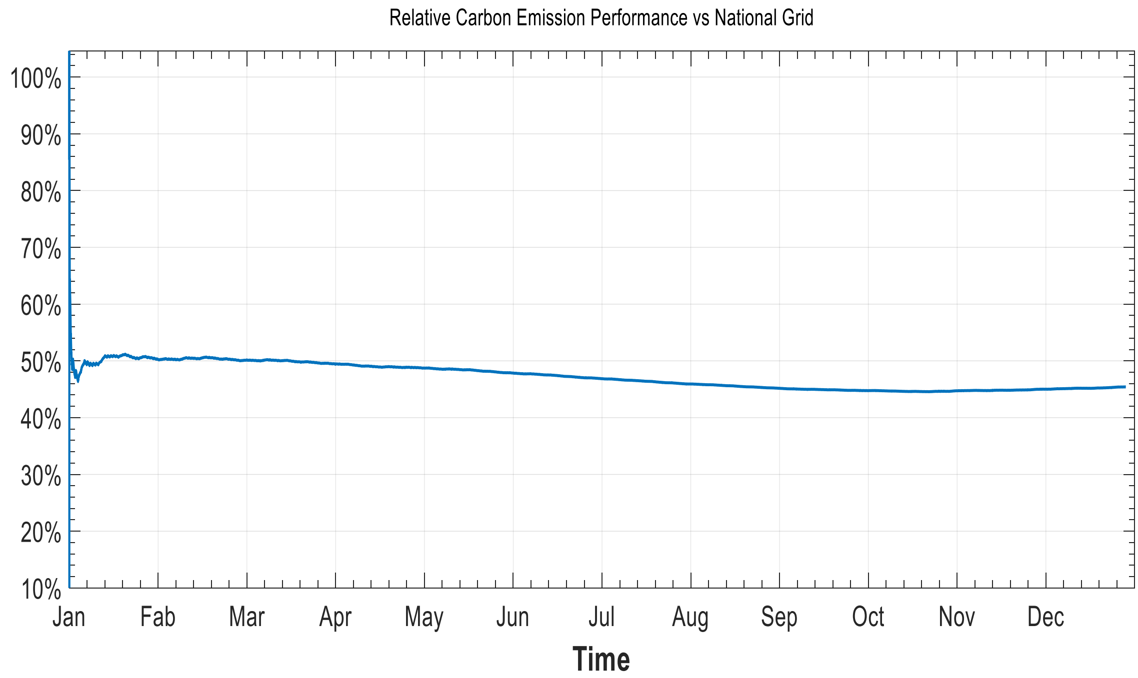



Figure 5.22 Relative Carbon Performance VS national grid when national grid and Gas Boiler suppliers only

## 5.4. Importing and Exporting Case

In this section the Local Electrical Grid set point are in two cases

First one, is importing 100Kw from national grid as show in figure [5.23] and the second case, is exporting 100 Kw to national grid as show in figure [5.24]. These two cases can show the control strategy and the control system can work in under any condition and any electrical set point required.

