MAS-500

Building integrated photovoltaics with thermal energy storage

A Techno-economic performance assessment under grid constraints

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Abstract

The purpose of this study is to investigate the use of thermal storage in building integrated photovoltaic (BIPV) systems for reducing energy demand during peak hours and to increase the self-consumption. With the rapid increase in electrical appliance use, the energy usage is becoming increasingly demanding on the power grid. With the increase of demand comes inevitable changes to the electricity tariffs, and the utility may decide to limit the usage of electricity at certain hours of the day. Therefore, it is important to study the techno-economic performance of buildings with different storage options. A BIPV system for a typical household is analyzed in a mathematical model to study the effects of electric water heater (EWH) under grid constraints. Through the control of EWH based on current restrictions it was observed that the EWH successfully increased the self-consumption of the building with 4 %. The economic assessment saw a decrease in levelized cost of energy (LCOE) of 7 ØRE/kWh. These indicators can be further improved by increasing tank size as well as maximum allowable temperature. Furthermore, by making the household more reliable on the water heater, the self-consumption can also increase. Overall, the proposed logic for current regulation of the EWH proved to lower the the peaks, though further research has to be done in relation to applicability of EWH as a storage option.

Preface

I would like to extent my gratitude towards Professor at UiA, Mohan Lal Kolhe for feedback and scientific guidance throughout the writing process. I would also like to thank my girlfriend for patience and understanding, and also making me laugh when times are though. Due to the unique situation of Covid-19, the learning and writing process has been different. Nevertheless, it has shown me the value of a clear plan and working towards a goal, and has also strengthened my ability to work independent.

The knowledge given to me through the process of writing has sparked an interest in solar power. The field is also something I would like to pursue as a career.

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Acronyms

AC alternating current.

BIPV Building integrated photovoltaics.

EWH Electric water heater.

IRR Internal rate of return.

kW Kilowatt.

kWh Kilowatt hours.

kWp Kilowatt ’peak.

NPV Net present value.

NVE Norges vassdrags- og energidirektorat.

nZEB near zero energy building.

PV photovoltaics.

ZEB Zero energy building.

Nomenclature

$C_{I\&C}$	Cost of installation and commissioning
C_{INV}	Cost of inverter
C_{NCF}	Net cash flow of system
$C_{PV,sys}$	Total capital investment of system
C_{PV}	Cost of PV arrays
d	Discount rate
e_0	Operation cost rate
E_i	Energy served from system
F_i	Fuel cost
i	year
I_0	Capital investment
j	Number of inverter replacement
m	Percentage of capital investment
M_i	Operation and maintenance cost
N	Lifetime of PV system
n	System lifetime
OM_{PV}	Operation and management cost
R_{INV}	Inverter replacement cost
v	Total number of inverter replacements

Chapter 1

Introduction

To make the electrical grid greener and more demand-side focused and to make the transition into a ”smart grid,” it is recommended by the European commission that all new houses built in 2020 and forward should be near zero energy buildings(nZEB)[1]. To manage the energy demand for new buildings and reduce its dependency on the grid, generating renewable energy through solar power can reduce the net energy demand. Building-integrated photovoltaics (BIPV) systems will contribute to making buildings near net-zero energy. Due to the intermittency of solar power, energy storage will contribute to making the system more energy-efficient and demanding side focused. Azmi [2] reported that through proper energy storage, the energy performance of the buildings could be improved in regards to grid constraints.

There have been studies focused on BIPV systems, both grid and off-grid, as reported by P. Sharma et. Al.[3], it is reported that these energy systems do not consider the impact of grid constraints. The continuation of the study researched the techno-economic impact of battery storage in a BIPV system under grid constraints[4], though it is important to further investigate BIPV systems for techno-economic assessment, incorporating different storage options, such as thermal storage, with the inclusion of grid constraints.

Exploring alternative storage options is important for making building near-zero energy. Considering Nordic countries, where solar intermittence is a concern, getting the most out of the BIPV system through proper storage is important. Hirvonen et. Al[5] reports that electric heating can significantly increase the self-consumption of buildings. Considering the added expense battery storage would bring, and the environmental impact of digging for precious metals and their production, different storage options must be studied. Thus the use of electric water heater (EWH) for energy storage may reduce the environmental impact and bring economic costs down for both consumer and energy distributor.

