Department of Mechanical and Aerospace Engineering

Project Title: An investigation into the potential for energy transition to heat pumps in a practical smart grid using monitoring data and considering demand side response.

(Findhorn Case Study)

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Abstract

This thesis provides an investigative study of the electrical low voltage distribution network response when domestic heating systems transition from biomass boilers to heat pumps and procures a viable data driven solution that utilizes renewable generation. The investigation is conducted using Findhorn Eco-village in Scotland as a focal case study, primarily due to the availability of real time data. Findhorn intends to install fifty eight 6kWe air source heat pumps at Pine-ridge estate for fifty eight dwellings to replace biomass boilers. Load modelling of the electrical distribution line is performed with MATLAB using a diversity factor of 0.6 to see the possibility of having all heat pumps turned on. The outcome of the results show that only fifteen of these heat pumps can be switched on at the same time before the 95Sqmm 4 Core feeder line exceeds its current carrying capacity of 200A. Furthermore, data from the demand side is downloaded from Findhorn monitoring portal, characterized using Python programming language and analyzed to develop algorithms for smart control. The main idea for the data analysis is to explore options to use more renewable generation instead of grid imported electricity which is expensive and less clean. In order to achieve a 65% reduction in the expenditure associated with acquiring 58 air source heat pumps, an alternative strategy involving the clustering of energy centers to cater to eight customers per heat pump is explored and recommended. However, this approach entails increased piping infrastructure as a trade-off. At each intended energy center, the design comprises of a single 14kWe heat pump, a thermal store and six solar thermal panels. The heat pump charges the domestic thermal hot water store to 50°C and supplies the radiators for space heating at a temperature of 45°C.

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1.0 Introduction

One of the most practical way to reduce carbon emission drastically is by the transition to heat pumps and electric vehicles [1]. As a result of the corresponding increase in electricity demand due to these, low voltage distribution networks are encountering fresh obstacles concerning their reliable and stable functioning and the associated rise in operational and investment expenses. Gaining a deeper understanding of low voltage distribution networks and conducting thorough data analysis is crucial in effectively tackling the technical problems linked to the implementation of low-carbon technologies. This necessitates collecting as much data as possible from distribution and consumer side to facilitate simulations, modelling, forecasting thereby improving informed decision making.

1.1 Background

Traditional domestic heating systems use biomass and gas boilers for space heating and for domestic hot water supply. These technologies are heavily dependent on the combustion of hydrocarbons which releases more carbon dioxide into the atmosphere and poses a severe threat to health and the environment. Hundreds of years of burning fossil fuel for heating and power generation has been the primary cause of climate change and global warming. More and more countries are experiencing flooding and high temperatures as the sea level keeps rising due to greenhouse effect. This has necessitated the invention of low carbon technologies to accelerate carbon emission reduction. These low carbon technologies like electric vehicles and heat pumps depend heavily on electricity to operate. As more and more people transition to heat pumps and electric vehicles, the electrical demand keeps rising uncontrollably. The power grid infrastructure has been in existence before renewable generation. Renewable energy generation is known to be intermittent, rising to high peaks at certain seasons of the year. Wind power generation is at its peak during winter and solar generation is at its peak during the summer months. During these peak periods, grid infrastructure may collapse without adequate planning and preventive measures put in place. As more load is introduced to the power grid network, the low distribution network which is closest to the customer side will be severely impacted. Replacing transformers and feeder cables with higher capacity equipment also known as network reinforcement seems to be a solution but takes longer time to deploy and is very costly. By monitoring the grid network and applying smart control to curtail excess load, there will be less need for reinforcement. Well-defined controls and algorithms implemented with a smart grid solutions can mitigate against the obvious impending power grid failures. However, more data needs to be collected and the systems needs to utilise machine learning to make develop more accurate algorithms. Solar and wind power, the most ubiquitous of all the renewable energy sources will need to be correctly forecasted and combined with battery storage technologies to create a very stable, robust and optimal power grid. In this thesis, real time data is obtained from Findhorn Eco Village located on eastern shore of Findhorn Bay. Future construction of houses in Findhorn and the United Kingdom are expected to comply with PassivHaus Standards which ensures excellent insulation.

Figure 1: Map Showing Location of Findhorn Eco Village, Scotland

The data is analysed to investigate the impact of increased load on the grid due to energy transition from use of standalone and district biomass to heat pumps. The outcome from this thesis will be widely applicable to social landlord housing complexes, tower blocks and terraces. By optimizing local assets such as wind turbines, this lowers operating costs especially when combined with battery storage.

1.2 Aim

The aim of this thesis is to investigate the potential for energy transition to heat pumps from biomass boilers in an existing distribution network at Findhorn Eco village and devise workable strategies and methods to intelligently manage the load pressure on the transmission grid, using data from the demand side. The objectives of this thesis are;

1. To model and analyse the electrical impact of addition of 58 Air source heat pumps on the local distribution network and procure economical solutions to cope with excessive load on the distribution lines other than reinforcement.

2. To pinpoint prospects for employing solar photovoltaic to power the heat pumps as an alternative to procuring costlier grid electricity, and to leverage thermal storage techniques for optimizing solar penetration during the peak period of solar activity in the summer season.

3. To utilize a data approach using real time data and machine learning to further predict load demand for a more efficient optimization of the distribution network using smart grid monitoring and control.

1.3 Approach

The approach to achieve the set aims and objectives are listed below;

1. Understand the existing distribution network and its capacities based on single line drawings, site maps, electrical standard specifications and heat pump sizing calculations.
2. Understand existing network connected loads, generation, heat pumps, electric vehicles, existing models and plans including assumptions around network loadings.
3. Model Low voltage distribution network with MATLAB, applying diversity factor to analyse the impact of excess load on the low voltage distribution network.
4. Access and analyse actual network performance based on monitoring data including establishing analysis methods (data import, screening, and characterisation).
5. From the results of the data analysis, to Identify opportunities for load shifting and utilization of renewable solar photovoltaic and thermal store.

1.4 Scope

This thesis will focus on heat pumps as an alternative to biomass and gas boilers for domestic hot water and space heating and also as a viable low carbon technology. This thesis also narrows down investigation on the electrical impact of the transition to heat pumps, on the local distribution network. Further investigation is conducted utilizing data sourced from the summer season, specifically the month of July, when solar energy generation is notably higher in contrast to the winter season.

Figure 2: Findhorn Social Housing with Heat Pump, PV and Solar Thermal

2.0 Literature Review

In this section, previous academic research papers and journals are reviewed to gather key information and insight which will be useful for methodology, analysis and results chapters. In addition, this section also identifies limitations and weaknesses of these previous papers.