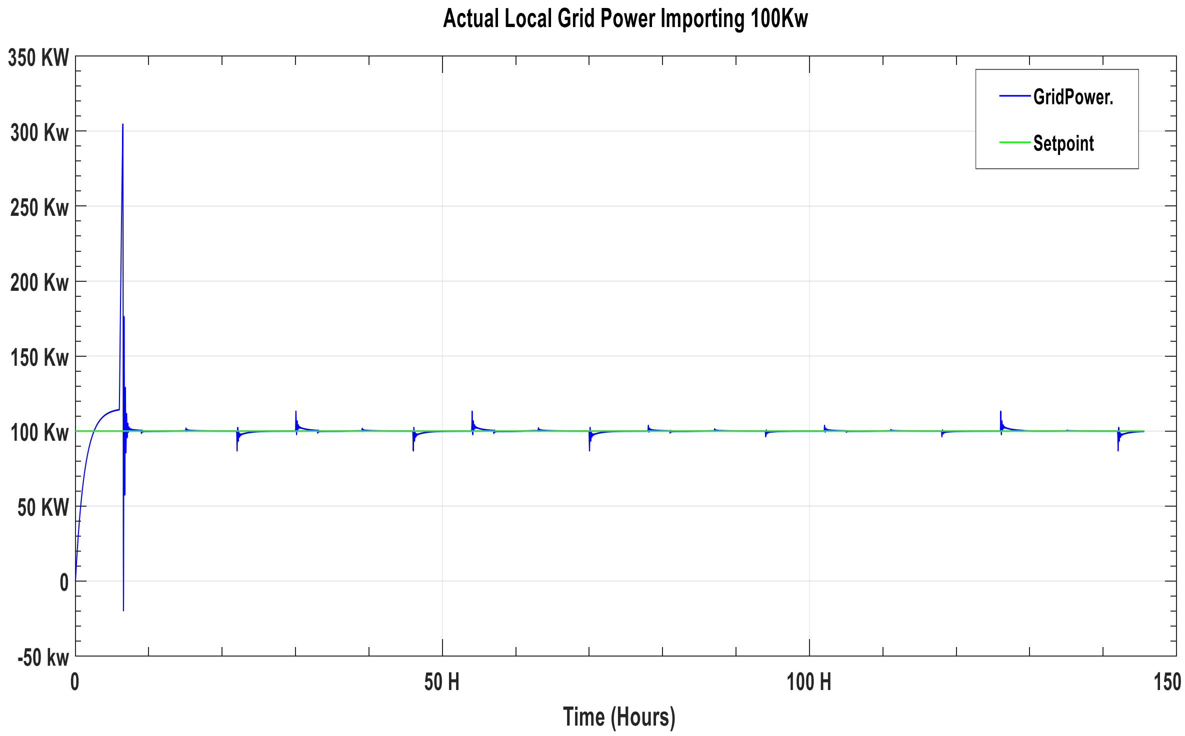



Figure 5.23 Local Electrical Grid Demand for first 6 days in January

The Setpoint is Importing 100 Kw from national grid

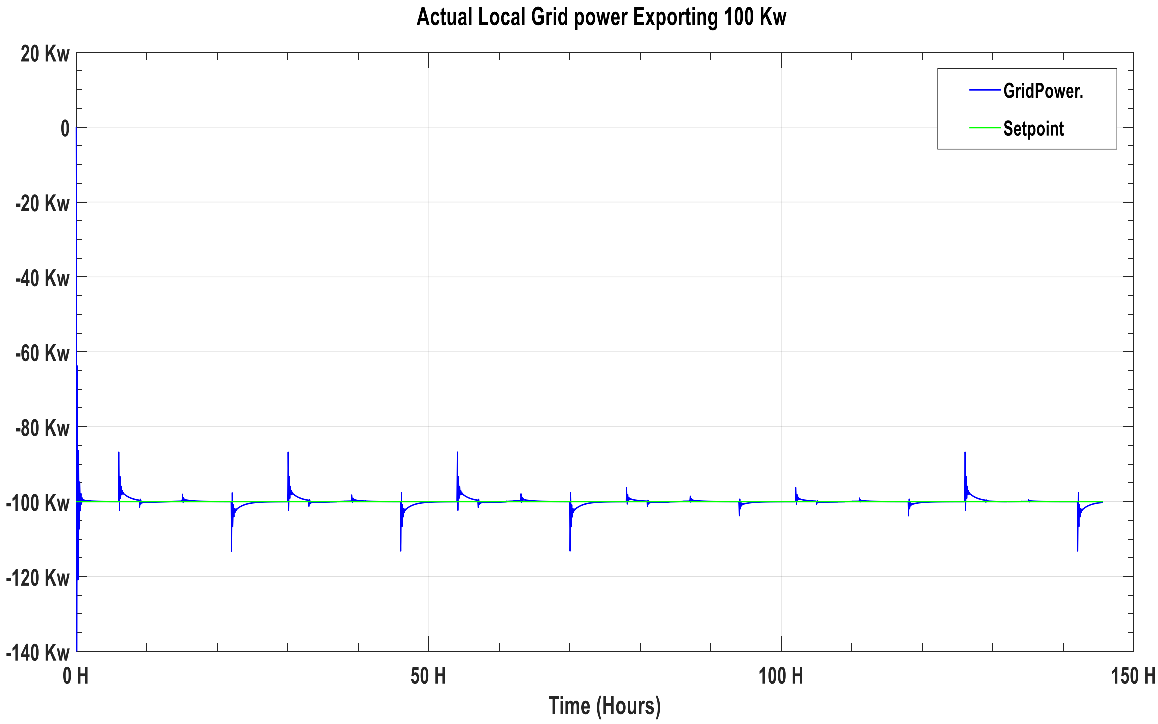



Figure 5.24 Local Electrical Grid Demand for first 6 days in January

The Setpoint is Exporting 100 Kw to national grid

## 5.5. Methodology of Calculating the Co2 Emission of The Local Energy System

The method of calculating carbon intensity in this thesis is

CIG = all energy must be in kWh

The national grid carbon intensity = GIG * Net Grid Energy

Net Grid Energy = 1 $\int_{3600*1000}^{t} Import - export\,.dt$

While the import and export in watt only

1 kWh = $\frac{1}{3600*1000}\ s$

The Gas consumption in the system is

Total Gas kWh = Gas used for Boiler + Gas used for the CHP engine

Gas CO2 = CI Gas * total Gas used

The carbon intensity of national grid in 2013 is 0.527 kg / kWh [127] but the carbon intensity for summer 2017 is 0.35156 kg CO2/ kWh [128] because of changing in the amount of national grid carbon intensity used the average of five years of carbon intensity which is 0.439 kg / kWh while the carbon intensity generated by burning natural gas is 0.185 kg / kWh.

# Chapter Six
# Discussion and Conclusion

## 6.1. MATLAB/Simulink Model of Local Energy System

A MATLAB/Simulink model has been developed based on the IDEAS paper [94] and it is result of cooperation and team working of Dr. Matt Stewart and Ameer Al-khaykan and leads by Professor John Counsell. Cooperation with Arup Company, PEEL utilization and PRE- Company for suppling data and the local energy requirements. This great cooperation and effort of longs time produced this huge model to simulate the application of an advanced control system topology for a fully integrated CHP and PV system (CHPV). It has been demonstrated in simulation to operate with excellent performance when applied to a typical educational building based on a real-life case study. (e.g. LJMU's new education building in Liverpool City). While, the other two cases studies (Green Bank student village and Media city in Manchester) models are used for calibration and validation the MATLAB model and to be sure the control methodology can work in different criteria, conditions and any number of zones. The Copperas Hill Building model has been used to present results that demonstrate that an electrical led control system for the CHP engine can track a desired national grid power demand profile (in this case zero import and export power) or (island case) whilst simultaneously tracking the building's desired temperature for thermal comfort. The dynamic MATLAB model includes:

- 5 zones of educational building, the design considering the (number of appliances and its amount of heat generated, ventilation system, domestic hot water, furniture, number of people, glazing, type of wall design and breaks.
- CHP engine working by gas fuel.
- Heat storage to store the surplus heat and reused when the system need it.
- Gas boiler turn ON to supply extra heat in very cold days when the heat generated by the CHP engine is not enough to meet the heat demands.
- Hot Water Network which is ring of pipes full of hot water to supply the heat to the zones.
- Heat exchanger to transfer the heat from the hot water network to the zones.
- Private of electrical wire to connect all the system together with CHP engine and national grid on one side and the electrical demands of local energy system.
- Renewable energy which represented by photovoltaics (PV) arrays.

The inverse dynamic approaching is a brilliant seed to design any size or type of local energy system. as each zone is working independently and it is easy to do any heat set point required but the strongest feature each zone is easy to redesign to any size required. For example, each zone can be

- part of building or floor of building as Copperas Hill Building in Liverpool city.
- The zone can be a full building or group of buildings as Green Bank Student Village, Sefton park in Liverpool and Media City in Salford, Manchester.

For example, each cases study has different requirements and different size of zones.

the system however, uses optimum start on zones temperature control enables better utilization of heat generated by the CHP and the thermal store can be used to minimize the need for gas boiler supplementary heating. The introduction of PV or any other demand side renewable power generation system can be integrated with the demand side’s Private Wire Network (PWN) and be accommodated by ensuring the CHP engine is controlled to follow net electric demand as opposed to the heat demand.

## 6.2. The Control System Design Methodology and Controllability.

As the literature review showed the gap of Controller Design Method, the Reliability and resilience because most of previous works and research using the scheduling system of demands or optimisation. Which mean there is no a specific control method or control system can control and tracking the local energy demands in both sides (electrical energy sides and heating energy side) for a fully year and four seasons. For that the previous designer depending on the old load profile and they suppling the energy depending on it. Which is mean if any change happened in the load for any reason the systems will shortage in power and it is needing to reset it manually which give the system no Reliability and Resilience. in same time, there are no much operation options such as (island case, exporting case and importing case) to give more flexibility and reliability to the local energy system.

This thesis however, presents new a control method can that guarantee tracking and stable of the energy demand of both vectors (electrical and heat) and is electrical led. The controller tracking of the electrical demands of each zone second by second while the thermostats tracking the temperature required minute by minute to meet the in each building zone demands are match at all the time in the year.

The design method passed through two stages:

1- The first try to design the controller for local energy system started with single building and single zone [93]. The control methodology was to control the air temperature inside of the building by pumping the heat energy direct to the building and control the temperature by the thermostat set point but the results show

- The system is very hard to control especially since the transmission zero of the system was in the original and very hard to keep it stable and guarantee tracking.
- The controller system is (2*2) for single building as we have one feedback but if we need to extend it to two zones the system required is (3*3) if we have 100 buildings or zones

the system required for it (100*100) which will be very complicated and impossible to control as figure (6.1) shows

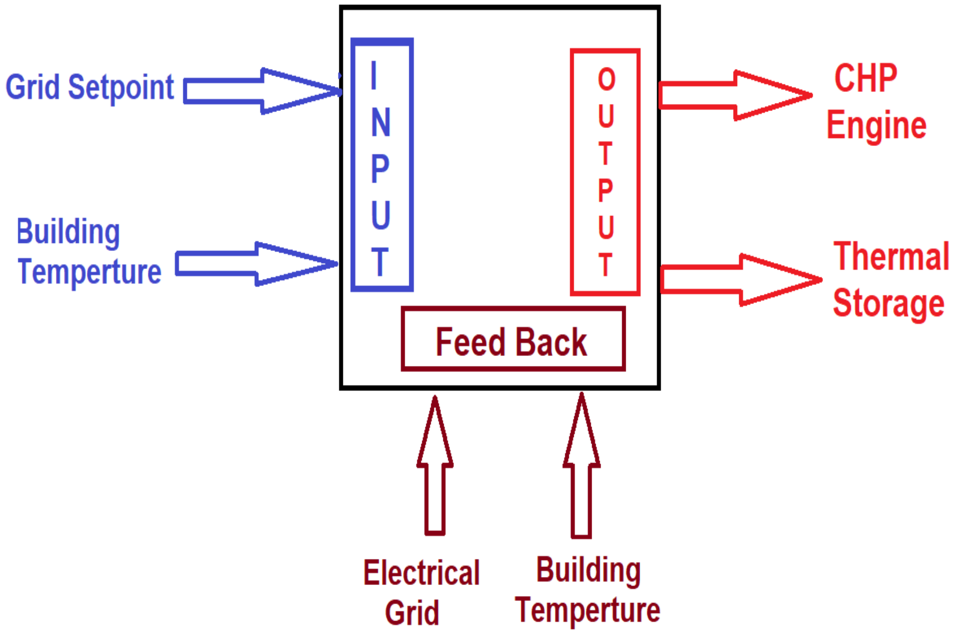



Figure [6.1] First Control Design Method [118]

We found out the system will never work by this method. For that we used the second stage or new methodology.