1.1 Background

In many European countries, the electricity demand continues to rise[6], and it is becoming increasingly difficult to meet the individual demand for electricity without over-expanding the power grid. The European Commission has identified the building sector as one of the key sectors in achieving the 20/20/20[1] targets of EU. Figure 1.1 presents the electricity consumption of the different sectors in Noway in 2017.[7].

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[1] 20% of greenhouse gas emissions compared to 1990, 20% energy savings by 2020 (compared to a business as usual scenario) and 20% share of renewables in 2020[1]

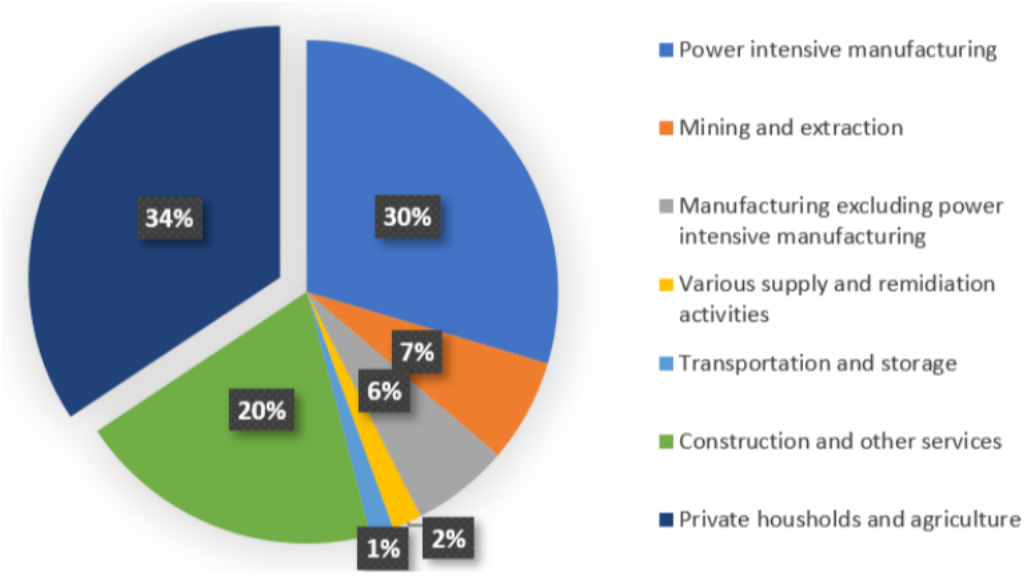

Figure 1.1: Share of Electricity consumption in Norway - 2017

The statistics show that 34% of electricity consumption comes from households and agriculture, thus making this sector a notable contributing factor. As mentioned, the European Commission has recommended that all new houses built in 2020 and forward should be near zero energy buildings. The target for Norway considering the 20/20/20 goals is that all new construction built in 2020 should be near zero energy (2014 for public buildings)[1].

A zero-energy building (ZEB) is a house or building with a net annual energy demand of zero. The use of energy in the building does not have to be zero, as long as the generation of renewable energy sources compensates for the demand[8]. A near-zero energy building (nZEB) is defined by the European Commission as a building with very high energy performance, in accordance with Annex 1[1]. Due to this legislation, it is important to develop the most effective solutions for reducing reliance on the grid. Research can prove both technically and economically valuable.

In 2017, NVE[2] submitted a proposal for new energy pricing mechanisms, due to the increasing power consumption in Norway[9]. The proposal was submitted considering the changes in the power grid due to the increase in population and power usage. NVE mentioned that there is a need for adjustment of power tariffs as the consumption is increasingly demanding on the grid when we want to use the electricity at the same time.

Energy pricing based on subscribed power per month was one of the proposals outlined by NVE. The end-user receives a pricing signal to reduce the consumption in hours where the demand is high. In the short term, the end-user will have the incentive to adapt to keep the consumption within grid limits. In the long term, end-users will have an economic incentive to take measures making it profitable to select a subscription-based on lower grid constraints[9].

BIPV systems can contribute to keeping the grid demand below the limit. However, grid purchase and load consumption can be further reduced through the implementation of thermal storage. Through the shifting of water heater load, the demand during peak hours can be lowered. Figure 1.2 illustrates the concept of using storage options with BIPV.