2.1 Energy Transition

As the urgency to switch to renewable energy sources increases with the impending target to phase out power generation from fossil fuels in order to reduce carbon emission and maintain the earth's global temperature at 1.5°C, several concepts, models and propositions are being put forward to mitigate against the obvious challenges the energy industry would face presently and in future. Changes and modifications are being experienced in power generation for utility and transportation sectors. For example, the use of gas and biomass boilers for house heating is gradually being replaced with heat pumps since heat pumps come with higher benefits for the environment in terms of sustainability and equipment functionality. Heat pumps are known for their high efficiency compared to other heating systems, as they can generate more heat energy than the amount of electricity they consume. A heat pump with co-efficient of performance of 3.0 will give out heat three times every unit of electricity consumed. More electric vehicles are being produced with faster and more efficient battery charging and storage technologies. However the electric demand to power these new technologies is gigantic and will consequently impact the power grid. The European Union has plans to accelerate the shift to electric vehicle by deploying millions of EV public charging points leading to an explosive rise in the number of battery EV in Europe.

Figure 3: 22kW Fast Charge EV at Findhorn

The impact of this large scale transition to electric vehicles and heat pumps could decrease the residential sectors carbon emissions by 30%. [2]

2.1.1 Orchestration of Renewables Generation

P. Tuohy et al. presented the ORIGIN approach with primary focus on Findhorn, a 75 building residential area with renewable solar and wind generation. One of the most important aspect in the increased implementation of heat pumps and electric vehicles is the potential strain on demand profiles and electricity demands. The reason for setting up the ORIGIN project (Orchestration of renewable integrated generation in neighbourhood) was to utilize more of the local renewable resource and reduce import from the grid thereby cutting cost and increasing clean energy optimization.[3]

The project developed an optimization algorithm which used inputs from weather forecasts, renewable energy generation, and customer generated outputs for display on handheld devices and for remote control of temperature and electricity loads. The scheme achieved reduction in imports from the grid by 13% thereby increasing the dependency on the 675kW wind turbines in Findhorn.

Figure 4: Wind turbines at Findhorn rated 225kW

Incentivization approach was explored which got an initial response of 47% of households leading to 6MWh reduction in grid imports during 6 months trial period

[3]. Based on a demand response programme (DRP), customers were advised to reduce load as much as they possibly could to attract monetary rewards from utility companies or bill credits. The paper serves as a baseline for findings in this thesis.

2.1.2 PYLESA

Series of models and algorithms have been developed to aid the planning of the local energy systems and PYLESA, though in its nascent phase has lots of potential. It has functionalities able to model energy systems which are smart and integrated on the local side of the energy chain [4]. One of the short comings of PYLESA is that it runs only using hourly timestamps. This limits its ability to capture transients which may have their own unique characteristics.

In the new dispensation of clean energy power generation and distribution, customers play indirect participatory role in the achieving climate goals by having their consumption monitored using smart meters. Consumer data is utilised as input into models which are used to investigate power flow in the low voltage distribution network.

2.1.3 Energy Transition in Sub-Saharan and South Africa

Nwaiwu (2021) critically assessed the digitisation of energy systems in Africa. This study provides in-depth study of the African energy terrain with focus on Sub Saharan energy giant, Nigeria and South Africa. The study examined the implementation of digital technologies in the renewable energy sector. The goal was to explore how these technologies are being utilised to establish new models of energy generation and consumption that are environmentally sustainable [5]. Nwaiwu reviewed the policies that are obtainable in these African countries compared to European policies. The paper further lays emphasis on the prognosis that digitisation is a catalyst for energy transition, fundamentally changing the way energy is generated, distributed and consumed. Countries in Africa are facing power blackouts and power generation is at an all-time low, ridiculously the national grid suffers total collapse leaving millions in total blackout. This coupled with the explosive population is a setback for the sustainable development goals. In the last twelve years, Nigeria's national grid suffered at least 222 collapses [6].Generator import increased exponentially leading to uncontrollable carbon emission. The minister of power in Nigeria only last year approved the installation of SCADA system for the National Grid. The urgent call for an overhaul of the energy sector in these regions cannot be over emphasized. The problem of climate change is a global one and so all countries, regardless of development stage is expected to catch up and make the subject of energy transition to low carbon technologies a priority. With more flexible policies that tend towards sustainability, the goal of successful transition becomes feasible. Furthermore, Nwaiwu conducts a qualitative approach citing case studies where smart grids and block chain technologies were used within the energy sector contributing greatly to the existing knowledge of these technologies from an African perspective.

Even though the paper highlights the benefits block chain technology provides for the energy sector, it also acknowledges that block chain technology does not guarantee that the power is generated from a renewable source. The paper's major focus and concern is commercial viability.

2.1.4 Policy impact in India

Though not anticipated during its construction, several traditional grids in countries are incapable of accommodating renewable generation and distributed energy resources for systems with generation even below 1MW. The incorporation of smart technology can salvage the situation and help preserve the power grid, backed up with strong robust government policies.

Chakraborty et al [7] provide a link between grid modernization polices and actual benefits of these measures. The journal compares achieved benefit and predicted benefit of using these modern policies with the hope to equip policy makers and researchers with useful information regarding technical and commercial losses as a result of energy transition and its impact on the grid. India, coupled with its gigantic population is working tirelessly to upgrade its traditional power grid. The Indian government's main objective is to improve the power quality and reliability, to enhance customers and reduce power theft which is a major setback in India. India generates as much as 370GW [7]. India is hoping to leverage on the modern communication and information technology features of the smart grid and hopefully transition into renewable energy generation in combination with low carbon technology which is the way to go in order to join the combat against climate change and global warming. The journal further highlights several policies developed by the Indian government to accelerate this transition, encouraging the deployment of smart metering, payment of power bills over the internet and via mobile phone applications, load balancing along distribution lines, all geared towards optimization and reduction in commercial losses. These policies were implemented in Howrah, Bankura, East Midnapur and Purulia which have regions with the highest population.

The journal commends high voltage distribution system for its superiority compared to low voltage distribution system. The impact of the new energy policies in India is also quantified not leaving out the cost benefit with pay back of between four and six years. The weakness of the paper is that it didn't consider the demand side. The policies were tilted towards mainly transmission infrastructure.

2.2 Demand Forecasting

There are numerous benefits of being able to predict electricity demand using scientific means and methods. It guarantees a highly efficient resource planning scheme. Energy providers are able to plan better and allocate resources more efficiently. This entails optimizing power generation, distribution and storage capacities to meet expected demand. It prevents underutilization of energy assets leading to cost savings and improved operational efficiency. It also enhances the stability of the grid by anticipating demand peak periods so that energy providers can ensure sufficient power generation capacity to meet the increased load, thereby preventing grid failures, voltage fluctuations and blackouts. It also aids energy suppliers to optimize their procurement strategies based on predicted demand. Furnished with accurate predictions, energy suppliers can negotiate favourable contracts, plan for more capacity and strategically purchase energy in the wholesale market leading to cost saving and increased productivity.