2- The second method to control the local energy system is controlling the local electrical grid and the temperature of the Hot Water Network (HWN) and we can connect any number of buildings or zones to the hot water Network and we still have one feedback as shows in figure [6.2]. While the transmission zero is stable as shown in chapter four.

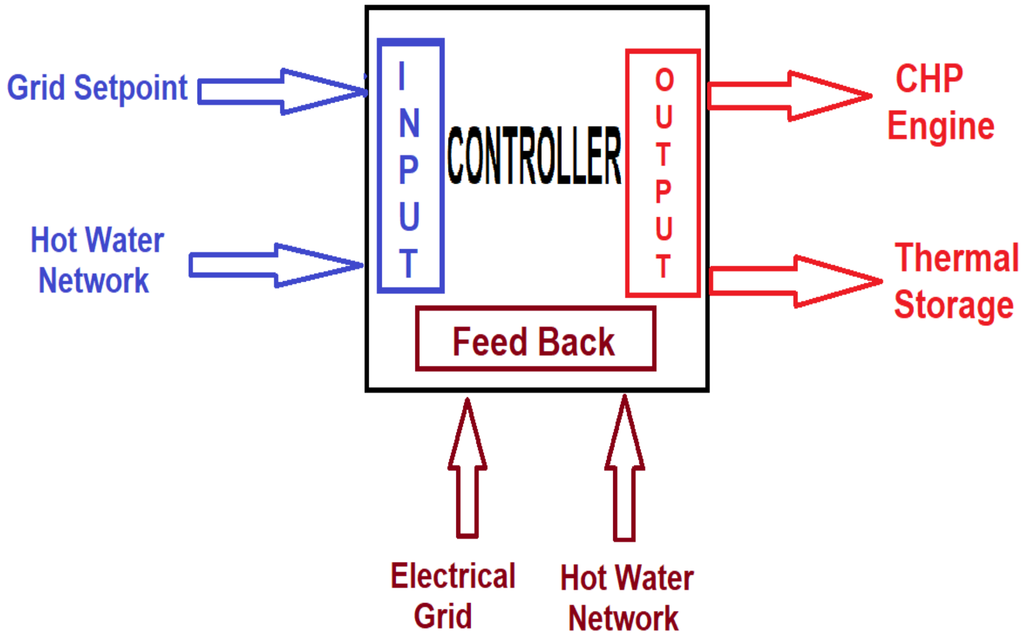



Figure [6.2] Second Control Methodology

The results in chapter five shows the control system working in very nice and smooth during all the year and for seasons.

The number However, of zones or building will not change the size of the controller and it will be same size (2*2).

## 6.3. Conclusion

In conclusion, a MATLAB/Simulink model has been developed and used to design an artificially intelligent (i.e. model based estimation of $\mathbf{U}_{eq}$) feedback control system for a Combined Heat & power with fully integrated PV (CHPV) system with heat storage and a centralized supplementary gas boiler heating system. It has been demonstrated in simulation to operate with excellent performance with only requiring a small amount of physical knowledge of the system to guarantee closed-loop stability and near perfect tracking of heat network water temperature, building zone comfort temperatures and import/export grid power demand for the total system. It does not require any knowledge of the PV generated and building load in terms of heat and power. It has been highly successfully applied to a typical educational building based on a real-life case study. (e.g. LJMU's new education building in Liverpool with acknowledgement here to Arup North West UK's contribution to provide basic data on this building) and operated in a grid islanded case i.e. import/export grid demand set to zero. The model for the case study described in the paper has been used to present results that demonstrate that a novel electricity grid import/export power tracking control system for the CHPV system which tracks a desired national grid power demand profile (in this case zero import and export power) whilst simultaneously tracking the building's desired temperature for thermal comfort. The use of optimum start on building temperature control enables better utilisation of heat generated by the CHP and the thermal store can be used to minimise the need for gas boiler supplementary heating. The introduction of PV or any other demand side renewable power system integrated with the demand side's Private Wire Network (PWN) can be accommodated by ensuring the CHP engine maintains the desired grid import/export power (e.g. grid power controller set point).

To shows the Local Energy System what can make different:

- **Gas Used**: Amount of Gas used for all CHPV system with the gas boiler is 10.128*$\mathbf{10^6}$ KWH per year. While Amount of gas used for heating only by using gas boiler for same system is 9.9168 *$\mathbf{10^6}$ KWH per year which it is almost same amount.
- **CO2 Efficacy =** $\frac{amount\ of\ Co2\ emission\ by\ using\ CHPV\ system}{amount\ of\ Co2\ emission\ by\ using\ National\ Grid\ only}$

**CO2 Efficacy =** $\frac{\mathbf{1873.600}\ Ton}{\mathbf{3575.3}\ \ Ton} * \mathbf{100}\% = \mathbf{52.391}\%$

- **running cost:** the local energy system design can save about half of CO2 emission than the ordinary methods but also can save more than half the running cost.
- **The reliability:** the reliability of the Local Energy System when the CHP engine shutting down for any reason.
- **Flexibility: the controller can led the system in any scenario (Island – exporting – importing)**

# Chapter Seven
# Future Work

## 7.1. Introduction

The most current energy demands, (heating and electrical power demands) and the amount of energy consumption in worldwide are not sustainable. In the same time, the efforts to prevent energy crises and environmental damage, greenhouse, a combination of improved energy efficient technologies and renewable energy sources such as PV, wind turbines and CHP are become more important.

This research, is a methodology to design the controller for any local energy system has CHP engine and renewable power. There are many technologies that can be added to improve it and make it suitable for all circumstances and increasing its efficiency.

There are two main suggestions for future work to improve the system performance.

- Electrical storage.

- Absorption chiller.

## 7.2. Electrical Storage (Battery).

The electrical storage is important to save the electrical energy that has been generated by the photovoltaics during the day time and save it for the night time to reduce amount of the fuel consumptions which led to reduce the running cost and CO2 emission.

On the other hand, the electrical storage will help the electrical system performance. On the words, the control system is fast enough to the follow the electrical demand second by second but the CHP engine (actuator) is not fast enough to response to the controller signal for that there are small fluctuated or swinging around the electrical setpoint (e.g. zero) as figure [5.10] in chapter five shows. For that by using electrical storage can prevent this ripple and getting better electrical control performance.

## 7.3. Absorption chiller.

This system designed for three case studies all of them are in UK and meet the requirement of UK weather. On the other words, this system very suitable for cold countries or countries has short summer season or not very high temperature in summer season. For that the electrical cooling system is efficient to make this system suitable for all weathers and any region in the world is required an Absorption chiller to for cooling system.

What is An Absorption Chiller?

The Absorption chiller is a machine uses a heat source to generate chilled water rather than electrical source that is used in vapor compression cycle [115].