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[2] Norges vassdrags- og energidirektorat

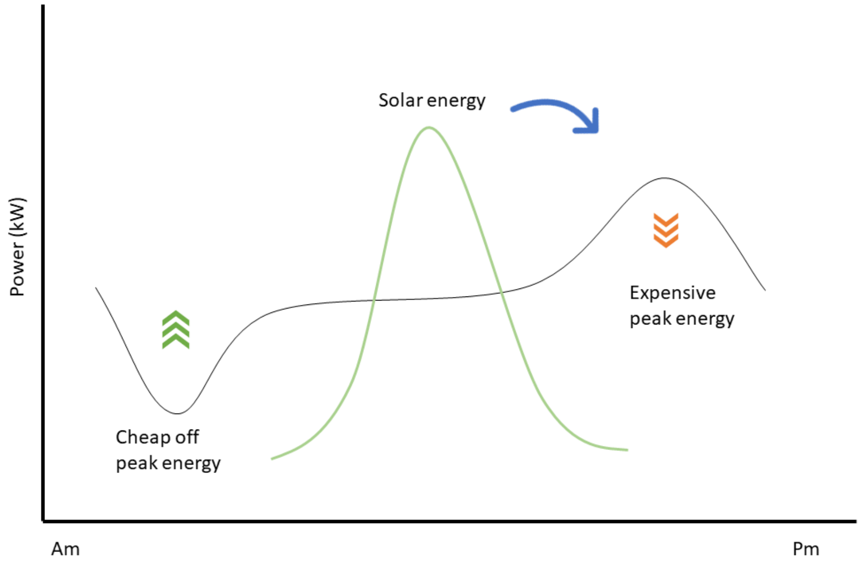

Figure 1.2: Load shifting and valley filling

The available solar energy can, with the usage of energy storage, shift the load to after peak hours, optimally to a point in which the energy is cheaper (e.g., Early hours). Electric battery storage options such as lead-acid or lithium-ion batteries are popular options for storing energy although vary in lifespan and costs. The lead-acid battery is less expensive than the lithium-ion but has a lower lifespan. Although electric batteries are highly reliable and offer dispatchable electricity, investigating different storage options is beneficial in terms of promoting the use of PV systems. Depending on the location and through proper management, storage can offer an increase in self-consumption and reduction of energy cost.

1.2 Report structure

The outline of this report is as follows.

- **Chapter 1 - Introduction**
  This chapter presents the introduction to the problem along with a background for problem definition. The background outlines the demand for research in the area and expresses the idea behind photvoltaic (PV) systems in combination with storage.

- **Chapter 2 - Research question**
  Research questions are developed based on the problem definition referenced in Chapter chapter 1,section 1.1.

- **Chapter 3 - Theory**
  This section presents the theory for the task. Here, important concepts and equations is introduced to complete the work for this project.

- **Section 4 - Literature Review**
  A review of the literature is presented to gain understanding and insight on the topic at hand. Previous studies made on the topic are evaluated and presented and will be further discussed in reference to the knowledge and results gained from the work.
- **Section 5 - Thermal storage with PV system, role of water heater**
  In this section, the methodology for this work is presented. The role of the thermal heater working as storage is presented along with the BIPV system. Here the physical system is presented, and procedure for obtaining results will be explained.
- **Section 6 - Results**
  The results section will present the outcome of the work.
- **Chapter 7 - Discussion**
  A discussion of the results will be presented in combination with the literature to further understand the impact of the work.
- **Chapter 8 - Conclusion**
  The final chapter will be a conclusion based on the discussion section. A definitive answer to the research questions will be presented, and suggestions for further research will be recommended.

Chapter 2

Research question

In this work, a BIPV system with thermal storage will be studied. Solar irradiance data is utilized together with a synthetic residential load profile. A model thermal storage is implemented in the system to assess techno-economic performance with regards to grid constraints. Some assumptions is made based on consumer behaviour for water draw as well as utility electricity tariffs. A system design for a household located in southern-Norway is presented where intermittent PV power generation introduces the need for thermal storage. The thermal storage will contribute to lowering the load demand during water draw and increase the self-consumption of the building. To obtain results of the BIPV system, a mathematical model is developed in MatLab. Irradiance data, residential load data, and thermal storage operation is incorporated in the model. A proposed logic is developed for the building operational performance with thermal storage regarding grid constraints. An illustrative concept of the BIPV system is presented. Calculations on the economic performance will be presented and discussed. The techno-economic performance presented will be based on the research questions:

1. How does different storage options compare to each other in a Nordic environment? The thermal storage option will be compared to other options studied in the review of literature.

