Master thesis

Master Program in Energy Smart Innovation in The Build Environment (120 Credits)

Hybrid Energy Storage System Model in MATLAB, Based on Solar Energy for Residential Applications

Thesis in Construction Engineering with Specialization in Renewable Energy, 30 credits

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Abstract

The increasing integration of renewable energy sources, particularly photovoltaic (PV) systems, in residential buildings necessitates effective energy storage solutions to manage the intermittent nature of solar power. This paper presents the design and simulation of a hybrid energy storage system (HESS) for residential applications, utilizing MATLAB as the primary tool for modeling and analysis. The proposed HESS combines Li-ion batteries and an accumulator tank, this dual-storage approach allows for more comprehensive energy utilization, covering both the electrical and thermal needs of a household, such as electricity for appliances and hot water or to meet heating demand. Our approach involves detailed modeling of the PV generation profile based on real-time solar irradiance data, and the corresponding load profile of a typical residential building. The energy management strategy implemented in MATLAB prioritizes solar power usage and efficiently switches between storage devices while meeting the instantaneous power demands. Simulation results demonstrate the HESS's capability to smooth out the fluctuations in solar power generation, maintain a stable power supply, and reduce reliance on the grid. The study underscores the potential of hybrid storage systems in enhancing the sustainability and reliability of residential PV systems, providing a practical pathway towards energy self-sufficiency, cost-effectiveness, and resilience in the face of growing energy demands and environmental concerns.

Keywords: Hybrid Energy Storage System, Photovoltaic System, Residential Building, Renewable Energy, MATLAB, Energy Management, Li-ion Battery, Accumulator Tank.

Preface

We are doing our thesis as a part of our "Energy Smart Innovation in The Built Environment" course. We are deeply grateful to everyone who has supported us throughout this process.

First and foremost, we would like to express our sincere gratitude to our thesis supervisor Fredric Ottermo whose guidance, patience, and expertise have been invaluable. Your insightful feedback and unwavering support have significantly shaped this work, and we are truly fortunate to have had the opportunity to learn from you.

We also like to thank our program director Mohsen Soleimani for his timely guidance which helped in complete this thesis. We also like to thank our families and friends who provided moral support in finishing our thesis.

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1. Introduction

In the pursuit of sustainable living and reducing the dependency on fossil fuels, renewable energy sources have emerged as pivotal solutions. The integration of renewable energy sources into residential applications plays a vital role in advancing sustainable energy solutions, but effective measures like combining with electricity storage is required to balance electricity production and consumption owing to the seasonal nature of renewable energy sources. Among these, solar energy stands out as a promising avenue for generating clean and abundant power. PV is already widely installed and normally the excess energy is directed to the external energy grid. However, the substantial installation of photovoltaic (PV) systems connected to the grid poses a strain on the grids, especially during periods of high PV production, such as in summer (Möller & Krauter, 2022). This may lead to the slow expansion of renewable energy systems. A hybrid energy system is a solution to this, providing long-term energy storage to reduce the necessity for grid expansion.

This thesis explores the integration of a photovoltaic (PV) system in a residential setting in Gothenburg, Sweden, to illuminate the transformative potential of solar technology in modern households. Located on the west coast of Sweden, Gothenburg experiences varying weather patterns typical of Scandinavian climates. Despite its northern latitude, Gothenburg receives a considerable amount of sunlight, especially during the summer months when daylight hours are extended. Harnessing this solar resource through PV technology presents a viable opportunity to contribute to the region's energy transition goals while reducing greenhouse gas emissions and mitigating climate change impacts. The primary objective of this thesis is to evaluate the feasibility and effectiveness of utilizing a PV system to power a two-story residential house in Gothenburg. The selected residential property serves as the test bed for implementing a comprehensive renewable energy solution. A PV array is installed on the roof to capture sunlight and convert it into electricity. The generated power is utilized to meet the household's energy demand, including lighting, appliances, and space heating. To ensure an uninterrupted power supply and maximize self-consumption, excess electricity is stored in a lithium-ion battery system for later use. As an innovative storage solution, in addition to battery storage, an innovative approach of integrating an accumulator storage tank is adopted to utilize surplus solar energy effectively. Once the lithium-ion battery reaches full capacity, any excess power generated by the PV system is diverted to an accumulator tank for water heating purposes. This integrated energy management strategy not only optimizes self-consumption but also enhances the overall efficiency and sustainability of the PV system.

Incorporating lithium-ion batteries for energy storage in residential settings offers several distinctive advantages. Lithium-ion batteries boast a high energy density, enabling them to store a significant amount of energy in a relatively compact space. This characteristic is particularly beneficial for residential applications where space may be limited. It exhibits a low self-discharge rate, that is it can retain stored energy for longer durations without significant loss. This feature ensures reliable and consistent energy availability, crucial for meeting household demands efficiently. Additionally, lithium-ion batteries are known for their longevity and durability, with the capability to withstand numerous charge-discharge cycles over their lifespan. This reliability reduces maintenance requirements and enhances the overall cost-effectiveness of energy storage solutions for homeowners. Moreover, lithium-ion batteries offer fast charging and discharging capabilities, allowing for rapid response to fluctuations in energy demand or supply. This flexibility is invaluable for optimizing energy management in residential settings, where varying consumption patterns may occur throughout the day. Overall, the unique characteristics of lithium-ion batteries make them an ideal choice for energy storage in residential houses, contributing to increased self-sufficiency, energy efficiency, and sustainability (Matan, 2023).

Incorporating an accumulator tank for surplus energy utilization after lithium-ion battery storage presents several distinctive advantages in residential energy systems. The accumulator tank serves as a thermal storage unit, allowing excess energy from the PV system to be efficiently stored in the form of heat. This thermal energy can then be utilized for domestic purposes, such as to meet the heat demand and hot water. By leveraging surplus energy in this manner, the system maximizes energy utilization and minimizes grid feed-in (or wastage in the case of an off-grid system), contributing to overall energy efficiency and cost-effectiveness. Additionally, the use of an accumulator tank provides a buffer for fluctuating energy production and consumption patterns. During periods of peak solar generation, when the lithium-ion battery is fully charged, excess energy can be diverted to the accumulator tank for storage. Subsequently, during periods of low solar generation or high energy demand, the stored thermal energy can be tapped into to supplement the household's energy needs. This dynamic energy management capability enhances system resilience and reliability, ensuring a consistent energy supply for the household.

Overall, the integration of an accumulator tank in conjunction with lithium-ion battery storage presents a holistic approach to surplus energy management in residential PV systems. By harnessing thermal energy storage capabilities, grid dependency is reduced, and this setup enhances energy efficiency, reliability, and flexibility, contributing to sustainable and resilient energy solutions for residential households.

2. Literature Review

In recent years, hybrid energy storage systems (HESS) have emerged as a promising solution to address the limitations of standalone energy storage technologies and optimize the efficiency and dependability of renewable energy systems. By combining various storage technologies, HESS provides several benefits, including improved energy efficiency, strengthened grid stability, and greater integration of renewable energy sources. Furthermore, HESS plays a crucial role in mitigating the intermittency associated with renewables by offering a dependable and readily available energy supply. Beyond technical advantages, HESS also brings economic benefits, such as reduced reliance on grid electricity and the potential to generate revenue through services like peak shaving and demand response. Overall, HESS represents a versatile and scalable approach to incorporating renewable energy sources into the grid, setting the stage for a sustainable and resilient energy landscape.

Hydrogen fuel cell and battery: In the realm of hybrid energy storage systems (HESS), the integration of hydrogen fuel cells with batteries has garnered significant attention. Traditionally associated with solar photovoltaic (PV) systems, batteries find a new synergy when combined with a hydrogen sub-system. In this hybrid configuration, excess energy generated by solar PV can be utilized to produce hydrogen, subsequently powering the fuel cell during periods of heightened demand. This integration has sparked interest in incorporating hydrogen into solar-powered microgrids. While both storage systems share the ability to store solar energy for later use, they exhibit distinct characteristics. Notably, fuel cells boast high specific energy and reliability compared to conventional batteries, along with a longer operational lifespan.

The work done by Han et al. introduced a hierarchical energy management system integrating PV and a battery-hydrogen storage device, leveraging non-dispatchable renewable energy sources. Excess energy is stored as hydrogen gas via an electrolyzer to bridge demand gaps effectively (Han et al., 2019). Another one is by Torreglosa et al, who presented an energy-dispatching model for a standalone hybrid system, utilizing PV, wind, batteries, and hydrogen storage. Employing model predictive control (MPC), the system achieves higher global efficiency by optimizing battery SOC and hydrogen tank levels. Both studies demonstrate the benefits of hybrid energy systems, including increased battery lifespan and cost reduction. Integration of hydrogen storage with renewable sources offers enhanced energy management and efficiency, addressing intermittency challenges while promoting sustainability. These findings underscore the viability of hybrid energy solutions in improving grid stability and reducing reliance on traditional energy sources (Torreglosa et al., 2015).

Hybrid batteries and supercapacitors energy storage system configuration: The combination of batteries and supercapacitors in an energy storage system offers a versatile solution that can effectively address various power and energy requirements, particularly in renewable energy systems like photovoltaic (PV) power systems. Batteries are well-suited for storing large amounts of energy over extended periods, making them ideal for applications requiring high energy storage capacity. On the other hand, supercapacitors excel in delivering short bursts of high power due to their fast charge and discharge capabilities. By integrating both technologies, hybrid energy storage systems can leverage the strengths of each component to provide a balanced solution that covers a wide range of power and energy demands. Batteries handle long-term energy storage needs, while supercapacitors accommodate rapid fluctuations in power demand, ensuring efficient energy management and system stability. This hybrid configuration enhances the overall performance and reliability of renewable energy systems, allowing for better utilization of solar energy and improved grid integration.

Jing et al. conducted a study on a battery-supercapacitor hybrid energy storage system for standalone photovoltaic (PV) powered systems. They explored factors influencing battery efficiency and various hybrid configurations to alleviate battery stress. Their three-level hybrid energy storage system (HESS) configuration demonstrated superior performance for off-grid rural applications compared to passive and semi-active HESS setups. Building upon this, Chang et al. proposed an optimal control strategy aiming to extend battery lifespan and reduce dynamic stress. Their approach involved integrating a low-pass filter with a fuzzy logic controller (FLC), which resulted in improved battery life and maintained the supercapacitor within a healthy state of charge (SOC) (Jing et al., 2018).

Similarly, Ma et al. developed a battery-supercapacitor energy storage system utilizing hybrid renewable energy sources (PV-wind). They employed a passive configuration to accommodate prolonged charge/discharge cycles and short peak power surges, thereby prolonging the battery's lifespan. Overall, these studies highlight the efficacy of hybrid energy storage systems in optimizing performance and extending the lifespan of batteries in off-grid applications with renewable energy sources (Ma et al., 2015).

Hydrogen and supercapacitor configuration: The hybridization of hydrogen fuel cells and supercapacitors offers a promising approach to energy storage, similar to the interplay between batteries and fuel cells. In this configuration, the fuel cell functions as a battery, storing renewable energy when it's available, while the supercapacitor handles excess energy, smoothing out high transients and rapid load fluctuations. However, alternative research models reverse this setup, utilizing the fuel cell as the primary power source and the supercapacitor as the main storage for supplying and absorbing power during load transients. This integration of two distinct energy storage systems adheres to the essential parameters required for an effective energy storage solution: high energy and power density. Fuel cells boast high energy density, complemented by the supercapacitor's high power density. One significant limitation of fuel cells is their relatively slow response to charging due to a limited power slope. This can lead to fuel shortages and impact service life. The supercapacitor's rapid response capability addresses this drawback, aligning well with the fuel cell's characteristics and enhancing overall system performance and longevity.

Luta and Royi analyzed the optimal sizing of a hybrid fuel cell and supercapacitor storage system for off-grid renewable energy applications, employing photovoltaic (PV) as the primary renewable energy source. The study focused on determining component sizes based on technical feasibility and cost-effectiveness. The supercapacitor was utilized to manage transient peaks and rapid fluctuations in energy demand. Results highlighted the impact of integrating both systems on the overall cost of the proposed system, revealing its potential expense for commercial implementation (Luta & Raji, 2019). Similarly, Jayalakshmi et al. utilized a similar configuration with PV and fuel cells as primary sources, employing the supercapacitor as a load power stabilizer in a power control hybrid system for standalone applications. Three control strategies were employed: maximum power point tracking (MPPT) for PV, inverter control for voltage and frequency regulation, and current control for overall power balancing. Findings demonstrated the effectiveness of these control strategies in maintaining constant voltage with minimized frequency distortion, enhancing the experience for end-users (Jayalakshmi et al., 2016).

Battery and pumped hydro storage: The energy storage research field is increasingly focused on pumped hydro storage systems (PHS), available in open and closed loop setups. PHS offers low maintenance, long lifespan, high energy density, environmental friendliness, and high roundtrip conversion efficiency. These traits suit PHS for supporting fluctuating renewable energy sources (RES) like isolated hydrokinetic (HKT), photovoltaic (PV), and wind energy systems. However, challenges include low power, requiring large water flows or height differentials, and slow response rates for balancing lower power deficits. So, pumped hydro storage (PHS) can be combined with other energy storage systems (ESS) to use their combined storage abilities and better support renewable energy sources (RES) that change unpredictably. Different storage technologies possess unique technical properties, prompting the exploration of hybrid storage system (HSS) topologies.

Kumar and Biswas conducted a study to investigate whether it is practical to integrate both a pumped hydro storage (PHS) system and a battery storage system (BSS) powered by photovoltaic (PV) solar panels. Their findings showed that incorporating a small BSS alongside the PHS system could have substantial benefits. Specifically, this addition allowed for a reduction in the size of the upper reservoir in the PHS setup. Because of this reduction, there was a decrease in the amount of excess energy generated by the system. In essence, by combining a BSS with PHS, the overall system could better manage the energy flow, optimizing the storage and utilization of renewable energy from the PV panels. This insight suggests that integrating multiple storage technologies could enhance the efficiency and effectiveness of renewable energy systems, contributing to a more sustainable energy landscape ("Techno-Economic Optimization of a Stand-alone PV/PHS/Battery Systems for Very Low Load Situation," 2017). In their study, Guezgouz and colleagues introduced an innovative hybrid pumped hydro-battery storage scheme tailored for standalone renewable energy systems. They employed the grey wolf optimizer as the method for determining the optimal sizing of components within the system. The findings of their research demonstrated notable improvements in reliability while maintaining cost-effectiveness. By combining pumped hydro storage with battery storage, the system could better meet energy demands and ensure a consistent power supply, even during periods of fluctuating renewable energy generation (Guezgouz et al., 2019).

3. Research Question

The purpose of the thesis can be broken down into two concrete Research Questions (RQs), which are listed below:

- RQ1: What strategies can be employed to develop a photovoltaic (PV) system that minimizes reliance on the grid while maximizing self-consumption of generated energy?
- RQ2: How can we model a viable and reliable hybrid energy storage system for residential use, with a focus on integrating photovoltaic (PV) technology as the primary energy source?

4. System Architecture

Using a hybrid energy storage system (HESS) along with a residential building's photovoltaic (PV) system can be an efficient and sustainable way to manage energy consumption and reduce reliance on the grid. The residential building in Frölunda, Sweden is equipped with a rooftop PV system to harness solar energy. This system converts sunlight into electricity during the day, providing clean and renewable energy to power the building's electrical appliances and systems. A hybrid energy storage system is installed to store excess energy generated by the PV system during the day for later use, particularly during times when sunlight is insufficient, i.e., at night or during cloudy days. This hybrid energy storage system consists of a lithium-ion battery, which is efficient for storing and discharging electricity, and an accumulator tank, which stores energy when the Li-ion battery is fully charged. Energy from the accumulator tank can be further used for space heating. The HESS can also facilitate load management by prioritizing the use of stored energy for critical loads or during peak demand periods. This helps to reduce electricity costs and alleviate strain on the grid, especially during times of high energy demand.

Incorporating per-hour space heating demand and electricity load demand data is essential for accurately sizing and designing a solar panel system to meet the energy needs of households in Frölunda, Sweden. By analyzing the hourly variations in energy consumption throughout the year, we gain valuable insights into the specific requirements for heating and electricity usage during different times of the day and across seasons. This granular approach allows for the optimization of solar panel configuration, ensuring that the system can effectively generate and deliver the necessary energy to power both space heating and electrical appliances at any given time. By aligning solar panel capacity with the fluctuating demands of the household, we can maximize energy self-sufficiency, minimize reliance on the grid, and achieve optimal cost-effectiveness and environmental sustainability in Frölunda's residential energy systems.

The fundamental components of the proposed energy system model consist of a lithium-ion battery, an accumulator tank, and a photovoltaic (PV) system. Figure 1 illustrates the structure of this energy system. The PV system functions as the primary energy source. Through an inverter, solar energy generated can be directly utilized for household electrical loads, i.e., direct consumption. Any excess energy is then stored in the lithium-ion battery via a DC/DC converter acting as a charge controller. This stored energy can subsequently be transferred back into the household grid through an inverter if energy production falls short of demand. In instances where the lithium-ion battery reaches full capacity and solar energy production still exceeds demand, the surplus energy is directed to the Accumulator tank. This additional storage can be tapped into for space heating, particularly when the lithium-ion battery is fully discharged. By employing such an advanced energy system, self-consumption of PV system energy can be enhanced while reducing reliance on the grid and minimizing grid feed-in.

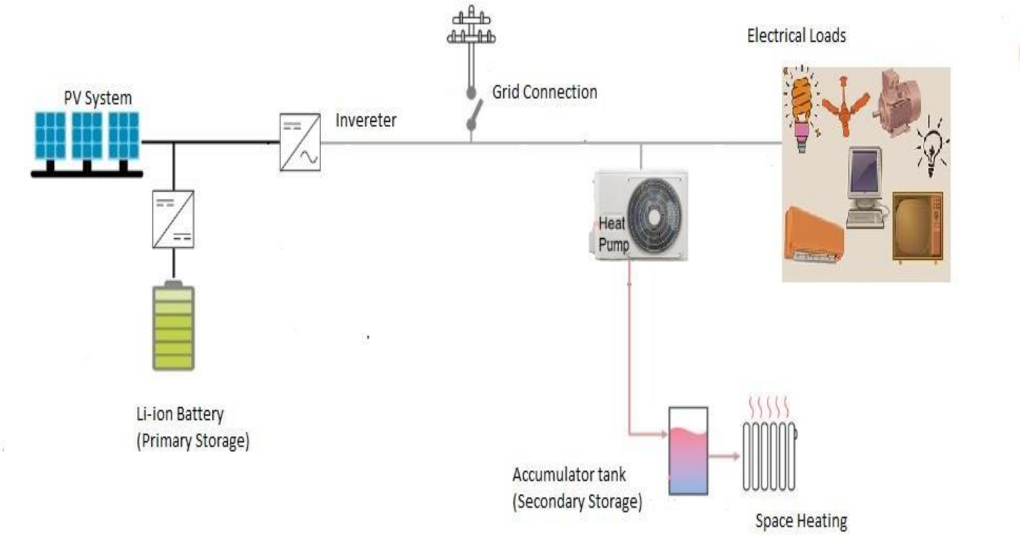

Figure 1: Hybrid Energy System.

The first step involves assessing whether surplus energy is available in the accumulator tank for heating purposes. This check ensures that any excess energy generated by the PV system is utilized efficiently to meet secondary energy demands, such as water heating, and space heating thus maximizing the system's overall energy utilization. Following this, we evaluate the state of the battery, determining whether it is charging or discharging based on the net power (P_{net}) available. This decision-making process ensures optimal management of the battery's storage capacity, balancing the inflow and outflow of energy to maintain a stable energy supply. If the storage level exceeds its maximum capacity, surplus energy is directed to the accumulator tank. This mechanism prevents energy grid feed-in (or wastage) by storing excess energy for later use, further enhancing the system's efficiency and resilience against fluctuations in energy availability. At the same time, if the storage level falls below zero, indicating an energy deficit, the process initiates the drawing of electricity from the grid to meet the household's energy demand. This feature ensures an uninterrupted energy supply to the household, even during periods of low PV generation or high energy consumption.

