Department of Mechanical and Aerospace Engineering

Design a secure hardware and software platform that will allow supervisory smart controls of energy centres to use 100% renewable energy for Heating, Transportation and Power

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Abstract

The conversion of heating demand and transportation to electrification to reduce carbon emissions increased the system's dependence on renewable production. Moreover, the Local Renewable energy generation is becoming more prevalent in buildings and areas to reduce emission and the cost of energy bills. Load shaping and demand side management employing real-time tariffs, storage, and control mechanisms are critical factors in incorporating the local renewable and low-cost system. The objective of this project is to introduce and examine existing hardware and software options for systems that can enable smart supervisory control, as well as to suggest a system architecture for smart control of an energy centre with heat pumps, storage, and renewable power.

The case study considered in this project of West Whins(WW), where a hardware software platform architecture is being proposed for the heating and hot water system for smart supervisory control. The step-by-step design approach is used to study the capabilities of data monitoring and communication hardware devices which are utilised for supervisory smart control at local and remote end. The suggestion for the best system is evaluated on characteristics such as availability, ease of installation, complexity, and cost. Overall, the suggested design may be used and physically implemented at WW, and the future work of control algorithms based on weather forecast, demand projection, and variable tariffs can be created in software to maximise local renewable energy consumption while lowering overall system costs.

Moreover, the future integrated system with storage, EV, and heat pump is also being studied to investigate the efficacy of the system's smart supervisory control. The integrated system can use the knowledge of suggested hardware-software design at WW to develop smart supervisory control at other systems and locations with relevant modifications. Furthermore, future smart metering is investigated in the study, which may aid in the replacement of OEM devices in the future to minimise system complexity and real-time management. The installation of smart metres can support the energy centre with low-cost connectivity for monitoring and control through RF-mesh and WIFI. Installation of smart metres will also aid in automatic energy billing and user interface. The proposed system can be used for long term hardware installation for smart supervisory control.

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Thanks especially to Graeme Flett, whose suggestions and previous work on the project provided me with a deep understanding of the project. He assisted me in thinking about the big picture and analysing all possible outcomes. Furthermore, I'd like to thank Paddy Atkinson for his knowledge sharing and customer experience with the project. I am grateful to Paddy for allowing me to perform a case study on the ongoing project and contribute my knowledge. I would like to thank Rocio Lopez Perez for her excellent work on the Open Energy Monitoring kits and documentation; it was extremely clear and intelligible, and it aided in understanding the open energy monitoring kits.

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Nomenclature

Symbol	Description
AC	Alternative current
API	Application Programming Interface
ASHP	Air Source Heat pump
COP	Coefficient of Performance
CT	Current Transformer
DC	Direct Current
DCU	Data Concentrator Unit
DHW	District Hot water
ESRU	Energy System Research Unit
ETP	Energy Technology Partnership
EV	Electric Vehicle
FPHE	Flat plate heat Exchanger
FTC	Fixed Temperature Control
GPIO	General Purpose Input-Output
HP	Heat Pump
KPI	Key Performance Indicator
M-bus	Modbus
NW	North Whins
OEM	Open Energy Monitor
PET	Park Ecovillage Trust
PV	Photo Voltaic
$\mathbf{Q_{out}}$	Heat Output
RF	Radio Frequency
R-Pi	Raspberry-pi
SH	Space heating
ST	Silver Trees
$\mathbf{W_{in}}$	Electrical energy Input
WW	West Whins

1. Introduction

This section will provide a project overview, including background information, a problem description, the project's goal, and the strategy used to produce the deliverable necessary for the project's success.

1.1 Background

Many efforts have been made across the world to improve load shaping and demand management using real-time tariffs, storage, and control methods (1). The UK government target to achieve 80% electrification of heating and transportation till 2030, which will add significant load on Grid (2). The renewable energy generation, demand side management and load shaping will help in grid balancing, however these are difficult to predict as they depend on variables like weather, consumers patterns and type of load. Energy storage, real-time monitoring, and smart controls will aid in mitigating the problem, and smart algorithms will aid in optimising the usage of local renewables. Smart controls will also be advantageous, as flexible tariffs will assist customers in planning their energy finances, allowing them to export the stored energy at peak time. The integrated system now a days having all the components like heat pumps, battery storage, EV, PV, thermal store, and other load, where the smart supervisory control can help in managing the variability of load and optimised operations of all devices in cost effective manner.

The Energy System Research Unit (ESRU) of the University of Strathclyde and the Park Ecovillage Trust (PET) in Findhorn have collaborated on an Energy Technology Partnership (ETP) initiative (3). Findhorn have local wind turbines, private wiring, thermal storage, PV, Battery storage system, and heat pump, which makes this site a good combination to study the system behaviours through monitoring and perform smart controls, to optimise the use of local renewable available. The smart controls will help them to minimise the import from grid and maximise the self-consumption of local renewable. It will be economical advantage if the Findhorn can export the excess energy at the time of peak.

There are previous projects done for Findhorn are ORIGIN project 2015 for monitoring and control, monitoring of the system at energy centre through open energy monitoring kit, modelling fixed order controls on PyLESA (4) (3) (1) (5). However, due to presence of different components and integration and dependency of one system on another made it difficult to implement a smart supervisory monitoring and control system for local renewable, heat pump, storage system at Findhorn.

1.2 Problem Statement

Earlier projects at Findhorn energy centre were limited to monitoring, with no smart control setup at all. The challenge in integrating smart controls is developing a system that can automatically feed real-time data, and smart algorithms can decide how to run devices optimally. A smart supervisory control that can monitor and operate heat pumps, storage, and local renewable generation is missing at Findhorn.

The main challenge revolves mainly around developing a hardware-software layer of devices capable of monitoring, processing data, and deciding control based on weather forecasts, demand forecasts, flexible tariffs, and other factors as required. System integration for data collection, processing, and control implementation is highly complex. To accomplish model-based predictive control, it is necessary to analyse the hardware and software protocols employed and their potential to conduct smart controls.

1.3 Project Aim

The objective of this project is to establish a smart supervisory monitoring and control capability for the heat pumps, storage-systems, and renewable energy centres at Findhorn (WW, NW, ST). This functionality will provide performance visibility; and allow the efficient use of local renewables. The specific focus in this work is to provide a secure hardware and software platform enabling smart supervisory control to allow increased renewable fractions and reduced costs. The smart control functions to be investigated range from simple logic 'fixed order' to 'model based predictive' controls based on forecasts and system characteristics (demand, weather, prices, and renewable forecasts; state of charge). The recommendations will be made to reduce the complexity of the hardware, software layers and it can be applied for the generalise heat pump system as per the user requirements.
The Findhorn energy centre, which has local wind turbines, solar thermal, PV, batteries, and heat pumps, may be utilised as a case study to create a platform with hardware devices and a software protocol for smart controls.

1.4 Approach Statement

The following measures have been taken to accomplish the goal of the project:

- To develop a knowledge base, a critical review of the system at Findhorn was conducted. Furthermore, the different potential hardware devices and software protocols are being examined to better understand their capabilities for performing smart controls.
- The design concept is being examined to comprehend the design strategy for smart controls.
- Understanding the design approach of smart controls for designing the hardware-software interface for supervisory smart controls.

- Design specifications should be studied to understand the requirements under which the system should consider performing smart controls.
- Different design options must be analysed to understand the benefits and drawbacks of certain designs and give suggestions for the best design option for hardware- software platform.
- The Design option selection and the selection criteria should be identified.
- Visualization of completed project and project limitations for future work.
- Future suggestions and proposal of the system architecture for smart controls.

1.5 Deliverable

The project's outcome is an analysis of various options for providing a secure hardware-software platform enabling smart supervisory control for WW's heat-pump, thermal store, and solar thermal. Moreover, recommendations are made on the best suited option based on variables such as cost, robustness, installation time, and complexity.

1.6 Scope of the Project

The scope of this project is to provide a secure hardware software platform to perform the supervisory controls of heat pumps, solar thermal integrated with renewables and storage based on forecast and real time data gathering. This project is limited to the system design and analysis of various hardware and their interfacing with each other. The actual hardware connections and coding part for control algorithms will be achievable tasks, however due to time limitation it will be not covered in this project scope.

2. Critical Review of the system and the Hardware-software interface

2.1 Structure of Critical Review

To propose a supervisory smart control for a heat pump, it is necessary to comprehend the entire system as well as each component independently. To build a hardware-software interface, a thorough study is performed to understand the different communication protocols and devices that may be employed for data collecting and data processing. The following is the strategy followed to perform the review:

- First, it is critical to understand the existing system at West Whins (WW) to understand the system and the need for controls. A critical review has been conducted to understand the heat pump system at Findhorn West Whins, the site's local renewable energy generation capacity, and the details about the Mitsubishi and Ochsner's air source heat pumps.

- The OEM devices implemented for monitoring in prior projects were examined for their control and communication capabilities to execute the needed smart control function. All the OEM devices are compared in this section. Furthermore, the OEM user interface is being examined to comprehend prior work and future project scope.
- Research is being conducted to identify alternative hardware for OEM, understand the constraints, and decrease system complexity, cost, and reliability.
- After rigorously examining other devices such as the Raspberry Pi, communication methods, and coding platforms to ensure a seamless data flow.
- The variable factors responsible for smart supervisory controls, are also investigated to check their connection with software interface.

The next section is detailed review as per the approach explained above.

2.2 Analysis of System at Findhorn West Whins

The "West Whins" development at Findhorn Ecovillage is a 6-flat affordable housing complex powered by a central energy centre with a 14kW air source heat pump (ASHP) from Mitsubishi for space heating and domestic hot water supply via a wet system, a 550-liter hot water thermal store specifically for the DHW supply, two 64 kW immersion heaters and 13.8 m^2 solar thermal panels that directly charge the DHW store. The simple schematic of the system is shown below in figure-1 and the detailed system diagram can be seen in appendix-1 (3).

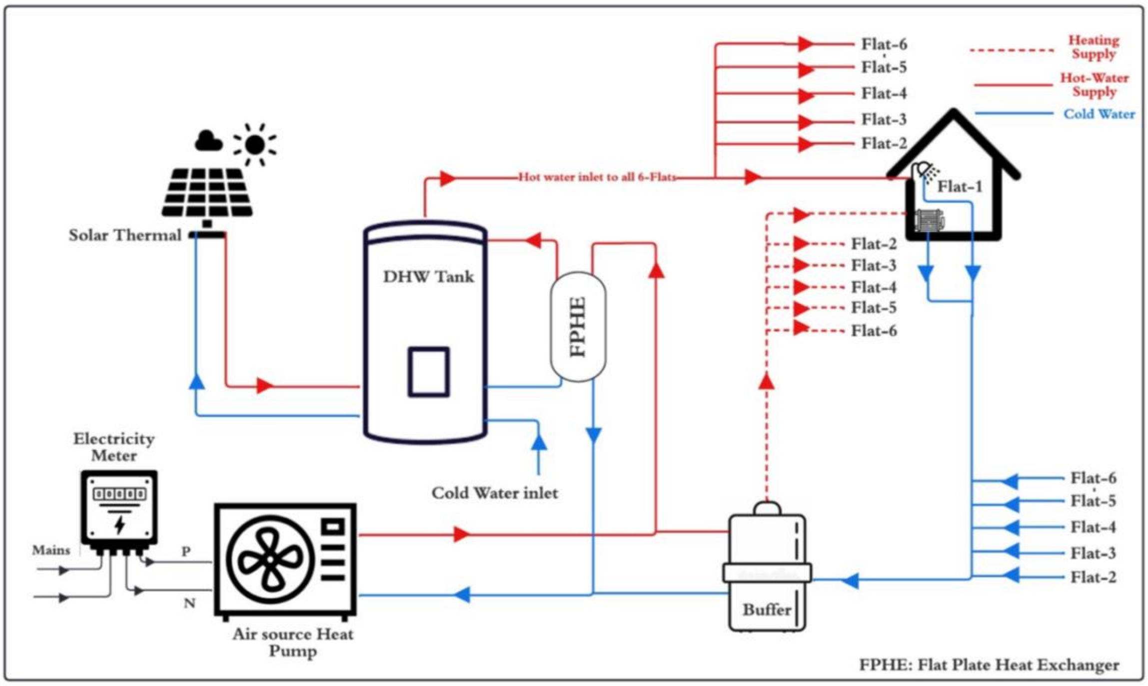


Figure 1: Simplified Schematic system for heating and hot water supply at WW (3)

The heating demand from all the flats is supplied directly from the heat pump with the help of 100-litre buffer tank. This is done largely for flow and pressure stability and to prevent short cycling. The system has simple switch control from Mitsubishi called FTC-5, and the heat pump is switched on when there is demand of heating from tenants. The feeding water temperature to radiator is 45^o, and the heat pump operates at a lower temperature when meeting heating demands than when meeting hot water demands.

The DHW hot water tank stores thermal energy at the setpoint temperature for the tank, which is 55 ^oC. If there is insufficient thermal energy, the heat pump recharges the tank to keep the temperature at 55 ^oC. The heat pump will prioritise charging the DHW tank to maintain the temperature for hot water supply if there is a heating demand and the DHW temperature drops below 55 degrees. Moreover, the tank has two immersion heaters which can be powered manual for back up energy and legionella prevention temperature cycle and heats the whole store to 60^{o}C degrees (4).