2. How much will the thermal storage increase the self-consumption compared to other storage options such as battery.

3. When imposed with grid constraints, how will the BIPV system perform both technically and economically?

Chapter 3

Theory

In the interest of reducing the grid consumption, EWH is one of the most beneficial and convenient household appliances to control being the largest consumer of electricity. The EWH also works as a storage and attains advantages compared to battery storage as it acsessible in every household. In this section, a description of important concepts related to a BIPV system is presented. First an overview of demand-side management strategies is presented followed by strategies for control of EWH and the impact of control. Lastly, theory behind assessing the economic performance of energy systems is presented.

3.1 Demand side management

Demand side management (DSM) is an approach for optimisation used to dictate and influence the customers use of electricity to avoid or produce changes in the utility's load curve/shape. The goal of DSM is to regulate the load curve for better balancing of the power system. Due to the lower utilisation of generation and networks (50%), DSM can significantly increase the efficiency of the power system[10]. Demand side management can be of interest to both the consumer and the provider of the energy system. Through DSM strategies, the consumer can lower their energy bill by adjusting the use and timing of their energy. Secondly, the energy system provider can benefit by avoiding high peaks, thus minimising the use of high power generators. Demand side management is an umbrella term, which has several functions for different applications and situations. Figure 3.1 presents an overview of DSM strategies.

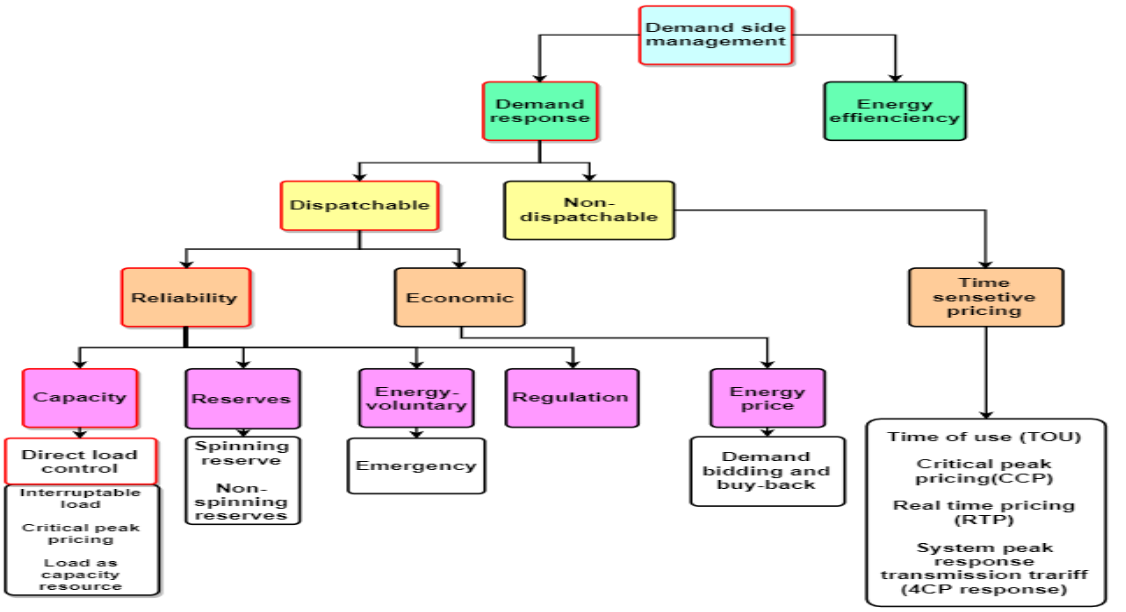

Figure 3.1: Overview of DSM strategies

Control of electric water heater can be described as a type of direct load control. The EWH is controlled based on available capacity of the grid. Demand response strategies can be placed within two categories, dispatchable (incentive based) and non-dispatchable (pricing based). Direct load control is a strategy focusing on the reliability of the grid, with the key aspect being to improve the capacity of the power system.

Direct load control, as with any of the DSM strategies, will have impact on the load curve. Figure 3.2 illustrates the most common changes to the load curve through implementation of DSM.