Additionally, the system incorporates provisions for accounting for the self-discharge of the storage system. By factoring in the gradual loss of stored energy over time, the simulation accurately reflects the real-world behavior of battery, providing realistic insights into their performance. Throughout the iteration, the analysis continues until the end of the year, allowing for a comprehensive analysis of the system's long-term behavior and performance under varying environmental conditions.

Combining a lithium-ion (Li-ion) battery and an accumulator tank for energy storage in a hybrid system offers several advantages, particularly in the context of residential buildings powered by renewable energy sources like photovoltaic (PV) systems. Here are some key benefits:

- **Enhanced Energy Utilization:** The Li-ion battery stores electrical energy, while the accumulator tank stores thermal energy. This dual-storage approach allows for more comprehensive energy utilization, covering both the electrical and thermal needs of a household, such as electricity for appliances and hot water or heating.

- **Improved System Efficiency** By storing excess solar power in both electrical and thermal forms, the system ensures that less energy is wasted. During periods of high solar generation, surplus electricity can charge the battery and heat water in the accumulator tank, improving overall energy efficiency.
- **Increased Renewable Energy Penetration:** By effectively storing and managing both types of energy, households can maximize their use of solar power, reducing reliance on the grid. This not only lowers electricity bills but also enhances energy security.
- **Load Balancing and Demand Management:** The HESS can help in peak shaving by supplying stored electrical energy during high-demand periods, reducing the load on the grid. Similarly, the thermal energy stored in the accumulator tank can be used for heating needs, thereby lowering peak electricity demand.
- **Extended Battery Life:** The accumulator tank can handle thermal loads that would otherwise require battery power. This reduces the number of charge-discharge cycles for the Li-ion battery, thereby extending its lifespan and reducing replacement costs.
- **Cost-Effectiveness:** Using stored thermal energy for heating and hot water reduces the need for electric heating, which can be more expensive. This results in significant cost savings over time.
- **Lower Initial Investment:** While Li-ion batteries are relatively expensive, incorporating an accumulator tank can be a cost-effective way to store additional energy without the high costs associated with adding more battery capacity.
- **Increased System Reliability and Resilience:** In case of a power outage, the Li-ion battery can provide backup electrical power, while the accumulator tank ensures that thermal energy needs are still met, enhancing the resilience of the household energy system.
- **Environmental Benefits:** By maximizing the use of renewable energy and reducing dependency on fossil fuels, the HESS contributes to lower greenhouse gas emissions and a smaller carbon footprint.

By integrating a Li-ion battery with an accumulator tank, the hybrid energy storage system capitalizes on the strengths of both storage types, creating a more efficient, reliable, and sustainable solution for managing residential energy needs. The calculation done by MATLAB code simulates the intricate interplay between PV generation, battery storage, accumulator tank storage, and energy consumption in the proposed residential house. By efficiently managing surplus energy, optimizing storage systems, and interacting with the grid as needed, the simulation showcases how renewable energy resources can be harnessed to meet household energy demands effectively and sustainably.

5. Methodology

The hybrid energy system outlined in this thesis is executed through MATLAB. The entire system can be categorized into three component models: the PV system, serving as the principal energy source; the Li-ion Battery, functioning as the primary storage; and the Accumulator Tank, acting as the secondary storage. Similarly, three main inputs required for the analysis are input weather data, the heating demand of the residential building, and its electrical load demand.

5.1 Input Weather Data

The weather data needed for the MATLAB simulation is sourced from the Photovoltaic Geographical Information System (PVGIS) website. Specifically, we gather irradiance, ambient temperature, and wind speed data for the Gothenburg region (*JRC Photovoltaic Geographical Information System (PVGIS) - European Commission*, 2016). Hourly and average ambient temperature, and wind speed data are illustrated in Figure 1, while Figure 2 displays hourly andaverage irradiance data. Average daily data are calculated by determining the arithmetic mean of all hourly data for each specific day. Figure 2(a) shows the variation of ambient Temperature and Wind speed with each hour throughout the year. Figure 2(b) shows the variation of ambient Temperature and Wind speed with each day throughout the year. The temperature curve has an arithmetic mean of 9.56 °C and a standard deviation of 6.05. The wind speed trend is used for the calculation of the probable cell temperature of the PV modules. The wind speed has an arithmetic mean of 3.52 m/s and a standard deviation of 1.66

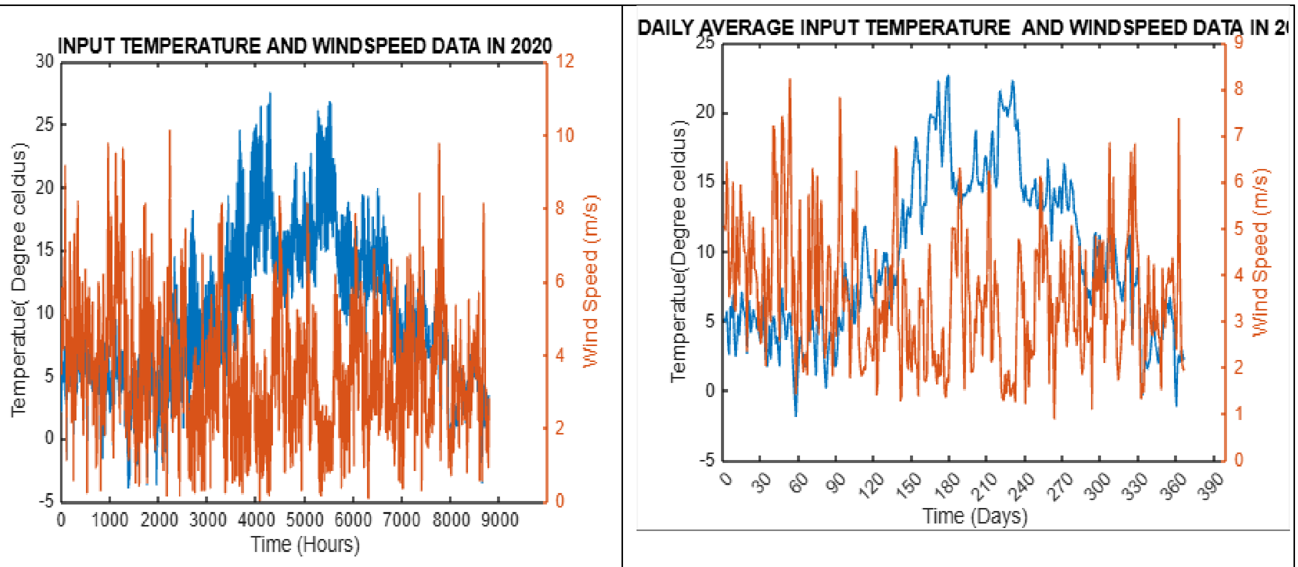

Figure 2(a)

Figure 2(b)

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Figure 2: Ambient Temperature and Wind speed vs. Time

Figure 3(a) shows the variation of Irradiance with each hour throughout the year. Figure 3(b) shows the variation of Irradiance with each day throughout the year. The irradiance data is used for the calculation of heating demand and the probable cell temperature of the PV modules to achieve more realistic PV energy yields.

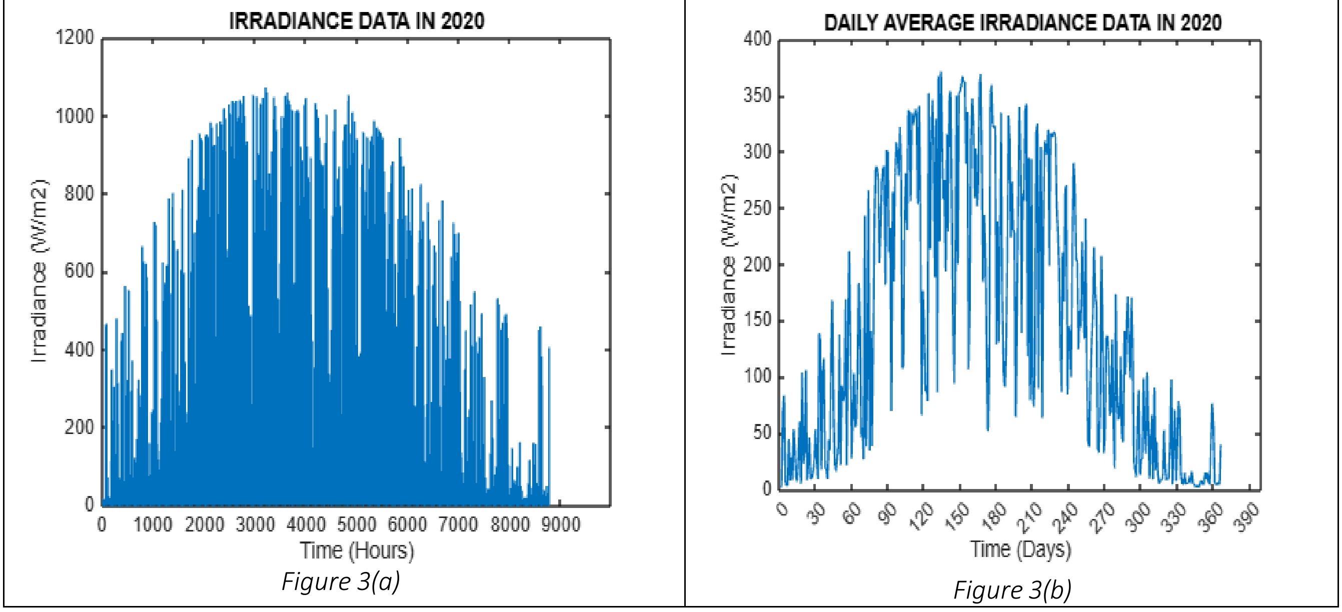

Figure 3(a)

Figure 3(b)

Figure 3: Irradiance vs. Time.

5.2 Input Heat Demand

This Thesis aims to design a PV system with hybrid storage for a residential house in Frölunda, Sweden. The house is a two-story building with a floor area of 80 square meters and a total area of 160 square meters. The heating system will be designed to provide thermal comfort with minimum energy consumption and cost. The building's characteristics for heat loss are analyzed, taking into account its orientation, insulation, and local climate conditions. The design and implementation of efficient space heating is an essential consideration when constructing the house. Frölunda, a city located in the southern part of Sweden, the cold winter climate further highlights the need for a reliable and effective heating system. The thesis project report presents an analysis of the design and selection of a space heating.

Heating loads are the amounts of heat needed to be added to a space by the Heating, Ventilation, and Air Conditioning system to provide the desired level of comfort within a space. Precise calculation of heating and cooling load has a direct influence on the energy efficiency, comfort of occupants, indoor air quality, and durability of the building. For this project, the local climate data at Frölunda is obtained from the Photovoltaic Geographical Information System (PVGIS). All the calculations have been performed in MATLAB.

5.2.1. Building Envelope

The envelope of a double-story house considered here has a height of 5 meters, a width of 8 meters, and a length of 10 meters. Each floor has a height of 2.5m and a floor area of 80 m^2. Table 1 gives details of the components area where the window size is 20% of the floor area and the considered door area is 5% of the floor area

Table 1: Components Area

SL NO	DESCRIPTION	FORMULA	VALUE	UNIT
1	Floor Area (A_{floor})	$=L\times W$	80	m^2
2	Roof Area (A_{roof})	$= L\times W$	80	m^2
	Wall Area (A_{wall})	$= (L+W) \times 4 \times H$	180	m^2
4	Window Area (A_{wd})	$=A_{floor} \times 20\%$	16	**m^2**
7	Door Area (A_{dr})	$=A_{floor} \times 5\%$	4	m^2
8	**Net Wall Area (A_{wall_net}**	$=A_{T\_wall} - A_{wd}- A_{dr}$	**160**	**m^2**

The ground floor has a total of 7 windows and the first floor has 6 windows. Two windows in the East with the dimensions 1.5 m × 1 m, four windows in the West, 2 with the dimensions 4 m × 2 m and 2 with the dimensions 1.5 m × 1 m, three windows in the North with the dimensions 1.5 m × 1 m, four windows in the South with the dimensions 1.5 m × 1 m.

5.2.2 Space Heating Demand

Space heating demand refers to the amount of heat required to maintain a comfortable temperature inside a building during cold weather conditions. To quantify the heating demand of a building heating load calculation has to be done, which is the rate of heat loss from the building. The heating load depends on several factors, including building size, orientation, and thermal properties of the envelope like walls, windows, doors, roof, and floor, and the solar gain and internal gains from occupancy, lighting, and equipment.

For this project, the local climate data at Gothenburg is obtained from the Photovoltaic Geographical Information System (PVGIS). Heat loss from a building is mainly caused by two factors, namely transmission and ventilation. On the other hand, heat gain is caused by solar gain as well as internal gains resulting from occupancy, lighting, and equipment (Frederiksen and Werner (2013)).

Heat Loss Due To Transmission (Qt): The building envelope plays a significant role in maintaining internal temperature of the building. The flow through the envelope, which includes walls, windows, doors, roof, and floor from the interior to the external environment is referred to as heat loss due to transmission. The rate of heat loss due to transmission depends on several factors such as the thermal resistance of the material used in the envelope, material thickness, and the surface area of the envelope.

Table 2: U-value (W/(m²K))

SL NO	DESCRIPTION	AREA (m²)	U - value (W/(m²K))	AU (W/K)
1	Exterior Wall	160	0.44	70.4
2	Windows	16	0.21	3.36
3	Door	4	3	12
4	Floor	80	1.2	96
5	Ceiling	80	0.26	20.8
		∑AU		**202.56**

Here,

$$Q_t = \sum A \times U \times \Delta T \times t \text{ (Wh)} \tag{1}$$

where:

- A is the area (m^2)
- U is the thermal transmittance ($W/(m^2K)$)
- $\sum AU = 202.56 \text{ W/K}$ from Table 2 above.
- $\Delta T = T_i - T$ is the temperature difference (K) between the Design Indoor Temperature and the Outdoor Temperature
- The Design Indoor Temperature is $T_i = 22$ °C.
- t is the time (h)

Heat Loss Due To Ventilation (Qv): Ventilation is important in a building to maintain healthy indoor air quality by removing pollutants and providing adequate levels of Oxygen. However, the ventilation also causes the exchange of air between interior and exterior which can result in heat loss. The loss of heated air to the external environment through the ventilation system is referred to as heat loss due to the ventilation.

$$Q_v = \nu \times \rho_{\text{air}} \times c_{p_{\text{air}}} \times \Delta T \times (1 - \eta) \times t \tag{2}$$

- Air mass flow (ν) in m^3/s
- Specific Heat Capacity of Air ($c_{p\,\text{air}}$) = 1005 J/(kg-K)
- Air Density (ρ_{air}) = 1.25 kg/m^3
- The efficiency of the Ventilation system (η) = 70%

Solar Gain (Q_{sol}) : The process by which the heat from the sun enters the building through the windows and contributes to the overall heat gain of the building refers to the solar gain through the windows. It reduces the heating demand during winter months as the heat from the sun helps to warm the internal air. The solar gain through the windows is influenced by the area of the window, the type of glass used, the orientation of the window, and the shading provided by the surroundings.

$$Q_{\mathrm{sol}} = \sum S \times g \times A_{\mathrm{wd}} \times t \tag{3}$$

- Solar protected glass (S): 0.2
- Floor area (A_{floor}): 80 m^2
- Window size is 20% of floor area
- Area of window (A_{wd}): 16 m^2
- Solar gain coefficient (g) : 2

Internal Gain: Internal heat gain includes the heat gain from people, lighting, and equipment. This heat gain can contribute to the overall heat load of the building, and it reduces the heat demand. Internal heat gain is an important parameter while designing a building.

The gains supplied by the lighting and equipment, considering the number of apartments (n) as 2 and the area of the floor are heated to more than 10 °C

$$Q_e = (4.5n + 0.045\, A_{\mathrm{temp}}) \,/\, 24 \tag{4}$$

The gains supplied by the occupants,

$$Q_p = (1.5n + 0.015\, A_{\mathrm{temp}}) \,/\, 24 \tag{5}$$

- A_{temp} = Area of floor heated to more than 10 ℃ (m^2)
- n = Number of apartments

Space Heating Demand(Q_{SH}) : Space heating demand refers to the amount of heat required to maintain a comfortable temperature inside a building during cold weather conditions. Heat loss from a building is mainly caused by two factors, namely transmission and ventilation. On the other hand, heat gain is caused by solar gain as well as internal gains resulting from occupancy, lighting, and equipment. MATLAB programming to find the total space heating demand is attached in Appendix I. Figure 4(a) shows the variation of Space heating demand with each hour throughout the year. Figure 4(b) shows the variation of Space heating demand with each day throughout the year. As seen in the figure, the heating demand is between 102 kWh per day during the winter period and 0 kWh during the summer period.

$$Q_{SH} = Q_t + Q_v - (Q_{sol} + Q_e + Q_p) \tag{6}$$

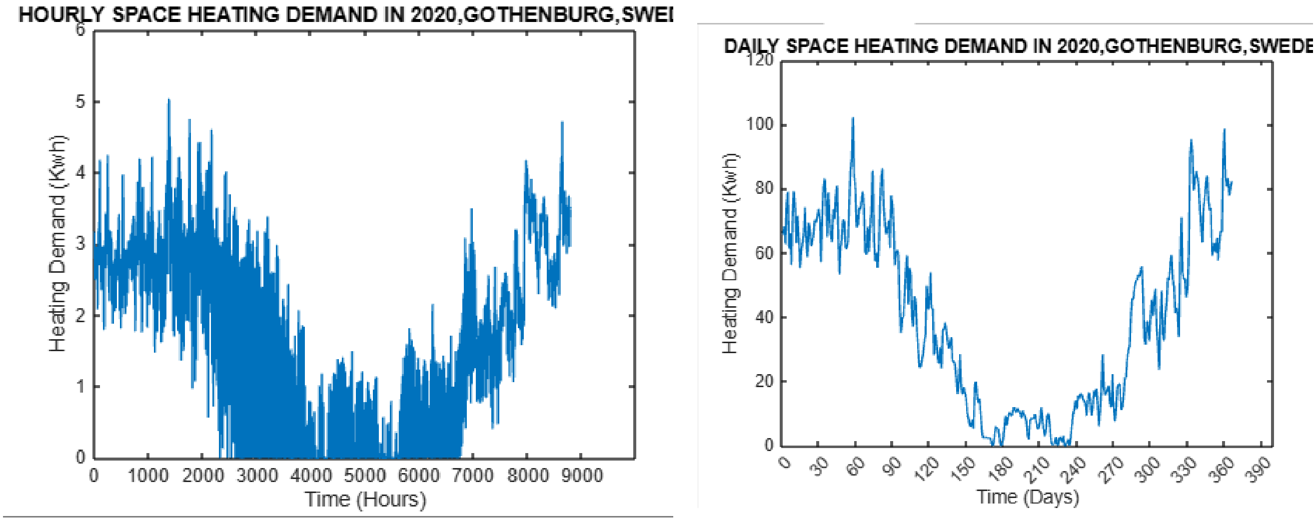

Figure 4(a)

Figure 4(b)

Figure 4: Space heating demand vs. Time

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5.3. Input Electrical Load

The electrical load in a house refers to the total amount of electricity consumed by all the appliances, devices, and systems connected to the electrical wiring. This includes lights, kitchen appliances, and other electrical equipment necessary for modern comfort and convenience. Understanding the electrical load is crucial for designing and maintaining the electrical system in a house to ensure it can handle the demand safely without overloading circuits or causing electrical hazards It can vary depending on factors such as the size of the house, the number and types of appliances, and the lifestyle of the occupants Historic hourly data for electrical load of a similar house or household in Frölunda was not possible to attain. Instead, available load data from a semi-detached house in the nearby city Varberg was used. Due to the proximity of the locations, this load can be assumed to be representative even for the Frölunda location. This meticulous approach provides a detailed understanding of the fluctuating energy requirements throughout the day, across seasons, and in response to various external factors such as weather conditions and human activities. Figure 4 displays hourly and daily electrical load data. The electrical load curve has an arithmetic mean of 13.67 kWh and a standard deviation of 5.70. Figure 5(a) shows the variation of Electrical load with each hour throughout the year. Figure 4(b) shows the variation of Electrical Load with each day throughout the year.