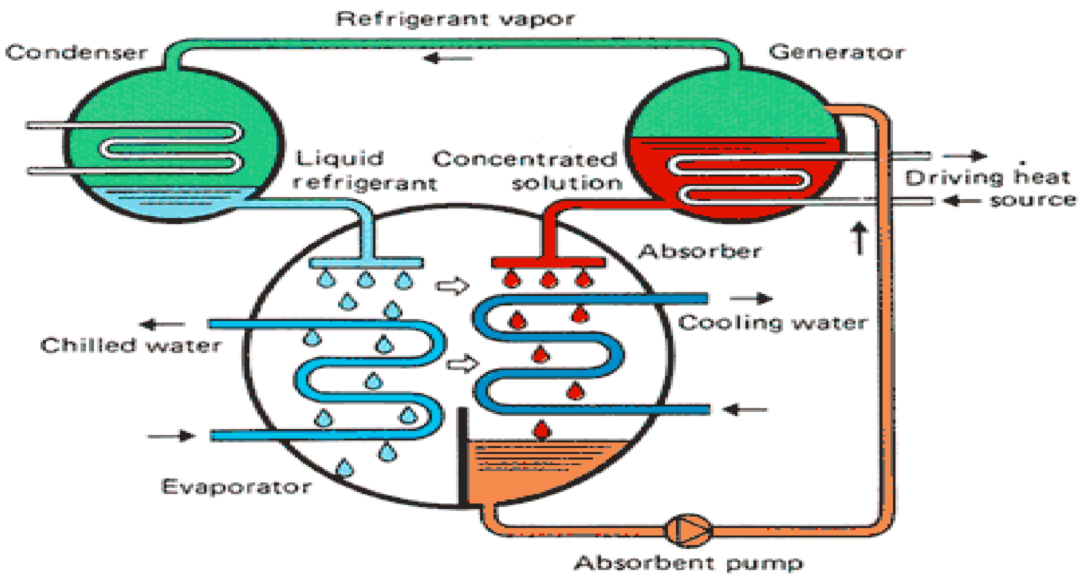



Figure [7.1] Absorber chiller

By using this machine in the local energy system will increase the system efficiency and reducing electrical demand in summer season as there is no electrical cooling system required for cooling.

On the other hand, the system will use all the heat generated by the CHP engine in summer for cooling the system and no waste heat during the summer season. Which will mean the system will reach to the maximum of using the heat.

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# Appendix A

## Five Independent Zones Simulink and Design

Copperas Hill Building in Liverpool city is a single, immense structure. It is multi-purpose, divided into equal 5 zones all of which have a similar design. Each zone contains an electrical cooling system and photovoltaics arrays on the roof, as shown in figure A1.