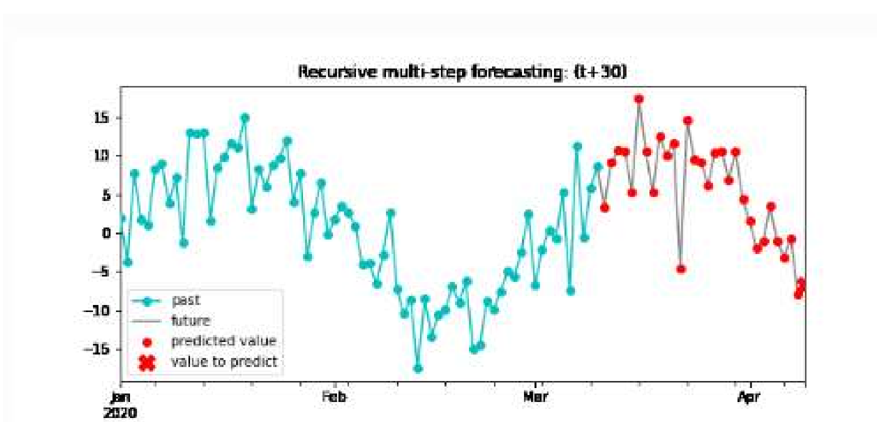

Figure 5: Multiple forecasting using time step series

Through machine learning, valuable insight is gotten from energy demand predictions. By using chronological time series, the forecast is achieved by either modelling the series using its past behaviour or using external variables.[8]
Joaquin et Javier explain how to predict electricity demand using skforecast, a simple library in python and scikit regression model for forecasting.

2.3 Distributed energy and active monitoring

Renewable distributed generation provide cleaner low cost electricity with more environmental benefits compared to the centralised grid which is highly dependent on fossil fuel. It reduces the cost of transmitting power over long distance transmission lines. Brandao Danilo describes active instrumentation and monitoring for smart grids. This paper explains in details ACTSENSOR power instrument and analysed results using MATLAB. Typhoon hard ware-in-the- loop simulation tool was used to validate the controls. The power instruments used for measurement are part of multiple sub power systems that communicate via protocols like Modbus TCP/IP and Distributed Network Protocol 3 according to IEC61850 in a bidirectional power flow [9]. With active monitoring, very low response time is achieved for fault resolution as the process is automated using intelligent algorithms. The reliability of the grid system is in line with the IEEE standard 1366-1998. In addition, what makes Brandao's paper unique is the triple loop control which is a method that applies the separation of the active and reactive components from selected harmonics with ability to reject harmonic currents thereby improving stability of the grid. This loop control method also offers seamless switch between the grid connected mode and the islanded mode. Cintuglu et all present a comprehensive study of the islanding process in line with IEEE1547.4 Grid code. It is a challenge deciding the appropriate mode for each distributed energy resource due to renewable energy intermittency [10].

2.3.1 Island Cascading in Micro grids

Mehmet et all provide extensive examination of the islanding procedure and the subsequent regulations of frequency and voltage in various islanding configurations that comply with the IEEE1547.4 Grid code [10] . The paper investigated three different forms of islanding in a smart grid operated with synchronous generator and inverter based distributed energy resource DER. During the islanding operation, micro grids are vulnerable to intermittency of renewable generation and may result in large scale blackout. During a fault, a micro grid may be disconnected from the main grid and still maintain its voltage and frequency level and controlling these power parameters become very difficult. The frequency of a power system is directly influenced by the balance of active power, while voltage is controlled through the reactive power [10]

In summary, the paper proves that it is possible to continue operation when the microgrid slips into island mode unintended with proposed control put in place.

2.4 Load Imbalance

Galvin et Ruth developed models used to analyse the power flow in medium voltage distribution system in Ireland utilising Python scripts for automation and VBA codes in excel for statistical summary of the medium voltage feeders for the period under study.[11] The macros also provide a functionality that allows for a theoretical calculation to ascertain if load balancing could resolve the problems of overloading. Load balancing involves sharing or distributing the load across different distribution components to ensure optimization of the distribution network. Galvin et Ruth's objective was to identify bottlenecks or areas of congestion on the network as a result of electric vehicles, heat pumps and photovoltaic which are clean energy technologies and propose solutions, if possible consider the usage of battery storage to preserve the stability of the grid. The locations and number of battery storage services will also enhance the grid stability in addition to N-1 contingency planning which helps in redundancy when one component or section of the power system suffers failure. In traditional network solutions, excess power not utilised at the distribution level is fed back into the grid via the transformer at the substation in reverse mode.

Figure 6:11kV Transformer at Findhorn High Voltage

The weakness of the paper is that the analysis is dependent on data collected over an excessively long period of eleven years and does not consider time constraint or obsolescence. Also, only worst case scenarios were considered between the models to keep at barest minimum, simulation times while running the analysis.

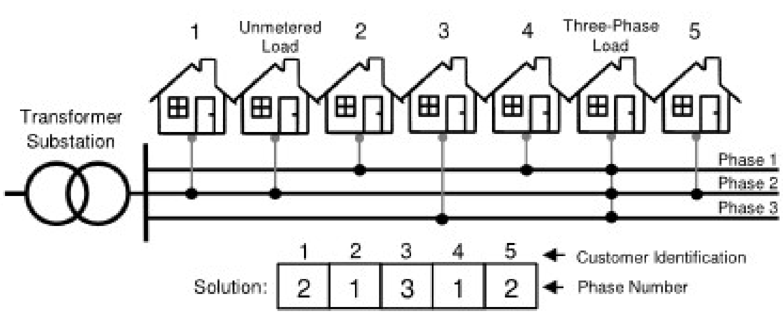

Figure 7:Example solution for load balance problem [12]

Connecting heat pumps and EV charging points will increase the load on low voltage network. Sometimes this may lead to load imbalance on the three phase wire system. Load imbalance can lead to overheating and reduce the life of induction motors. [12] Load imbalance is corrected by redistributing single phase loads across phases. Active and passive electronic systems correct voltage imbalances using deterministic crowding algorithm, a variant of genetic algorithm to find a new phase reconfiguration that reduces the imbalance level at the feeders or the transformer. The traditional method for correcting load imbalance is for an operator to visit residential area to perform changes causing downtime for other customers. A smarter method is to address load balancing through remotely managed phase switching devices[12]. These devices are connected to each customer's power line and switches the phase without suspending power supply. The installation of phase switching devices is expensive and would require funding. The paper explains the imbalance index B_t as a measurement of the deviation of the phase current with highest magnitude T_{tmax} from average phase currents I_{tmean} measured at time t. The resulting value is expressed in percentage. Yang Fan's body of work presents a model which offers options for testing a coordinated and uncoordinated low voltage distribution network [13]. The paper lacks actual data from the demand side, relying on assumed and estimated values for its model. He further recommends load reduction throughout the day as a solution. A better approach which my thesis will investigate is to shift the load to peak renewable generation periods which is more realistic for the customer.

2.4.1 Smart Grid

The existing literature by El Hawary [14] introduces smart grid and its future benefits while also highlighting concerns. A significant body of the paper addresses the exploration of Distribution Automation and the utilization of embedded intelligence. It highlights the importance of self-healing capabilities, operational optimization and the ability to recover from abnormal events. The paper provides a comprehensive overview of the functional and integration requirements for distributed energy resources. Additionally, it delves into the smart consumption infrastructure components of distribution management systems, automated metering infrastructure, smart homes and smart appliances. Having a good understanding of the demand side is very important in maintaining a stable and optimal power grid[15].