2.3 Analysis of Local Renewable Generation at ETP Findhorn

There are now three 225kW wind turbines at Findhorn that are directly connected to the grid. In addition, the Park has 75kW of solar energy capacity that is wired into the New Findhorn Direction (NFD) distribution system. The energy demand which is not fulfilled from Wind or PV generation is imported from grid and the two types of tariffs are currently considered in Findhorn by energy providers (4) (6):

- Single Tariff: 21.03 per kWh
- Dual Tariffs: 22.03 per kWh from Morning 07:30 AM to 11:30 PM and 18.76 per kWh for overnight.

2.4 Air source Heat Pump Operation and Performance

The air source heat pump (ASHP) converts heat from the ambient air into a low-temperature liquid refrigerant. The pump compresses the liquid to raise its temperature using electrical energy. It then condenses back into a liquid to release its stored heat. Heat is sent to radiators or underfloor heating (6).

The coefficient of performance (COP) is used to determine the efficiency of heat pumps, the COP formula is as follows:

$$\text{COP}=\frac{Q_{out}}{W_{in}} \qquad \text{Equation-(1)}$$

Where, Q_{out} = Heat output from ASHP, and W_{in} = Energy input to ASHP. The normal range of COP for ASHP is in between 2 to 4. The system at Findhorn at WW has ASHP from Mitsubishi, however, the new planned sites like north Whins(NW) will be installing Ochsner's Water source Heat Pump. The key features for Mitsubishi and Ochsner's heat pump are discussed in the points below:

2.4.1 Heat Pumps by Mitsubishi

As one of Mitsubishi's most cutting-edge heating systems, the Ecodan family of air source heat pumps are intelligent, incredibly adaptable, and compatible. They also can be optimised to lower CO_2 emissions and operating costs.

The Ecodan ASHP has compatible to communicate through Wi-Fi with MELCloud system, it has mobile metering, monitoring and control (7)l. The figure below shows the user interface of MELCloud (8).

Figure 2: MELCloud User Interface & Wall controller Unit for Ecodan- FTC-5 (8)

Image credit: Mitsubishi MELCloud User Manual, 2021

The Ecodan Fixed temperature control Unit-5 (FTC-5) is capable to allow control the heat pump manually using the wall unit shown in Figure-2, as well as remote control using the WIFI communication with MELCloud. To perform the control operations either rule based or smart controls the communication is important part. The control command should be transferred to the heat pump, so that heat pump can perform the desired operations. To perform the communicate the Mitsubishi is giving provisions with the help of separate hardware units explained in next paragraph.

To use the MELCloud a small WIFI unit need to be installed with heat pump which will enable the WIFI and allow MELCloud to receive and send the commands. Moreover, the Mitsubishi heat pump also support Modbus communication through a Gateway and allow control operation through it. The separate hardware requires for WIFI interfacing (Wi-Fi PAC-WF010-E) and Modbus communication (A1M Modbus Gateway) are show in Figure 3 below (7).

Figure 3: WIFI Interfacing Hardware and Modbus Gateway for Mitsubishi

Image credit: Mitsubishi MELCloud User Manual, 2021

2.4.2 Heat Pump by Ochsner

The Ochsner is another manufacturer of heat pumps. The Ochsner’s systems are intelligent as well as it incorporates smart grid and control functions. However, there is no evidence that this system can be communicated by external hardware with node-red or any other alternative. Some of the key features of Ochsner can be seen below in detail (9):

- **Smart Grid Ready Using flexible tariffs**

The Smart Grid capability allows users to acquire favourable prices for running a heat pump in the future grid. This mode balances out peaks; Smart Grid-enabled heat pumps turn on if extra electricity is available at a low tariff and store it as hot water.

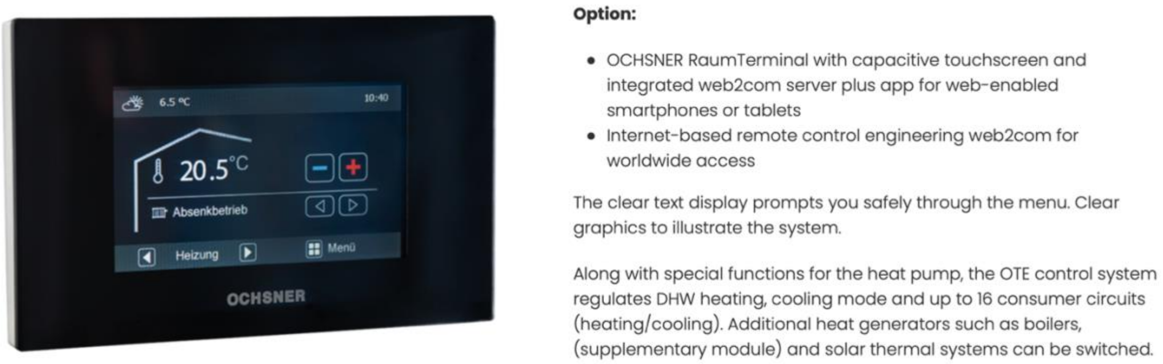
- **Remote Operations**

OCHSNER may be connected into Smart Home systems at any moment through central building management systems and Smart Grid connections. Not only that, but heat pumps may be managed from anywhere in the globe using a PC, tablet, or smartphone.

- **Silent mode of Operation in Summers**

The fan speed is lowered in quiet mode according to a predetermined proportional function based on the outside air temperature. This guarantees that the system's already exceptionally low noise emissions in ordinary operation are further decreased, for example, during DHW or pool heating in the summer. OCHSNER includes this feature as standard in all GMLW series appliances.

Ochsner can provide a user interface which can allow consumers to operate it remotely as shown in figure below (9):



Option:

- OCHSNER RaumTerminal with capacitive touchscreen and integrated web2com server plus app for web-enabled smartphones or tablets
- Internet-based remote control engineering web2com for worldwide access

The clear text display prompts you safely through the menu. Clear graphics to illustrate the system.

Along with special functions for the heat pump, the OTE control system regulates DHW heating, cooling mode and up to 16 consumer circuits (heating/cooling). Additional heat generators such as boilers, (supplementary module) and solar thermal systems can be switched.

Figure 4:Ochsner's Heat Pump Monitoring and Control Touch Display (9)

Image credit: Ochsner Heat Pumps Website

The challenge with this system is same it can perform the predefined functions and it will be difficult to incorporate several factors into the system without using any external hardware device. The challenge here is to understand that Ochsner's system can communicate with raspy or any other external device or not?? The Findhorn new development site are in progress to install the heat pump from Ochsner, so this system will be future scope of study for monitoring and control.

2.5 **DHW Tank Operations**

The DHW tank has Solar heater (SH) coil at bottom, which charges the bottom 30% of the tank. Moreover, the indirect heat exchanges (FPHE) shown in Figure 1 runs by ASHP, charges the upper 70% of the tank. There are 2 Immersion Heater present in the tank for backup heating and legionella protection. The bottom Immersion heater is used to charge the tank on 60 degrees once per week for legionella cycle (3).

When the temperature sensor at a height of 30% above the tank's bottom drops below a predetermined low temperature setpoint, the HP heat exchanger is turned on. Until the sensor registers the supply temperature of 55°C, it will keep functioning. The HP is configured to prioritise the DHW tank demand over the SH demand.

The Heat Pump(HP) immediately provides SH on demand. A 100-litre buffer shown in Figure 2 has been built to prevent short cycling of the HP. The radiators in the home should be fed at a nominal flow temperature of 45°C. The individual SH demand is measured by heat metres that are put on each of the SH supply lines to the residences (3) (10).

2.6 **Analysis of Open energy Monitoring kit**

For the purposes of monitoring and control, the Open Energy Monitoring Kit (OEM) is analysed. The OEM is evaluated based on its data processing capabilities, hardware, and software, as well as its emoncms user interface (11).

OEM is pre-assembled open-source, pre-assembled energy monitoring kits with hardware that is based on the Arduino and Raspberry Pi platforms. They also provide a web application called emoncms with the kit that may be used for data processing, storage, and visualisation. Moreover, OEM has a vibrant online community and forum online platform where users and developers may interact and exchange ideas.

The OEM have various hardware which can be selected according to the requirements, and all have different capabilities and communication protocols for Data processing. The OEM has communication Protocols like Radio Frequency(RF), and WIFI for wireless comms and, Modbus and ethernet for wired comms. In the sections below, the comparison and detailed analysis of OEM hardware and software will be performed.

2.6.1 Comparison of Various OEM Hardware

The OEM has different hardware with different functionality and capabilities. The OEM hardware are emonPI, emonTH, emonTX, emonBase which comes up with power adaptors, and necessary sensors to be connected (10).

The table below shows the various properties of OEM hardware in details, to understand and compare the capabilities of OEM Hardware.

Table 1: Comparison of different OEM Hardware's

	emonTX	emonPI	emonTH	emonBase
LCD Display	No	Yes	No	No
Powered by	AC Adaptor	5V DC Adaptor	Battery Powered	5V DC Adaptor
AC Voltage Sensor Input	1	1	0	0
Number of CT sensor Input	4	2	0	0
3-phase measurement	Recommended	No	No	No
Powered by Batteries	Yes	No	yes	No
Integrated Raspberry-pi base station	No	Yes	No	Yes
SD Card Provision for Data Storage	No	Yes	No	Yes
Communication Protocol	RF	RF and WIFI	RF	RF and WIFI
Control Option	No	No	No	No
Collects Data	Yes	Yes	No	No

Hosts Emoncms	No	Yes	No	Yes
Measurable Electrical Quantities	apparent power, real power, power factor, RMS voltage and current on four mains circuits	apparent power, real power, power factor, RMS voltage and current on four mains circuits	Temperature and humidity	N/A

Moreover, an RJ485 connector would be used to connect the DSB1820 sensors to detect temperature using the emonTX and emonPI. After registering the device, any device can display the emoncms user interface to monitor the data gathered by the hardware; this interface is password-protected for all users.

2.6.2 Comparison of OEM communication Protocols

The OEM devices capture and transfer data via both wired and wireless connection. The sensors, such as the current transformer (CT), temperature sensors (DSB1820), and AC voltage adapters, are wired together at the hardware's designated places. These sensors will gather data, which is then sent through remote communication to the hub (emoncms). The many protocols that OEM hardware supports include (10):

1. Ethernet/WIFI: WIFI is supported in emonPI and emonBase Hardware's
2. RF: RF is supported in emonTX, emonPI, emonTH, and emonBase

The devices and their communication can be shown in Figure 5 below:

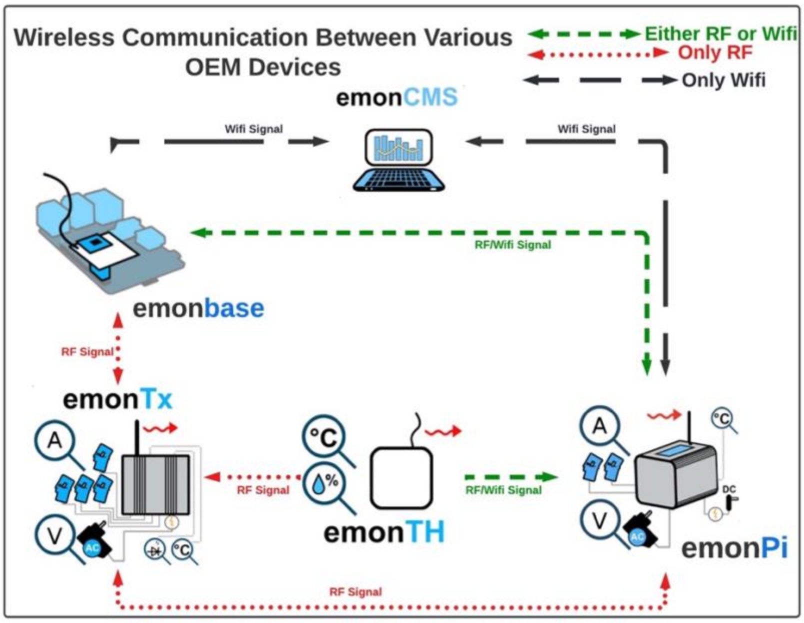


Figure 5: Communication Protocol Between Various hardware's of OEM (11)

2.6.3 Analysis of emoncms.org

Data from the emonPI-connected devices is automatically collected by emoncms local (12). All the data that is available locally will also be available on emoncms.org after a link has been made between emoncms local and emoncms.org (11). Through the Node-Red programming environment, other devices may be added to emoncms. Flett et al. (3) already included M-Bus data using this technique.
Rocio Lopez in her thesis has investigated into monitoring and creating apps and dashboard for Findhorn. She used the features of emoncms to create user dashboards and Graphs according to the input feeds from WW Site data collected by hardware installed (4).

2.6.4 Limitation of OEM Kits

The complete analysis of OEM devices suggests these are very easy to useful, compact, and open sources devices for energy and heat pump monitoring. However, these devices have some limitation at Hardware and software levels which are explained below (13):

Hardware Limitations: The system is complicated since it uses separate hardware for different operations. Together, OEM devices can benefit in monitoring, but buying separate hardware for various operations results in an increase in system cost and complexity.