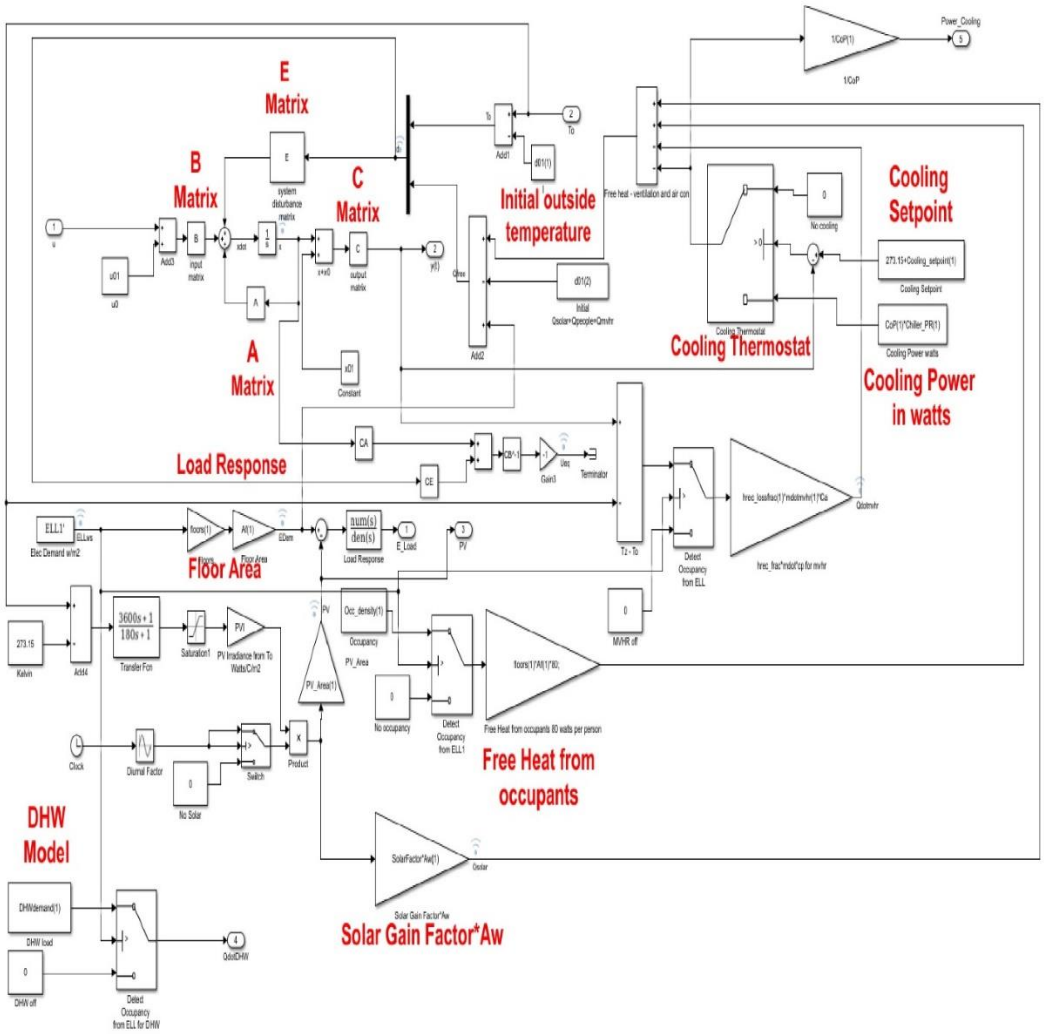


Figure A1 First zone of Copperas Hill building MATLAB Simulink

The MATLAB program, should synchronize the Simulink design with the writing programming in M-file to define all parameters of the system to the program, as shown below for all five zones.

```
    %------ Define Building Parameters -----
% U-value of Floor { W/(m^2*K) }
Uf = [1.5,1.5,1.5,1.5,1.5]
% Surface Area of Floor { m^2 }
Af = [960,960,960,960,960]
% U-value of Roof { W/(m^2*K) }
Ur = [1.5,1.5,1.5,1.5,1.5];
% Surface Area of Roof { m^2 }
Ar = [960,960,960,960,960];
              % BUILDING STRUCTURE
              % ------------------
% Wall Construction
% C { J/(kg*K) }  |  t { m }   |  r { kg/m^3 }
Cplaster = 1000;
Cbrick = 800;
Cconcrete = 1000;
Ccavity = 1450;
```

```
tplaster = 12.5e-3;

tbrick = 1e-3;

tconcrete = 300e-3;

tcavity = 1e-3;

rplaster = 700;

rbrick = 1700;

rconcrete = 2000;

rcavity = 30;

% U-value of Building Structure { W/(m^2*K) }

Us = [2, 2, 2, 2, 2];

% Thickness of Structure { m }

% SOURCE: 9inch brick+layer of plaster

tw = tplaster+tbrick+tconcrete+tcavity;

% Heat Capacity of Structure { J/(kg*K) }

% SOURCE:  J/(kg.K) Specific Heat Capacity of

Structure & Internal Mass

Cs = (tplaster/tw*Cplaster) + (tbrick/tw*Cbrick)

+ (tconcrete/tw*Cconcrete) +...

    (tcavity/tw*Ccavity)

% Heat Capacity of Structure {J/m^2*K }

Kt = (tplaster*rplaster*Cplaster)+

(tbrick*rbrick*Cbrick)+...
```

```
(tconcrete*rconcrete*Cconcrete)+(tcavity*rcavity
*Ccavity);
% U-value of Internal Mass (+Furniture) {
W/(m^2*K) }
% SOURCE: (W/m²K)   Heat Transfer Co-Efficient
of the Furniture & Internal Mass
Uim = 2.5;
%based on 2 sided single brick (1/Uim) =
(1/7.7)+(0.12/0.8)+(1/7.7)
% Mass of Internal Mass (+furniture) in Zone {
kg }
200kg/m2 of floor area
Mim = 500*sqrt(Af)/5; % 5 heavy 50 light
% Surface Area of Internal Mass (+Furniture) {
m^2 }
% SOURCE: 2*floor area
Aim = 20*sqrt(Af)/5;


% Door U value W/m2K
Udoor = [1.7 1.7 1.7 1.7 1.7];
% Area of doors m2.
Adoor = [10 0 20 0 10];
```

```
% Heat Capacity of Internal Mass (+Furniture) {
J/(kg*K) }
% SOURCE:
http://www.engineeringtoolbox.com/specific-heat-
capacity-d_391.html
% 1700 J/(kg*K) is the value for Wood
Cim = 1000;
% Heat Transfer Coefficient of Still Internal
Air { W/(m^2*K) }
% SOURCE: Standard Value
hi = 7.6923;
% Heat Transfer Coefficient of External Air {
W/(m^2*K) }
% SOURCE: Standard Value
he = 25;
% Case study building parameters
floors = [6,6,6,6,6];
% Surface Area of Structure { m^2 }
Floor_height = [5,5,5,5,5];
%assumes 1 building into 5 parallel slices
Aperim(1) =
Floor_height(1)*((2/3)*4*sqrt(Af(1))*floors(1));
```

```
Aperim(2) =
Floor_height(2)*((1/3)*4*sqrt(Af(2))*floors(2));
Aperim(3) =
Floor_height(3)*((1/3)*4*sqrt(Af(3))*floors(3));
Aperim(4) =
Floor_height(4)*((1/3)*4*sqrt(Af(4))*floors(4));
Aperim(5) =
Floor_height(5)*((2/3)*4*sqrt(Af(5))*floors(5));
% Surface Area of Windows { m^2 }
Aw=[Aperim(1)*0.1,Aperim(2)*0.1,Aperim(3)*0.1,Ap
erim(4)*0.1,Aperim(5)*0.1];  % fractions relate
to caibration in JC excel method
% Surface area of the structure { m^2 }
As = Aperim - Aw - Adoor;
% U-value of Windows { W/(m^2*K) }
Uw = [1.7,1.7,1.7,1.7,1.7];  %
% Mass of Structure { kg }
ms = Kt*As/Cs;
% Mass of Internal Structure { kg }
msi = ms/2;
% Mass of External Structure { kg }
% SOURCE:
```

```
mse = ms/2;
% Mass of Internal Air in Zone { kg }
% SOURCE:Va (Volume of Air from FROM BREDEM CELL
AC6)* Pa (Density of Air STANDARD VALUE)
int_fh = [4,4,4,4,4]; % internal ventilated
floor height
ma = [Af(1)*floors(1)*int_fh(1),
Af(2)*floors(2)*int_fh(2),
Af(3)*floors(3)*int_fh(3),
Af(4)*floors(4)*int_fh(4),
Af(5)*floors(5)*int_fh(5)]* 1.205;   %E.G.
22000m3*1.205kg/m3
% Furniture assumed to made of wood with a
volume fraction defined by
% ffrac. Modified code
ffrac= 0.05; Cwood = 2250; rwood = 600;
mf = ffrac*rwood*ma/1.205;  %fraction of zone
that is wood.
% Modified System Model Constants
mzone = ((1-ffrac)*ma) + mf;
Czone =  (1-ffrac)*Ca + ffrac*Cwood;
```

```
% Infiltration and Mac Vent calibrated from
steady state calibration or rates specified.
% 0.25 design infiltration (NCM/SBEM/IES)
MAC = [1.00, 1.00, 1.00, 1.00, 1.00];  %Arup =
0.25
mdotv(1) = ((1-ffrac)*MAC(1)/(3600))*ma(1); %
Modified to remove furniture fraction
mdotv(2) = ((1-ffrac)*MAC(2)/(3600))*ma(2);
mdotv(3) = ((1-ffrac)*MAC(3)/(3600))*ma(3);
mdotv(4) = ((1-ffrac)*MAC(4)/(3600))*ma(4);
mdotv(5) = ((1-ffrac)*MAC(5)/(3600))*ma(5);

% Total design ventilation of 3 ACR for building
type. MVHR 70% from Arup.
MVACR = 3;
ACMVHR = [MVACR-MAC(1), MVACR-MAC(2),MVACR-
MAC(3),MVACR-MAC(4),MVACR-MAC(5)];
mdotmvhr(1) = ACMVHR(1)*(1-ffrac)*ma(1)/(3600);
mdotmvhr(2) = ACMVHR(1)*(1-ffrac)*ma(2)/(3600);
mdotmvhr(3) = ACMVHR(1)*(1-ffrac)*ma(3)/(3600);
mdotmvhr(4) = ACMVHR(1)*(1-ffrac)*ma(4)/(3600);
mdotmvhr(5) = ACMVHR(1)*(1-ffrac)*ma(5)/(3600);
```

```
%------ Heater -------%
% Maximum Heat Output of Heater { W }
% SOURCE:
% Qmax = 25000;
% Heater Ratios
ra = 1;
rsi = 0;
rim = 0;
% Equivalent Thermal Conductivity of Structure {
W/(m*K) }
kw = (he*hi*tw*Us(n))/(he*hi-((he+hi)*Us(n)));
% Comfort Temperature Ratios   1/2 air plus 1/2
mrt.
fa  = (1.0);
fsi = (0.0);
fim = (0.0);

    % ----- Define State-Space Matrices -----
% xdot = Ax + Bu + Ed, y = Cx + Du + Fd
J1 = 1/(mzone(n)*Czone);
J2 = 1/(msi(n)*Cs);
```

```
J3 = 1/(mse(n)*Cs);

J4 = 1/(Mim(n)*Cim);

% J5modified to include doors

J5 = Uw(n)*Aw(n) + Uf(n)*Af(n) + Ur(n)*Ar(n) +
Udoor(n)*Adoor(n)+ mdotv(n)*Ca;

J6 = Uim*Aim(n);

J7 = ((4*kw*hi)/((4*kw)+(hi*tw)))*As(n);

J8 = (2*kw/tw)*As(n);

J9 = ((4*kw*he)/((4*kw)+(he*tw)))*As(n);


% System Matrix, A (4x4)

a11 = -J1*(J5 + J6 + J7); a12 = J1*J7; a13 = 0;
a14 = J1*J6;

a21 = J2*J7; a22 = -J2*(J7 + J8); a23 = J2*J8;
a24 = 0;

a31 = 0; a32 = J3*J8; a33 = -J3*(J8 + J9); a34 =
0;

a41 = J4*J6; a42 = 0; a43 = 0; a44 = -J4*J6;

A = [a11 a12 a13 a14;a21 a22 a23 a24;a31 a32 a33
a34;a41 a42 a43 a44];

% Input Matrix, B (4x1)
```

```
b11 = J1*ra; b21 = J2*rsi; b31 = 0; b41 =
J4*rim;
B = [b11;b21;b31;b41];
% Output Matrix, C (1x4)
c11 = fa + fsi*((tw*hi)/((tw*hi)+ (8*kw))); c12
= fsi*(8*kw)/((tw*hi) + (8*kw)); c13 = 0; c14 =
fim;
%c11 = fa; c12 = fsi; c13 = 0; c14 = fim;
C = [c11 c12 c13 c14]
% Feedforward Matrix, D (1x1)
d11 = 0;
D = [d11];
% System Disturbance Matrix, E (4x2)
e11 = J1*J5; e12 = J1;
e21 = 0; e22 = 0;
e31 = J3*J9; e32 = 0;
e41 = 0; e42 = 0;
E = [e11 e12;e21 e22;e31 e32;e41 e42];
% Output Disturbance Matrix, F (1x2)
f11 = 0; f12 = 0;
F = [f11 f12];
% (CB)^-1 for inverse dynamics
```

```
CB = C*B; CBinv = inv(CB);

% Ueq = -CBinv*(CAX(s) + CEd(s))
CA = C*A;
CE = C*E;

% Initialise parameters/disturbances for small
perturbation model
% SMALL PERTURBATION CALCS
load('To.mat');
Toi = To(2,1); Qfreei = 0;
% initialise MVHR heat gain
Qmvhri = 0;  % mdotmvhr(n)*Ca*(288 - Toi); Zero
at start.
% initialise electric demand  Note same for all
5 zones.
ELLi=floors(n)*Af(n)*ELL(2,3);

% Initialise distrurbance input vector for IDEAS
state space
d0 = [Toi; Qfreei+ELLi-Qmvhri];
```

```
% method 1: u0 = 0 (no initial heat input,
calculates initial temperatures
% based upon initial disturbances)
x0 = -A\E*d0;
u0 = 0;
% method 2: calculates u0 based upon initial
temperatures
%x0 = [Tzo;Tzo;Tzo;Tzo];
%u0 = -B\(A*x0 + E*d0);

% initialise water network temperature
Thx0 = (u0/HA(n))+x0(1);

%initial comfort
y0 = C*x0
end.
```