2.4.2 Grid reinforcement

Guo (2023) reviews the low voltage distribution network across 26 open access grids in Europe from over thirty scientific reports. The low voltage distribution grid in Europe consists of a radial network comprising of three phase and four wire configuration operating with a single transformer and multiple feeder cables. The limitation of insufficient data resurfaces placing a minor dent on the papers results. Sufficiently large amount of grid data are not available for public use. However, the report helps to streamline the impact of low-carbon technologies on the grid and provides options to mitigate impact like grid reinforcement[1].

No prior study or literature has been done to assess how the low voltage network reacts to the direct impact of energy transition to heat pumps in a detailed and concise way. This thesis utilizes sufficient and real time data for analysis and forecasting to support grid optimization and foster accurate economic evaluation taking into consideration the low voltage grid components like transformers and feeder cables.

3.0 Methodology

This thesis maintains primary objective of investigating the impact of energy transition on the grid at the low voltage distribution level. Literature is sourced from the University of Strathclyde Compendex (Engineering Vilage). For the literature search, the University of Strathcyde planning template and literature search document tools are used. Key words used for the search are “energy transition”, “smart grid”, “micro grid”, “low voltage network” and “monitoring data”.

3.1 Electrical Low Voltage distribution Model

For the low distribution network study, voltage, power and current level are observed from the Open source energy visualization (emoncms) to verify the present load and demand on the phases. The single line diagrams (SLD) for Findhorn are reviewed with specific emphasis on a fast developing dwelling called Pine ridge which is predicted to have an installation of fifty eight (58) heat pumps each 6kW to replace the biomass boilers. The distribution line to Pineridge utilises a 95sqmm 4Core Copper line which further splits into two lines 70sqmm and 50sqmm 4 core copper cables. The circuit breaker is rated 200A for the 95sqmm line. Since it is a three phase line, the loads are connected to single phases. Domestic heat pumps use single phase induction motors [16].There is a tendency for the network to experience load unbalance when the heat pumps are connected as some lines are predicted to bear more load than the others based on how the pumps are installed and usage. A load model is developed using MATLAB to assess potential load constraint cause by large scale adoption of heat pumps. A critical factor to consider is the diversity factor. It is assumed that not all the heat pumps are going to be switched on at the same time [16]. Hence a diversity factor of 0.6 is used when simulating the addition of the heat pumps and analysing the impact on the network. Major impacts of overloading a line is load imbalance and voltage fluctuations. Furthermore, an algorithm is developed to enable the grid control system to monitor the power, current and voltage transmitted along the single lines and take corrective actions to prevent over heating of the line and also to preserve substation equipment like transformer. A flow chart is developed using LUCID software. Overloading is envisaged based on the addition of heat pumps. In order to cope with this, reinforcement may be considered which involves replacing existing transformers with higher capacity transformers and higher current carrying capability cables. However, a more economical approach is the use a smart grid system to monitor the line and mitigate against overloading by using real time data. Another solution is to schedule some customers to utilize solar Photo Voltaic to power their Heat pumps during the summer, rather than depending on the grid.

3.2 Data Analysis

The aim of carrying out a data analysis on energy generation and demand data is to explore the options for FLEX and load shift in order to reduce energy costs and harness more renewable energy. Open source energy visualization (emoncms) offers real time monitoring and data from Findhorn. The dataset for the load and power supply from the wind turbines and from the grid is downloaded using Python API and Spyder Integrated Development Environment (IDE). The data set is exported to Microsoft excel, cleaned and characterised to identify patterns and trends. The mean and standard deviation of the dataset is calculated using excel. The data sets are downloaded at 30mins minutes interval daily. Data set used in this thesis is from June 14, 2023 to June 27, 2023. Data downloaded is total active power for the load feeder and the total active power generated by the wind turbines. The +2Sigma is calculated for all the data sets points using the mean and standard deviation, to represent the deviation of the segmented datasets using time intervals 12am -3am, 3am-6am, 6am-9am, 9am-12:00pm, 12:00pm-3pm, 3pm-pm, 6pm-9pm, and 9pm - 12:00am.

These standard deviations are used to quantify the variability or spread of data within each group and make comparisons to better understand their similarities or differences.

A linear regression analysis is carried out to visualize the relationship between the total demand at Findhorn Eco village and the renewable wind generation to explore options for load shift.

4.0 Analysis and Results

This chapter presents the full analysis and results carried out during the writing of this thesis. All data obtained are real time data from Findhorn Ecovillage monitoring portal called openenergymonitoring.

4.1 Load Imbalance and Voltage Regulation

It is envisaged that load imbalance will occur as a result addition of heat pumps to replace biomass boilers due to the electrical nature of the load leading to uneven distribution of load among the three phases. Presently, the three phases are balanced as observed below from a one week data.

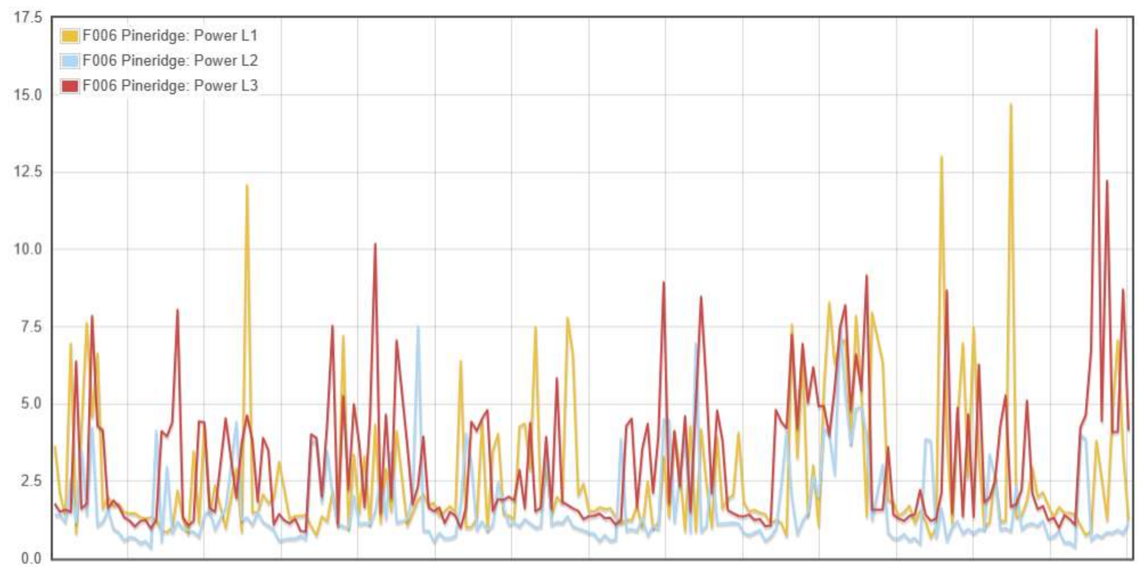

Figure 8: One week Real time active power consumption at Pineridge

The specifications of the low voltage distribution line at Pine ridge is 95sqmm 4Core Cu line with 200A circuit breaker. Average daily power at Pine-ridge is 27.1kW.