Software Limitation: For instance, emoncms.org prohibits the usage of the post processing module. This implies that the input module must perform all the data processing necessary to build the dashboards first. On emoncms, there are just core modules accessible, thereby limiting the possible modules. Moreover, the emoncms can be updated by its developers only and the other customers can edit the features given by developers as open source.
Furthermore, the internet connection and remote connectivity are crucial components of OEM devices; if connectivity is lost, the data monitoring on emoncms stops; alternatively, the data may be kept on an SD card, but only for a certain amount of time. If OEM devices experience repeated power outages, the SD card may also get corrupted, resulting in data loss.

2.7 Analysis of Other Hardware suitable for controls with or without OEM

After analysing and studying OEM features, monitoring capabilities and limitation of OEM devices, the other hardware’s need to explore which can be used as an alternative option to reduce the system complexity and increase robustness of the system. The OEM devices have pre-assembled Raspberry-pi in some hardware’s, however that is limited for functions as specified by the developers. Therefore, it is required to investigate the broader capabilities of these hardware’s. The brief discussion about the different hardware’s can be seen below:

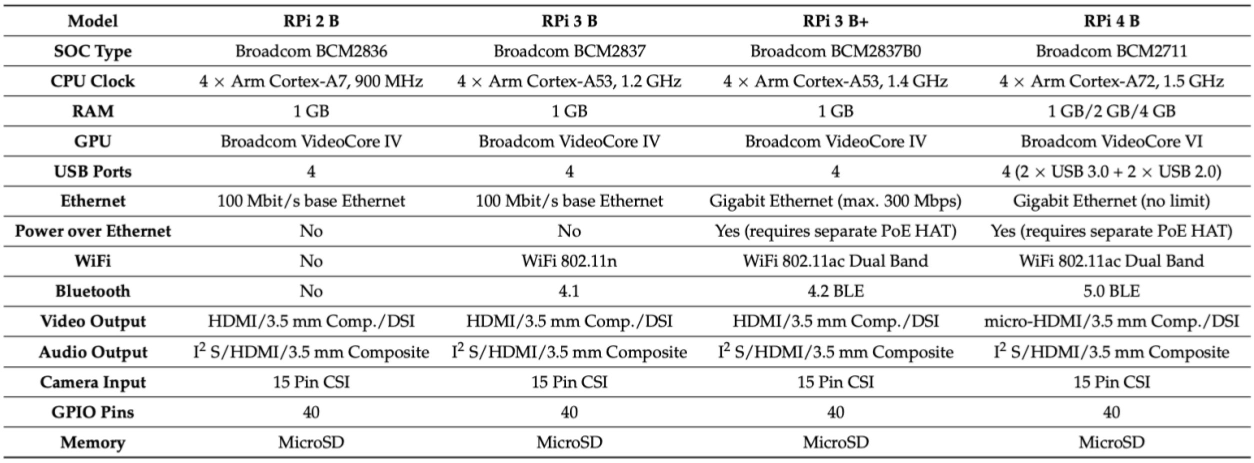
2.7.1 Raspberry-pi Capabilities

The Raspberry-pi(R-pi) is used as a microcomputer to process the data and perform the required operation like data algorithms. The OEM's emonPI has prebuild Raspberry-pi with Arduino which is responsible to monitor and analyse the energy systems and heat pumps (14).

The R-pi is an open source and relatively affordable Linux-powered computer that also features a set of general-purpose input/output (GPIO) pins that let you operate electronic devices for physical computing and investigate the Internet of Things (IoT). Since the first introduction of the Raspberry Pi in 2012, several upgrades and variants have been made available. The most recent generation of the Raspberry Pi includes a quad-core CPU clocked at over 1.5GHz and 4GB RAM, in contrast to the original model's single-core 700MHz CPU and just 256MB RAM. Moreover, with the Raspberry Pi, the user could construct their own home automation projects, which is well-liked in the open-source community since it gives you control over the process rather than relying on a proprietary closed system.

The system characteristics of various raspberry-pi hardware shown in table below:

Table 2: Raspberry-pi Various Hardware specification and comparison (14)



Model	RPi 2 B	RPi 3 B	RPi 3 B+	RPi 4 B
SOC Type	Broadcom BCM2836	Broadcom BCM2837	Broadcom BCM2837B0	Broadcom BCM2711
CPU Clock	4 × Arm Cortex-A7, 900 MHz	4 × Arm Cortex-A53, 1.2 GHz	4 × Arm Cortex-A53, 1.4 GHz	4 × Arm Cortex-A72, 1.5 GHz
RAM	1 GB	1 GB	1 GB	1 GB/2 GB/4 GB
GPU	Broadcom VideoCore IV	Broadcom VideoCore IV	Broadcom VideoCore IV	Broadcom VideoCore VI
USB Ports	4	4	4	4 (2 × USB 3.0 + 2 × USB 2.0)
Ethernet	100 Mbit/s base Ethernet	100 Mbit/s base Ethernet	Gigabit Ethernet (max. 300 Mbps)	Gigabit Ethernet (no limit)
Power over Ethernet	No	No	Yes (requires separate PoE HAT)	Yes (requires separate PoE HAT)
WiFi	No	WiFi 802.11n	WiFi 802.11ac Dual Band	WiFi 802.11ac Dual Band
Bluetooth	No	4.1	4.2 BLE	5.0 BLE
Video Output	HDMI/3.5 mm Comp./DSI	HDMI/3.5 mm Comp./DSI	HDMI/3.5 mm Comp./DSI	micro-HDMI/3.5 mm Comp./DSI
Audio Output	I^2 S/HDMI/3.5 mm Composite	I^2 S/HDMI/3.5 mm Composite	I^2 S/HDMI/3.5 mm Composite	I^2 S/HDMI/3.5 mm Composite
Camera Input	15 Pin CSI	15 Pin CSI	15 Pin CSI	15 Pin CSI
GPIO Pins	40	40	40	40
Memory	MicroSD	MicroSD	MicroSD	MicroSD

The Raspberry Pi features many GPIOs that can process several input and output functions at once and perform multiple tasks concurrently. It supports RF, WIFI and wired communication protocol. While it is easy to use and open source with lots of capabilities, it is suitable for taking data from sensors like temperature sensors directly and from heat meters or energy meters through Modbus or Optical communication. However, the R-pi has limitations in terms of analogue to digital converter(ADC) signals, which can be used to measure AC signals for voltage and current measurements. Due to the absence of ADC in R-pi, it is limited to energy measurements, and it will require another hardware which have ADC which can sense the signal and transmit to R-pi, in the format it requires through GPIO. That is why the OEM is using the combination of R-pi and Arduino.

2.7.2 Arduino Capabilities

An 8-bit microcontroller development board called Arduino has a USB programming port for connecting to a computer and other connection connectors for connecting to external devices like speakers, motors, and other types of sensors. It features input and output pins, with the input pins having the option of being either digital (0–13) or analogue (A0–A5), while the output pins are only digital (0–13) (15). The Arduino integrated development environment is open source and includes a cross-compiler, a debugger, and a serial monitor to control the inputs and outputs. The Arduino board design is likewise open source. Arduino can be powered by a 9V battery, a power source, or by the USB connection from the computer.

The Arduino has ADC, which can help in measurement of AC quantities with the help of sensors like CT. The Arduino coding requires a knowledge base of microcontrollers and embedded coding, and it can be used for the desired functionalities. The Arduino coding can be uploaded to hardware using a special programmer; however, the R-pi doesn't need any programmer for coding.

The comparison between R-pi and Arduino can be seen in table present in appendix-2.

2.8 Introduction to various software Protocols for communication

Remote control procedures involving fixed controls or model-based controls require real-time data gathering and processing, which is a major aspect. Communication between the devices is required to gather real-time data or to understanding device status. The functions of monitoring and control are carried out using a variety of communication protocols, such as WIFI, RF, and Modbus. The following is a detailed summary of the communication protocols:

2.8.1 Wi-Fi Communication

The most widely used WLAN protocol for IoT devices, Wi-Fi (Wireless Fidelity), operates on the 2.4 GHz UHF and 5 GHz ISM frequencies and is based on the IEEE 802.11 standard. Devices that are between 20 and 40 metres from the source of Wi-Fi can access the Internet. Depending on the antenna count and channel frequency chosen, it can transmit data at a maximum rate of 600 Mbps. Building IoT-based applications is a prominent use of Espressif ESP series controllers in embedded systems. The most popular WIFI modules for embedded applications are the ESP32 and ESP8266 (16). The OEM, and R-pi has inbuilt ESP module for WIFI communication for monitoring and smart controls. However, to use WIFI communication for data transmissions a stable internet is required and losing in connectivity can end up losing data. Moreover, Wi-Fi infrastructure costs are minimal, and deployment is simple, it consumes a lot of power and has a somewhat limited range.

2.8.2 Radio Frequency and Mesh Network

A technique known as radio-frequency identification (RFID) utilises electromagnetic fields to detect items or tags that have information recorded on them. The maximum range of RFID is around 200 metres, and because of the large disparity between the two ranges, they are referred to as short-range distance and long-range distance. Given the vast differences in range, the frequency at which RFID functions also varies greatly; it starts at kHz and goes up to GHz, or, depending on the application and communication distance, the frequency ranges from low frequency (LF) to microwave (16).

Each RF module has a unique ID address that it will use to communicate and transfer data to other RF modules. Antennas can be used to extend RF range. Data is sent utilising the RF Mesh using different RF modules with unique addresses. RF communication is limited to sending data from one module to other, it has no capabilities to transfer data to cloud or transfer at very long distance.

The RF Mesh communication usually being used in smart meter communication, where there is communication mesh created from one meter to another to transfer the data. The advantage of this communication is the data can be transmitted from one meter to other and the internet is not required at all the locations. . The main RF Mesh benefit is that it can connect utility customers with smart grid systems in the densest and most complicated urban environments, while having the functionality to communicate with more traditional grid systems, whether fibre optics or cell phone towers are difficult to manage, or operation is costly.

The below figure shows the RF mesh communication of smart meters, the Data concentrator unit (DCU) on nearby poles(Access point) contains RF and WIFI module both which help in collection of data from smart meters through RF and transfer it to cloud with the help of WIFI.

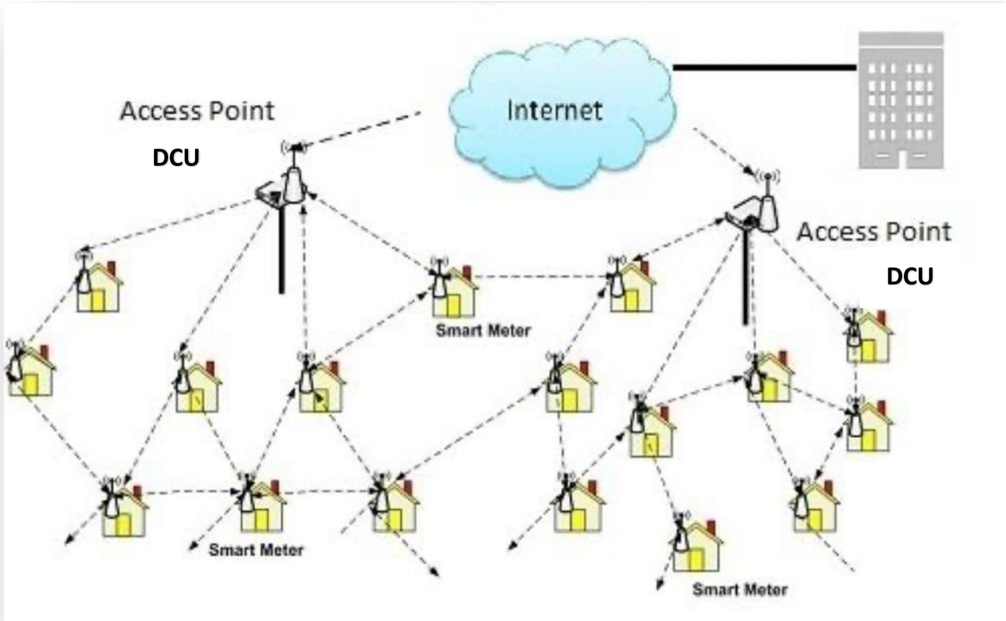


Figure 6: RF Mesh communication of smart meters (17)

2.8.3 Wired connection

Connecting devices with wire and transferring data is the traditional way of doing the data transmission from one device to other. The wired communication is robust and most stable. However, this cannot make sense where there are multiple devices at longer distance.

2.8.4 Modbus

A master-slave communication protocol called MODBUS may accommodate up to 247 slaves linked together in a bus or star network. A simplex connection over a single line is used by the protocol. In this method, the communication messages go in two opposing directions along a single line. The master- slave communication can be reading, writing, or broadcasting. It is a wider communication protocol used in industries for the control of electrical and electronics devices. However, it is again a type of wired communication and require direct connection with devices. Modbus is most typically used in conjunction with RS-485, a hardware standard that allows several devices to be linked on the same bus (18).

Each Slave device on the bus must have a unique ID, known as a Slave ID. Each Modbus command sent by the Master will include this Slave ID, and only the Slave with that Slave ID will respond.