**This segment shows the electrical cooling system design for the five zones.**

```
          % cooling system varaiables
Cooling_setpoint = [24,24,24,24,24];  %cooling
setpoint normal 24C all day
Chiller_PR =
[160000,160000,120000,120000,120000];
CoP = [2,2,2,2,2];
CHILLERocc_detect = [5,5,5,5,5];
```

The photovoltaics arrays Simulink program is:

```
          % PV parameters and Solar Gain
SolarFactor = 0.1;
 PVI = 5.0; %
 SH_off = 0.7; % sun hours offset fraction of 1.
 PV_Area = 2*[600,600,600,600,600];
```

# Appendix B

## Heat Exchanger Simulink Design

A heat exchanger is a device used to transfer heat between a solid object and a fluid, or between two or more fluids [105]. In this system, the heat exchanger is used to transfer heat energy between the hot water network and each zone. There are five heat exchangers, one for each zone, each one controlled by a thermostat as shown in figure B1.

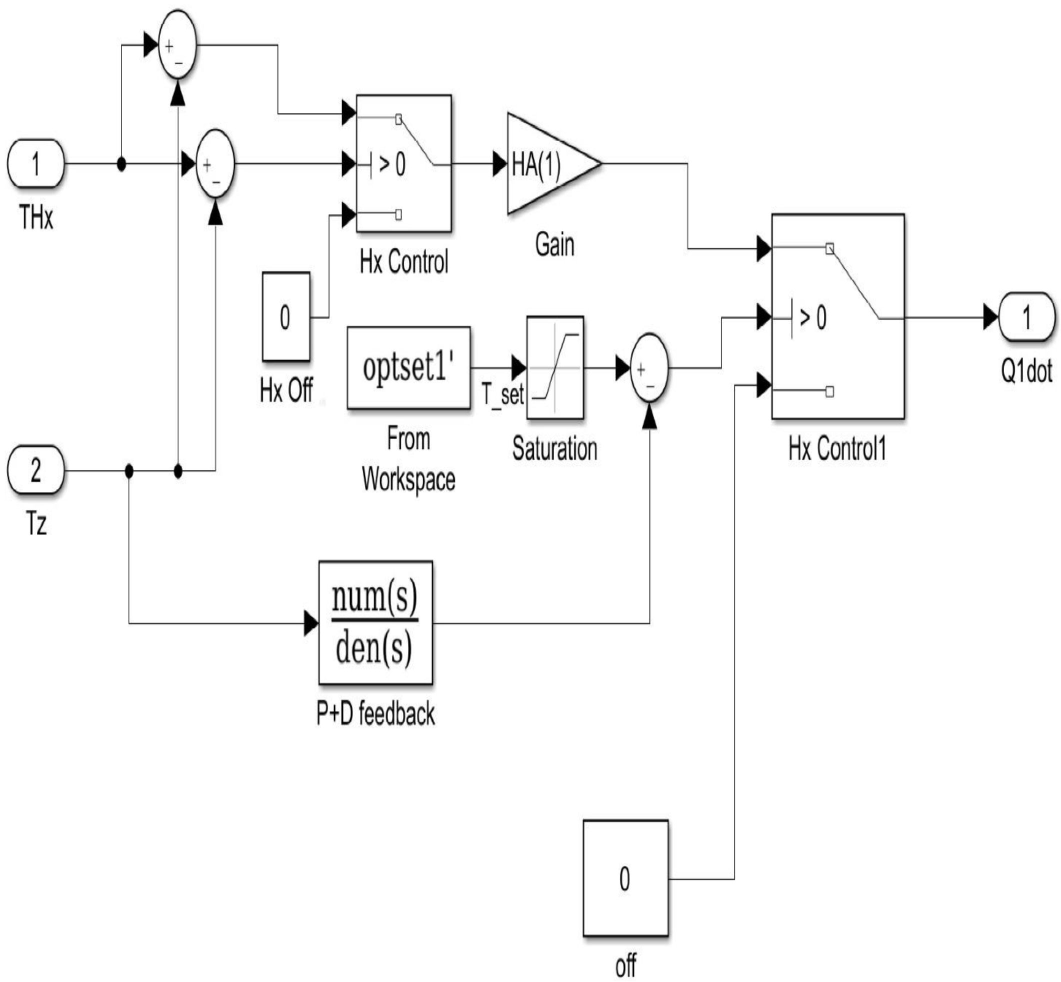


Figure B1 Heat Exchanger MATLAB Simulink

```
% Heat Exchanger
hex = 120; %Heat transfer coefficient of the
heat exchanger W/K/m2
Aex = [50,50,50,50,50];  %Effective Hx area
HA=hex*Aex;  % overall heat transfer W/K.
```

# Appendix C

## Hot Water Network Simulink Design

The hot water network is a network of pipes used to transfer and distribute heat energy to the zones by heat exchanger. The hot water network in this system is connected to the CHP engine, gas boiler and thermal store from side and the zones by heat exchanger from other side as shown in figure 3.11. The hot water network Simulink design in MATLAB is shown in figure C1.

```
                % Hot Water network
 Lp=160; % length of water pipe in m
 Dp=0.1;
 mw=(3142*(Dp/2)^2)*Lp;   %mw=12568; % mass of
water in network pipes
 Cp=4180;  % specific heat capacity
 mdotw = 7.5; %mass flow water kg/s
 UAp = 0.5*3.142*0.1*Lp;  %Overall heat transfer
from pipes to ground
 Taug = 24*3*3600;  %Time constant of the
ground. i.e. 3 days
```

```
% Water network control set points
TWN_setpoint = 273.15+85; %  Water network
temperature setpoint in degC
TWN_boiler = 273.15+80; % Minimum network
temperature setpoint in degC when boiler kicks
in.
TWN_store = 273.15+95;
```