4.1.1 MATLAB simulation

MATLAB model is used to simulate to determine the maximum number of heat pumps that can be connected before the line experiences The growing adoption of heat pumps in United Kingdom presents a challenge to the low voltage distribution network primarily due to the utilization of induction motors to drive pump compressors [16]. Inductive motors have unique characteristics that can impact stability and performance. In the MATLAB model, the heat pump is simulated as an Inductive load.

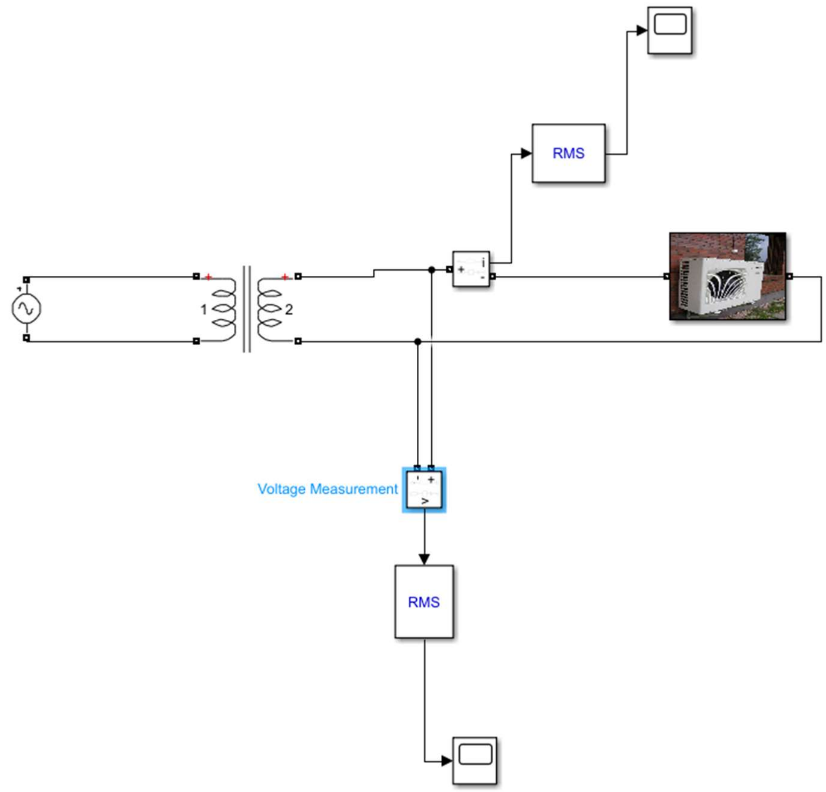

Figure 9: LV network model using Matlab

The model includes a 1000kVA (rated power), Voltage ratio 11,000/400v Transformer. A single phase of the transformer is used for the simulation. The voltage measurement device is connected across the secondary windings of the transformer while the current measurement is connected in series. An inductive load is connected in series to represent the heat pump with total demand included in steps. The value of the current and the voltage is measured for different instances. Load comprises of an average of 12kW demand added to the power for the heat pumps per customer. Diversity factor of 0.6 is used. For a 6kWe heat pump, total extra load is 58*6 =348kWe (1044kWth with coefficient of performance of 3). It is assumed that not all the pumps would be switched on at the same time. See table summarising results below.

Table 1: Effect of adding extra heat pumps on Line current (Pine ridge)

Demand without HP at Pine ridge (kW)	No. of HP	Power factor	Heat Pump load (kWe)	Load + heat pump	Div factor	Total load *Div factor	Phase	Line Current (A)	Reinforcement Y/N
27.1	0	0.9	0	27	0.6	16.26	3	45	N
27.1	10	0.9	60	87	0.6	52.26	3	145	N
27.1	15	0.9	90	117	0.6	70.26	3	195	N
27.1	20	0.9	120	147	0.6	88.26	3	245	Y
27.1	25	0.9	150	106	0.6	106.26	3	295	Y

The maximum number of heat pumps that can be connected before the line gets overloaded is 15. Any additional load added will cause over heating of the line and the circuit breaker will trip off. The feeder distribution line will need to be reinforced. Another solution may be to use a lower capacity heat pump of say 3kWe. With a coefficient of performance of 3, this means that the heat pump would give 9kWth for one heat pump and 522kWth which is still too large.

4.1.2 Load balance and voltage regulation algorithm

In the scenario of a low voltage power supply network, it is specified from IEC60038 that the voltage should not deviate more than 10 percent above or 6 percent below the designated voltage of 230Volts at frequency of 50hertz. Based on specified limits, allowable range is 216v to 254v and this can be observed from the data monitoring below.

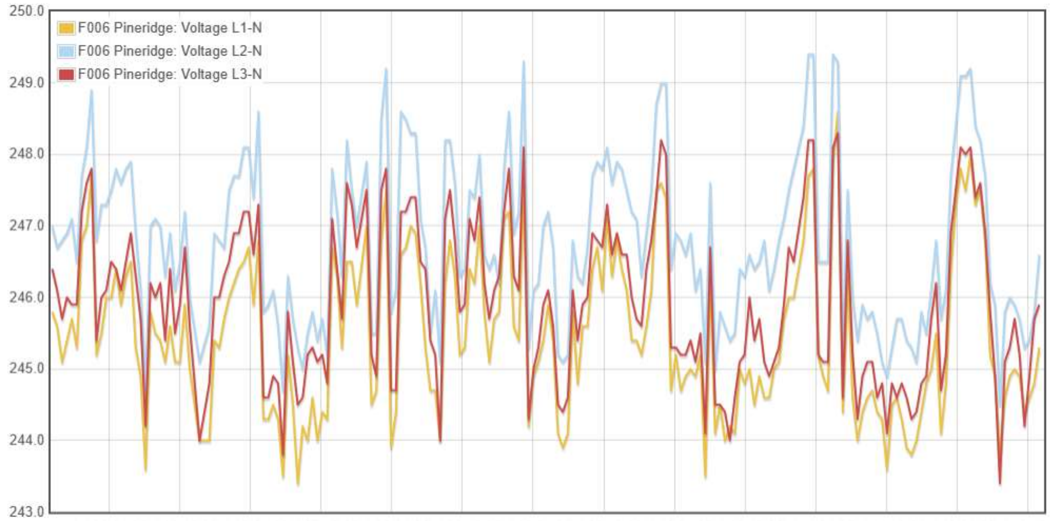

Figure 10: One week Pine ridge line to neutral voltage

The following logic sequence is developed to regulate load imbalance and line voltage on the low voltage distribution network to curtail the effect of extra load imposed on the network by the addition of heat pumps.

```
Start
├─ Monitor Loads
│   └─ Calculate Load Imbalance
│       ├─ Load Imbalance > Threshold?
│       │   ├─ Yes:
│       │   │   ├─ Identify Phase with Highest Load
│       │   │   ├─ Identify Loads to Shift
│       │   │   └─ Balance Loads Across Phases
│       │   └─ No:
│       │       └─ Continue Monitoring Loads
│       └─ Go to Monitor Voltages
└─ Monitor Voltages
        └─ Voltage Outside Desired Range?
            ├─ Yes:
            │   ├─ Voltage Too High?
            │   │   ├─ Yes:
            │   │   │   └─ Activate Reactive Power Compensation
            │   │   └─ No:
            │   │       └─ Activate Voltage Regulation
```

| └─ Voltage Too Low?

| ├─ Yes:

| | └─ Activate Voltage Regulation

| └─ No:

| └─ Continue Monitoring Voltages

└─ No:

    └─ Go to Monitor Loads

End

This Flow chart for the developed algorithm to monitor load balance and voltage regulation is shown below.