2.9 Introduction to Software Interface to write Controls

After looking into the hardware, software and communication protocol, the next very important stage is to write codes for controls. The smart control cannot be possible without interfacing various hardware, software and link them through the coding. There are various types of coding which developers use to perform different operations of the devices, however node red, MQTT and Python are being discussed for this project due to limited scope. The research suggest that the coding can be done in any language, and it is totally dependent on the developer and the type of functions and usability of the coding language. The coding requirement for heat pump supervisory control has been capable of processing various API's and perform the operations. The coding is not in the scope of this project however the overview and analysis of coding need to be done for deciding the hardware and software interfacing. The brief description of some coding language is investigated as follows:

2.9.1 Node-Red

Node-RED is a programming tool for creating new and intriguing connections between hardware components, APIs, and web services. With the help of the extensive selection of nodes in the palette that can be deployed to its runtime with a single click, it offers a browser-based editor that makes it simple to wire up flows. Users can store practical functions, templates, or flows to a built-in library for later usage. The node red can be launch by R-pi on browser. The API for weather, demand and flexible tariffs can be given in node red as input nodes and the functions can be perform for the smart controls of heat pump (19). Moreover, the emonPI could run additional software in addition to the default OEM programmes, such as Node-Red, which can be used for more intricate monitoring and control functions using protocols like MQTT or Lightwave RF. To acquire data from the West Whins heat pump using the already-existing M-Bus system, the Node-Red feature was evaluated for this project.

2.9.2 MQTT

The Internet of Things uses the OASIS-standard communications protocol MQTT (IoT). It is intended to connect remote devices with a very tiny code footprint and little network traffic using a publish/subscribe message transport. MQTT is being utilised in a wide range of sectors, including the automobile, manufacturing, telecommunications, oil and gas, etc. MQTT is bidirectional, lightweight, efficient, reliable and security enable communication protocol. This is being used in OEM as well for using emoncms and other modules (20).

2.9.3 Python and Java

Python and Java are the very strong coding language for the developers. Python is an interpreted language with dynamic typing, while Java is a statically typed and compiled language. Java is quicker at runtime and simpler to debug because to this one distinction, while Python is simpler to use and understand. Python and Java both can be used for R-pi and OEM devices. The future work in this project will be analyse the best language of coding to write the codes for smart supervisory control of heat pump. This task will help the developer to define their scope and understand the hardware capabilities used in this project.

2.10 Factors Used in Smart Control decision making

Real-time data and algorithms are needed for the model-based predictive controls of heat pumps to make decisions about how to control the heat pumps in the system. It's crucial to utilise the monitoring data gathered from OEM, along with weather forecasts, demand forecasts, and flexible tariffs, to select the controls while examining the system at WW and comprehending the numerous components employed in heating and hot water delivery (1). To comprehend the supervisory controls, the significant aspects are briefly examined in this portion of the literature review.

2.10.1 Demand Profile

There are 6 flats at WW, and the demand profile for all the properties are different as it is dependent on user pattern for heating and hot water. The Rocio’s project on monitoring of heat pump s at WW investigated the demand profile and generated the dashboard for individual flats. The previous project done by Rocio will help to analyse the user demand patterns and use them for supervisory smart controls.

2.10.2 Flexible Tariffs

The current two tariffs which are in use in WW are single and dual tariffs explained in point 2.2. The smart controls in future will be require future flexible tariffs to be considered. Octopus Agile, time of day and time of use tariffs can be implemented in OEM, and these will be required for smart controls of the system as well (4).

Octopus Agile: Energy distributor Octopus Energy focuses on offering clients 100% green electricity rates (21). With a dynamic tariff known as Octopus Agile, power costs fluctuate based on the half-hourly retail price of energy. By enticing consumers to shift their consumption to off-peak hours, when power is less expensive, this rate violates DSM (22). To enable consumers to design smart devices to operate during off-peak hours, Octopus has now made its Agile Octopus API public (23).

Future wind Tariffs: The future wind tariff offers significant pricing differences between windy and non-windy hours in addition to the day/night differential, which encourages load shifting (24).

2.10.3 Local Renewable Generation

Another important consideration for smart heat pump controls will be the local renewable energy generation. To ensure the effective use of local renewable energy, the thermal storage and nearby wind turbines at the Findhorn energy centre will serve as the main sources of heating and charging the DHW. However, the heat pump will turn on and charge the DHW to meet the demand if there is less renewable energy due to weather conditions (3).

2.10.4 DHW stored Energy

The OEM kits installed by Graeme and dashboards created by Rocio in her previous project will help to understand the energy storage status of DHW tank with the help of temperature sensors. The already stored energy will also impact the smart control operations based on model based predictive control.

2.10.5 Weather forecast

the local renewable generation and weather forecast will help to understand the renewable energy generation at site, and it will help to decide to operate the heat pump on green energy and charge the DHW tank when surplus of energy available like sunny day for solar thermal. The weather forecast for next day or next hours will help decide the smart control system about the switching of heat pump and charging of DHW tank (1).

2.11 Summary of Critical Review

All the components studied above in critical review helped to create a knowledge base to understand the key components required for system level design of supervisory smart controls. The hardware devices studied like OEM, R-pi. Arduino, or communication protocol studied like RF, WIFI will help in designing the hardware-software platform in upcoming section for smart supervisory control. The analysis of system and hardware will help in deciding the devices as per their capabilities and the limitations. Moreover, the detailed study of the system components will help in understanding the smart controls and data transmission in detail.

3. Design Concept of Smart Control

Smart controls are the integration of energy-consuming equipment, communications technology, analytics, and control systems to enhance energy efficiency and meet operational requirements (25). Designing the concept of smart controls will require identifying the process level and the hardware devices.

Field devices and sensors attached to controllers or directly to a system headend, are monitored by the basic control system. The control system receives data from sensors and field devices. This data is then gathered and monitored in real time, and the algorithms are processed by a supervisory control, which then commands the control signal to the local controller, and that's how smart control works.

The diagram below illustrates the smart control concept in four stages, from data measurement and monitoring to data processing and control. These four steps are critical for understanding the hardware and software interface necessary in designing of smart supervisory controls.

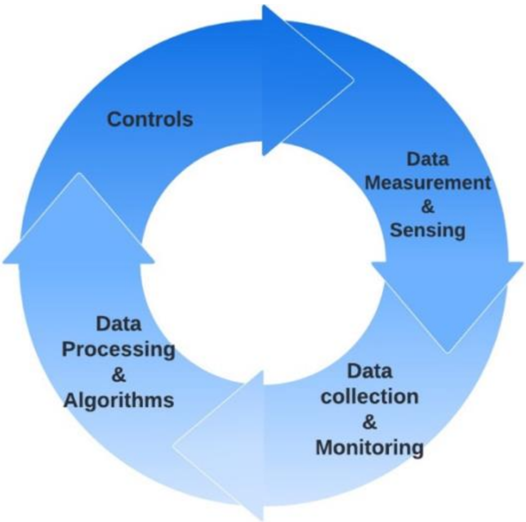


Figure 7: Data Process Cycle for Smart controls

Data Measurement: This step is very basic and crucial stage as the control is always dependent on the system behaviour and measurement of the data with the help of sensors. The sensor collects the data and transfer it to the next stage through wired or wireless communication. In the case of WW, the data collection is being done by heat meters, energy meters, CT’s and Temperature sensors for the heating and hot water system through solar thermal and ASHP (3).

Data Collection and Monitoring: The data collected or measured by the sensors transferred to next stage where the devices like OEM or R-Pi will collect the data and help in monitoring if required. The data is transferred through wired or wireless connections like Modbus or RF (11). The OEM devices at WW allow the measured data to be displayed on emoncms.org in dashboards and apps, where the user can visualise the real time performance of the system.
The monitored data then be used in the next stage where the processing will take place.

Data Processing & Algorithms : The local control and supervisory control commands will be handled at this level. The data collected from monitoring devices such as OEM and R-Pi, as well as other sources such as weather API, tariffs, and other useful system data, is processed in Node-red or any other software platform. The algorithms of smart controls will decide the system operation based on the real time data or future forecast and generate the control command (19). The control signals are transmitted to the next hardware where the control commands can be directly transferred to the devices like heat pump in WW.

Controls: This stage will receive the commands from the supervisory control system and the received command help in performing the smart control operation automatically for the various devices.

The whole smart control system is combination of various hardware, software devices which communicates with each other, the data and signal flow take place to perform the control operations automatically based on the real time algorithms. The layer diagram can be seen below with the various devices and the data type for smart controls of different devices. The base layer is data measurement taking place with sensors, heat meter and energy meters. The measured data from sensors will be collected by devices like OEM or R-Pi to allow monitoring, it will now be processed with algorithms in next stage in supervisory control system for Example R-pi Node-red and remote server in below diagram.

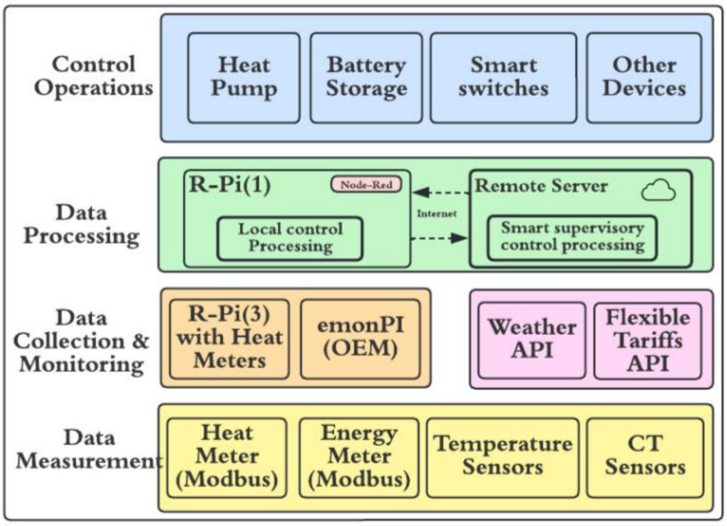


Figure 8: The smart control systems diagram with different layers

After understanding the different layers of data flow and the smart control system it is required to understand the design approach for designing the hardware software layer and communication protocol for smart controls.

4. Design Approach for Smart Controls

After analysing the design concept and the different layers in the system, the system design for smart control is investigated. The WW at Findhorn is now being seen as the case study where the system consists of ASHP by Mitsubishi, Solar thermal, DHW, buffer as an integrated system. The design approach has now been analysed to understand the requirements and step by step design processing.

The design approach needs to be followed to accomplish the smart controls of heat pump is as follows:

- Examine the current system of WW and design specifications to decide the suitable sensors and devices for smart control.
- Analyse the system step-by-step using different hardware devices and software protocols available as options.
- Analyse all the option appraisal and compare them in terms of cost, reliability, installation time and other factors.
- Install hardware for monitoring and control as per the best suited option and monitor the data.
- The data algorithms will be designed by software developer for performing the smart supervisory controls.

However, this project’s scope is limited to first three points in the approach, and the project outcome will be able to suggest a system level diagram for Findhorn WW system for hardware software interfacing to perform smart controls. Furthermore, in the next points the design specification will be studies to understand the data required and the hardware devices required for monitoring and smart controls.

5. Design Specifications for Smart Controls

The primary component of smart controls is data collecting and processing. The design specification will assist in understanding the sort of data required, how the data will be fed, and what devices will be utilised for data collection (26). Local hardware devices integrate sensors to provide the user with the needed data format. The design specification and data type necessary for conducting smart controls will be examined in this section.

The data type and sensor information for local renewable generation, grid side, and demand side for WW are suggested in the next sections. The table in the next section suggest the initial researched data points for smart controls. However, additional considerations such as wind turbine maintenance, wholesale energy price fluctuations, and other variables will always be considered when designing smart controls.

5.1 Identification of Sensing and Actuation Points for smart controls at WW

This section includes a list of sensors or devices required to gather data for monitoring and control, as well as the quantities to be monitored in the table below:

Table 3: Quantities and sensors Required for Monitoring and Control

	System	Sensor/device for Data collection	Signal or data type Required
Local Renewable Generation at Findhorn Energy Centre	Wind Turbine’s	Weather Forecast API	Next hours, and days data about weather in API format
		Wind generation API from software like WindSync*	The API for real time generation, monitoring and maintenance for wind turbines
	Solar Thermal & PV	Weather Forecast API	Next hours, and days data about weather in API format
		Solar Meters with Modbus	The generation data in kWh
Grid	Import/Export	Import/export in kWh	Real time, Daily, weekly, and monthly kWh Export/Import
	Tariffs	Import/Export Flexible tariff Forecast API	Forecast API from Octopus Go/Agile or other utility company.
Demand Side for WW	DHW Tank	3-DS18B20 Temperature sensors	Top, middle, and bottom temperature of the DHW tank in (°C)
	Immersion Heater	Energy meter and pulse sensors	Energy input in kWh
	ASHP	Heat Meter with Modbus connector	Inflow and outflow temperature (°C), and input Energy in kWh
			COP of Heat Pump
		Electric Meter and pulse sensors	Real time, Daily, weekly, and monthly electricity use

			Real time, Daily, weekly, and monthly heat output.
	Solar Thermal	Solar Meter and CT Sensors	Tank bottom temperature reading.
			Instantaneous power supplied to the tank.
			Panel temperature versus solar section of tank temperature.
			Real time, Daily, weekly, and monthly solar energy delivered to the tank.
	DHW Supply	Heat Meter with Modbus connector	Total flow from tank versus total flow received by dwellings (water losses).
			Cold water versus hot water use.
		Electric Meter	Comparison of top tank temperature and supplies at each residence (temperature losses).
	Heating Demand	Heat Meter with Modbus connector	Real time, Daily, weekly, and monthly heat output.