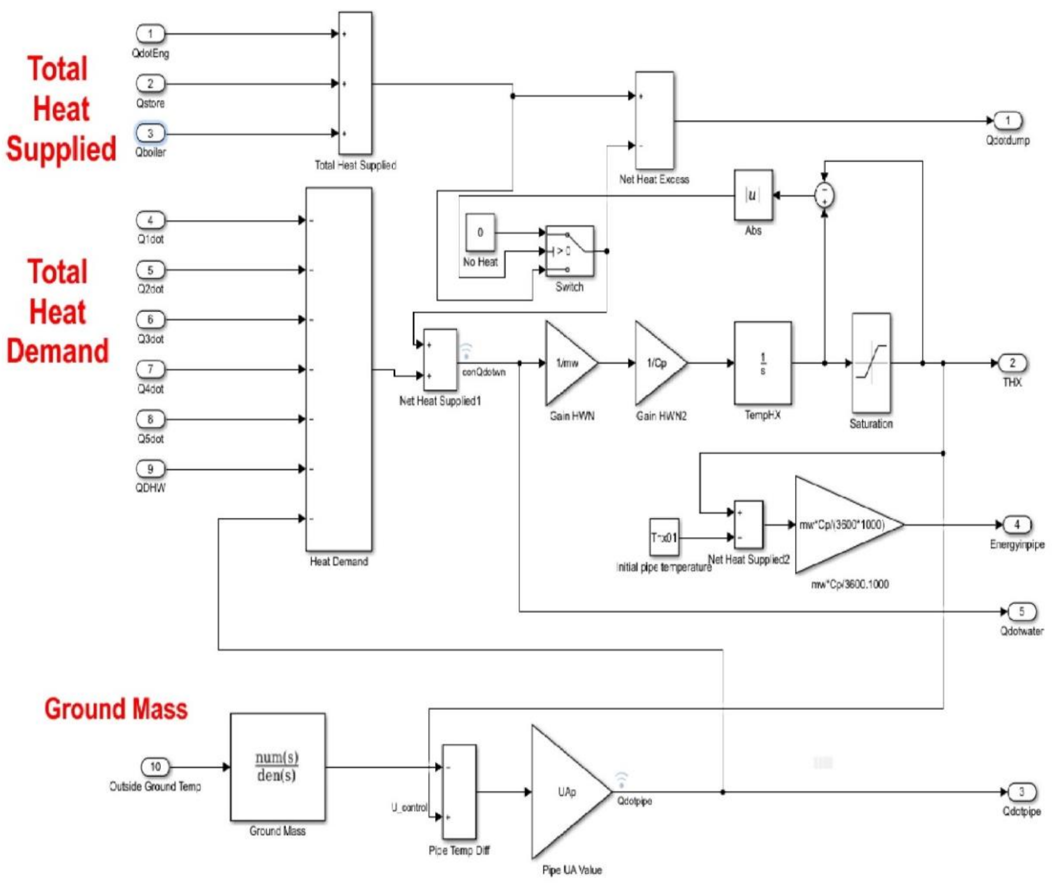


Figure C1 Hot Water Network MATLAB Simulink

# Appendix D

## Thermal Storage Simulink Design

Thermal Heat Storage is used to store excess heat from the CHP engine. This heat is then pumped back into the system, or hot water network (HWN), when the system is short of heat energy or when the system needs more heat to meet energy demands at peak times. In this system, the heat storage is a big water tank which is cylindrical in shape. It is connected to the hot water network at one side and the CHP engine at the other side, as shown in figure 3.11. The hot water storage Simulink design and programming are shown in figure 3.15 below.

```
           % Thermal Store parameters
 KS = 1.0;  % Fraction of CHP heat made
available to the store 1 = 100%
 Dstore = 1*3.0; % diameter of water store in
meters
 Hstore = 1*10.0; % height of water store in
meters.
```

```
 Astore = 1*((3.142*(Dstore*Dstore/4))  + 
(2*3.142*Dstore*Hstore));    % total surface 
area of the tank m2
 ms = 1000*(3.142*(Dstore*Dstore/4))*Hstore; 
%mass of water in the tank   10000
 Ustore = 0.05;   % U value of store W/K/m2
```

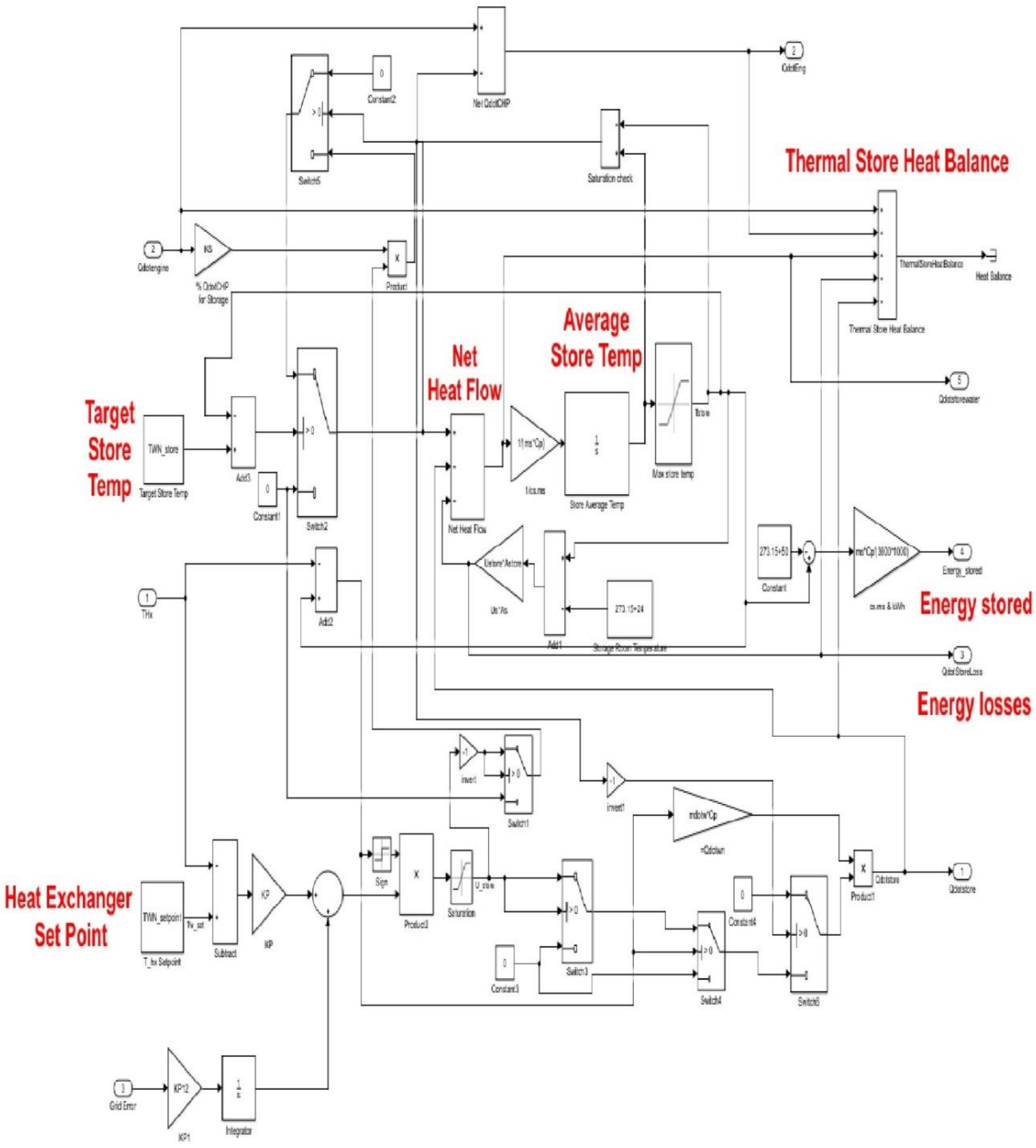


Figure D1 Thermal Store MATLAB Simulink

# Appendix E

## Energy Centre Simulink Design

This section is the heart of all the local energy systems containing the CHP Engine and Gas Boiler. Both of these represent the mean heat source of electrical power and heat energy. When the heat energy generated by the CHP engine is not adequate enough to keep the zones at a suitable temperature, the Gas Boiler will turn on automaticaly and produce enough heat to meet the shortage. The simulink design and programing is shown in figure E1 below.

```
        % Energy Centre and Water Network
 % CHP Engine
 Keng=1*413000/24;  % Note assumes first order
response SS Gain watts/%control signal  Arup
413000
 tau=300;  % time costant in seconds of the
engine
 KE=0.42;  %
 KQ=0.42;  %
% Central Gas Boiler
KBoiler = Keng*1.0;  %Boiler Gain watts/%control
signal 0 to 100%   Keng
 CBefficiency = 0.80;
```