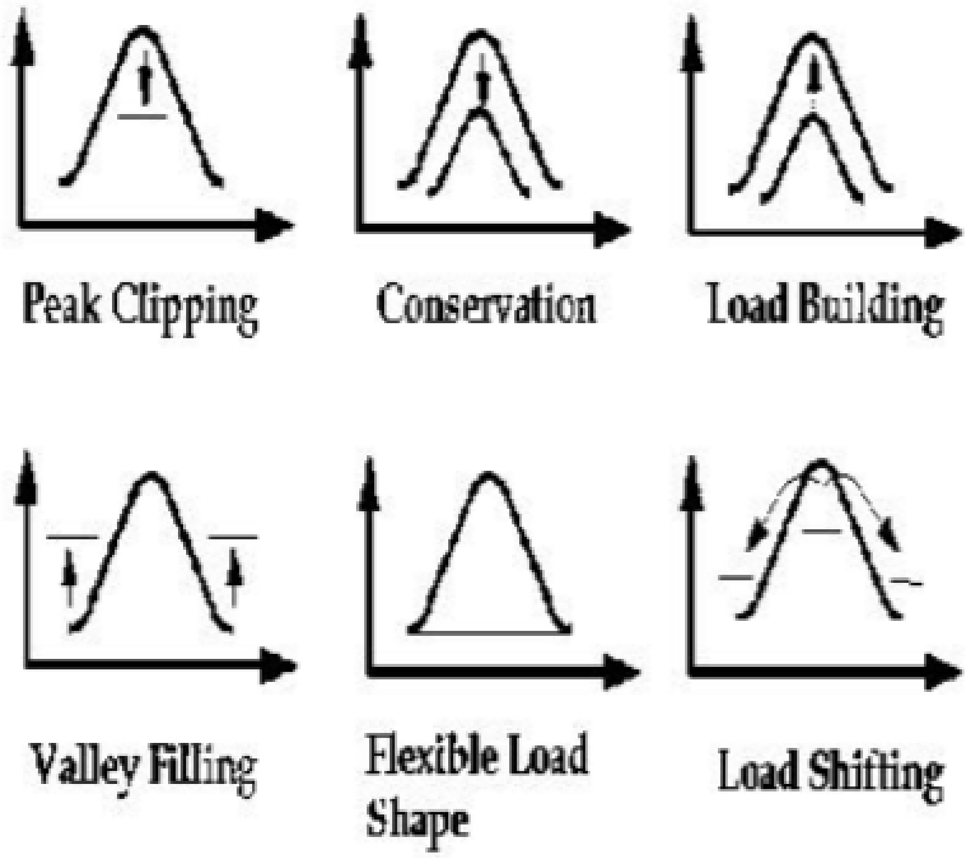

Figure 3.2: Possible changes in the load curve through implementation of DSM[11]

3.1.1 Peak clipping

Peak clipping is a strategy used to reduce the peak of a load curve. This strategy uses direct load control, by shutting down equipment for short periods of time or through distributed generation stations.

3.1.2 Valley filling

This strategy encourages off-peak consumption. This method increases the efficiency of the system and is beneficial as the production costs are lower in off-peak hours, thus the average electricity price becomes lower.

3.1.3 Load shifting

This strategy is hybrid of peak clipping and valley filling. This strategy is used to move peak load to a period of lower consumption. The total consumption throughout the day remains the same.

The use of EWH as a storage option may take use of several different strategies. Peak clipping may occur by reducing the load needed at peak hours, due to a higher water temperature in the tank when solar panels are producing electricity. Valley filling can occur in the same manner, as thermal loads are shifted due to charge up of EWH. The EWH is working as a combination of peak clipping and valley filling to get a load shift of thermal demand.

3.2 Building integrated photovoltaics

Building integrated photovoltaics are photovoltaic materials used to replace conventional building materials. BIPV are increasingly being implemented in building constructions as an ancillary source of power. Buildings may also be retrofitted with similar technology.

One of the advantages of integrating photovoltaics on new buildings, is that intial cost of intallation may be reduced, by reducing the amount of building materials and labor normally used. The installation of photovoltaics may also be included in the mortgage further making it profitable and provide more incentive for consumers to favor BIPV[12].

Grid purchase is the amount of kW demanded from the grid at any time. When houses are implemented with a PV system, naturally the grid purchase will decrease due to PV production accounting for loads during day-time. Nevertheless, there is still a grid demand during early evening hours. With the implementation of water heater as a thermal storage option, the grid purchase should in theory decrease due surplus PV production is transferred to the water heater.