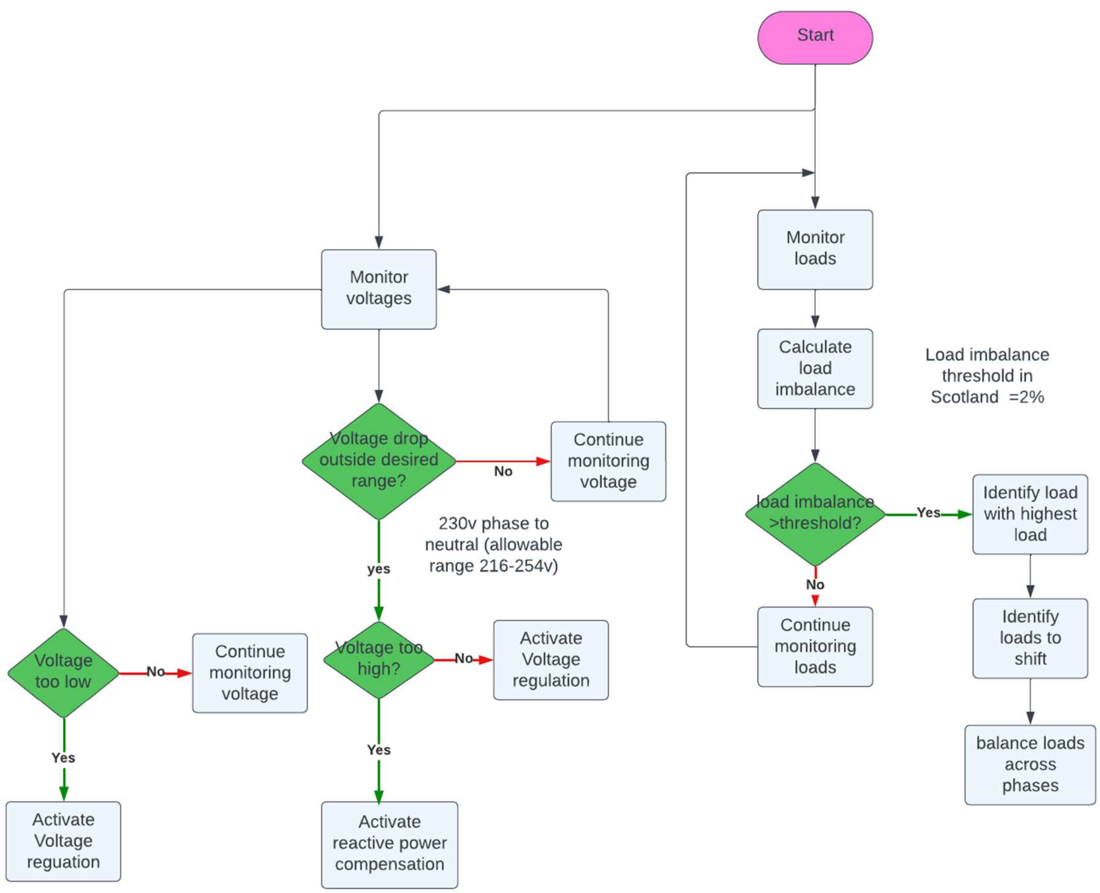

Figure 11: Flow chart for load balance and voltage regulation algorithm

4.2 Load Shift Opportunity

The measurements come with a frequency of 30 minutes, a typical for smart meters. It represents an ideal case to define the algorithm applying learning and training data using forecast algorithms. The dataset used in this thesis was obtained from Findhorn monitored data on OpenEnergyMonitor.org. All data was downloaded using python API (see appendix). The data contains power generated by wind turbines, demand profile for social housing, from June 14 2023 – June 27 2023.

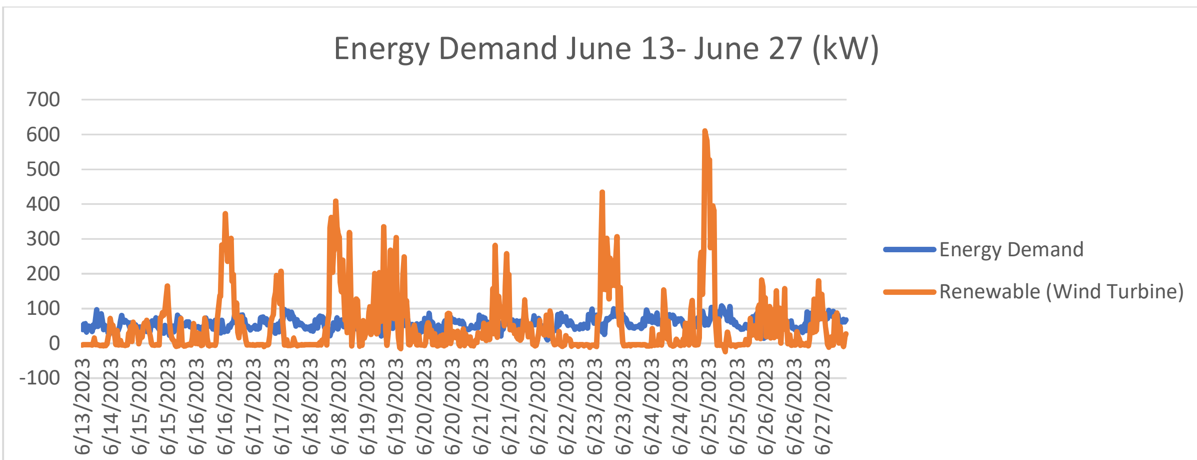

Figure 12: Energy Demand and Wind Turbine Generation June 14- 27(2 weeks)

The energy generated by wind turbines is intermittent. During the peak wind power generation period, energy can either stored in batteries or sold to the residents at a less tariff less than grid price but still enough to make profit. Occupants buy at 60 pence per kWh from the grid, hence Findhorn can sell power at lower tariff say 50 pence per kWh. The excess power is exported at 30 pence per kWh.