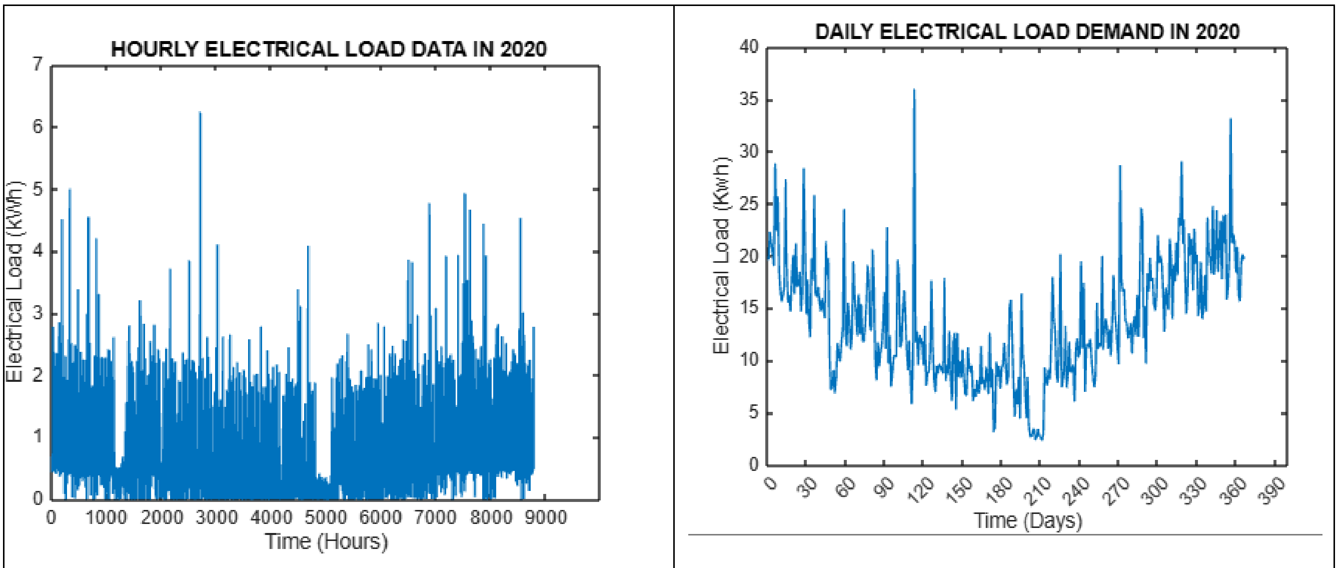

Figure 5(a)

Figure 5(b)

Figure 5: Electrical Load vs. Time.

5.4 PV System Model

In the PV system, the irradiance, ambient temperature, and wind speed serve as crucial input parameters that influence the performance and output of the photovoltaic (PV) panels. Irradiance represents the amount of solar radiation received by the PV panels, while ambient temperature and wind speed affect the temperature and cooling of the panels, which in turn impact their efficiency. By monitoring these input parameters, we assess the environmental conditions under which the PV system operates and optimize its performance accordingly. For instance, higher irradiance levels typically result in increased power output, while extreme temperatures can affect panel efficiency. Similarly, wind speed plays a role in cooling the panels and can affect their temperature and performance.

The output parameters, PV current, and PV voltage provide insights into the electrical characteristics and performance of the PV panels. These parameters help evaluate the efficiency and effectiveness of the PV system in converting solar energy into electrical power.

By analyzing the relationship between input parameters (irradiance, ambient temperature, and wind speed) and output parameters (PV current and PV voltage), you can fine-tune the operation of the PV system, optimize energy production, and ensure its reliability in providing clean and sustainable energy for our applications.

PV modules are defined for the standard test conditions $G_S = 1000\ \mathrm{W/m^2}$, $T_S = 298.15$ K that is 25 °C. Table 3 gives details of the PV system used here, the values for G and T_c represent the actual irradiance and cell temperature, and α and β are the specific temperature coefficients for the current and the voltage which are also specified in the PV characteristics. The coefficient kr (1.542 (K·s) / m) for monocrystalline cells (Möller & Krauter, 2022).

Table 3: PV system characteristics (Type: SMA310M-6X10DW)[15]

PV System Characteristic	**Values**
Maximum PowerPoint at STC (P_{MPS})	310 Wp
Maximum Power Point Voltage (V_{MPS})	33.3 V
Maximum Power Point Current (I_{MPS})	9.31 A
Open Circuit Voltage (V_{OC})	40.5 V
Short Circuit Current (I_{SC})	9.81 A
Temperature Coefficient V_{OC} (β)	−0.28%/K
Temperature Coefficient I_{SC} (α)	−0.02%/K
Number of modules in series	11
Number of parallel strings	2

Cell temperature is a critical factor that significantly influences the performance and efficiency of photovoltaic (PV) cells in solar energy systems. The temperature of the PV cell is a key determinant of its electrical characteristics and output. Variations in ambient conditions, such as solar irradiance, ambient temperature, and wind speed, can lead to fluctuations in cell temperature throughout the day and across seasons. Accurately calculating cell temperature is essential for optimizing the design and operation of PV systems. This information allows for the development of effective thermal management strategies to mitigate the adverse effects of temperature on PV cell performance, ensuring maximum energy generation and system efficiency (Möller & Krauter, 2022).

The actual cell temperature T_c (K) can be calculated from the equation.

$$T_c = (0.93 \times T_a) + (0.031 \times G) - (K\text{r} \times \omega) + 3.6 \qquad (7)$$

- Tc - actual cell temperature (K)
- Ta - Ambient Temperature (K)
- G - Actual irradiance (W/m^2)
- ω -wind speed (m/s)

Figure 6(a) shows the variation of solar cell temperature with each hour throughout the year and figure 6(b) shows the average cell temperature with each day throughout the year.

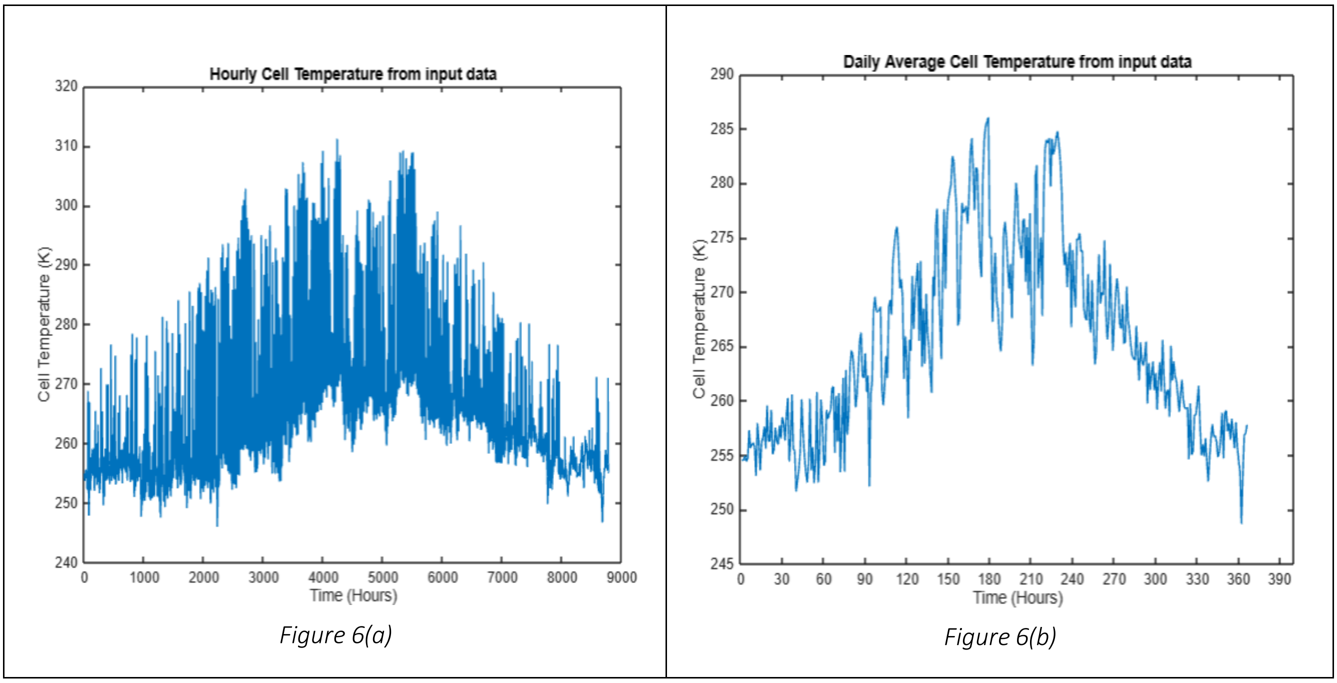

Figure 6(a)

Figure 6(b)

Figure 6: Cell Temperature vs. Time.

To calculate the maximum power point current (I_{MP}) of the PV cell based on the actual irradiance (G) and cell temperature (T_c) we use the equation below.

$$I_{MP} = I_{MPS} \times \left(\frac{G}{G_S}\right) \times [1 + \alpha \times (T_c - T_s)] \qquad (8)$$

- I_{MP} - Maximum power point current (A)
- I_{MPS} - Maximum Power Point Current at standard test condition (A)
- G – Irradiance(W/m2)
- G_s – Irradiance at standard test condition(W/m2)
- α - Temperature Coefficient I_{SC}
- T_c – Cell temperature
- T_s - Temperature at standard test condition

To calculate the maximum power point Voltage (V_{MP}) of the PV cell based on the cell temperature (T_c) We use the equation below.

$$V_{MP} = V_{MPS} \times [1 + \beta \times (T_c - T_s)] \tag{9}$$

- V_{MPS} - Maximum Power Point voltage at standard test condition (V)
- β - Temperature Coefficient V_{OC}
- T_c – Cell temperature
- T_s - Temperature at standard test condition

To calculate the short-circuit current (I_{SC}) of the PV cell based on the actual irradiance (G) and cell temperature (Tc) We use the equation below.

$$I_{SC} = I_{SCS} \times (G / G_s) \times [1 + \alpha \times (T_c - T_s)] \tag{10}$$

- I_{SC}- Short circuit Current (A)
- I_{SCS}- Short circuit Current at standard test condition (A)
- G – Irradiance(W/m^2)
- G_s – Irradiance at standard test condition(W/m^2)
- α - Temperature Coefficient I_{SC}
- T_c – Cell temperature
- T_s- Temperature at standard test condition

To calculate the Open circuit voltage (V_{OC}) of the PV cell based on the cell temperature (Tc) We use the equation below.

$$V_{OC} = V_{OCS} \times (1 + \beta \times (T_c - T_s)) \tag{11}$$

- V_{OCS} – Open circuit Voltage at standard test condition (V)
- β - Temperature Coefficient VOC
- T_c – Cell temperature
- T_s- Temperature at standard test condition

The PV cell current I_c depends on the PV output voltage as well as the two parameters K_1 and K_2. To calculate the 2 parameters K_1 and K_2 we use the following equations (Möller & Krauter, 2022).

$$K_2 = \frac{\frac{V_{MP}}{V_{OC}} - 1}{\log(1 - I_{MP}/I_{SC})} \tag{12}$$

$$K_1 = (1 - {}^{I_{MP}}/_{I_{SC}}) \times \exp[{}^{-V_{MP}}/_{(K_2 \times V_{OC})}] \tag{13}$$

- V_{MP} - Maximum power point Voltage of the PV cell (V)
- I_{MP} - Maximum power point Current of the PV cell (A)
- V_{OC} - Open circuit voltage of the PV cell (V)
- I_{SC} - Short-circuit current of the PV cell (A)

The cell Voltage (V_c) is equal to the Maximum power point Voltage of the PV cell.

$V_c = V_{MP}$

The cell Current (I_c) can be calculated from the below equation.

$$I_c = I_{SC} \times (1 - K_1) \times \exp[{}^{V_C}/_{(K_2 \times V_{OC})} - 1] \tag{14}$$

- K_1& K_2- Parameters
- V_{OC} - Open circuit voltage of the PV cell (V)
- V_c - PV cell voltage (V)
- I_{SC} - Short-circuit current of the PV cell (A)
- I_c – PV cell current (A)

Maximum Power Point Voltage and Current (V_{MP}) and (I_{MP}) represent the voltage and current, respectively, at the maximum power point of the PV cell. These values determine the maximum power output of the cell under given environmental conditions, such as irradiance and temperature. (V_{MP}) is influenced by temperature variations, while (I_{MP}) is adjusted based on the ratio of Irradiance (G) to Irradiance at standard test conditions (G_s) and the temperature coefficient.

V_{OC} and I_{SC} characterize the electrical behaviours of the PV cell under specific conditions. V_{OC} is the voltage across the cell terminals when no current flows (open circuit), while I_{SC} is the current flowing through the cell when the terminals are shorted. These parameters provide insights into the PV cell's electrical characteristics and help determine its performance.

By multiplying cell Voltage and cell Current we can calculate the cell Power.

$$P_c = I_c \times V_c \tag{15}$$

The power output of the PV cell, represented by (P_c) is the product of the cell voltage (V_c) and current (I_c). This calculation yields the instantaneous power generated by the cell and is essential for assessing its overall performance and efficiency.

By understanding and manipulating these parameters, we can design and optimize PV systems to maximize energy production and efficiency, contributing to the advancement of renewable energy technologies and sustainability efforts.

As per our PV production and load requirement of the house we considered 11 PV panels in series and 2 such strings in parallel. So, a total of 22 panels are considered for powering our proposed house.

A string consisting of 11 PV cells is connected in series, so the total PV output voltage. Two such strings are connected in parallel, so the total PV output current.

$$V_{PV} = 11 \times P_c \tag{16}$$

$$I_{PV} = I_c + I_c \tag{17}$$

$$P_{PV} = V_{PV} \times I_{PV} \tag{18}$$

Figure 7 and Figure 8 illustrate the total PV Current, Voltage, and Power. MATLAB Programming for the whole PV system model is attached in Appendix II.

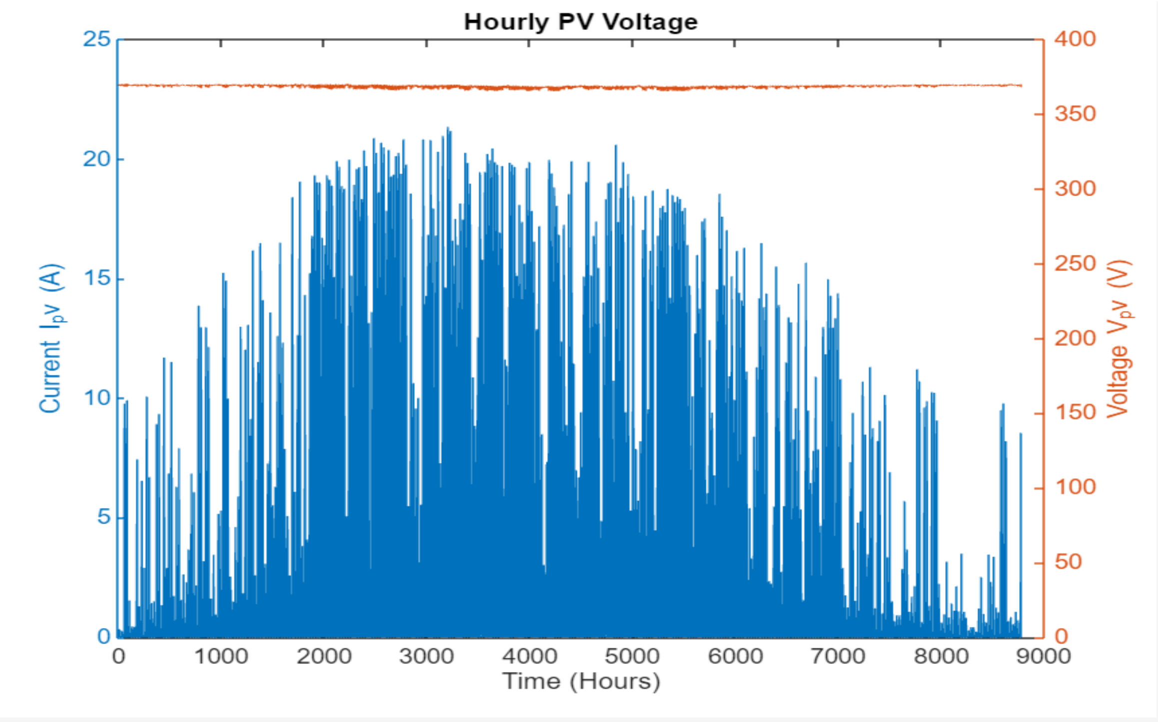

Figure 7: PV Current and Voltage vs Time

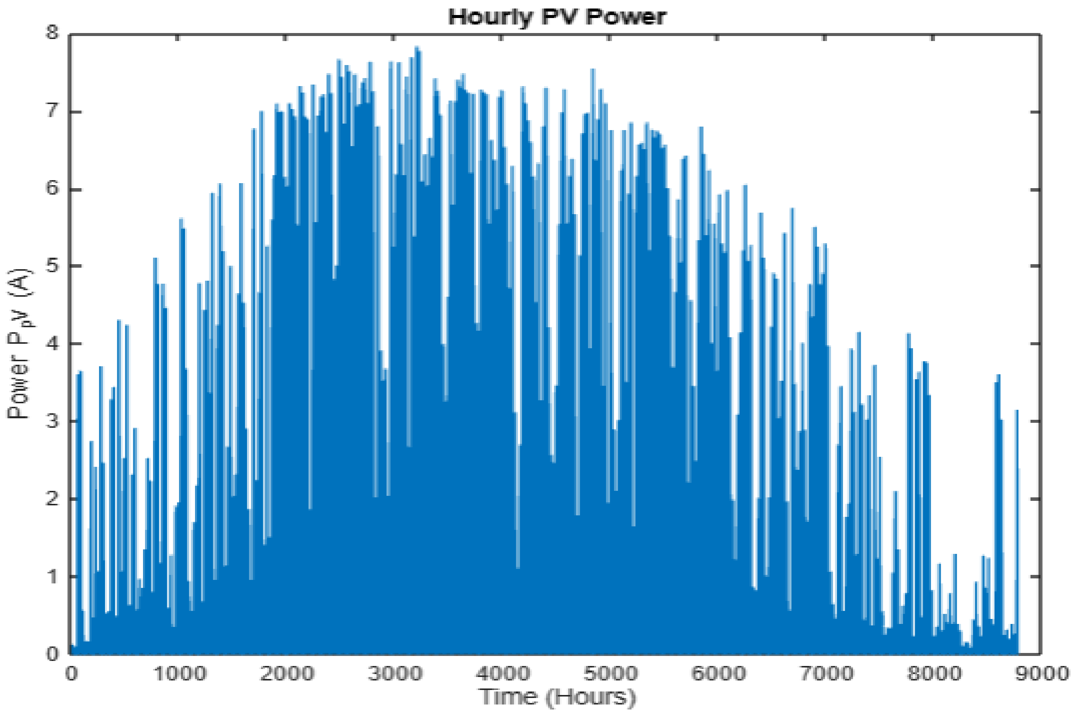

Figure 8: PV Power vs Time

5.5 Lithium-Ion Battery Model

Lithium-ion Battery serves as the primary energy storage of the proposed system, that is the excess energy after direct consumption in the household is stored here, which is in turn used in times of low PV production, especially at night or cloudy days. Table 4 gives the detailed characteristics of the battery being used. By accurately determining the battery size, the self-consumption of the PV system can be enhanced, thus improving energy management.