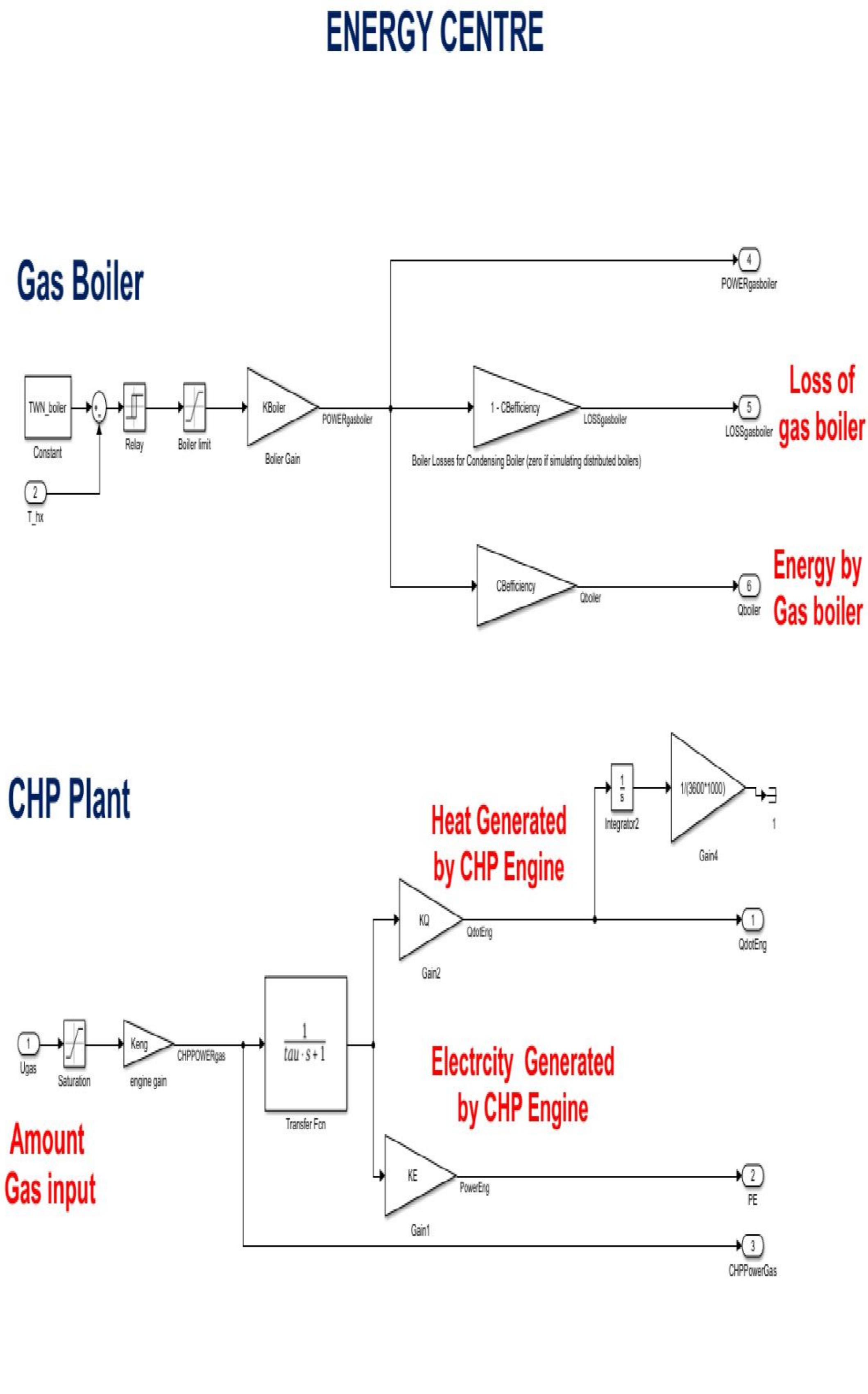


Figure E1 Energy Centre MATLAB Simulink

# Appendix F

## System Controller Simulink Design

This part of the local energy system represents the brain of the system. It controls the amount the gas injected inside the CHP engine dependant on electrical demand. The controller follows the electrical demand second by second to optimise itself and reduce the amount the gas used to a minimum. At the same time, the temperture inside the hot water network is controlled keeping it at a sufficient level to feed all the five zones. The control system MATLAB design is shown in figure F1 below.

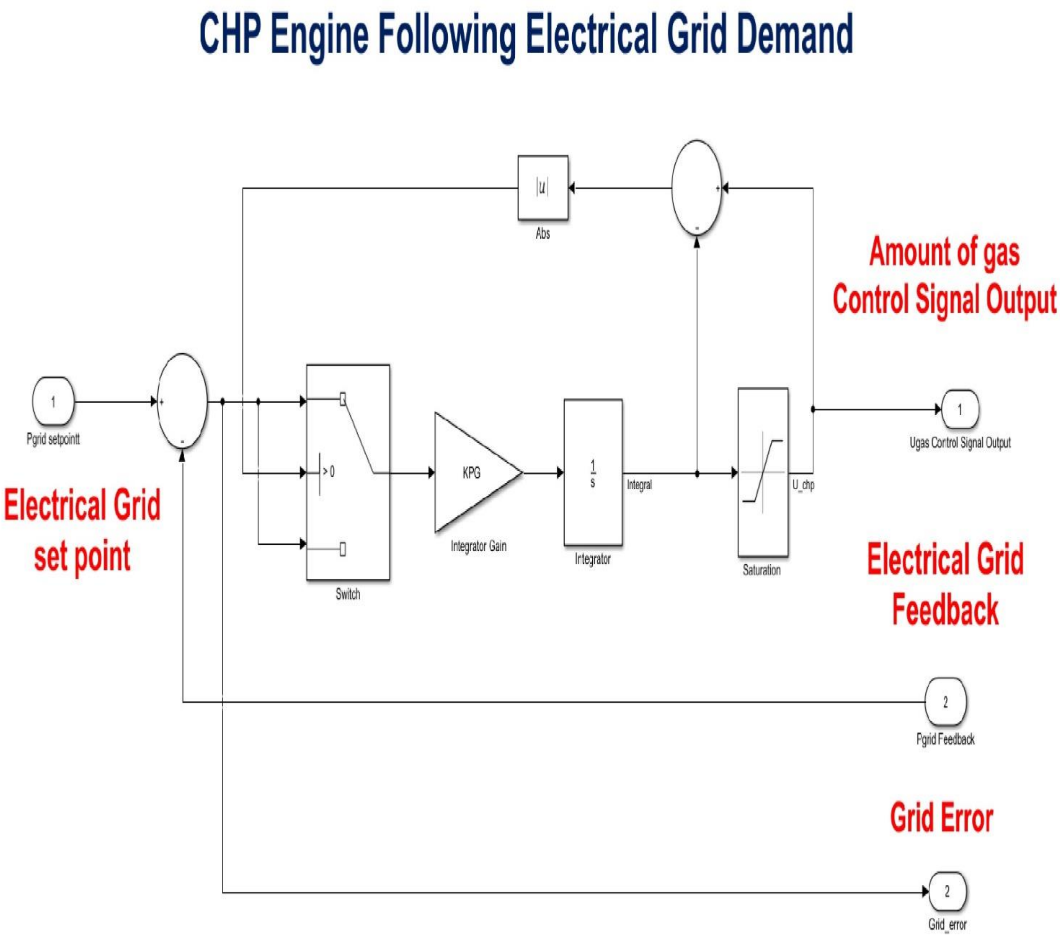


Figure F1 System Controller MATLAB Simulink

```
%  Controller parameters and setpoint.
Note sigma allows electrcity bandwidth to be
faster than heat
 g = (1/(3*tau));  rho = g*g/4;
 sig1 = 1; % for hot water network temperature
 sig2 = 20; % for grid power
```

```
invcb11 = sig1*mw*Cp/(0+ (mdotw*Cp*10));
invcb12 =  -sig2*(KQ*Keng)*0.5/((0+
(mdotw*Cp*10))*KE*Keng);
invcb21 = 0; invcb22 = -sig2/(KE*Keng);
KIG= 0; KI= 0;
KPG=g*invcb22; KP=g*invcb11; KP12 = g*invcb12;
Grid_Setpoint =0 ; % grid set point in watts +
export while negative import
```