3.3 Economic assessment of BIPV

For assessing the economic performance of the BIPV system, the Net present value (NPC) and Levelized cost of energy (LCOE) will be evaluated with and without storage based on the technical results from the mathematical model. The economic calculations are based on the methodology reported in [[13],[14]]. Key contributions to figuring LCOE incorporate capital costs, fuel costs, fixed and variable tasks and support ($O\&M$) costs, financing costs, and an assumed utilization rate for each plant type. The significance of every one of these components changes depending on technology. For technology with no fuel costs and smaller operation and management costs, for example, solar and wind, the LCOE changes almost proportional to the estimated capital cost[15]. Levelized cost of energy analysis is calculated using equation 3.1.

$$LCOE = \frac{\sum_{i=1}^{n} \frac{I_0+M_i+F_i}{(1+d)^i}}{\sum_{i=1}^{n} \frac{E_i}{(1+d)^n}} \tag{3.1}$$

Where

i = Year
n = System lifetime
I_0 = Capital investment
M_i = Operation and maintenance cost
F_i = Fuel cost
d = Discount rate

The captital investment of the system is based on total Net cash flow (NCF) of the system referenced in [16]. The NPC is given by equation and consist of the total capital investment ($C_{PV,sys}$), the present value of operation and maintenance cost (OM_{PV}) and the present value of system replacement cost (R_{PV}). The net cash flow of the PV system ($C_{NCF,PV}$) is defined using equation 3.2.

$$C_{NCF,PV} = C_{PV,sys} + OM_{PV} + R_{INV} \tag{3.2}$$

The total capital investment of the PV system is the sum of component investment, PV array cost, inverter cost, and installation and comissioning cost. Given by equation

$$C_{PV,sys} = C_{PV} + C_{INV} + C_{I\&C} \tag{3.3}$$

The operation and maintenance cost of the PV system is defined using equation 3.4 or equations 3.5 and 3.6

$$OM_{PV} = OM_0 \left(\frac{1+e_0}{d-e_0}\right) \cdot \left[1 - \left(\frac{1+e_0}{d-e_0}\right)^N\right] \tag{3.4}$$

$$OM_{PV} = OM_0 \cdot N \tag{3.5}$$

$$OM_0 = m\left(C_{PV,sys}\right) \tag{3.6}$$

Where

e_0 = Operation cost rate
N = Lifetime of PV system
m = Percentage of captital investment

The inverter replacement cost R_{INV} is a function of the number of inverter replacements, excluding the salvage value.

$$R_{INV} = \sum_{j=1}^{v} C_{INV} \cdot \left(\frac{1+e_0}{1+d}\right)^{\frac{Nj}{v+1}} \tag{3.7}$$

Where v is the total number of inverter replacement over a lifetime of N=25 years PV system.

Net Present Value (NPV) is a typical estimation of future pay (or investment funds) from a PV installation. NPV is calculated in NOK and is determined by taking away the expense of the underlying venture from the total of the complete limited future incomes over the lifetime of the speculation (i.e., the current dollar estimation of future incomes, determined utilizing the rebate rate). In sunlight based, this underlying venture is the framework cost, and future incomes are the subsequent vitality reserve funds.

A common metric to estimate the value of future income for a solar-power installation is the net present value (NPV). The NPV (given in NOK) is calculated by deducting the cost of the initial investment from the sum of the total discounted future cash flows. In solar power, this initial investment is the system cost, and future cash flows are the resulting energy savings. The NPV can be calculated using equation 3.8

$$NPV = \sum_{i=0}^{n} \frac{Cashflow_i}{(1+d)^i} \tag{3.8}$$

Based on the above economic metrics, calculations on the BIPV system can be done to assess the economic implications of BIPV system with thermal storage.

Chapter 4

Literature Review

A review of the literature was done to justify the relevance of the research questions. Studies reporting on BIPV systems and their different storage options are reviewed to develop an understanding of state-of-art within the field and to compare results from similar technologies based on geographical location. The review will also be linked to the results and support its discussion.

Numerous studies have been done on techno-economic analysis of BIPV[[17], [18][19][20]]. Liu, Rasul, Amanullah, and Khan [19], performed a sensitivity analysis on the BIPV system. They concluded that larger PV systems require larger investments, though carbon emissions are reduced and creates greater financial benefits in selling surplus energy. The studies have not considered the implementation of storage and its implications on the electricity price and self-consumption, though yearly self-consumption in this system was around 61%. The study referenced feed-in tariffs (sale-back tariffs and purchasing tariffs) in Australia, where sale-back tariffs are more than twice as much as general domestic use tariffs.