- P_{rated} - Rated power in kW, sets the rated power of the lithium-ion battery to 12.8 kilowatts (kW). The rated power represents the maximum power that the battery can deliver under specific operating conditions.
- Q_{max} - Max Capacity in Ah defined as 312.5 ampere-hours (Ah), representing the maximum capacity of the lithium-ion battery. This value indicates the total amount of charge the battery can store, measured in ampere-hours.
- V_{n} - The nominal voltage of a lithium-ion (Li-ion) battery is a standardized voltage value that represents the average voltage output of the battery during typical discharge conditions. This voltage is used as a reference point for specifying and comparing batteries.
- Cell life - Specifies the calendar life of the lithium-ion battery as 10 years. Calendar life refers to the expected lifespan of the battery in terms of years, based on factors such as chemical degradation and aging.
- η_{rt} - The roundtrip efficiency of the battery is set to 0.95, indicating the efficiency of energy conversion during charge and discharge cycles. A value of 0.95 signifies that 95% of the energy stored in the battery during charging is successfully retrieved during discharging.
- SD - Defines the self-discharge rate of the lithium-ion battery as 0.0010 per day. Self-discharge refers to the gradual loss of charge in the battery over time, even when it is not in use. The specified value represents the rate at which the battery loses its charge per day.

$$\text{SD}_h = 1 - (1 - \text{SD})^{1/24} \tag{19}$$

- SD_h represents hourly self-discharge, this gives the daily rate to an hourly rate, assuming the self-discharge occurs uniformly over each hour of the day. This is the rate at which the battery loses its charge each hour. This is useful for detailed simulations of battery performance over shorter periods.

$$\eta = \sqrt{\eta_{\text{rt}}} \tag{20}$$

- efficiency represents one-way efficiency. The roundtrip efficiency accounts for both charging and discharging losses, the one-way efficiency provides an estimate of the efficiency for a single cycle of either charging or discharging

Table 4: Li-ion battery characteristics (LVS 16.0 f. BYD)[19]

V_n	12.5V
P_{rated}	12.8 kW
$Q_{\max}$	312.5 Ah
Cell life	10 years
η_{rt}	0.95
SD	0.0010

Figure 9 shows the storage level of the battery, throughout the year, efficiency and self-discharge are also incorporated for realist analysis. From the hourly battery storage level graph, it is evident that the battery is well-charged during the summer months due to high solar production. In contrast, during the winter, the battery is often not fully charged and can become fully drained because of low solar production and high energy demand. During spring and fall it is seen that the battery is often fully charged and discharged on a daily basis, indicating reasonable utilization of the storage. The MATLAB code developed to find the state of charge of the Li-ion battery is attached in Appendix III.

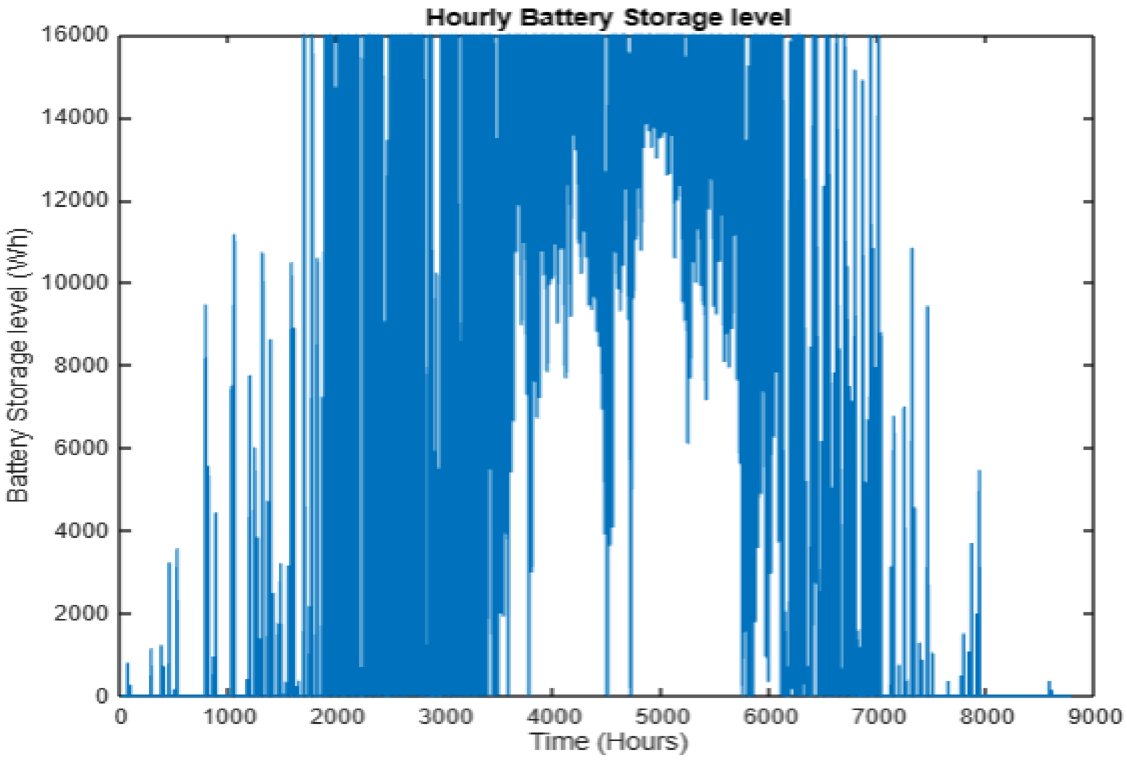

Figure 9 Battery Storage Level vs Time

5.6 Accumulator Tank Model

The accumulator tank serves as a secondary storage unit for excess energy produced by the PV system. After storing the lithium-ion battery and once the battery storage is full, the excess energy is used to heat the water in the accumulator tank. By accurately determining the tank size, we ensure sufficient storage capacity to store surplus energy for later use when demand exceeds supply. Adjusting the accumulator tank size allows for better energy management within the system. It enables to balance of energy supply and demand, ensuring a steady and reliable energy supply even during periods of low PV power generation or high demand. Table 5 gives the details of the accumulator tank used.

Table 5: Accumulator Tank Characteristics

Tank Storage Volume in litres	1000 Litre
Specific heat capacity of water (c_p)	4200 J/kg K
Density of water (ρ)	1000 kg/m^3
$\mathrm{COP}_{\mathrm{heatpump}}$	3
ΔT	60 – 20 = 40°C

From the above details, the accumulator tank size can be calculated. Calculating the size of the accumulator tank is essential in designing efficient and effective heating systems.

$$ATsize = \frac{V \times \rho \times c_\mathrm{p} \times \Delta T / \mathrm{COP}_{\mathrm{heatpump}}}{3600} \ (\mathrm{Wh}) \tag{21}$$

The calculation divides the energy required to heat the water in the accumulator tank by the COP of the heat pump, converting the result to watt-hours. The accumulator tank storage level is expressed in terms of electricity input, which is inversely proportional to the COP of the heat pump. This calculation determines the appropriate size of the accumulator tank needed to store thermal energy efficiently and meet the heating demands of the system while considering the efficiency of the heat pump.

Figure 10 shows the storage level of the Accumulator tank, throughout the year. The tank is charged when the battery storage exceeds its maximum limit. The hourly accumulator tank storage level graph shows that the tank can store up to a maximum of around 7800Wh, by using a 1m^3 tank. Note that the storage level is expressed in terms of the equivalent electric energy needed to produce the same heat using the heat pump. This storage capacity helps in meeting the heating demand during periods of excess power production. MATLAB code to find the state of charge of the Accumulator tank is attached in Appendix III.

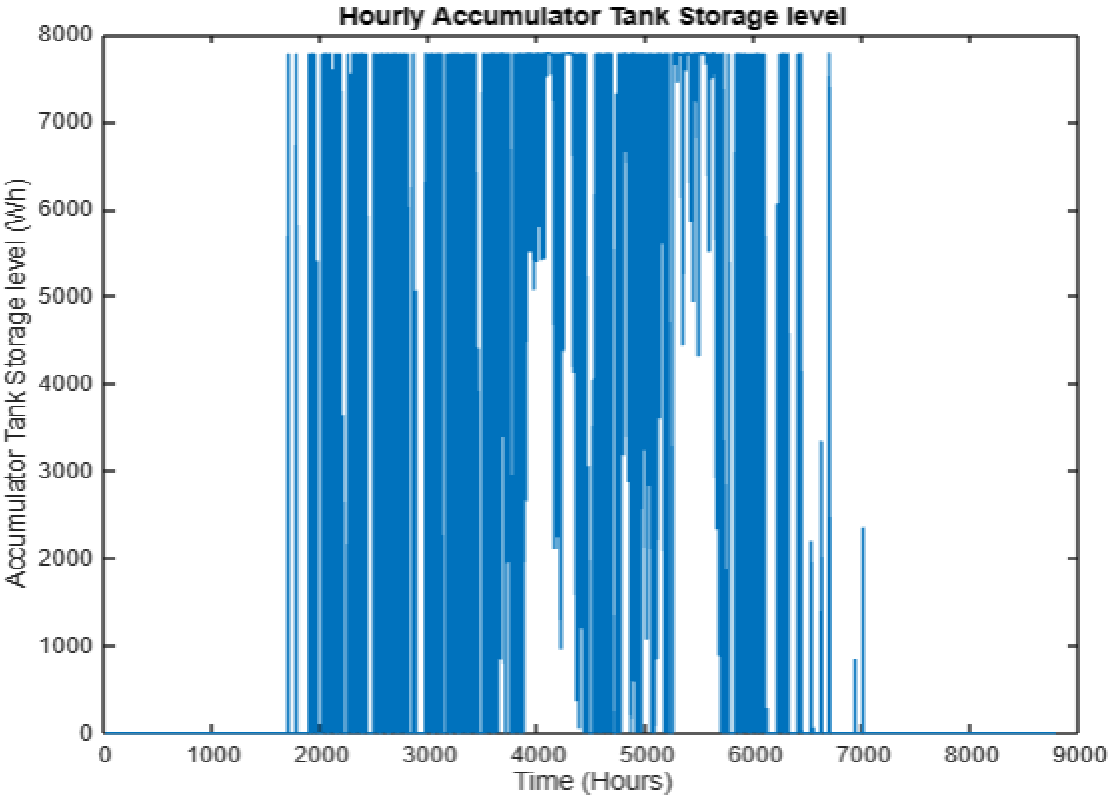

Figure 10: Accumulator tank storage level vs Time

5.7 Overall Model

The overall energy system model has three main sections: PV system, the Li-ion Battery, and the accumulator tank, which were already discussed in the earlier sections. Similarly, three main inputs are required for the analysis, weather data from the PVGIS site, Heating demand, and the Electricity load of the residential building in Frölunda, Sweden. The total power demand of the system includes both heating demand and electrical load demand. The net power that can be stored in the energy storage system is the difference between power produced by PV and the total power demand of the residential building. Figures 11 and 12 show the hourly and daily average power demand respectively.

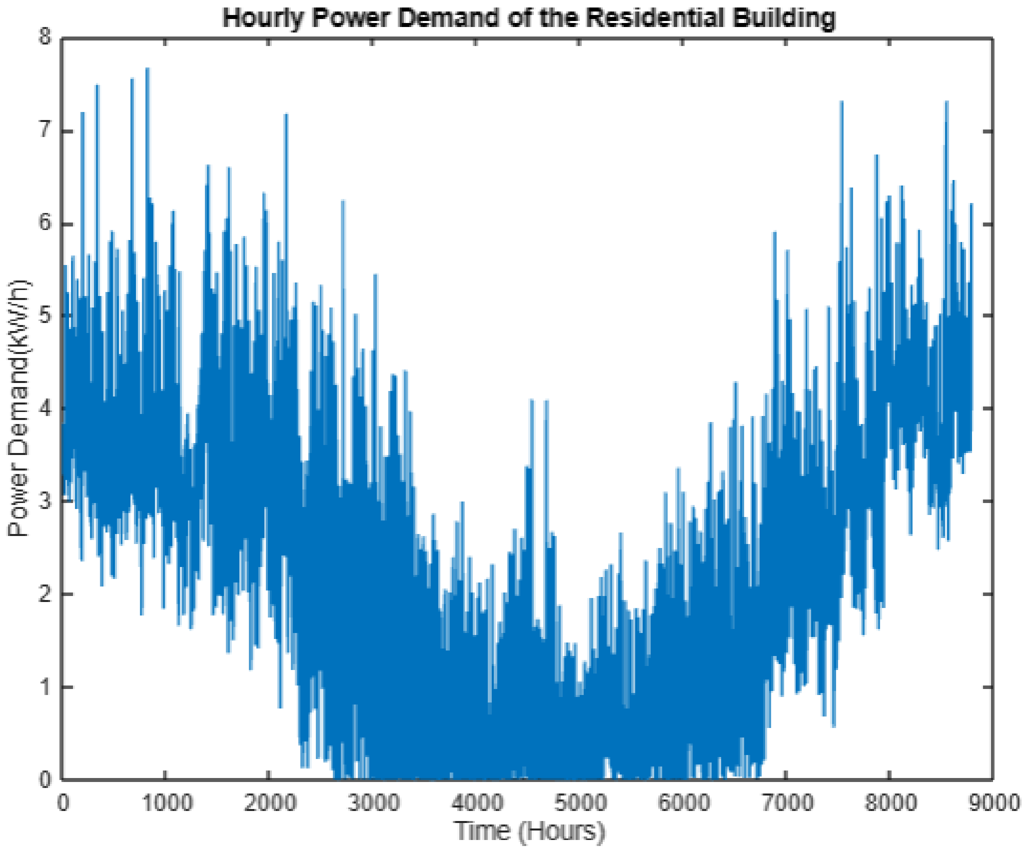

Figure 11: Total Power Demand vs Time

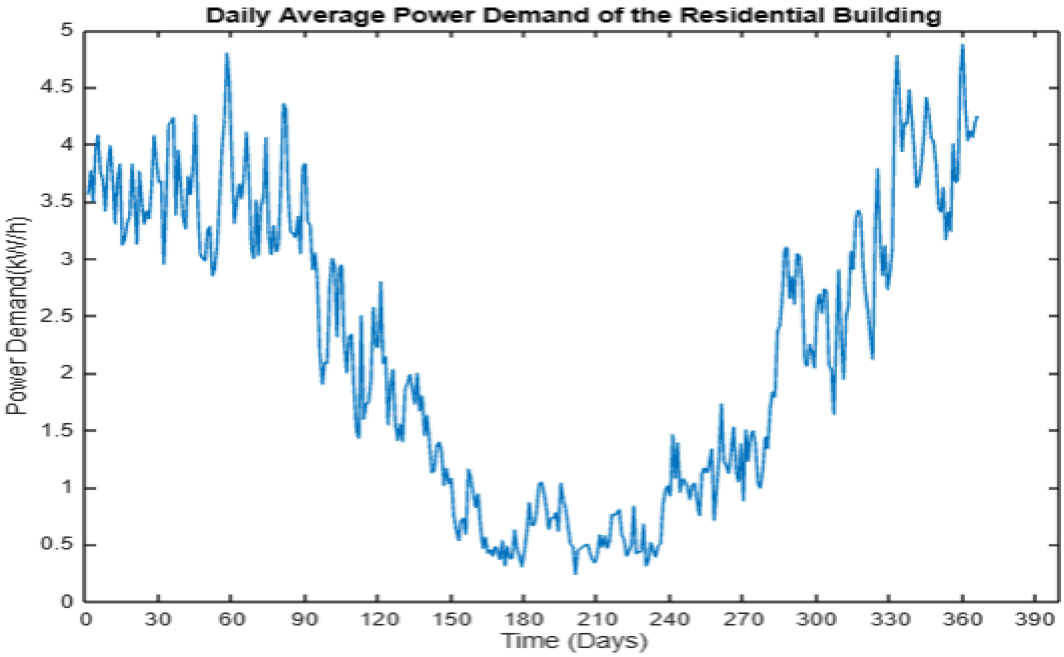

Figure 12: Daily Average Power Demand vs Time

$$P_{\mathrm{Net}} = P_{\mathrm{PV}} - P_{\mathrm{Demand}} \quad (22)$$

- P_{Net} = Net power in the system (Wh)
- P_{PV} - Power generated by the photovoltaic (PV) system (Wh)
- P_{Demand} - Power required by the load (Wh)

By subtracting the load power from the PV power, we will get the net power available after satisfying the load demand. The resulting value P_{Net} represents the surplus or deficit of power generated by the PV system compared to the power required by the load. Figure 12 plots the net power with time. A positive value indicates an excess of power, while a negative value indicates a shortfall, which may necessitate drawing additional power from the grid or utilizing energy storage systems.

The net power availability varies seasonally. From the graph, hourly net power availability is higher during summer due to increased PV production and lower heating demand. Conversely, net power availability is lower during winter months because of reduced PV production and higher home power demand.

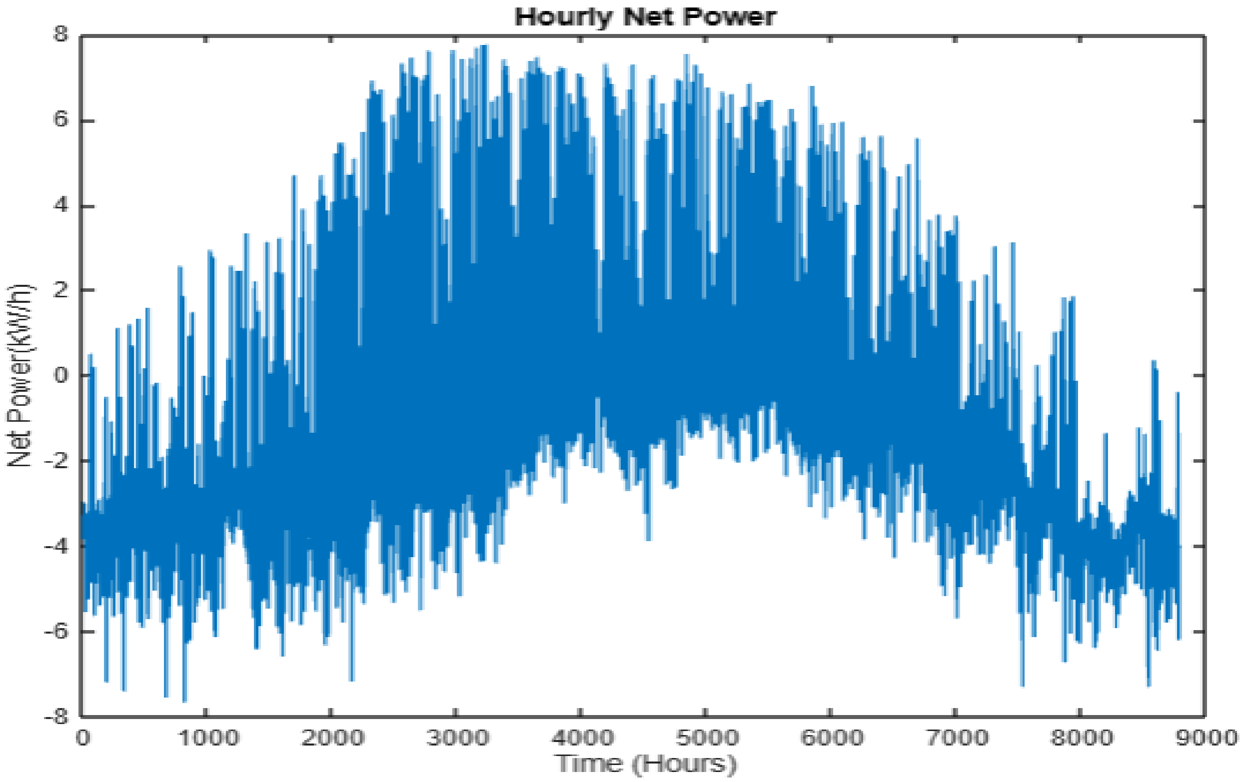

Figure 13: Net Power vs Time

The excess energy calculations in figures 13 and 14 are carried out using a Battery of 16000 kWh and an Accumulator tank size of 1 m^3. After the direct consumption, the excess energy is stored in the Li-ion battery and once it is full extra energy can be stored in the accumulator tank To reduce wastage surplus energy after filling the accumulator tank is fed into the grid. Similarly whenever we are short of any power that can be drawn from the grid.

Figure 14 gives a detailed overview of the grid interaction throughout the year. The hourly grid feed-in and power intake graph indicate that power intake from the grid is high during the cold months, whereas grid feed-in occurs mainly during the hot months. The maximum grid feed-in recorded is around 8850 W, and the maximum power consumed from the grid is around 8100 W. Such a sophisticated system implemented here has reduced the grid dependency significantly.