*WindSync is Scada software which can give real time monitoring about generation, the company can provide data in required API format to be used directly.

6. Design of system architecture for smart controls

This section analyses the system step by step as it transitions from the present system to the new system with various hardware linked for monitoring and smart control of heat pumps. The system architecture is an important component in understanding the different hardware alternatives and their ability to execute smart controls. The hardware and software interfaces are critical for data transfer and data processing in real time predictive controls. Remote connectivity among hardware components is also vital in processing real-time predictive control of heat pumps. The next sections examine the step-by-step system architectural design of monitoring and control of system at WW.

6.1 Overview of Selected Design Approach

To setup controls for any system, it is required to understand the system, the requirement for the data(to be monitored or measured), hardware devices used and the software protocols. While proposing a hardware software interface for smart supervisory control for heating and hot water system at WW, it is important to analyse the system step-by-step and installation of hardware devices to monitoring or control in a systematic way so that the pros and cons of the systems can be analysed. This will help to propose the best available option for setting a secure and low-cost smart control as per the requirements. The approach for the design is as follows:

1. The initial system of heating and hot water supply is explained when there is no option of monitoring of data is installed. This step is required to understand to know the system

hardware available at site like ASHP, FTC-5 wall unit by Mitsubishi, solar thermal DHW tank all together.

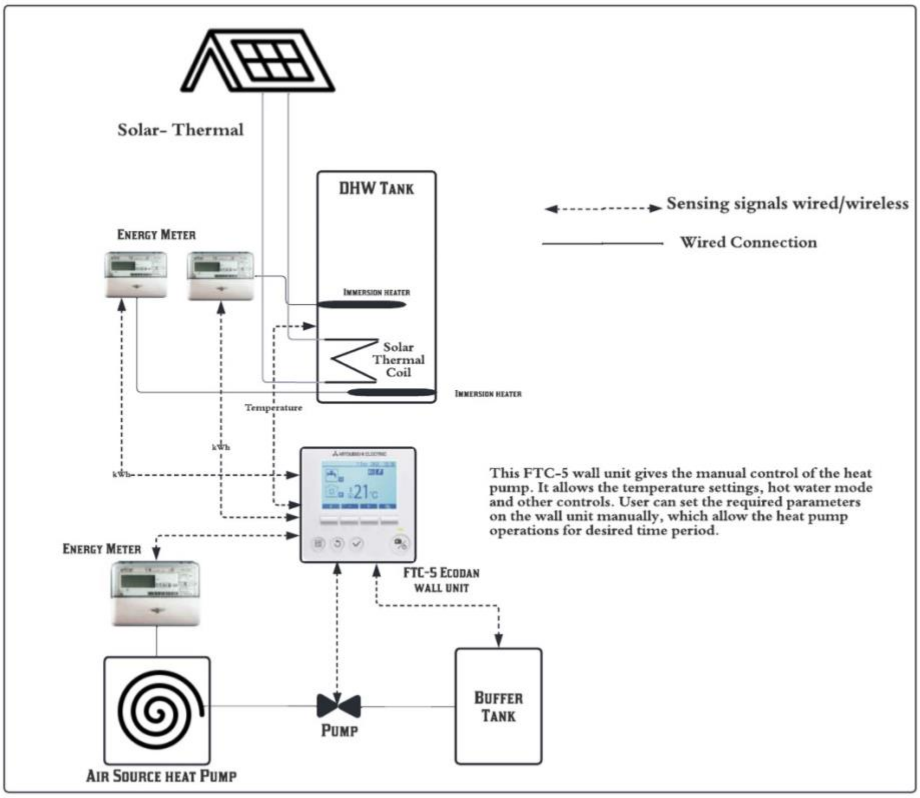
However, with the previous project the real time monitoring of this system is already done using OEM hardware, so the next step will be understanding the present existing system at WW.

2. The existing system at WW with installed real time monitoring using OEM devices, this system will be studied to understand the capabilities of hardware installed for monitoring and how these can be simplified. The limitation of this system is also analysed in terms of smart controls.
3. The next point will be analysed to introduce the hardware software interface for smart controls. This system will start with MELCloud. As MELCloud has capabilities to perform cloud-based application, and having a very good user interface, this system is analysed at the first stage in smart controls. However, due to dependency on Mitsubishi team for set up and installation lead to explore other alternative as well for this to perform smart controls.
4. Due to Limitations and dependency the alternatives for MELCloud are researched and A1M Modbus gateway is analysed with its capabilities to perform smart controls with the system. The system architecture using A1M is explained in the section.
5. The complexity and cost of A1M, and the detailed analysis of hardware design gave the realisation of bypassing the gateway and connecting heat pump directly with the external device to perform smart control. This section is showing the system architecture of the bypassing of A1M Gateway.

These all steps are being explained in detail in next sections from Section 6.2 to 6.6 with system diagrams.

6.2 The initial heating and hot water system at WW

The 14kW Mitsubishi heat pump is installed at WW; more details about it are available in section 2.2. The Mitsubishi ASHP contains an FTC-5 control unit for manual heat pump temperature settings and controls. The current system lacks smart control capabilities. The study conducted for this project indicates that the FTC-5 wall controller has the capability of read and write smart control to heat pump; however, this cannot be accomplished without the addition of additional hardware for data monitoring, algorithms, and command processing (3). The initial system diagram for Findhorn WW system without monitoring and controls can be seen below:



This FTC-5 wall unit gives the manual control of the heat pump. It allows the temperature settings, hot water mode and other controls. User can set the required parameters on the wall unit manually, which allow the heat pump operations for desired time period.

Figure 9: The initial system diagram of heating and hot water system at WW

However, the previous work done by the Flett et all have already set up the hardware devices for the real time monitoring of the system using OEM devices (3) (4). The monitoring has installed to allow the housing companies to monitor the real time performance of the system as well as to generate billing for the customers. The system architecture given in next section will provide the information about the existing system at WW. The system will provide with the details of OEM devices connected for the monitoring of the system.

6.3 The existing system at WW with real time Monitoring using OEM

The existing system at WW has monitoring capabilities as the OEM (emonPI) is already installed there and the real time data is being monitored.

The system at WW is monitored by two EmonPI hardware devices. The top, middle, and bottom temperatures of the DHW tank are measured using the first emonPI. The DS18B20 temperature sensors are connected at the designated location in DHW tank and with emonPI to measure the temperature. To monitor the input energy of the heat pump, the pulse input from the energy metre of the heat pump is directly linked to the same emonPI hardware (4). The emonPI installed and energy meter with pulse sensor can be seen in figure 9.

Figure 10: emonPI hardware and energy meter pulse input to heat pump at WW (3)

The second emonPI hardware is installed at energy centre to collect the M-bus data from heat meters connected at input of all flats and output of heat pump. The M-bus data from heat pump is collected by a R-pi installed there with the data from solar thermal meter. The R-pi communicate the data with the emonPI, which is being displayed and utilised as feeds to create dashboard, and apps on emoncms hub. Moreover, the research done by Flett et all suggest that the emonPI installed has capabilities to collect data and simulate various control and logic schemes that may be used in future applications (3).
The detailed diagram of whole system can be seen in Figure 10.

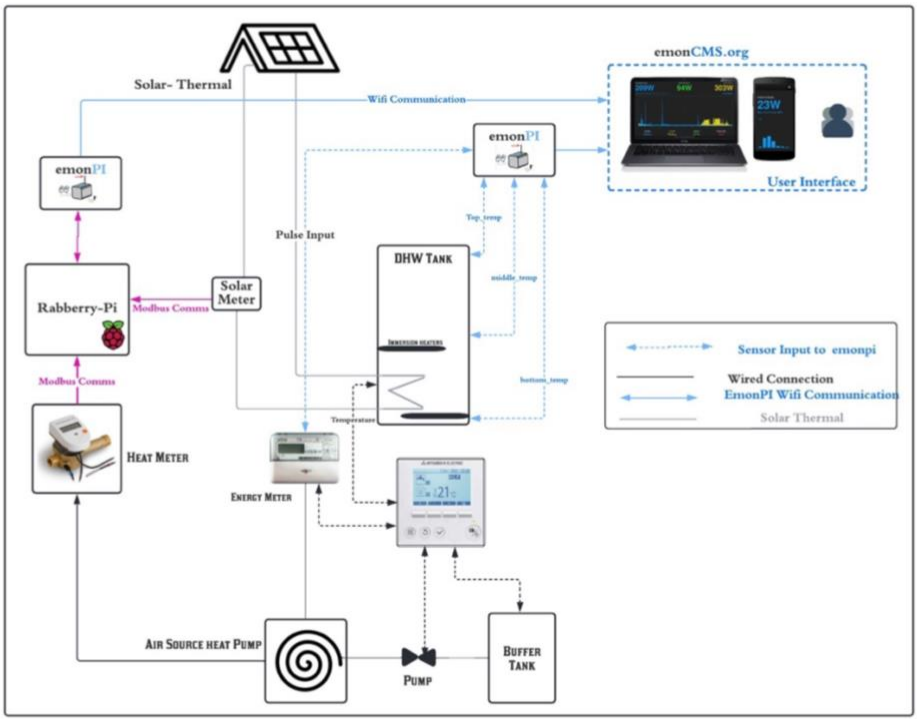


Figure 11:The existing system architecture at WW for Monitoring through OEM

The emonPI's remote communication and user interface capabilities will be beneficial in the design of smart control systems. The smart supervisory control will require the DHW tank status (already stored energy), as well as the demand from all properties for which the emonPI appears to be suited due to its easier deployment. The hardware of emonPI is easy to use and the emoncms provide flexibility of user interface to the customer. However, it cannot do heat pump switching and control.

After investigating the existing system, it was discovered that the control command supplied to the heat pump could not be directly sent into the heat pump hardware. It needs extra hardware components that can communicate signals to the heat pump and allow the heat pump to switch. The many possibilities for these devices that can assist in communicate control commands to heat pumps are shown in the upcoming sections.

The smart supervisory control also needs a system and hardware to perform the algorithms and process the command and for which there is another hardware will be required. For remote supervisory control the server will help in taking care of controls. The designs for hardware software communications with different hardware option can be seen in next sections.

6.4 Design smart supervisory control using MELCloud

The platform required to fill the communication gap between the supervisory control and the heat pump are investigated. The MELCloud can be one option for communication. The heat Pump by Mitsubishi have secured communication and control options. The FTC-5 Wall unit and the MELCloud communicate through WIFI, and their system is secured, so it is difficult to change anything at MELCloud and ASHP level. The smart controls can be performed using the supervisory control, which can do all the functions and processing of data and decide which operation of the Mitsubishi control system can be used at what time.

The supervisory control will require the data processing like weather API, tariffs, DHW previous data collected by OEM and demand forecast. The best suited software platform identified in research is Node-red which has capabilities to process various data and do the operations in very less time. The node-red can be operated by using hardware R-pi, so the initial research suggests that supervisory controls can be executed by using R-pi as hardware and Node-red as software platform. Figure 10 depicts the system architectural schematic for the smart control system using MELCloud (8). The R-pi and node red will assist in providing local smart controls; but, for digital twining, a remote smart supervisory control will be required to help integrate the different control systems with each other and oversee the system controls.