Lang, Ammann, and Giro[20] investigated the economic performance of rooftop PV regarding investment opportunities. Homie, a MatLab-based model (Household model for intelligent energy supply and use), was used to study cash and electricity flow in different types of buildings (small, large residential buildings) and offices. The economic potential was evaluated based on the internal rate of return (IRR) [1] and varying electricity pricings. Results from simulation on large residential buildings show a significant feed-in remuneration. In regards to IRR, studies show that Germany, with lower solar irradiation, had a higher IRR due to comparatively lower energy prices.

Furthermore, it was noticed that relation between electricity prices and IRR was not linear, suggesting that electricity prices could, in some cases, decrease considerably before IRR is effected. The study mentioned avenues for future research, where energy storage should be investigated to extend further understanding of rooftop PV potential, as well as economic value. A BIPV system with battery storage was investigated by Linssen, Stenzel, and Flee[17]. The work looks at the effect on different consumer profiles in households. The methodology conducted was based on a modeling approach for photovoltaic battery simulation. The tool was developed based on parameter variation in PV size and storage capacity as well as economic variation opportunities such as electricity price. Operation and maintenance costs were also referenced. The consumer profiles used were constructed based on an annual usage of 5400 kWh, using a 5-minute resolution. One load profile developed, were of a standard load profile (high baseload), an aggregated load profile of a larger group of households. The article introduced the concept of autarchy [2]. The results from the standard load profile showed that self-consumption and autarchy with PV and PV with the battery was increased in both cases. It was observed that the standard load profile, containing a higher base load reached significantly higher values for self-consumption and autarchy with the case of only PV. Adding the battery leads to a higher increase in self-consumption and

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[1] Internal rate of return - a discount rate that makes the net present value (NPV) of all cash flows equal to 0[21]

[2] the relation between energy used by the PV and energy consumed by the household

autarchy. When simulating with a more realistic, the self-consumption and autarchy were the lowest, which was also remarked for future studies, suggesting that the use of generated standard aggregated load profiles may result in too optimistic results in terms of total cost and battery sizing. Regarding the electricity prices mentioned, the assumed feed-in tariff used was more than two times lower than the electricity price.

In regards to other storage options and optimization, several studies have been conducted on the alternatives [[18],[2],[22]] Shabani and Mahmoudimehr[18] made the interesting approach of sun-tracking technology in a PV system, using pump storage to increase the potential for PV technology. It was highlighted that azimuth tracking technology leads to the closest yearly energy supply and demand compared to different PV systems, highlighting the call for research on different alternatives in PV systems and storage.

Williams, Binder, and Kelm studied thermal storage, heat pumps, and battery storage, [22] to compare self-consumption in buildings with integrated PV in Stuttgart, Germany. The proposed building had an area of 140 m^2 with four residents. The approach was based on simulation analysis of time-series of PV generation, local demand, and local demand for heat. A profile for hot water demand was developed, assuming that large water draws occur in the early hours around 6 AM and large duration water draws during evening hours. Results showed that the self-consumption of heat pump and storage could be increased from 55% to 65% self-consumption, depending on the heating load and storage tank size, pointing out that self-consumption is critically dependent on the size of the storage tank. Moreover, the useful tank size for carry-over electricity for stored heat from evening to night hours was 1000 L. Furthermore, the storage setpoint temperature was set to 53 $^\circ$. The algorithmic approach in simulations implemented a ”delayed charging” strategy for higher PV production months. Regarding tank sizing in regards to self-consumption and economic indicators, Baniasadi et al. [23] studied how to optimize electrical and thermal storage systems. Baniasadi remarked that thermal storage, in combination with electrical storage systems, is economically and eco-friendly options and provide more sustainable solutions for end-users compared to only electrical systems for energy management[23]. The studies were based on Monte Carlo simulation with one-year weather data as input to the model. In a sensitivity analysis, in regards to the battery and thermal storage sizing, it was indicated that in combination, the sizing of the tank should be from 1000-2000 L to achieve the lowest payback period on the system. Furthermore, the electricity cost is significantly decreased with a higher storage tank. Although the cost decrease is not linear, the optimal tank size is around 2000 l. The study was based on real-time price and time-of-use tariffs and did not sufficiently address the impacts of using a smaller, more typical residential storage tank. In regards to other economic parameters, it can be assumed that a tank size of around 1500 L would be optimal.