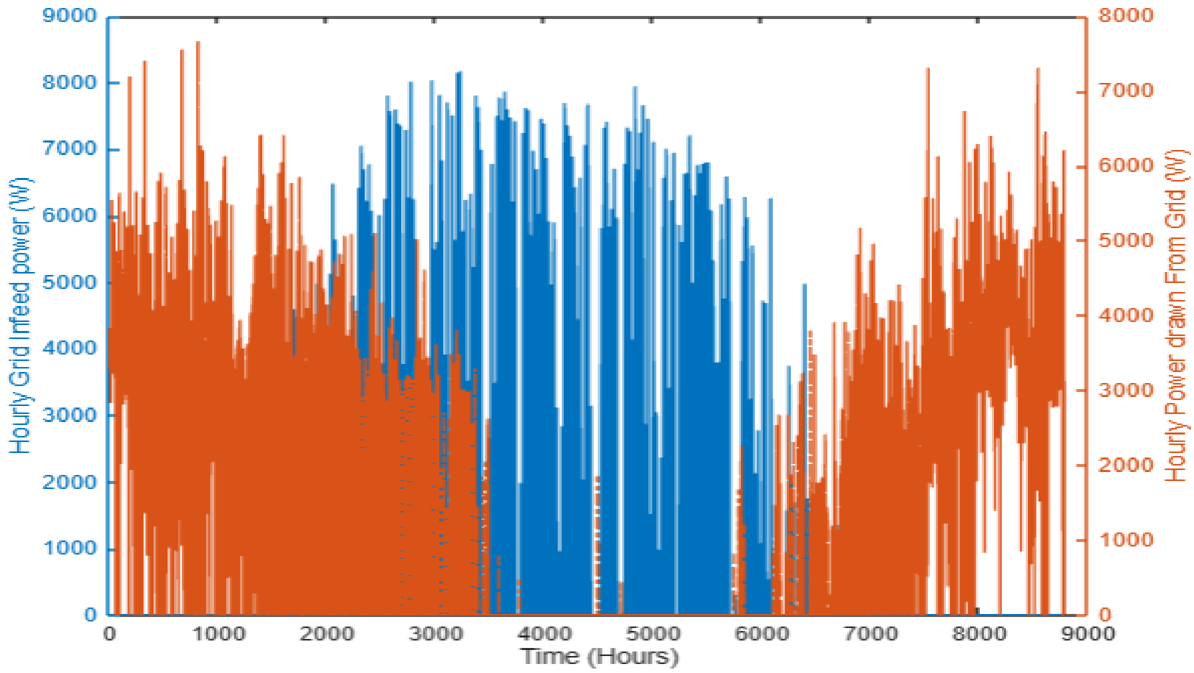

Figure 14: Grid Power vs Time

6. Results

By using such a hybrid, innovative energy management system, we were able to enhance the self-consumption of PV systems to a great extent, while reducing grid dependency too. For a better understanding of this result, three main ratios are considered here: the self-consumption ratio, the grid-infeed ratio, and the grid dependence ratio. These key performance ratios depend on total PV power production, total heating demand, power fed in and drawn from the grid, etc.

$$\mathrm{SC_{ratio}} = \frac{E_{prod} - E_{gridinfeed}}{E_{prod}} \tag{23}$$

$$\mathrm{GD_{ratio}} = \frac{E_{fromgrid}}{E_{load}} \tag{24}$$

$$\mathrm{GinF_{ratio}} = \frac{E_{gridinfeed}}{E_{prod}} \tag{25}$$

$\mathrm{SC_{ratio}}$ = Self Consumption ratio

$\mathrm{GD_{ratio}}$ = Grid Dependence ratio

$\mathrm{GinF_{ratio}}$ = Grid infeed ratio

E_{prod} = Total energy produced by a photovoltaic (PV) system in MWh throughout the year

E_{load} = Total energy consumed by loads in MWh throughout the year.

$E_{\mathrm{gridinfeed}}$ = Total energy fed into the grid in MWh throughout the year.

E_{fromgrid} = Total energy consumed from the grid in MWh throughout the year.

The total power produced by the proposed PV system throughout the year is 9.61MWh whereas the total load demand of the building (E_{load}), ie the heating, and electricity demand summed up and resulted in 19.57 MWh. Total energy fed to the grid ($E_{\mathrm{gridinfeed}}$), which is the surplus energy remaining after charging the accumulator tank, is calculated as the sum of Grid Infeed throughout the year, resulting in a value of 3.63 MWh and the total energy intake from the grid (E_{fromgrid}) is calculated as the sum of the total energy received from the grid when there is a shortage of production, resulting in a value of 13.15 MWh. So by using this hybrid energy storage system the self-consumption ratio of the PV system increased to 62 % whereas the grid dependence ratio and grid feed-in ratio reduced to 67% and 38% respectively. Figures 15 and 16 illustrate how the key performance ratios vary with different sizes of battery and accumulator tank.

Grid Dependency: Grid dependency, defined as the ratio of the total energy intake from the grid to the total household demand (including heating and electrical loads), stands at 65% with the chosen configuration. This means that 65% of the house's energy needs are met by the grid, while the remaining 35% is covered by the energy generated and stored within the system. This level of grid dependency is relatively stable across different configurations. Even when the battery or accumulator tank sizes are increased, there is no significant reduction in grid dependency. This suggests that the primary limiting factor is not the storage capacity but rather the seasonal variations in energy production and demand.

Grid Feed-In: Grid feed-in, the proportion of total energy produced by the PV system that is fed back into the grid, is 36% with an 8000 kWh battery. This indicates that over a third of the generated energy is surplus to the immediate needs of the house and storage capacities. Increasing the battery or tank size slightly decreases this percentage, but the change is minimal. This minimal impact underscores that the system's ability to utilize or store produced energy efficiently is already near its optimal point at the 8000 kWh battery capacity. Excessively large storage systems would not significantly enhance self-consumption but would rather lead to diminishing returns in efficiency gains.

Self-Consumption: Self-consumption refers to the proportion of PV-generated energy that is directly used by the household or stored for later use. At 66%, this value indicates that two-thirds of the solar energy produced is utilized within the home. Like grid dependency and grid feed-in, increasing the battery or tank size shows marginal improvements in self-consumption. The system is already capturing and using a substantial portion of the energy produced. Further increases in storage size would incur higher costs without proportional benefits in energy efficiency or grid independence.

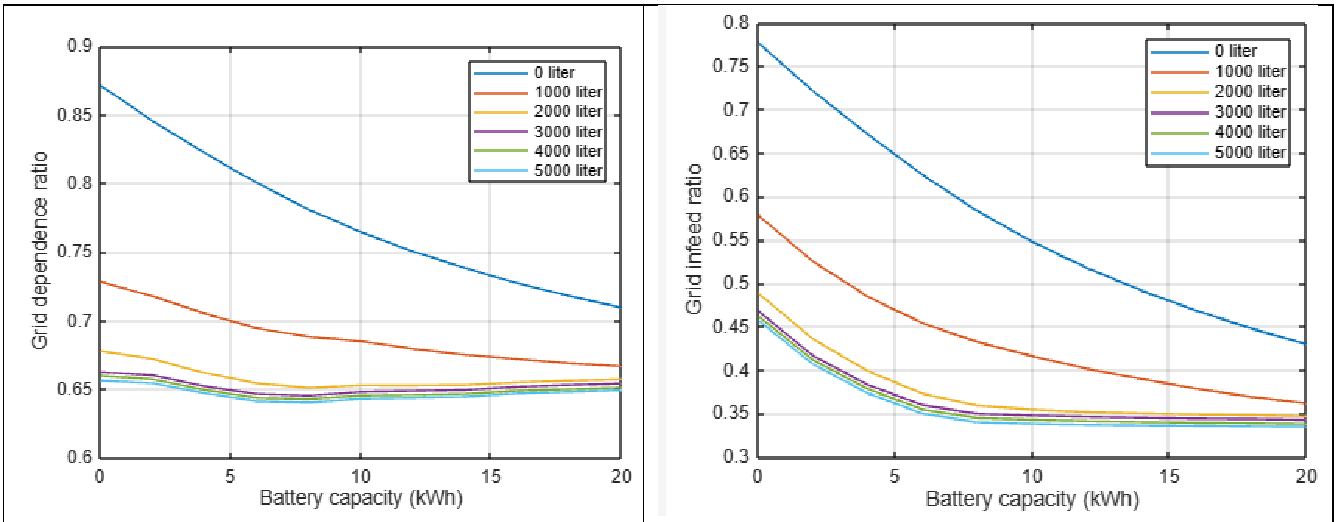

Figure 15(a)

Figure 15(b)

Figure 15: Grid Dependency and Grid Feed-in vs Battery Capacity

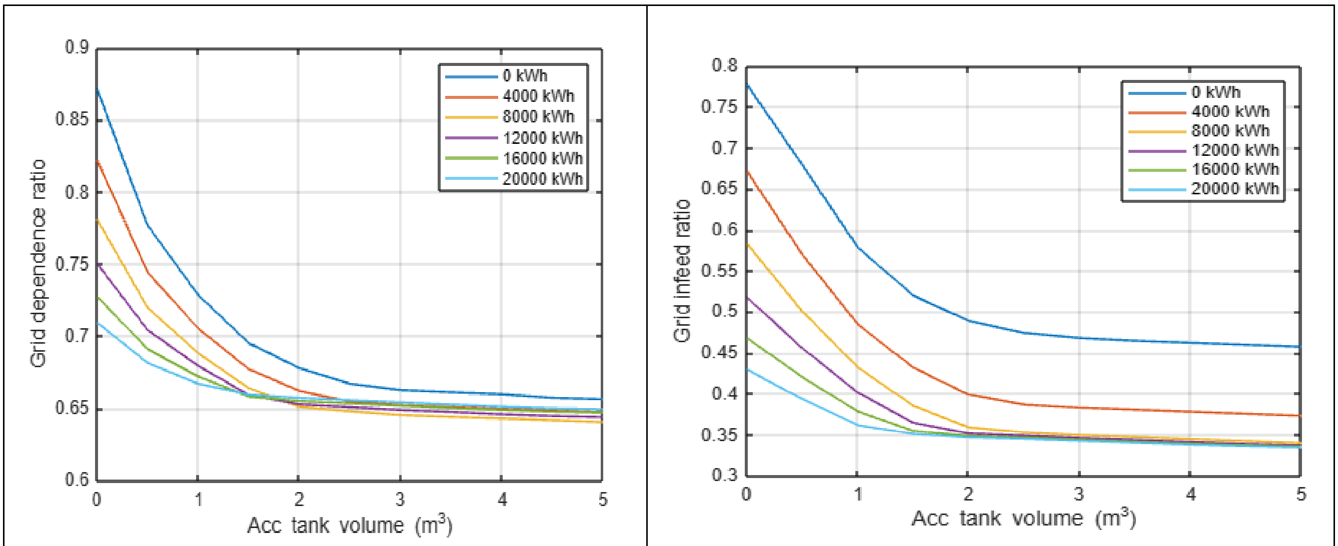

Figure 16 (a)

Figure 16(b)

Figure 16: Grid Dependency and Grid Feed-in vs Accumulator Tank Volume

We tried different combinations of battery sizes and accumulator tank sizes to determine the best economical and reliable combination for the proposed home. Table 6 shows how self-consumption ratio, grid dependence ratio, and grid feed-in ratio varies with these combinations. When comparing different combinations of battery storage size and accumulator tank storage size, it is evident from the data that selecting an 8000-kWh battery storage capacity and an appropriately sized accumulator tank of 2 m^3 yields optimal performance metrics. Specifically, the system exhibits a grid dependency of 65%, a grid feed-in rate of 36%, and a self-consumption rate of 66%. These values represent the balance between energy production, storage, and consumption in the household energy system. Figures 15 and 16 illustrate how the key performance ratios vary with different sizes of battery and accumulator tank.

Table 6: Different sizes of Battery and Accumulator tank

Combination of different sizes of Battery and Accumulator Tank		Accumulator Tank Capacity				
		0 L	1000 L	2000 L	3000 L	4000 L
Battery Capacity	0 kWh	GDratio: 0.87 SCratio: 0.22 GinFratio: 0.78	GDratio: 0.73 SCratio: 0.42 GinFratio: 0.58	GDratio: 0.68 SCratio: 0.51 GinFratio: 0.49	GDratio: 0.66 SCratio: 0.53 GinFratio: 0.47	GDratio: 0.66 SCratio: 0.54 GinFratio: 0.46
	4000 kWh	GDratio: 0.82 SCratio: 0.33 GinFratio: 0.67	GDratio: 0.70 SCratio: 0.51 GinFratio: 0.48	GDratio: 0.66 SCratio: 0.60 GinFratio: 0.40	GDratio: 0.65 SCratio: 0.62 GinFratio: 0.38	GDratio: 0.65 SCratio: 0.62 GinFratio: 0.38
	8000 kWh	GDratio: 0.78 SCratio: 0.42 GinFratio: 0.58	GDratio: 0.69 SCratio: 0.57 GinFratio: 0.43	GDratio: 0.65 SCratio: 0.66 GinFratio: 0.36	GDratio: 0.64 SCratio:0.66 GinFratio: 0.35	GDratio: 0.64 SCratio:0.66 GinFratio:0.34
	12000 kWh	GDratio: 0.75 SCratio: 0.48 GinFratio: 0.52	GDratio: 0.68 SCratio: 0.60 GinFratio: 0.40	GDratio: 0.65 SCratio: 0.65 GinFratio: 0.35	GDratio: 0.65 SCratio: 0.65 GinFratio: 0.35	GDratio: 0.64 SCratio: 0.66 GinFratio: 0.34
	16000 kWh	GDratio: 0.73 SCratio: 0.53 GinFratio: 0.47	GDratio: 0.67 SCratio: 0.62 GinFratio: 0.38	GDratio: 0.65 SCratio: 0.65 GinFratio: 0.35	GDratio: 0.65 SCratio: 0.66 GinFratio: 0.34	GDratio: 0.65 SCratio: 0.66 GinFratio: 0.34
	20000 kWh	GDratio: 0.70 SCratio: 0.57 GinFratio: 0.43	GDratio: 0.67 SCratio: 0.64 GinFratio: 0.34	GDratio: 0.66 SCratio: 0.65 GinFratio: 0.35	GDratio: 0.65 SCratio: 0.66 GinFratio: 0.34	GDratio: 0.65 SCratio: 0.66 GinFratio: 0.34

7. Analysis and Discussion

In this thesis, we aimed to power a house in Gothenburg, Sweden, using solar panels coupled with lithium-ion batteries for energy storage and an innovative accumulator tank for thermal storage. Excess power production, when the battery storage is full, heats the accumulator tank. The primary demands are the electrical load and heating needs of the home. Given the critical importance of heating and hot water in cold climates like Sweden, integrating an accumulator tank with PV panels and lithium-ion batteries offers a cost-effective solution. The heating demand peaks during the cold months, while PV power production is highest during the summer, dependent on solar irradiance. We calculated PV cell current, cell voltage, and PV power. Based on our energy requirements, we selected 22 panels connected in series and parallel combinations.

The PV power production graph versus hours throughout the year reveals daily and seasonal variations in solar energy generation. Each day shows a bell curve pattern, with power rising in the morning, peaking at midday, and declining in the evening. During summer, higher and broader curves reflect longer daylight hours and increased energy production. In winter, shorter and narrower curves indicate reduced power output due to shorter days and a lower sun angle. Cloudy or overcast days cause fluctuations and dips in the daily curves. This annual overview of energy availability is essential for planning energy storage and consumption, ensuring a stable power supply throughout the year. Additionally, PV cell temperature is significantly influenced by ambient temperature and solar irradiance, affecting the cells' performance and efficiency across seasons.

We utilize lithium-ion batteries for power storage during peak production periods. This ensures that excess solar energy is efficiently stored and used when production is low, enhancing energy availability and reliability for the household throughout the year. The net power, which is the difference between PV-produced power and the home’s load power, needs to be positive for the lithium-ion battery to store energy. Based on the energy level in the accumulator tank, this stored energy is utilized to meet the building's heating demand. The available power each hour is managed to either charge or discharge the battery. When excess power is produced beyond the immediate demand, the lithium-ion battery is charged. Here we have used a 16000kWh battery in the initial analysis. Conversely, when there is a power shortage, the battery is discharged. The rate of charging is determined by the battery's efficiency. After the battery is fully charged, any excess power is used to heat the accumulator tank. Here we have used a 1 m^3 tank. If the accumulator tank also reaches its maximum energy storage capacity, the surplus power is fed into the grid. If the energy storage is depleted and there is no net power available due to low production and high home demand, the household's energy needs are met from the grid. However, if the house is connected to a nearby district heating network, then it would probably be beneficial to do that. The analysis in this thesis does not apply to the district heating case but considers specifically the case of a heat pump used for heating demand.

The analysis done in MATLAB is pivotal for simulating the day-to-day operation of an energy system integrated with photovoltaic (PV) generation, battery storage, and an accumulator tank for water heating. Through a series of checks and calculations, the analysis orchestrates the efficient utilization of surplus energy, management of storage systems, and interaction with the grid to ensure the household's energy needs are met effectively. Our analysis is done on an hourly basis, reflecting the dynamic nature of energy generation and consumption throughout the year. By iterating over each hour, the simulation captures the fluctuations in energy supply and demand, providing a comprehensive understanding of the system's performance over time.

Economic Implications: Increasing the battery storage or accumulator tank sizes beyond the current configuration of the Battery (8000 kWh) and Accumulator tank (2 m^3) results in substantial cost increments. The costs associated with larger batteries and tanks involve not only the initial investment but also potential maintenance and operational expenses. Given that the performance metrics (grid dependency, grid feed-in, and self-consumption) show minimal improvement with larger sizes, the return on investment diminishes.

From the analysis, it is clear that the optimal configuration for the energy system in this thesis is an 8000 kWh battery and a 2000 litre-sized accumulator tank. This setup provides a balanced approach to energy storage and utilization, maintaining reasonable grid dependency and maximizing self-consumption without unnecessary increases in system cost. Larger storage capacities do not significantly enhance performance metrics and would only lead to higher installation and operational costs. Thus, the selected battery and tank sizes offer the most cost-effective and efficient solution for integrating solar power into the household energy system in Gothenburg, Sweden.

8. Conclusion

In this thesis, we aimed to power a two-story building in Gothenburg, Sweden, using photovoltaic (PV) panels, a lithium-ion battery for primary energy storage, and an accumulator tank for secondary storage. Our study focused on meeting the house's electrical and heating demands, critical in Sweden's cold climate. The system utilizes excess solar energy to heat the accumulator tank once the battery is fully charged, ensuring efficient use of generated power. The analysis revealed that heating demand peaks during the cold months while PV power production is highest in the summer. We selected 22 solar panels based on detailed calculations of PV cell current, voltage, and power. The daily and seasonal variations in solar energy generation were evident, with longer daylight hours in summer resulting in higher energy production. In contrast, shorter winter days led to reduced power output.

Lithium-ion batteries play a crucial role in storing energy during peak production periods, ensuring that excess solar energy is used when production is low. Our system configurations are tested for various battery and tank sizes, ultimately determining that an 8000 kWh battery and a 2000-liter accumulator tank provided the best performance. The surplus energy is fed into the grid, and any shortages are met by drawing power from the grid.

Key performance ratios were calculated: the grid feed-in ratio was 38%, the grid dependence ratio was 62%, self-consumption was 65%, and heat demand satisfied from the accumulator tank was 22%. These metrics indicate a balanced approach to energy storage and utilization. Increasing the battery or tank size beyond the current configuration showed minimal improvements in performance metrics, suggesting that the chosen sizes are optimal.

Economic implications also favor the selected configuration. Larger batteries and tanks would incur higher costs without significant performance gains. Therefore, the optimal configuration for the household energy system in Gothenburg, Sweden, is an 8000 kWh battery and a 2000-liter accumulator tank. This setup balances energy production, storage, and consumption effectively, providing a cost-efficient solution for integrating solar power into the household energy system.