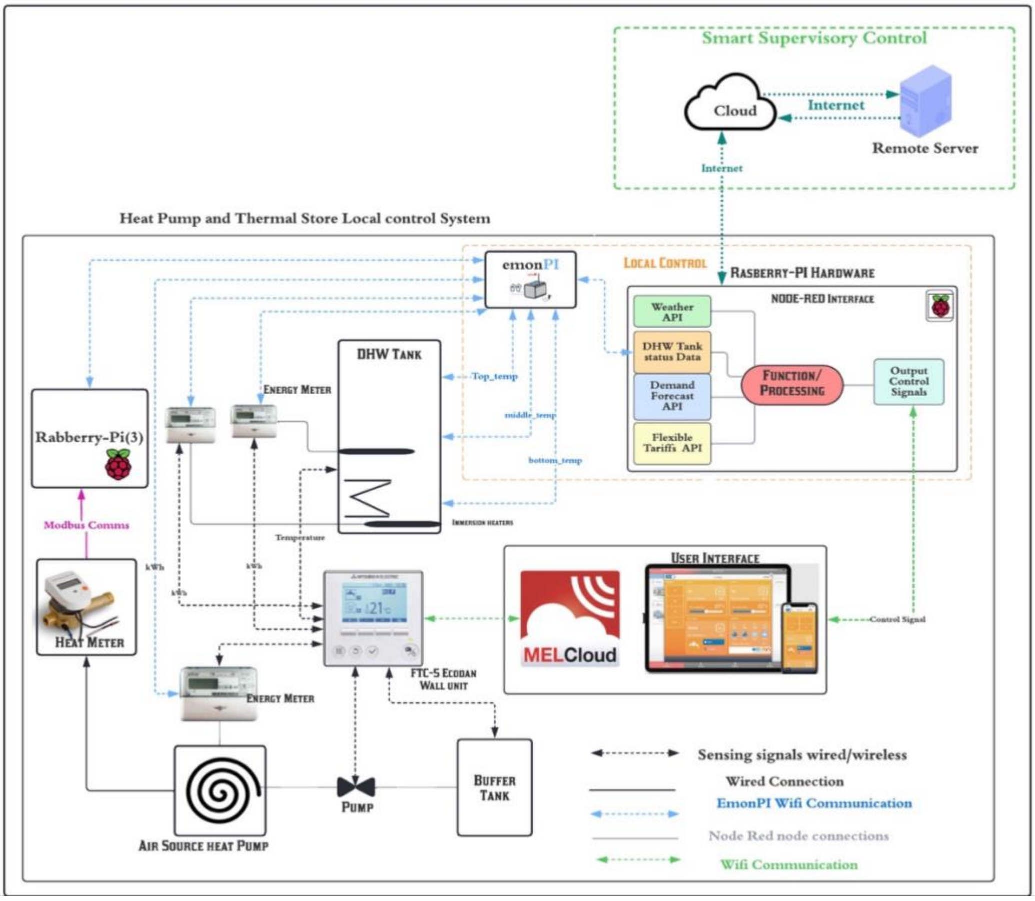


Figure 12: The system architecture for smart controls using MELCloud

The above system will use the emonPI open energy monitoring device to collect the data for DHW tank. The other APIs like weather, flexible tariffs and demand will be directly added to node-red and the functionality of the system is defined based on all the above factors. The system after processing the algorithms the control command will be communicate with MELCloud. The MELCloud will transfer the command to heat pump, and this is how the smart controls can be performed (27).

The node-red can directly communicate with MELCloud and command to perform operations can be automatically given to the MELCloud through node-red. This system can perform smart control based on algorithms and sensing the real time information. This system can be integrated with Mitsubishi Ecodan system, but it can only give the supervisory control.

MELCloud has a very excellent user interface, as seen in Figure 2, and allows for remote operation of the heat pump using WIFI. However, a discussion with certain industry individuals who have worked with MELCloud indicated that this service is difficult to obtain since it is dependent on Mitsubishi team for the installation and configuration of the communication and system is time consuming. All the dependencies and whole cloud-based system would limit the robustness of this system architecture, which is why alternate choices that are simple and lower system complexity are being studied. The A1M Modbus gateway is another option for reading and writing commands to the heat pump. This is being investigated in next section in detail.

6.5 Design smart supervisory control using MELCloud

The smart controls established by MELCloud shows a positive supervisory approach. However, the cloud-to-cloud communication come up with some limitation and in MELCloud the software support from Mitsubishi is a key factor. To reduce this dependency on Mitsubishi team, the other component can be used is A1M Procon Modbus gateway based on Heat pump Compatibilities (7). This Gateway has capabilities to read and write controls in the heat pump through Modbus Protocol. The hardware for A1M Modbus gateway can be seen in Figure 3 above. The communication system architecture for the WW system can be seen below:

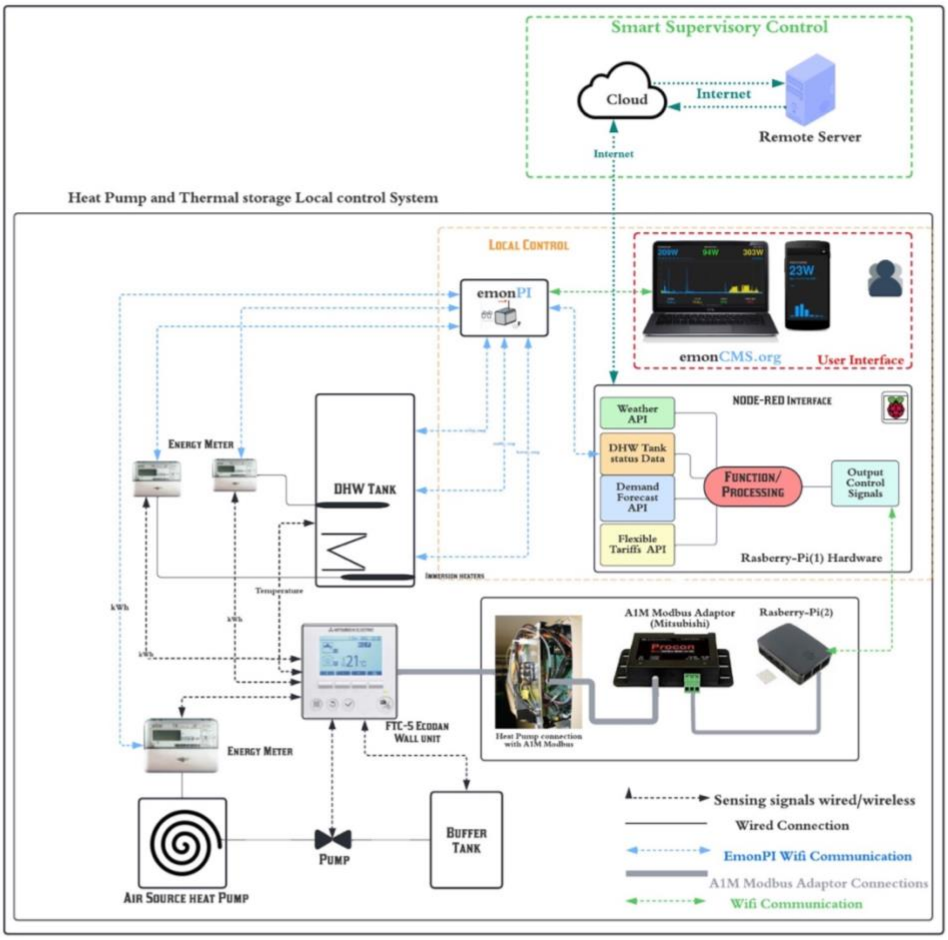


Figure 13:The system architecture for smart controls using A1M Gateway

The A1M connects with heat pump with heat pump CN105 connector and it has a RJ485 to connect with external device like Raspberry-pi as shown in above figure 13. In the above system the supervisory hardware will be same R-pi (1), which will process all the APIs like weather, tariffs, demand and DHW history in Node-red and will do the processing and do the supervisory control. The controls commands from R-Pi(1) will be transmitted to R-pi(2) through remote (WIFI) communication. The R-pi(2) will give the signal to A1M gateway, and the gateway will read or write the control commands to the heat pump, and this is how the data flow will be processed for smart control. In the further steps, the read writes command capabilities of A1M Modbus gateway are explained to understand the control capabilities in detail.

6.5.1 Control Capabilities using A1M Modbus Gateway

The Modbus gateway will provide a serial communication between the heat pump and the supervisory control. As it is designed by Mitsubishi and the user guides are available for how to read or write command through it, it is very convenient method to use in initial stage of heat pump control. The A1M help in changing the resistor values to read and write the control commands and the installation of the gateway is also very simple which make it reliable and secure for the ASHP by Mitsubishi (7).

The features of A1M Modbus gateway are mentioned in the Table 5 below :

Table 4: Specification and version detailing of A1M Procon Modbus Gateway

S.No.	A1M Procon Modbus Gateway details and functionality	Version/Specification
1	Option for – Reinitiate the communication if there is no communication for more than 1 minute	3.0.14
2	Monitoring and control Heat Pump	ASHP/WSHP Suitable
3	A1M can store real time data in registers and can transfer it to external device via RS485 Connector	Through Modbus RTU software Protocol
4	No external Power supply Required	It gets power through heat pump connector
5	WIFI Communication is not at provision	It has only RS485 RTU Modbus Protocol with ECODAN Series

Now, after understanding about the hardware of Modbus gateway, it is important to dig down into it and understand how the communication and command processing will work from software side. The control capabilities of the heat pump will also be analysed in this section with A1M gateway. The Modbus set the communication with the help of dip switches. The software developer can change the dip switch and enable the communication required for the systems operations.

The below table suggests the Dip switch and the functionality for ASHP by Mitsubishi and A1M Modbus Gateway.

Table 5: Dip Switch Functionality for A1M Modbus Gateway and ASHP by Mitsubishi

Modbus DIP SWITCH Functionality			
Switch Number	**Functionality**	**Details**	**Remark**
Switch -6	RS485 Communication Settings	ON- NO parity set (9600 Baud Rate)	The number of data bits is fixed at 8 and the number of stop bits is fixed at 1
		Off- Parity and baud rate set in software	
Switch-7	Protocol for communication selection	ON- Modbus RTU	
		OFF- BACnet MS/TP**	**This protocol is not valid for ECODAN heat pumps
Switch-8		ON- Enabled	

	Dead band Mode *	OFF- Disabled	*Only applicable to air-to-air type
Switch-8	Dead band Mode	ON- Enabled	
		OFF- Disabled	

The below table suggest a brief idea about the read write command and functionality which are supported by Mitsubishi’s ASHP through A1M gateway. The below table is brief introduction and the overall table with register addresses and other function can be seen in detailed table in installation manual of A1M PROON gateway (7).The software developer writing the codes for control can use the respective holding register for the respective functionality which can be seen in detail in appendix 3 and the table below give the overview of the capabilities of control.

Table 6: The control options and read write provision for FTC-5 control system

Control Options	Description	Read/Write	FTC5 Supported
Fault/Error Detection	Error	Read Only	Yes
Fault/Error Detection	Communication Problem	Read Only	Yes
System on/off	Detect system is on/off/on test run	Read and write	Yes
Operating Mode- Heat Pump	Detect the mode of operation of heat pump	Read and write	No
Operating Mode- DHW TANK	Detect the mode of operation of heat pump	Read and write	Yes
Set Tank Water Temperature	To set the water temperature of tank	Read and write	Yes
Heating/Cooling water Temperature of ZONE1/ZONE2	To set the water temperature of Zone1/Zone2	Read and write	Yes
Modular Room Control (MRC) Prohibit	To Prohibit the MRC FUNCTION	Read and write	Yes
Force DHW	To use dhw force function	Read and write	Yes
Prohibit DHW	To Prohibit the DHW Control Function	Read and write	Yes
Heating On Prohibit – Zone 1 /Zone 2/Zone 3	To Prohibit heating in various zones	Read and write	Yes
Capacity Mode	To run heat pump operation based on COP/Capacity mode	Read and write	Yes
Capacity control Ratio	To set the capacity control ration in %	Read and write	Yes
Heating Status	To know the heating status by heat Pump	Read Only	Yes
DHW temperature drop		Read and write	Yes
Heat Pump Run Time (hours)	To know the heat pump time in hours	Read and write	Yes
Energy Input	To know the energy inputs by heat pump in kWh	Read and write	Yes

The above table and research suggest that FTC-5 controller of Mitsubishi have control capabilities, however it should be controlled from a supervisory control as per the weather, flexible tariffs, and demand profiles. The design approach for supervisory control can be seen in next sections for smart control.

The A1M capabilities and communication pattern can suggest it is a mode of serial communication between the R-pi and the heat pump. The detail study showed that the signal which A1M is receiving and transmitting can be directly used in R-Pi. So, the bypass of A1M can reduce the dependency on Mitsubishi and will reduce the cost of system as the A!M unit price is around £200. The next option is considering the system design without A1M (7) (28).