A box plot further plotted with python for 24 hour energy demand to identify periods of peak demand and least demand.

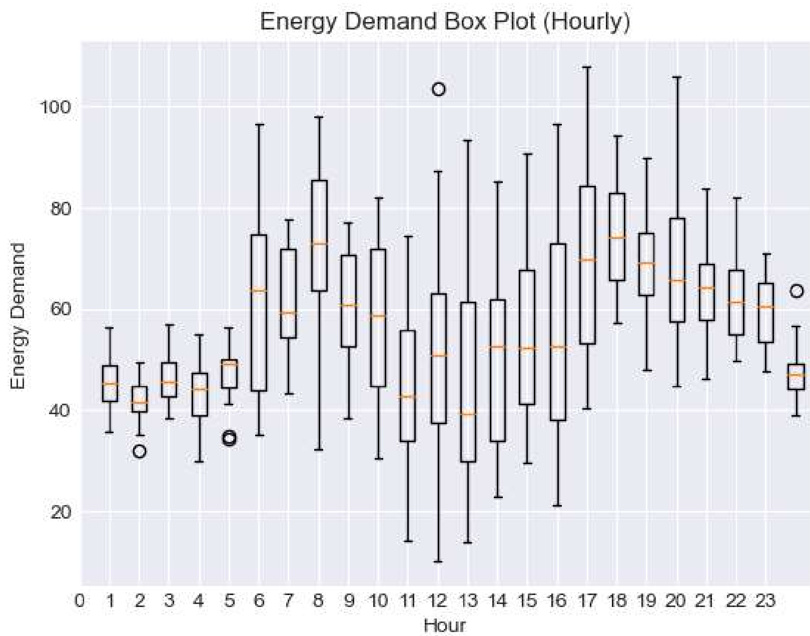

Figure 13: Box and whiskers Plot for daily energy demand

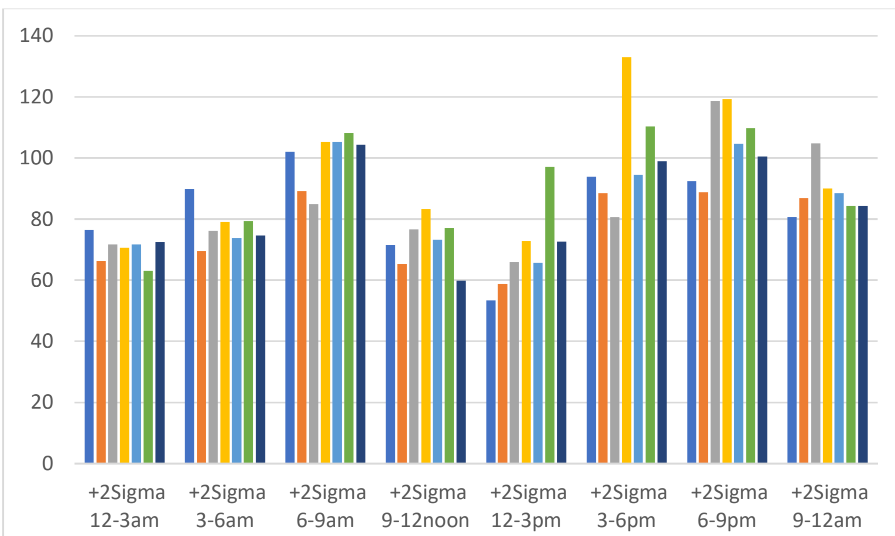

Figure 14: Seven days of data is used as learning dataset June 14 – June 20

This provides information on the time period during the day when the demand is at its peak. The highest demand is observed between 3:00-6:00pm when more occupants are at home and turn on most of their electrical appliances. The next period of high demand is morning time 6:00-9:00am.

4.2.1 Incentivization and Battery savings

The average consumption for a house of 3-4 occupants in United Kingdom is about 12kWh. A flexible tariff system combined with battery storage can lead to reasonable savings. An analysis was carried to see how much can be saved adopting a tariff plan (Octopus Go)[17].

- Between 12:30-4:30 am (4 hours), the Tariff = 9pence per kWh
- Between 4:30am-12:30am, Tariff = 40 pence per kWh

The battery is charged during the off peak period and used to power the house during peak period.

See Table below.

Table 2: Savings using flexible tariff (Octopus Go)[17]

ppkWh	Daily usage 12kWh	Yearly energy spending	Savings with battery(2020)	Savings with Battery (2023)
20	£2.40	£876.00	£526.60	**£236.52**
25	£3.00	£1,095.00	£744.60	**£455.52**
30	£3.60	£1,314,00	£963.60	**£674.52**
35	£4.20	£1,533.00	£1,182.60	**£893.52**
40	£4.80	£1,752.00	£1,401.00	**£1,112.52**

Information from the table shows that between 2020 and 2023, as the tariff went higher, savings from using batteries decreased by about 20%.

5.0 Discussion

From the results and analysis in the previous chapter, the installation of heat pumps in fifty eight apartments would be very expensive and implementing smart control would be difficult to achieve. For 58 heat pumps the expected electrical load is 348kWe and 1044kWth (thermal). The 95Sq mm 4-Core electrical cables do not have the capacity to accommodate the large current introduced by the heat pumps when they are all switched on even when the diversity factor of 0.6 is factored into calculation.

Considering a clustering approach, it is technically and economically advantageous to have energy centres which will act as mini districts to meet space heating and hot water demands and facilitate smart grid control.

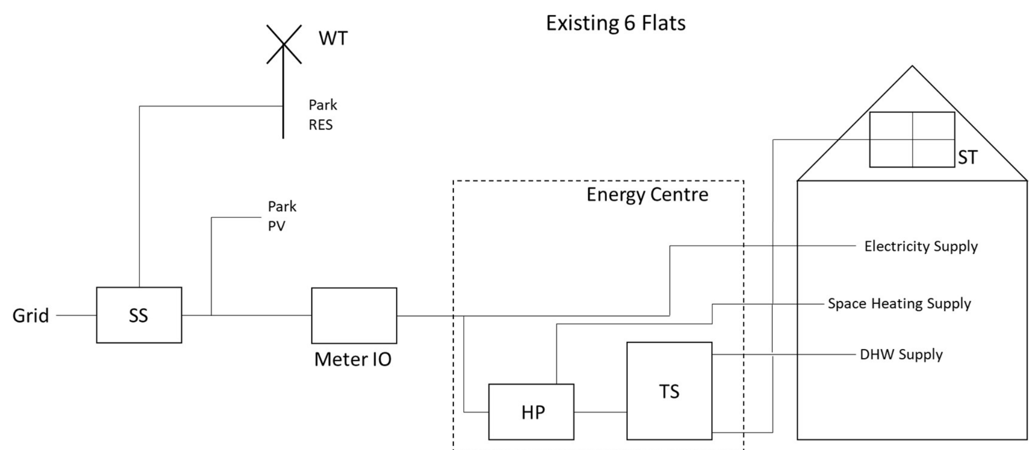

Figure 15: High Level Schematic of Energy Centre with heat pump (HP) and Thermal Storage (TS) [18]

The above central energy centre can service 6 customers. A 14kW air source heat pump (ASHP) is utilized for both space heating and supplying domestic hot water (DHW) through a wet system. There is a 550-litre thermal storage unit specifically designated for the DHW supply, and this storage is complemented by 6 solar thermal panels measuring 2.3m^2 each, which directly contribute to charging the DHW storage. Thermal layering in the tank enhances the effectiveness of thermal storage tanks [19].The priority is to maximize the solar thermal input ensuring electrical heating is from renewable sources as much as possible rather grid imported electricity. A typical scenario for real time data is displayed below.