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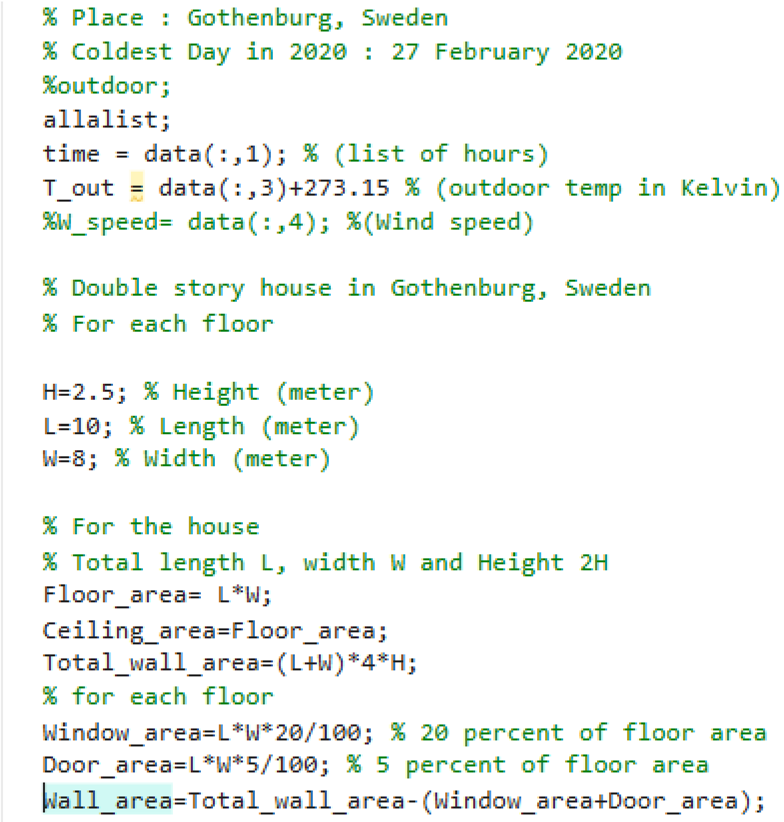
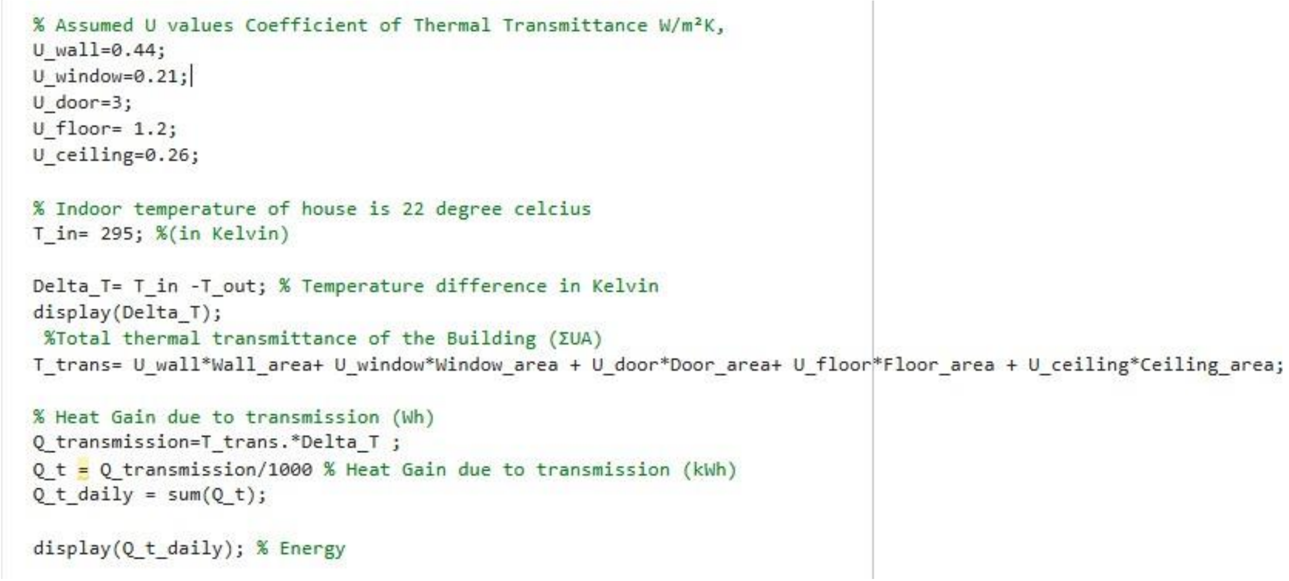
Appendices

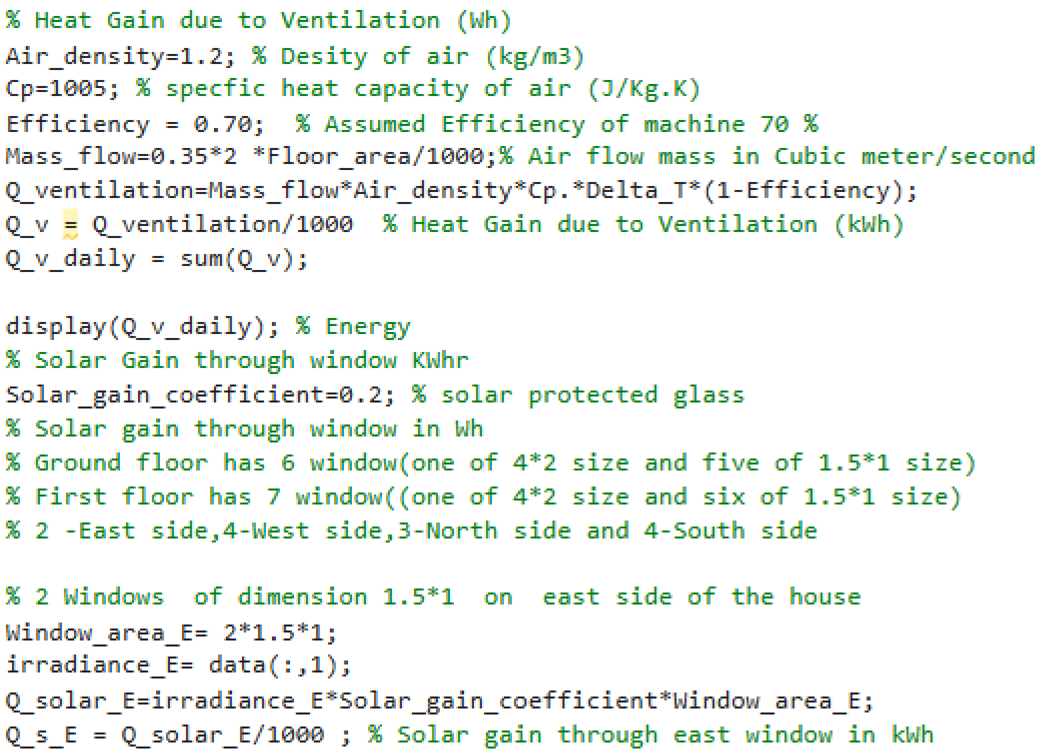
Appendix I – Space Heating Demand



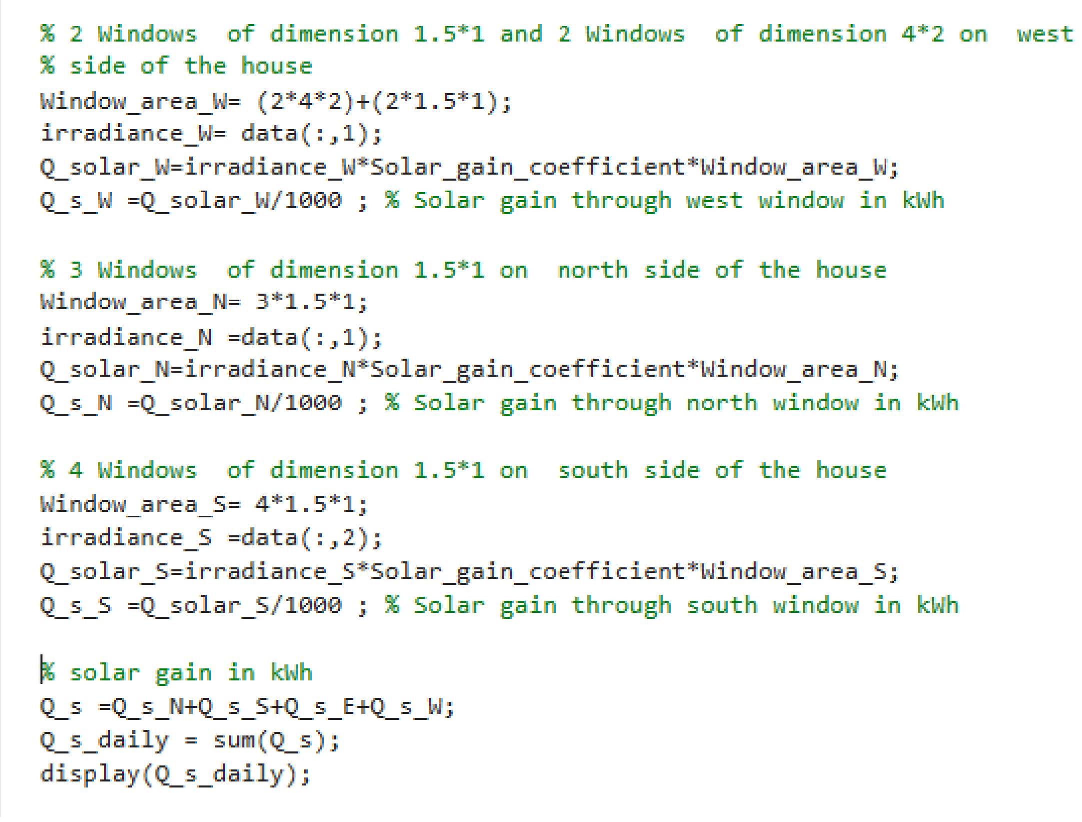
```
% Place : Gothenburg, Sweden
% Coldest Day in 2020 : 27 February 2020
%outdoor;
allalist;
time = data(:,1); % (list of hours)
T_out = data(:,3)+273.15 % (outdoor temp in Kelvin)
%W_speed= data(:,4); %(Wind speed)

% Double story house in Gothenburg, Sweden
% For each floor

H=2.5; % Height (meter)
L=10; % Length (meter)
W=8; % Width (meter)

% For the house
% Total length L, width W and Height 2H
Floor_area= L*W;
Ceiling_area=Floor_area;
Total_wall_area=(L+W)*4*H;
% for each floor
Window_area=L*W*20/100; % 20 percent of floor area
Door_area=L*W*5/100; % 5 percent of floor area
Wall_area=Total_wall_area-(Window_area+Door_area);
```



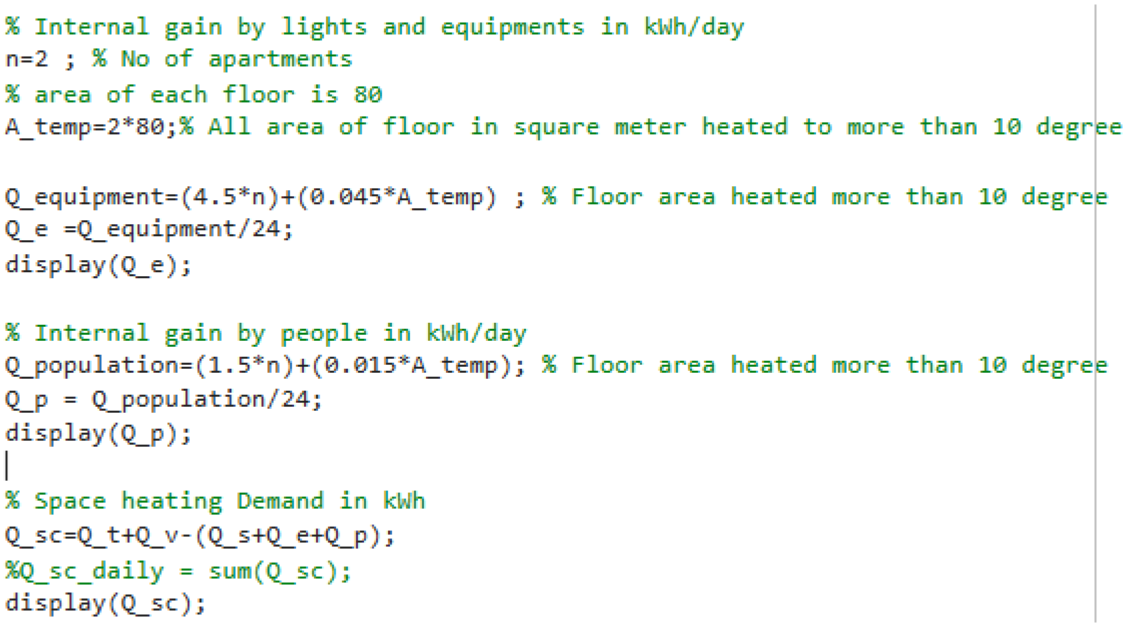
```
% Assumed U values Coefficient of Thermal Transmittance W/m²K,
U_wall=0.44;
U_window=0.21;
U_door=3;
U_floor= 1.2;
U_ceiling=0.26;

% Indoor temperature of house is 22 degree celcius
T_in= 295; %(in Kelvin)

Delta_T= T_in -T_out; % Temperature difference in Kelvin
display(Delta_T);
 %Total thermal transmittance of the Building (ΣUA)
T_trans= U_wall*Wall_area+ U_window*Window_area + U_door*Door_area+ U_floor*Floor_area + U_ceiling*Ceiling_area;

% Heat Gain due to transmission (Wh)
Q_transmission=T_trans.*Delta_T ;
Q_t = Q_transmission/1000 % Heat Gain due to transmission (kWh)
Q_t_daily = sum(Q_t);

display(Q_t_daily); % Energy
```



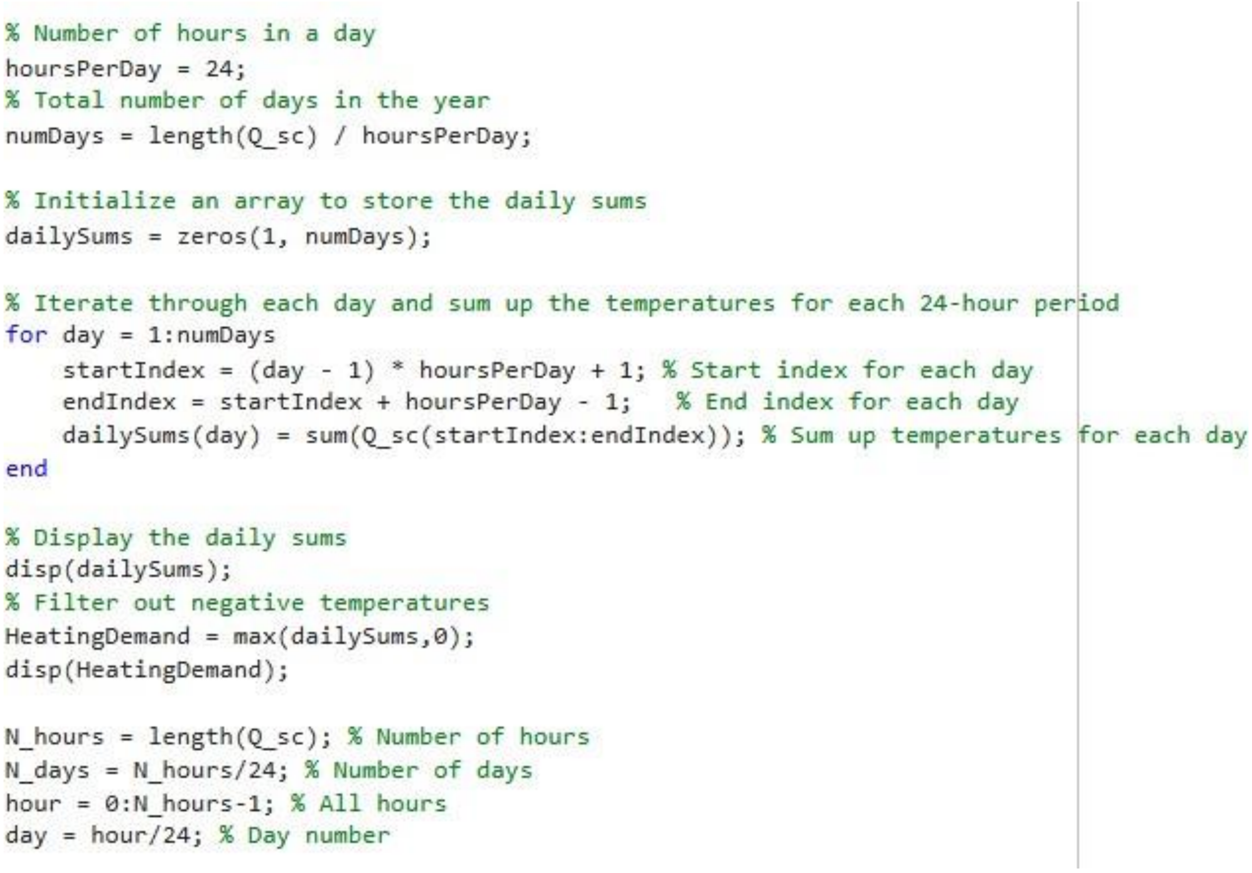
```
% Heat Gain due to Ventilation (Wh)
Air_density=1.2; % Desity of air (kg/m3)
Cp=1005; % specfic heat capacity of air (J/Kg.K)
Efficiency = 0.70;  % Assumed Efficiency of machine 70 %
Mass_flow=0.35*2 *Floor_area/1000;% Air flow mass in Cubic meter/second
Q_ventilation=Mass_flow*Air_density*Cp.*Delta_T*(1-Efficiency);
Q_v = Q_ventilation/1000  % Heat Gain due to Ventilation (kWh)
Q_v_daily = sum(Q_v);

display(Q_v_daily); % Energy
% Solar Gain through window KWhr
Solar_gain_coefficient=0.2; % solar protected glass
% Solar gain through window in Wh
% Ground floor has 6 window(one of 4*2 size and five of 1.5*1 size)
% First floor has 7 window((one of 4*2 size and six of 1.5*1 size)
% 2 -East side,4-West side,3-North side and 4-South side

% 2 Windows  of dimension 1.5*1  on  east side of the house
Window_area_E= 2*1.5*1;
irradiance_E= data(:,1);
Q_solar_E=irradiance_E*Solar_gain_coefficient*Window_area_E;
Q_s_E = Q_solar_E/1000 ; % Solar gain through east window in kWh
```