6.6 Design of smart supervisory control without A1M and MELCloud

After analysing the A1M gateway connector and the signal type which is going from heat to A1M and vice-versa, it is observed that the A1M can be bypassed. The A1M gateway is a serial communication device which is transmitting signal from Heat pump to R-pi(2) as seen in Figure 5. The researcher working on the Mitsubishi heat pump and air conditioners tried to directly connect the raspberry pi with pump by passing the A1M and it showed them the positive results. The connector CN105 diagram can be seen below with the signal details:

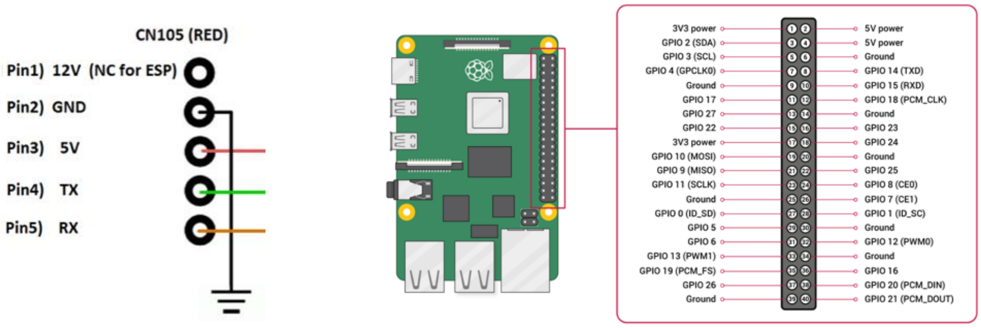


Figure 14:The CN105 Connector of A1M and Raspberry-pi Pinout Diagram (28)

As shown in above figure the signals coming out from CN105 are RX,TX,5V and GND, which are also available in Raspberry-pi connector. So, it is possible to connect this signal directly to the raspberry-pi connector and change the required register of heat pump through Raspberry-pi. The connection can be seen below (28):

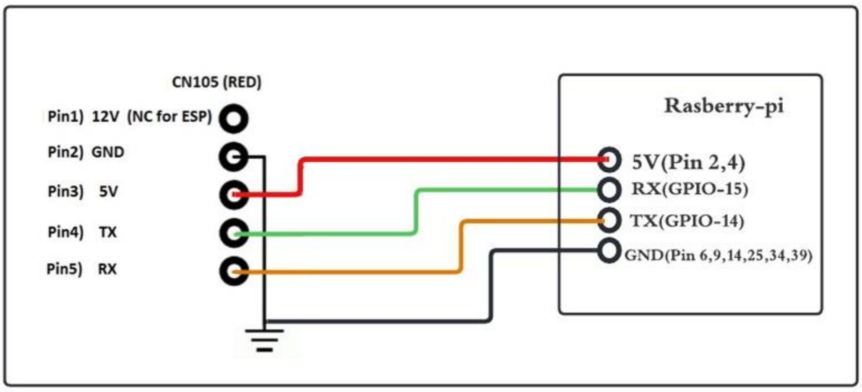


Figure 15:Connection CN105 Directly to Raspberry-pi

The main system diagram now changes and will be seen in below figure:

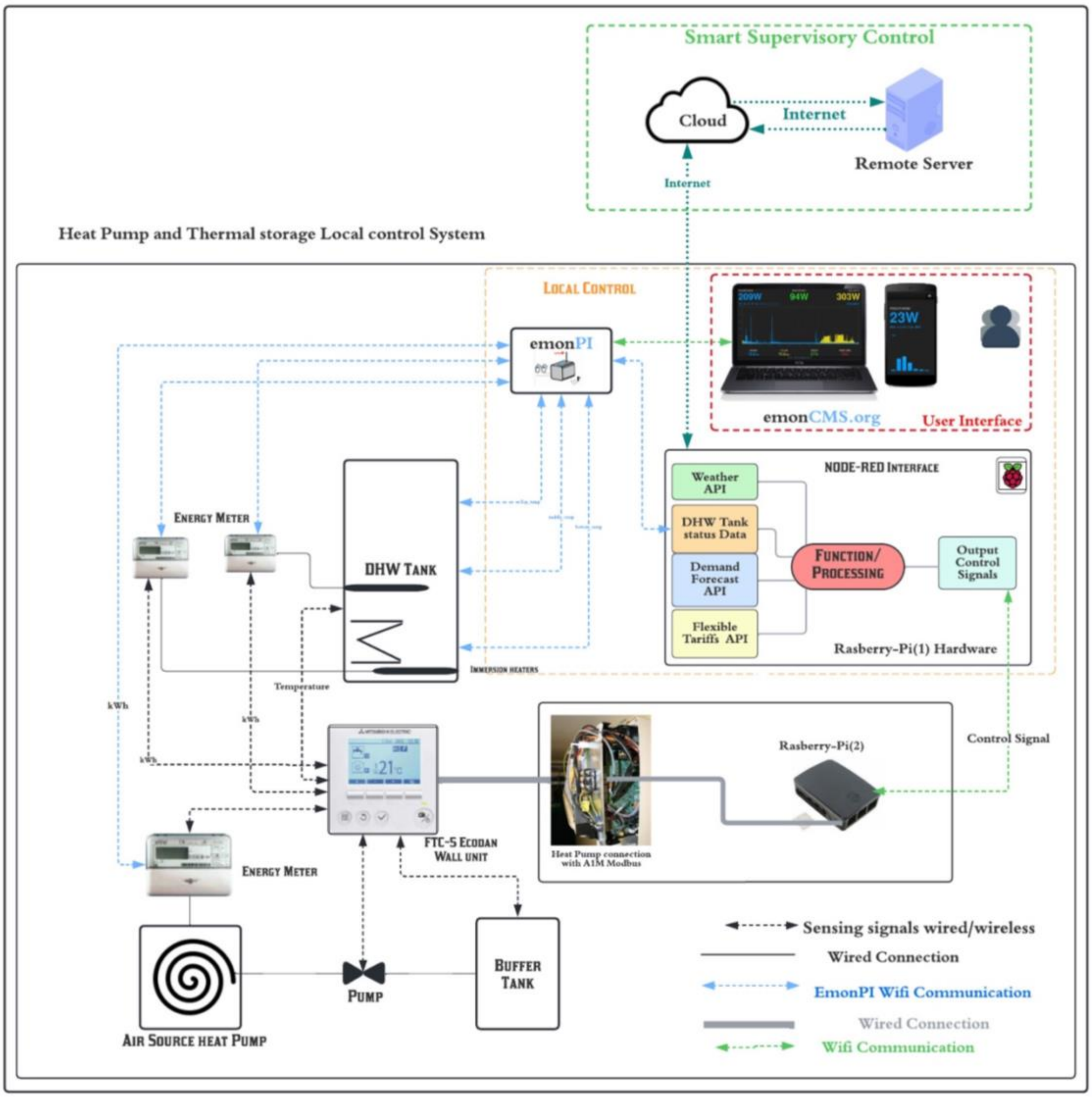


Figure 16: The system diagram bypassing the A1M gateway and MELCloud

The R-Pi directly connected with heat pump can do all the operation with proper software coding. This system comes with reduced complexity and dependency on Mitsubishi team and their devices. The supervisory control will work same as it is working in above two cases with A1M and MELCloud.

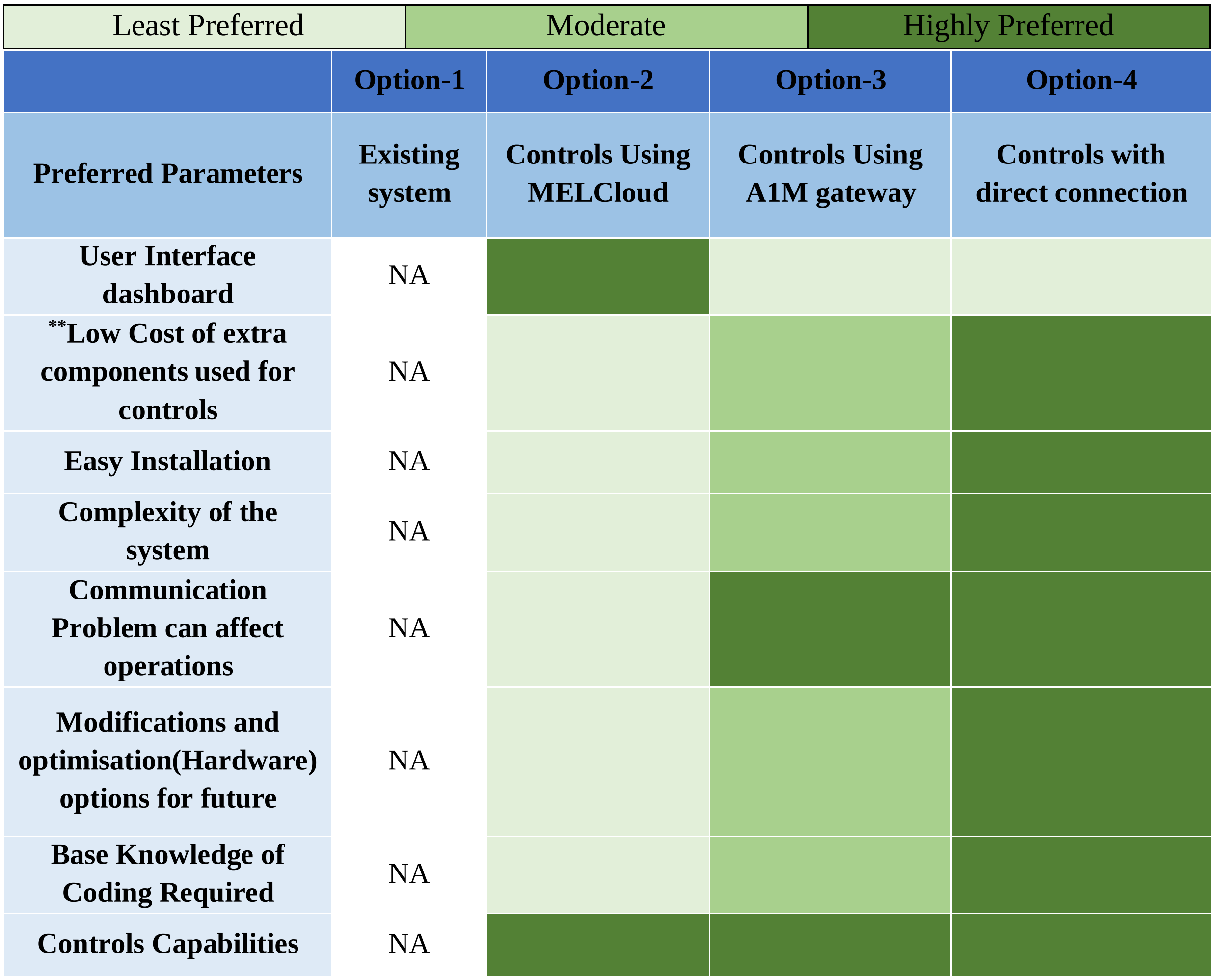
7 Design comparison and an option selection matrix for system design

The various options suggested in section 6 are now compared and analysed to propose a system for WW smart control operations. The comparison is important to make users aware about all the available options.

The table is initial considered on basic research and it can be updated in future as per the observations and the requirements.

Table 7:Design Comparison and selection matrix for systems designs

Colour Code for table can be seen in below columns: Light Green for least preferred, dark green for Highly preferred and the rest is for moderate.



Least Preferred	Moderate	Highly Preferred
░	▒	▓

	Option-1	**Option-2**	**Option-3**	**Option-4**
Preferred Parameters	**Existing system**	**Controls Using MELCloud**	**Controls Using A1M gateway**	**Controls with direct connection**
User Interface dashboard	NA	▓	░	░
****Low Cost of extra components used for controls**	NA	░	▒	▓
Easy Installation	NA	░	▒	▓
Complexity of the system	NA	░	▒	▓
Communication Problem can affect operations	NA	░	▓	▓
Modifications and optimisation(Hardware) options for future	NA	░	▒	▓
Base Knowledge of Coding Required	NA	░	▒	▓
Controls Capabilities	NA	▓	▓	▓

** The cost of MELCloud hardware is around £120 + Mitsubishi technician is requiring for setup and installation, cost of A1M is around £200.

As, seen in above table the most preferred option is coming out where the raspberry-pi is directly connecting to heat pump and there are no other devices like A1M, MELCloud are being used. This system will be more beneficial because it will avoid the dependency of user on the Mitsubishi team, and it will be cost effective as well. Moreover, it will also reduce the system complexity as the number of devices will be low.

The proposed smart control for heating and hot water supply design would offer local system control as well as send and receive signals from smart supervisory remote control. The smart supervisory remote control will be linked to various systems such as heating and hot water system control (proposed in option6), battery storage system controls, local renewable generation import/export, and it will aid in overall system controls considering all factors such as weather, flexible tariffs, energy market fluctuation, and demand forecast. The next section will show the brief system architecture and communication flow integrated system of various local controls and smart control, which can be taken in consideration in future projects because of the time constraints.

8 Design proposal for future integrated Supervisory control system

The system analysed in Section 6 provides heating and hot water to a residential housing complex with six flats. Based on smart algorithms, the created local smart control will aid in monitoring and controlling operation. However, in the future, the system will not just provide heating or hot water, but will also include heat pumps, battery storage, PVs, wind turbines, EV charging, and other loads. Because of the fluctuation of load and high demand, the system will grow more complicated, and the function of smart control will become more important in the future.

The overview of the smart control of future integrated system can be seen in Figure 17. As seen in figure all the load system like heat pump, battery storage, EV have their local smart control which will be similar combination of hardware devices proposed in section 6 of this report. Moreover, the local renewable generation and grid will also have their own monitoring and control system. These all system will communicate with smart supervisory control remotely using internet and the smart supervisory control will perform the analysis and algorithms and send signal to local control for switching.