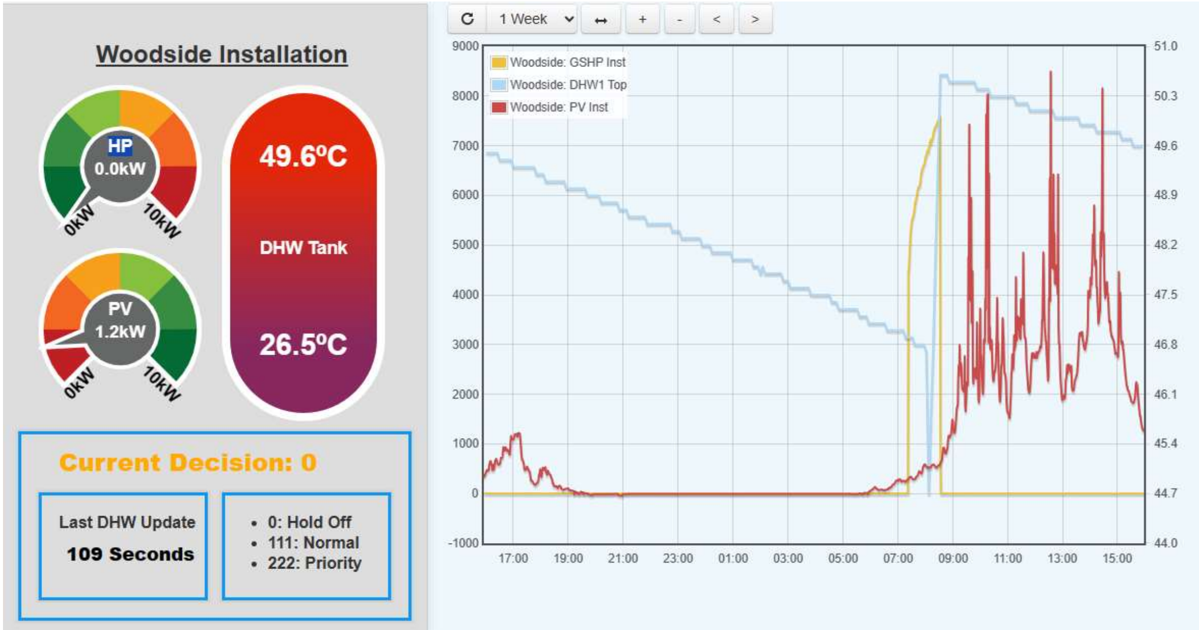

Figure 16: Dash board for viewing temperature, solar pv and heat pump values at woodside

Approximately seven mini districts (or energy centres) will be required to service the whole of Pine ridge. From the figure above, the heat pump will switch on (for pre-charge) to heat thermal storage tank to about 50°C between 7am and 9am (based on the control algorithm) in the morning when there is high demand for hot water as observed from demand profile and then switched off. The solar thermal kicks in from about 10am and maintains the temperature build (from the heat pumps) of the thermal store at the top of the tank at about 50°C. The temperature of the tank starts to decline gradually due to losses and is allowed to coast till the next charge cycle the following day. Charging of the thermal store is limited during periods of lower demand to reduce excess heat loss[18]. The heat pumps directly supplies the space heating at a flow temperature of 45°C to the radiators in the houses.

5.1 Achievements

This thesis was able to record achievements which are listed below;

- Successfully performed load modelling using MATLAB to ascertain the possibility of installing fifty eight (58) air source heat pumps at Findhorn, confirming that only 15 can be switched on at the same time in order not to overload the distribution line capacity and exceed the limit of the circuit breakers. This model can be applied to other housing development schemes considering transition to heat pumps.

- Developed a logic sequence to protect the distribution line from over voltage and load imbalance using standard specified values. This logic can be implemented in the smart control system for the grid with the use of smart grid relays.

- Analysed real time data for electrical demand and renewable generation for both solar and wind generation and identified opportunities to shift load to periods of renewable generation and also to utilize solar thermal to retain the temperature of the thermal store.

- Performed a cost saving analysis using battery installation to store power from solar or wind generation. By encouraging people to use renewable power generated during off peak period, the customers can spend less on power and save cost of electrical power with a return of investment of four years for battery installation.

5.2 Limitations

There were several limitations that was encountered while writing this thesis.

- The constraint of data privacy and restricted access to sensitive information also posed a limitation. The data and project documentation (including single line diagrams, drawings, and maps) provided by Findhorn were utilized to the fullest extent possible.

- Insufficient metering of all the nodes. At Findhorn, metering is yet to be installed at specific nodes, for example there was no metering to show grid imported electricity. Investigation was carried out using available data on the monitoring portal and making reasonable assumptions.

- Time constraint was a factor while writing this thesis but regardless the given time period to complete the thesis was maximized.

- The period of writing this thesis was during the summer season and the intention was to use real time data for more accurate and credible results. The winter season was not considered.

5.3 Future recommendations

A few recommendation for future work on this topic is as follows;

- Further future study can consider the impact of electric vehicles on the low voltage distribution network. The location and electrical load capacity of the electric vehicles charging points will be worth studying.

- Collection of larger amount of data for learning and training to develop more accurate forecasts through machine learning. Extend data collection period to cover the winter season where other renewable energy sources like wind turbines will be at peak generation.

- Consider the benefits of installing battery to store renewable energy during peak generation. It is also important to consider the payback period bearing in mind the high cost of batteries.

6.0 Conclusion

In conclusion, this thesis confirms that transition to heat pumps will impact the low voltage distribution network negatively if electricity demand from the heat pumps exceeds the current carrying capacity of the distribution line. Simulations and results have helped to accurately identify two major problems anticipated namely load imbalance and voltage degradation. A faster to deploy and more cost effective solution is proposed as an alternative to network reinforcement. Data from the demand side is used to develop smart control algorithms which can optimise the power grid by shifting period of high demand to align with periods of peak renewable generation. It is also worth noting that instead of purchasing heat pumps per dwelling as intended by Findhorn eco village, results prove that it is better to have a clustered approach where an energy centre with a single heat pump can service as many as eight customers or more depending on its capacity. In addition, building houses according to PassivHaus standards [20]will provide guaranteed insulation of the dwellings and will reduce heating demand. This thesis aims to provide a valuable reference to aid policy makers and distribution network operators in making well-informed choices concerning the low voltage distribution network.

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