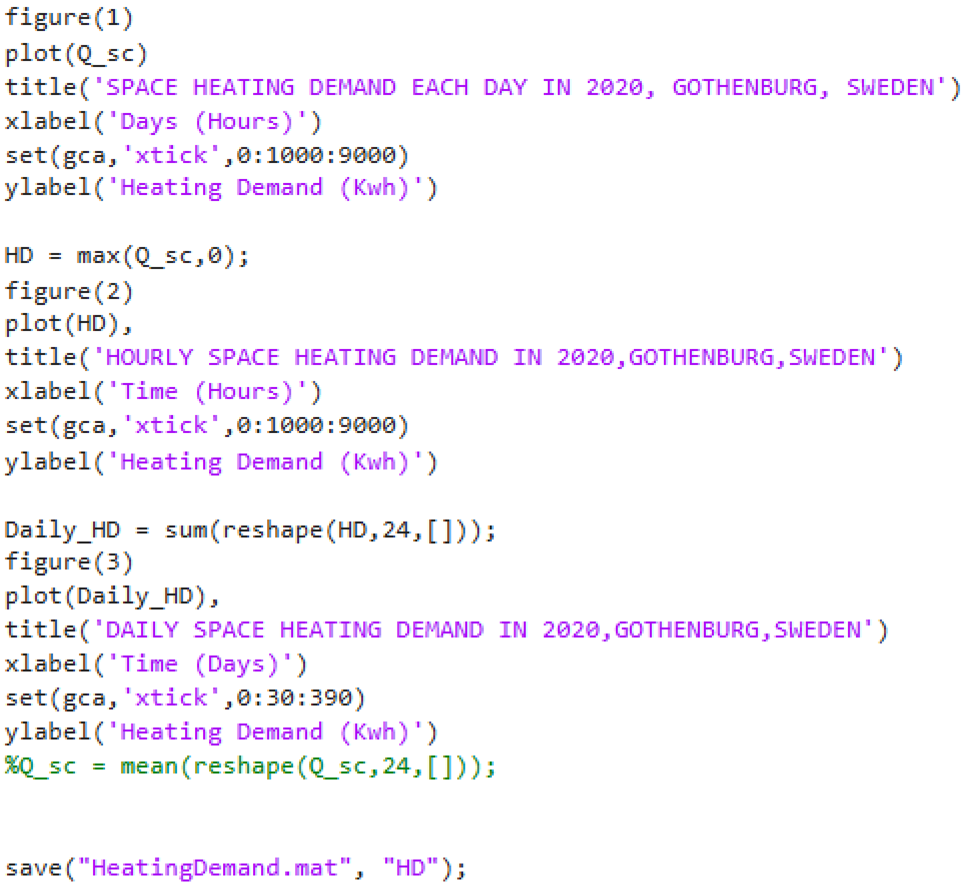
```
% 2 Windows  of dimension 1.5*1 and 2 Windows  of dimension 4*2 on  west
% side of the house
Window_area_W= (2*4*2)+(2*1.5*1);
irradiance_W= data(:,1);
Q_solar_W=irradiance_W*Solar_gain_coefficient*Window_area_W;
Q_s_W =Q_solar_W/1000 ; % Solar gain through west window in kWh

% 3 Windows  of dimension 1.5*1 on  north side of the house
Window_area_N= 3*1.5*1;
irradiance_N =data(:,1);
Q_solar_N=irradiance_N*Solar_gain_coefficient*Window_area_N;
Q_s_N =Q_solar_N/1000 ; % Solar gain through north window in kWh

% 4 Windows  of dimension 1.5*1 on  south side of the house
Window_area_S= 4*1.5*1;
irradiance_S =data(:,2);
Q_solar_S=irradiance_S*Solar_gain_coefficient*Window_area_S;
Q_s_S =Q_solar_S/1000 ; % Solar gain through south window in kWh

% solar gain in kWh
Q_s =Q_s_N+Q_s_S+Q_s_E+Q_s_W;
Q_s_daily = sum(Q_s);
display(Q_s_daily);
```



```
% Internal gain by lights and equipments in kWh/day
n=2 ; % No of apartments
% area of each floor is 80
A_temp=2*80;% All area of floor in square meter heated to more than 10 degree

Q_equipment=(4.5*n)+(0.045*A_temp) ; % Floor area heated more than 10 degree
Q_e =Q_equipment/24;
display(Q_e);

% Internal gain by people in kWh/day
Q_population=(1.5*n)+(0.015*A_temp); % Floor area heated more than 10 degree
Q_p = Q_population/24;
display(Q_p);

% Space heating Demand in kWh
Q_sc=Q_t+Q_v-(Q_s+Q_e+Q_p);
%Q_sc_daily = sum(Q_sc);
display(Q_sc);
```

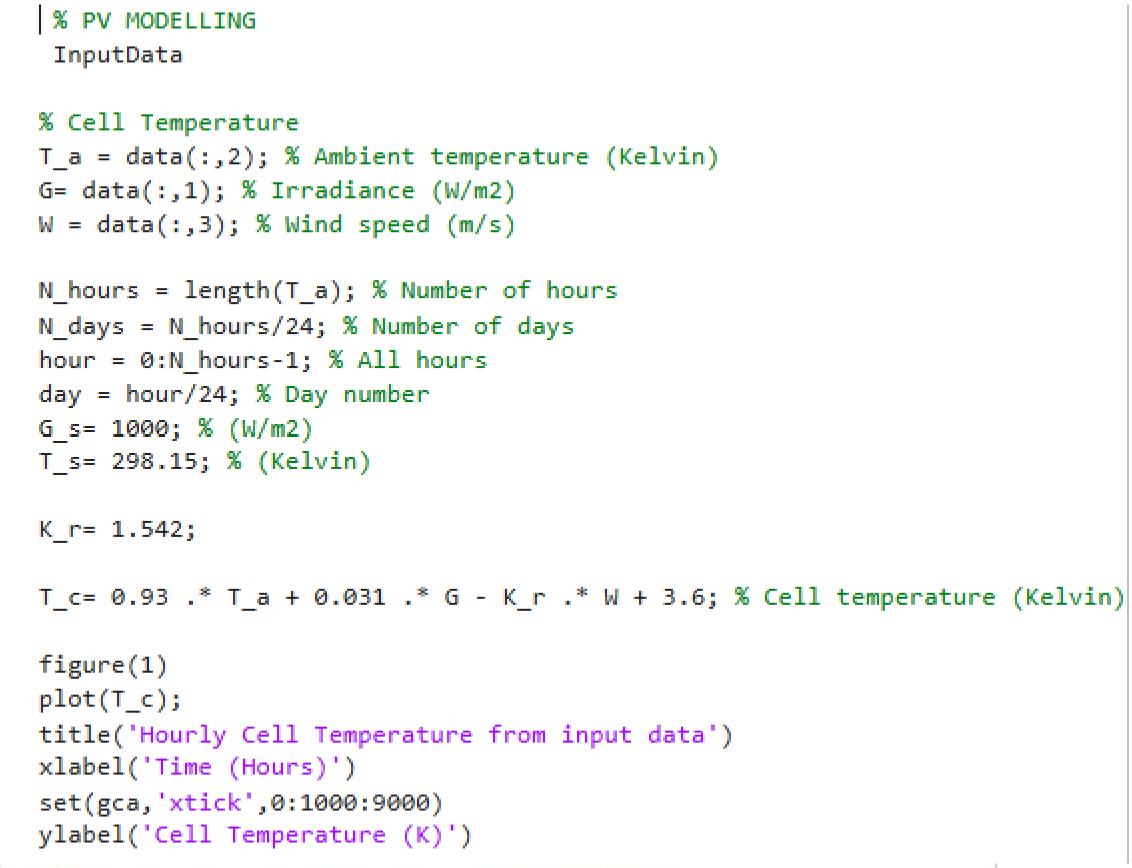


```
% Number of hours in a day
hoursPerDay = 24;
% Total number of days in the year
numDays = length(Q_sc) / hoursPerDay;

% Initialize an array to store the daily sums
dailySums = zeros(1, numDays);

% Iterate through each day and sum up the temperatures for each 24-hour period
for day = 1:numDays
    startIndex = (day - 1) * hoursPerDay + 1; % Start index for each day
    endIndex = startIndex + hoursPerDay - 1;   % End index for each day
    dailySums(day) = sum(Q_sc(startIndex:endIndex)); % Sum up temperatures for each day
end

% Display the daily sums
disp(dailySums);
% Filter out negative temperatures
HeatingDemand = max(dailySums,0);
disp(HeatingDemand);

N_hours = length(Q_sc); % Number of hours
N_days = N_hours/24; % Number of days
hour = 0:N_hours-1; % All hours
day = hour/24; % Day number
```

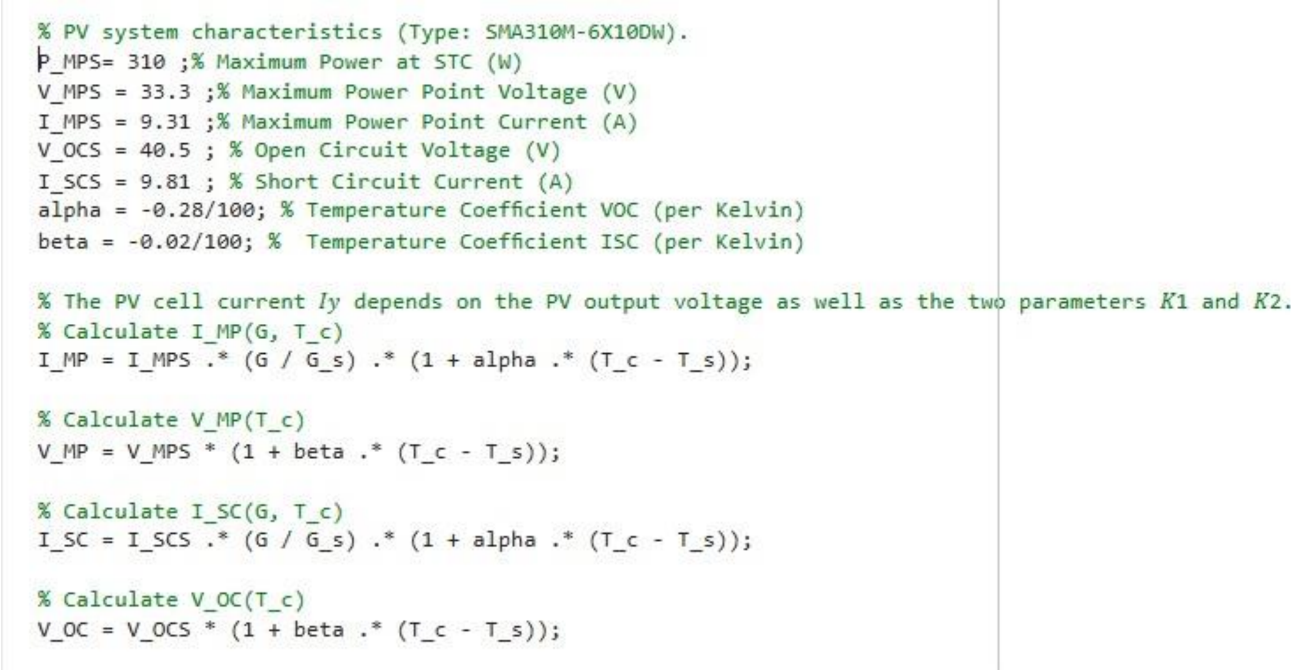


```
figure(1)
plot(Q_sc)
title('SPACE HEATING DEMAND EACH DAY IN 2020, GOTHENBURG, SWEDEN')
xlabel('Days (Hours)')
set(gca,'xtick',0:1000:9000)
ylabel('Heating Demand (Kwh)')

HD = max(Q_sc,0);
figure(2)
plot(HD),
title('HOURLY SPACE HEATING DEMAND IN 2020,GOTHENBURG,SWEDEN')
xlabel('Time (Hours)')
set(gca,'xtick',0:1000:9000)
ylabel('Heating Demand (Kwh)')

Daily_HD = sum(reshape(HD,24,[]));
figure(3)
plot(Daily_HD),
title('DAILY SPACE HEATING DEMAND IN 2020,GOTHENBURG,SWEDEN')
xlabel('Time (Days)')
set(gca,'xtick',0:30:390)
ylabel('Heating Demand (Kwh)')
%Q_sc = mean(reshape(Q_sc,24,[]));


save("HeatingDemand.mat", "HD");
```

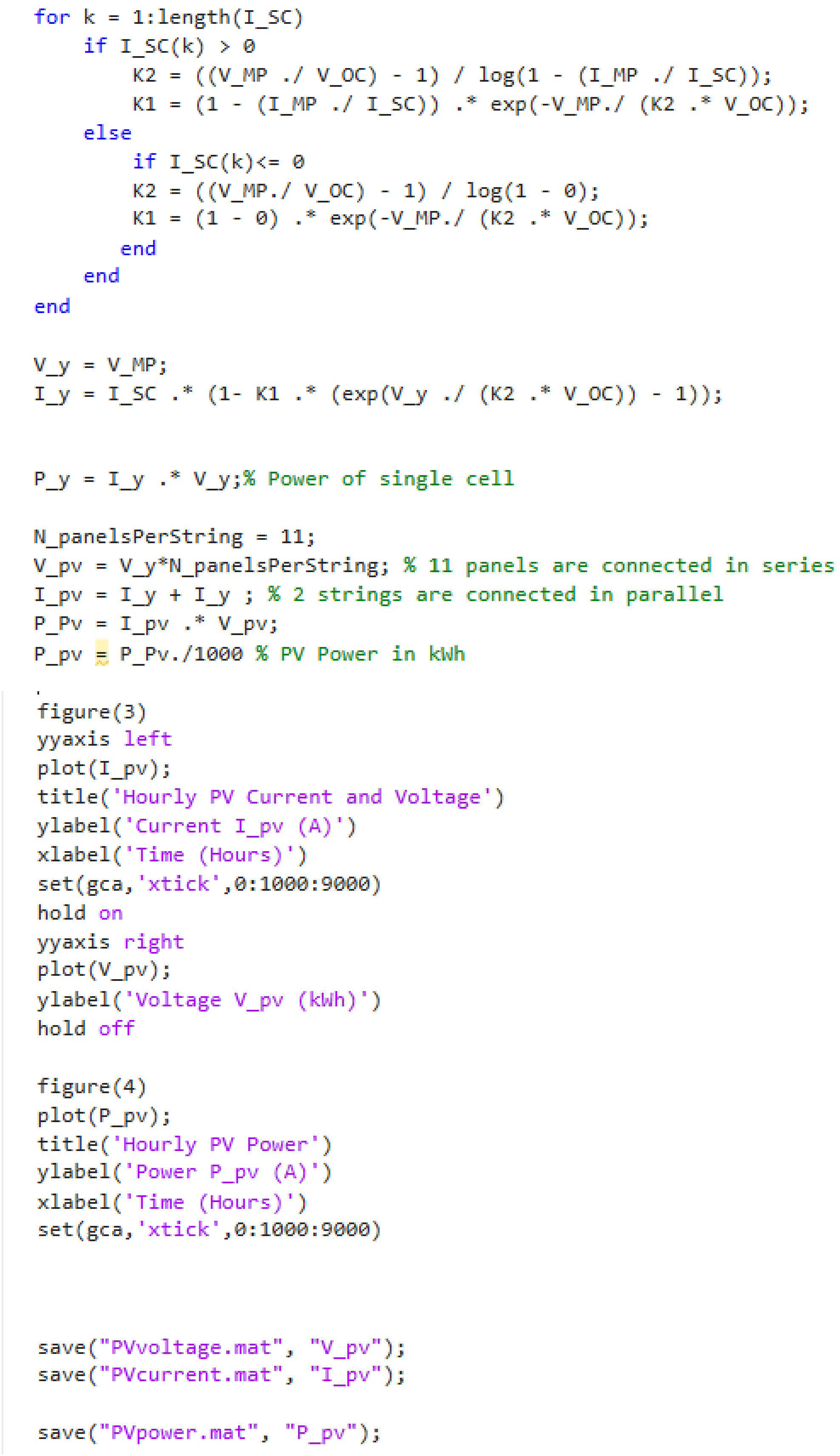
Appendix II – PV system



```
 % PV MODELLING
 InputData

% Cell Temperature
T_a = data(:,2); % Ambient temperature (Kelvin)
G= data(:,1); % Irradiance (W/m2)
W = data(:,3); % Wind speed (m/s)

N_hours = length(T_a); % Number of hours
N_days = N_hours/24; % Number of days
hour = 0:N_hours-1; % All hours
day = hour/24; % Day number
G_s= 1000; % (W/m2)
T_s= 298.15; % (Kelvin)

K_r= 1.542;

T_c= 0.93 .* T_a + 0.031 .* G - K_r .* W + 3.6; % Cell temperature (Kelvin)

figure(1)
plot(T_c);
title('Hourly Cell Temperature from input data')
xlabel('Time (Hours)')
set(gca,'xtick',0:1000:9000)
ylabel('Cell Temperature (K)')
```

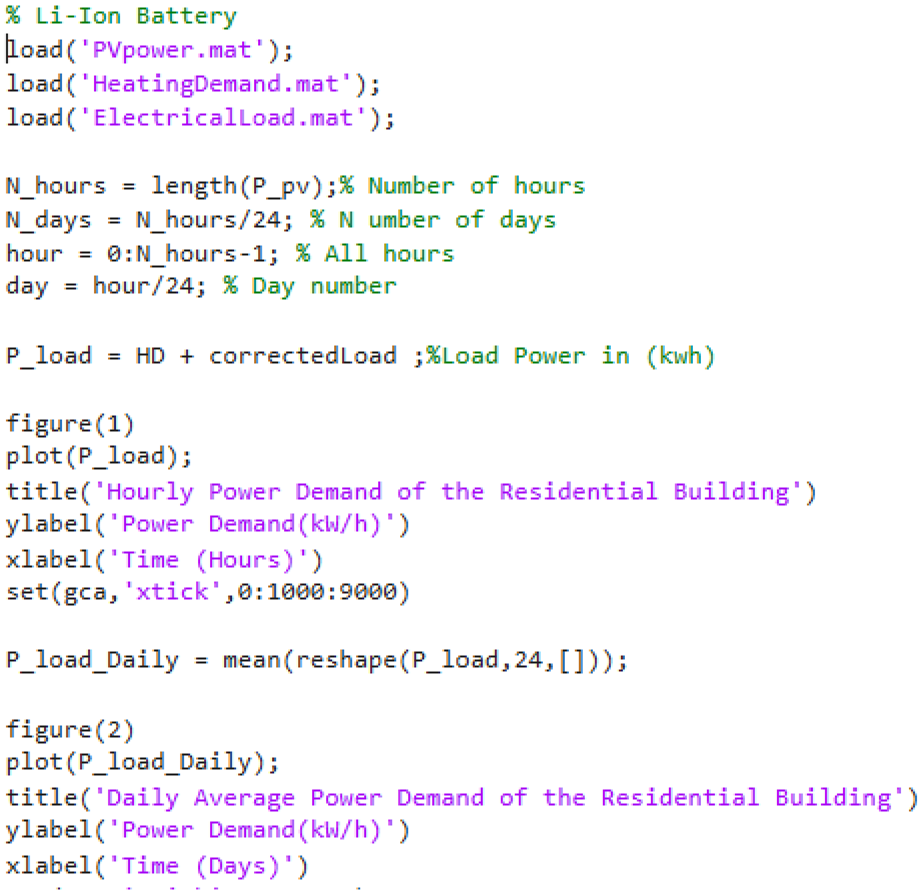


```
% PV system characteristics (Type: SMA310M-6X10DW).
P_MPS= 310 ;% Maximum Power at STC (W)
V_MPS = 33.3 ;% Maximum Power Point Voltage (V)
I_MPS = 9.31 ;% Maximum Power Point Current (A)
V_OCS = 40.5 ; % Open Circuit Voltage (V)
I_SCS = 9.81 ; % Short Circuit Current (A)
alpha = -0.28/100; % Temperature Coefficient VOC (per Kelvin)
beta = -0.02/100; %  Temperature Coefficient ISC (per Kelvin)

% The PV cell current Iy depends on the PV output voltage as well as the two parameters K1 and K2.
% Calculate I_MP(G, T_c)
I_MP = I_MPS .* (G / G_s) .* (1 + alpha .* (T_c - T_s));

% Calculate V_MP(T_c)
V_MP = V_MPS * (1 + beta .* (T_c - T_s));

% Calculate I_SC(G, T_c)
I_SC = I_SCS .* (G / G_s) .* (1 + alpha .* (T_c - T_s));

% Calculate V_OC(T_c)
V_OC = V_OCS * (1 + beta .* (T_c - T_s));
```