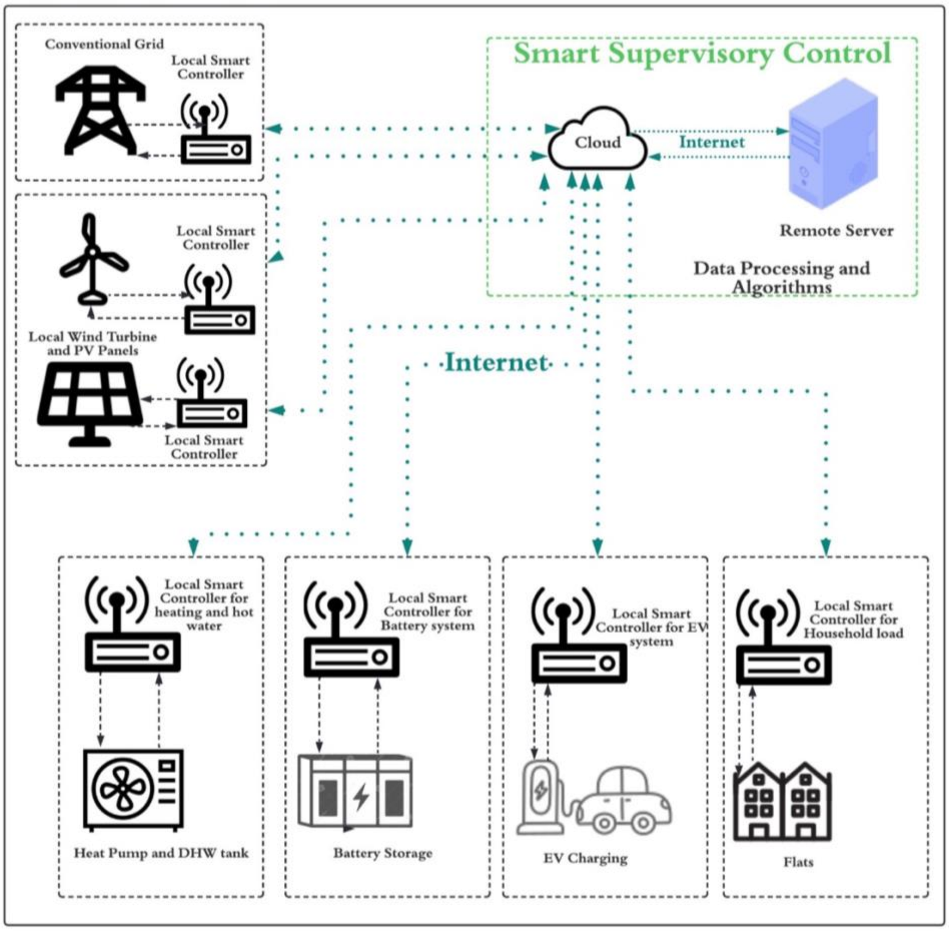


Figure 17: Smart supervisory control system diagram for future integrated system

The separate system will depend on each other for example when the tariffs are low the battery storage will be charged and the heat pump can also store energy, which can be used at the time of peak. The smart supervisory control will automatically perform the switching based on predictive smart algorithms.

8.1 Installation of Smart meter in Future integrated energy systems

The smart energy metres and smart heat metres can be used as monitoring devices in the future to decrease system complexity by monitoring all essential data through utility smart meters and sending it directly to the supervisory control. The smart meters can help replacing the OEM devices currently being used for data monitoring, and automatic billing process.

As the smart metres have capabilities to measure and communicate the data, these can help in reducing system complexity. RF-Mesh, GSM and WIFI are the technologies that can be utilised in smart metres for data transmission and communication. RF-mesh as discussed in section 2.8.2 is a low-cost, secure communication technology that can aid with smart supervisory control in a wide range of ways. This has the benefit of not requiring the installation of WIFI communication or internet facilities at all places; instead, RF mesh can broadcast signal to a single access point (DCU), assisting in the transfer of monitored data straight to the cloud as shown in Figure-6.

The design of local smart controls and operations of smart supervisory controls will help system work in cost effective and optimised manner based on real time data and forecasted data.

9 Overall Reflection on work done on the Project

This section contains insights on the work done for this project. These contain a record of the primary successes for the study, a discussion of the obstacles and constraints found, and concluding thoughts on prospective future work for system design and architecture for smart supervisory controls of heat pump.

9.1 Visualization of the completed task

This investigation of various hardware devices and communication protocols that might contribute with smart controls is done with various system designs. Previous projects' monitoring setups have been critically analysed, and research is being conducted to identify alternatives to the OEM equipment used for monitoring, and to design the system with greater flexibility. The OEM online forum is used to understand the ongoing project on smart controls, as well as the OEM limitations. The GitHub is used to understand the heat pump control and the coding capabilities to perform smart control through the projects going on related to smart controls and Mitsubishi topic around the world.

Furthermore, because there are no smart controls at the WW site, a design for hardware and software options for smart control is developed and evaluated by comparing it to alternative design possibilities. The least complex and flexible design is successfully proposed for physical installation at WW. The future study and scope of this hardware software design is also analysed to understand its usability for other similar system and integrated system with EV, PV, battery storage for smart supervisory controls.

Moreover, the smart meter installation for the sites like Findhorn is proposed for future developments which can help in reducing the system complexity due to hardware and allow users to perform operation like billing, real time monitoring on low-cost communication using RF-Mesh, WIFI.

Finally, the end user's desire to deploy the suggested system design for smart controls for heating and hot water system at WW demonstrates the project's success.

9.2 Project Limitation and Future Task

This project successfully proposed various hardware-software platform design alternatives for smart supervisory controls of a heating and hot water supply system combined with heat pumps and a thermal store. The project describes the design idea and device specifications necessary for smart controls. However, due to a lack of prior coding experience and time constraints, physical device development and coding for algorithms for smart supervisory controls will be a future task to complete.

Future research will also require the investigation of additional devices such as Arduino or embedded microcontrollers, that could integrate with R-pi to allow developers to construct control algorithms that are more optimised and flexible. The storage system for data must also be researched so that data may be stored as records for a certain period if communication or system failure occurs. The suggested design focuses primarily on the Mitsubishi heat pump and its built-in control capabilities; however, additional research will be required to analyse this design as a generalised hardware interface that may be utilised with different types of heat pumps, storage systems and other integrated system at site.

Overall, the combination of OEM devices and R-pi can support in the initial deployment of smart control; but, in the long run, it is necessary to reduce the complexity of the system by reducing the devices utilised for monitoring and data transfer. It is possible to do this by replacing the monitoring equipment with smart energy metres and smart heat metres that can monitor all data and send it straight to the supervisory control platform. However, this development will necessitate the installation of the new smart metres with on-site communication capabilities using RF-mesh, so it will be a long-term design concern in the future.

10 Conclusion

The critical review to understand the heating and hot water system and the capabilities of the system smart control at WW was completed successfully. The design idea, requirements, and technique are examined to offer a step-by-step design process for smart supervisory control of system to increase the fraction of local renewables and reduced cost. The project addresses the core issue of developing a hardware-software platform for constructing a smart supervisory control that can monitor and perform algorithms based on flexible tariffs, weather forecasts, and demand forecasts in real time. The devices, their connections, and communication protocols that used in the design of hardware architecture are offered as different options, which are compared on various parameters to suggest the best suited system for now.

The following recommendations are made of the project regarding the design of supervisory smart control:

- A thermal storage and heat pump-based heating and hot water system can be controlled by creating measuring, monitoring, and control using sensors, OEM devices, and R-pi based on weather prediction, demand forecast, and flexible tariffs. The suggested technology can aid in the optimization of heat pump operation and promote the utilisation of local renewable power at WW.
- The recommendations made about how this design of hardware, software can be used in different systems like storage, EV's and the communication can be processed in smart supervisory control for integrated system.
- The proposal is also made for future installion of smart meters, which can help in reducing the system complexity and give user the advantages of real time monitoring, automatise billing and low-cost communication of data for smart controls.

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12 Appendices

12.1 Appendix-1

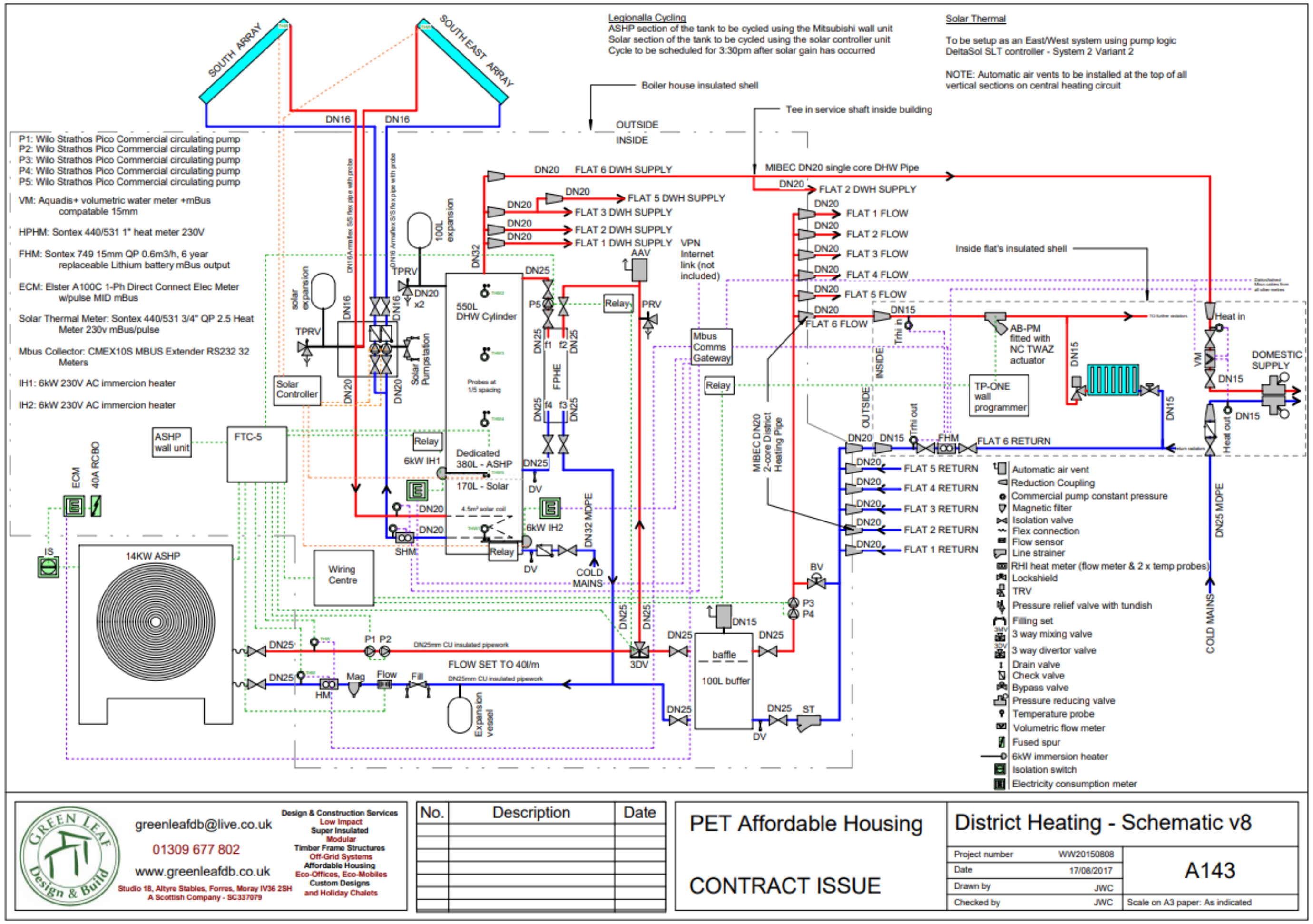

Figure 18: Detailed schematic of the system at WW (3)

12.2 Appendix-2

Table 8: Comparison between Raspberry-Pi and Arduino (15)

Raspberry-Pi	Arduino
Raspberry Pi is a Single Board Computer or SBC	Arduino is a Microcontroller based development board
It is based on Series Microprocessor	It is based on Atmel Microcontrollers. Arduino UNO uses ATmega328P Microcontroller
Requires Operating system (Linux) to Boot	No operating system is required
Because of its potent CPU and Linux-based operating system, the Raspberry Pi SBC can carry out several tasks at once.	Arduino is usually used for running a single task (or a very small no. of simple tasks) repeatedly, repeatedly
All the necessary components like Processor, RAM, Storage, Connectors, GPIO Pins, etc. are situated on the Raspberry Pi Board itself	The Microcontroller on the Arduino Board (like ATmega328P) contains the Processor, RAM, ROM. The board contains supporting hardware (for power and data) and GPIO Pins
Raspberry Pi SBC has several GPIO Pins (the famous 40-pin Raspberry Pi GPIO), using which you can connect different sensors, IO Devices, etc.	Any microcontroller's GPIO peripheral is crucial, and the Arduino UNO is no exception. These pins are known as Digital IO (to connect LEDs and buttons) and Analog IN (to connect analogue devices) (to connect analogue devices).
Using the 40-pin GPIO Pins, you can add additional features / functionalities to Raspberry Pi with HAT (Hardware Attached on Top) expansion boards	A similar way to add extra features and functionalities in Arduino is using Arduino Shields (which are also connected through the IO Pins)
As Raspberry Pi is essentially a computer, you must properly shutdown after using it or before powering it down	As Arduino is a Microcontroller board, you can plug and unplug the power as you want
The main programming languages for developing application in Raspberry Pi are Python, Scratch, Ruby, C, C++	Arduino can be programmed using C or C++ Programming Languages
The logic level of Raspberry Pi's GPIO is 3.3V. So, be careful when connecting hardware to the GPIO Pins	The logic level for Arduino is 5V. There won't be any issues connecting the sensors and modules to Arduino because the most of them are made for the platform. To be safe, though, double-check each module and connection.
Raspberry Pi must be powered using an USB Power Adapter as it requires 5V 3A power	Arduino can be powered from a computer's USB Port (make sure the USB Port's current limit is not exceeded)
Internet can be connected using Wi-Fi or Ethernet	For Arduino, additional module or shields required to connect to internet