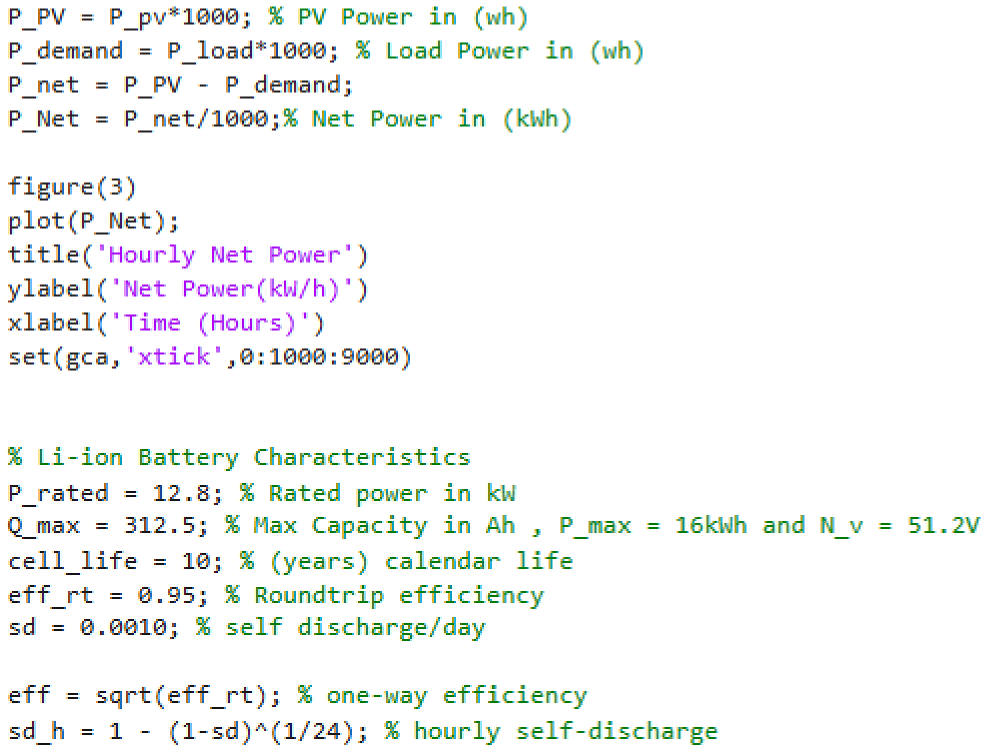


```
for k = 1:length(I_SC)
    if I_SC(k) > 0
        K2 = ((V_MP ./ V_OC) - 1) / log(1 - (I_MP ./ I_SC));
        K1 = (1 - (I_MP ./ I_SC)) .* exp(-V_MP./ (K2 .* V_OC));
    else
        if I_SC(k)<= 0
        K2 = ((V_MP./ V_OC) - 1) / log(1 - 0);
        K1 = (1 - 0) .* exp(-V_MP./ (K2 .* V_OC));
       end
    end
end

V_y = V_MP;
I_y = I_SC .* (1- K1 .* (exp(V_y ./ (K2 .* V_OC)) - 1));


P_y = I_y .* V_y;% Power of single cell

N_panelsPerString = 11;
V_pv = V_y*N_panelsPerString; % 11 panels are connected in series
I_pv = I_y + I_y ; % 2 strings are connected in parallel
P_Pv = I_pv .* V_pv;
P_pv = P_Pv./1000 % PV Power in kWh
.
figure(3)
yyaxis left
plot(I_pv);
title('Hourly PV Current and Voltage')
ylabel('Current I_pv (A)')
xlabel('Time (Hours)')
set(gca,'xtick',0:1000:9000)
hold on
yyaxis right
plot(V_pv);
ylabel('Voltage V_pv (kWh)')
hold off

figure(4)
plot(P_pv);
title('Hourly PV Power')
ylabel('Power P_pv (A)')
xlabel('Time (Hours)')
set(gca,'xtick',0:1000:9000)



save("PVvoltage.mat", "V_pv");
save("PVcurrent.mat", "I_pv");

save("PVpower.mat", "P_pv");
```

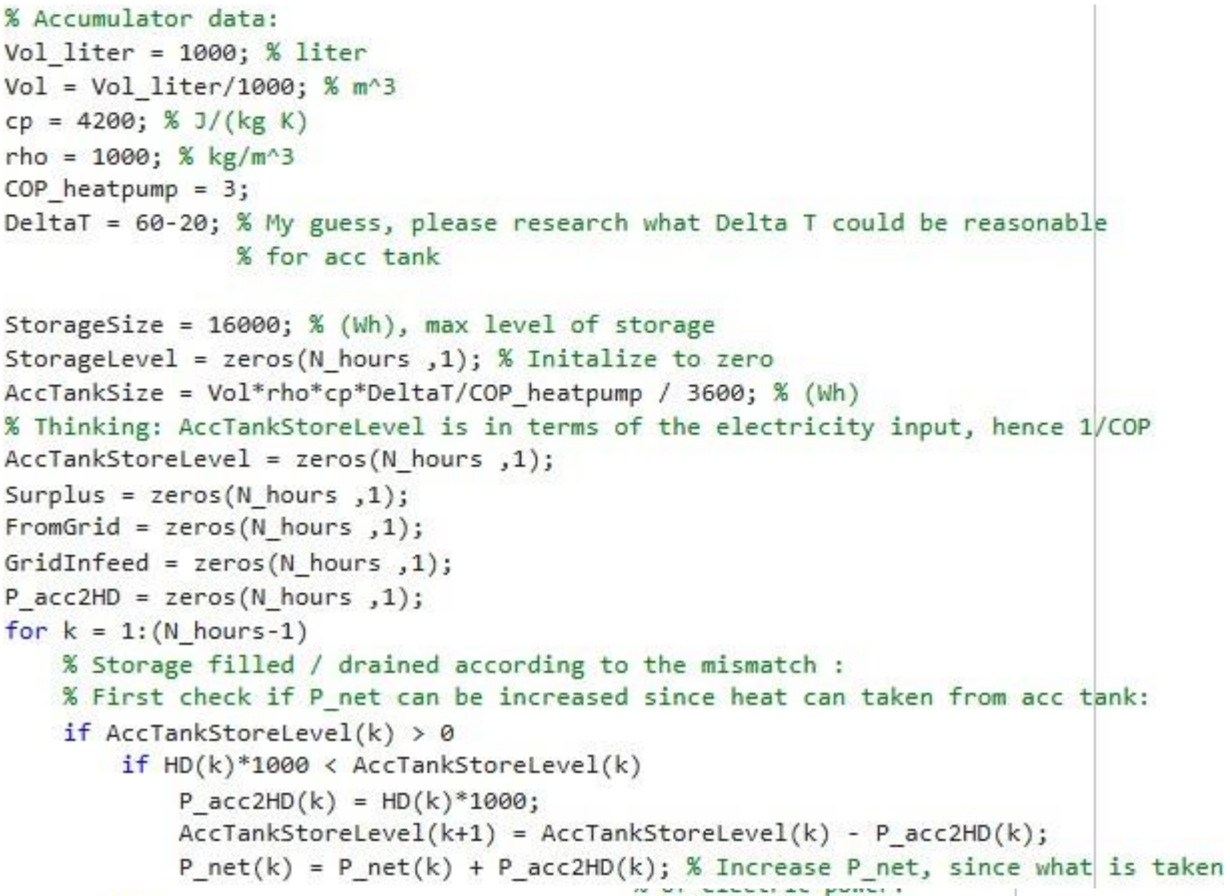
Appendix III – Battery and Accumulator Tank Storage



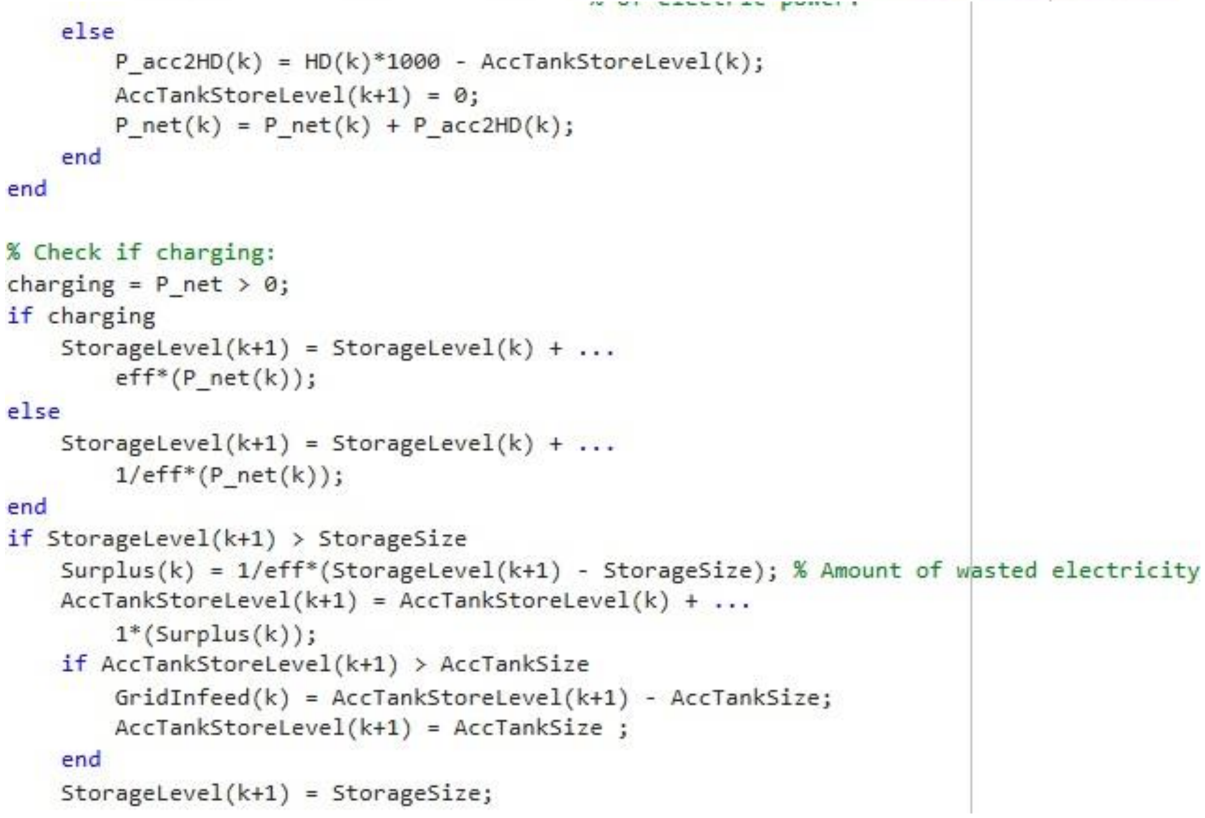
```
% Li-Ion Battery
load('PVpower.mat');
load('HeatingDemand.mat');
load('ElectricalLoad.mat');

N_hours = length(P_pv);% Number of hours
N_days = N_hours/24; % N umber of days
hour = 0:N_hours-1; % All hours
day = hour/24; % Day number

P_load = HD + correctedLoad ;%Load Power in (kwh)

figure(1)
plot(P_load);
title('Hourly Power Demand of the Residential Building')
ylabel('Power Demand(kW/h)')
xlabel('Time (Hours)')
set(gca,'xtick',0:1000:9000)

P_load_Daily = mean(reshape(P_load,24,[]));

figure(2)
plot(P_load_Daily);
title('Daily Average Power Demand of the Residential Building')
ylabel('Power Demand(kW/h)')
xlabel('Time (Days)')
```



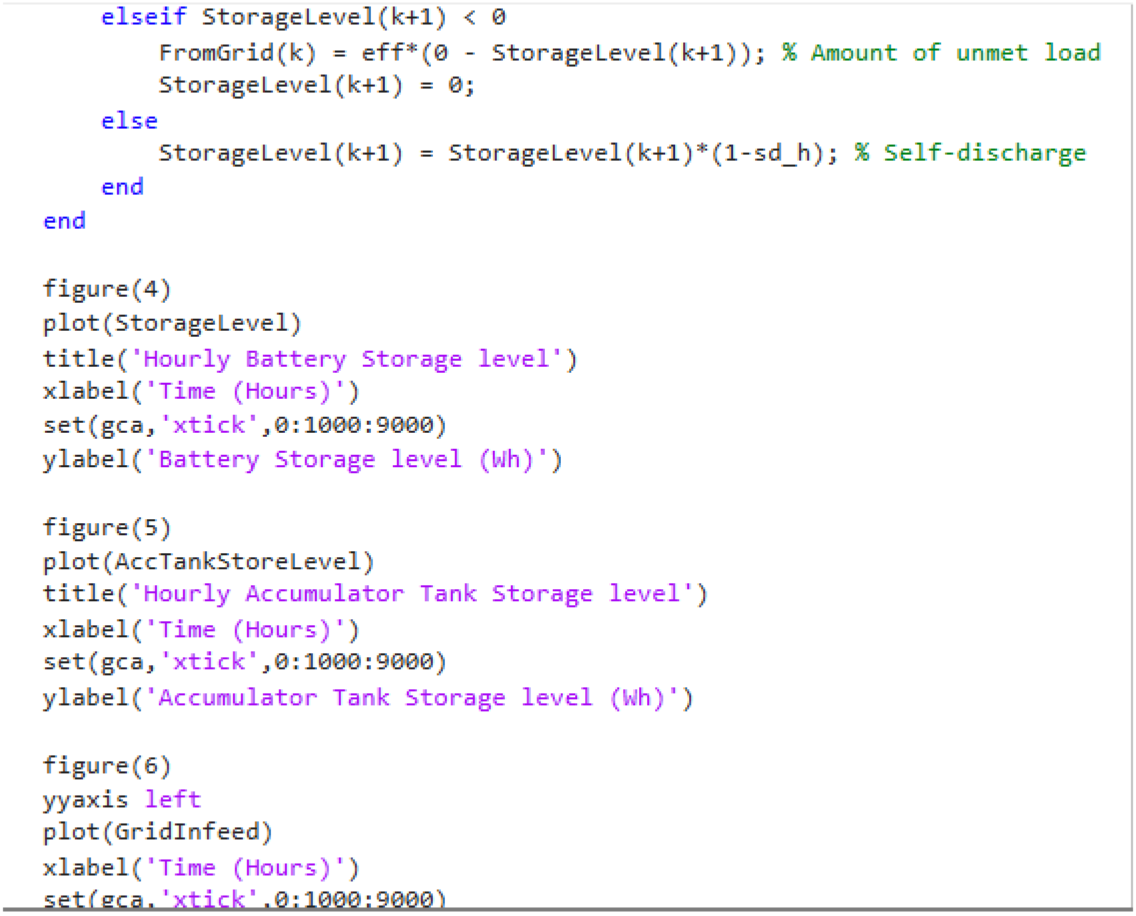
```
P_PV = P_pv*1000; % PV Power in (wh)
P_demand = P_load*1000; % Load Power in (wh)
P_net = P_PV - P_demand;
P_Net = P_net/1000;% Net Power in (kWh)

figure(3)
plot(P_Net);
title('Hourly Net Power')
ylabel('Net Power(kW/h)')
xlabel('Time (Hours)')
set(gca,'xtick',0:1000:9000)


% Li-ion Battery Characteristics
P_rated = 12.8; % Rated power in kW
Q_max = 312.5; % Max Capacity in Ah , P_max = 16kWh and N_v = 51.2V
cell_life = 10; % (years) calendar life
eff_rt = 0.95; % Roundtrip efficiency
sd = 0.0010; % self discharge/day

eff = sqrt(eff_rt); % one-way efficiency
sd_h = 1 - (1-sd)^(1/24); % hourly self-discharge
```



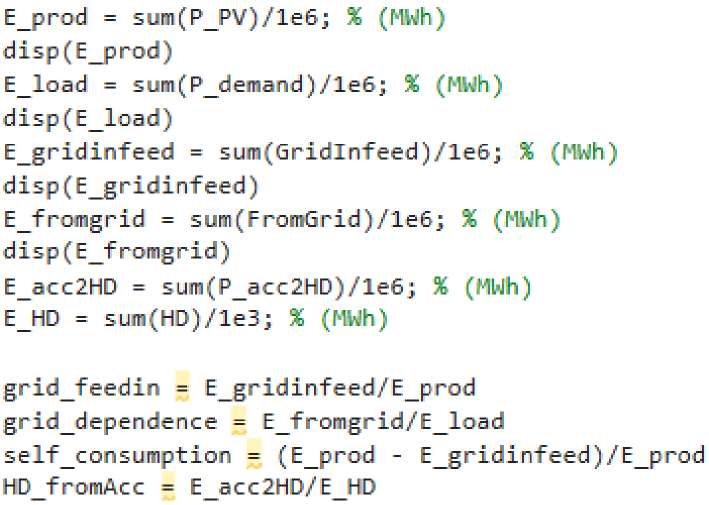
```
% Accumulator data:
Vol_liter = 1000; % liter
Vol = Vol_liter/1000; % m^3
cp = 4200; % J/(kg K)
rho = 1000; % kg/m^3
COP_heatpump = 3;
DeltaT = 60-20; % My guess, please research what Delta T could be reasonable
                % for acc tank

StorageSize = 16000; % (Wh), max level of storage
StorageLevel = zeros(N_hours ,1); % Initalize to zero
AccTankSize = Vol*rho*cp*DeltaT/COP_heatpump / 3600; % (Wh)
% Thinking: AccTankStoreLevel is in terms of the electricity input, hence 1/COP
AccTankStoreLevel = zeros(N_hours ,1);
Surplus = zeros(N_hours ,1);
FromGrid = zeros(N_hours ,1);
GridInfeed = zeros(N_hours ,1);
P_acc2HD = zeros(N_hours ,1);
for k = 1:(N_hours-1)
    % Storage filled / drained according to the mismatch :
    % First check if P_net can be increased since heat can taken from acc tank:
    if AccTankStoreLevel(k) > 0
        if HD(k)*1000 < AccTankStoreLevel(k)
            P_acc2HD(k) = HD(k)*1000;
            AccTankStoreLevel(k+1) = AccTankStoreLevel(k) - P_acc2HD(k);
            P_net(k) = P_net(k) + P_acc2HD(k); % Increase P_net, since what is taken
```



```
        else
            P_acc2HD(k) = HD(k)*1000 - AccTankStoreLevel(k);
            AccTankStoreLevel(k+1) = 0;
            P_net(k) = P_net(k) + P_acc2HD(k);
        end
    end

    % Check if charging:
    charging = P_net > 0;
    if charging
        StorageLevel(k+1) = StorageLevel(k) + ...
            eff*(P_net(k));
    else
        StorageLevel(k+1) = StorageLevel(k) + ...
            1/eff*(P_net(k));
    end
    if StorageLevel(k+1) > StorageSize
        Surplus(k) = 1/eff*(StorageLevel(k+1) - StorageSize); % Amount of wasted electricity
        AccTankStoreLevel(k+1) = AccTankStoreLevel(k) + ...
            1*(Surplus(k));
        if AccTankStoreLevel(k+1) > AccTankSize
            GridInfeed(k) = AccTankStoreLevel(k+1) - AccTankSize;
            AccTankStoreLevel(k+1) = AccTankSize ;
        end
        StorageLevel(k+1) = StorageSize;
```



```
    elseif StorageLevel(k+1) < 0
        FromGrid(k) = eff*(0 - StorageLevel(k+1)); % Amount of unmet load
        StorageLevel(k+1) = 0;
    else
        StorageLevel(k+1) = StorageLevel(k+1)*(1-sd_h); % Self-discharge
    end
end

figure(4)
plot(StorageLevel)
title('Hourly Battery Storage level')
xlabel('Time (Hours)')
set(gca,'xtick',0:1000:9000)
ylabel('Battery Storage level (Wh)')

figure(5)
plot(AccTankStoreLevel)
title('Hourly Accumulator Tank Storage level')
xlabel('Time (Hours)')
set(gca,'xtick',0:1000:9000)
ylabel('Accumulator Tank Storage level (Wh)')

figure(6)
yyaxis left
plot(GridInfeed)
xlabel('Time (Hours)')
set(gca,'xtick',0:1000:9000)
```



```
E_prod = sum(P_PV)/1e6; % (MWh)
disp(E_prod)
E_load = sum(P_demand)/1e6; % (MWh)
disp(E_load)
E_gridinfeed = sum(GridInfeed)/1e6; % (MWh)
disp(E_gridinfeed)
E_fromgrid = sum(FromGrid)/1e6; % (MWh)
disp(E_fromgrid)
E_acc2HD = sum(P_acc2HD)/1e6; % (MWh)
E_HD = sum(HD)/1e3; % (MWh)

grid_feedin = E_gridinfeed/E_prod
grid_dependence = E_fromgrid/E_load
self_consumption = (E_prod - E_gridinfeed)/E_prod
HD_fromAcc = E_acc2HD/E_HD
```