Thygesen and Karlsson investigated which storage system would give the highest level of PV self-consumption[24] in a 138 m^2 building with four residents. The study investigated a 48 kWh battery system versus a hot water storage tank. A reference system was developed with storage systems added and simulated for a two year period, with 3-minute intervals. A PV electricity controller was developed. The electrical heater was connected to the controller, switching it on if PV output is larger than building load. The max point temperature was 95 $^\circ$C, with a tank volume of 225 liters. Electricity calculations were based on Levelized cost of energy[3], and showed that

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[3] Levelized cost of energy (LCOE), is a measure of the average net present cost of electricity generation for a generating plant over its lifetime[25]

the battery system proved twice as expensive in terms of LCOE compared to the thermal storage. The authors mention that the LCOE model is not an optimal method for assessing a system's profitability, but rather supplementing with future electricity costs when purchasing or selling. The two systems proved similar self-consumption levels, observing a 32% increase with hot water storage, up to 88%.

Hirvonen, Kayo, Hasan, and Sirén presented a study on thermal storage options in Nordic conditions[5], comparing heat pump to electric heating. The direct electric heating tank consisted of two separate layers, serving different purposes. Domestic hot water taken from the top layer having tank temperature increase to a maximum of 70 °C. The lower part of the tank was used for space heating. The tank sizing used in the study were 300 L. Self-consumption increased from 15% to 70% using direct electric heating. It is important to note that the space heating demand was relatively great in this study, accounting for 54% of total demand. Hot water demand was 17.9%. Additionally, the energy pricing for feed-in tariffs was assumed to be based on Finnish standards and is half the electricity buying price. In another study, looking at optimal system sizing for heat pumps and thermal storage [26], Fischer et al. concluded that integrating PVs on already existing houses does not require an increase in thermal storage size. It is also implied that through overheating of thermal storage, that additional storage capacity is economically viable.

In regards to potential grid constraints, Sharma, Mohan, and Sharma[4] presented a study on the techno-economic performance of BIPV using battery storage under grid constraints as a continuation of previous work on BIPV with battery storage; the results showed that under monthly-fixed and yearly-fixed power contribution from the grid, the PV system with battery storage could perform a better energy throughput. In regards to net present costs (NPC), it was shown to be higher when implemented with energy storage. Furthermore, in reference to policymakers, the demand side should favor high self-consumption when implementing PV. It was also concluded that the BIPV system with energy storage is beneficial both economically and technically when integrated with appropriate energy tariff and control strategies to reduce annualized energy costs. Azmi [2] mentions that through proper energy storage, energy performance could be further increased in regards to grid constraints.

Several studies have been done on utilizing PV power for auxiliary heating using hybrid photovoltaic-thermal systems, implemented with solar thermal collectors. Regarding true PV, studies on energy storage are mostly focused on batteries, not thermal storage[5]. Assumptions made in this work are based on the research articles reviewed.

4.1 Industry development - Danfoss Denmark

With regards to researching thermal storage options and their technical performance, HORFOR (greater Copenhagen utility) district heating was established in Denmark as a demonstration project in 2018. Through district heating and sector coupling, the heat pump on the Flexheat plant supplies three cruise ship terminals and UNICEF warehouse through a thermal boiler. The FlexHeat facility has a heating capacity of 1MW, enabled by the heat pump based on groundwater. The tank is 100 cubic meters and corresponds to a 4 MWh battery. The estimated CO2 savings are 315 tonnes annually[27]. This project highlights the potential of thermal storage and why it is essential for researchers to study its potential usage.

Chapter 5

Role of water heater, thermal storage with BIPV system

This study's general goal is to assess the technical and economic performance of using building-integrated solar panels with thermal storage. In a household, the water heater can be used as a thermal storage option. By controlling of current to the water heater, self-consumption can be increased, and further avoiding load above grid limits. The goal is to charge the water heater during high solar electricity production and distribute the stored energy when demand is high or when the load is approaching grid constraints, thereby reducing the need for grid purchase. A control for the current is designed in the MatLab environment and data based on solar irradiance, and the residential load is used to develop a mathematical model where a profile for monthly-fixed grid constraints is developed based on the residential load profile. A profile based on water draw is designed based on assumptions taken from the literature review. In addition to modeling a building capable of having an energy demand below the grid constraints, the study will investigate if the household is capable of becoming a near zero-energy building. Economic assessments are done based on results from the mathematical model.

5.1 System description

A general overview of the system is shown in figure 5.1. The solar panels are building integrated, but can also be retrofitted on the roof of the building. A solar inverter enables electricity to appliances. Input from the power grid covers the remaining household load, though limited by the subscribed power to the household (grid constraints). The thermal load (water heater) is controlled based on current available from the grid and solar production.

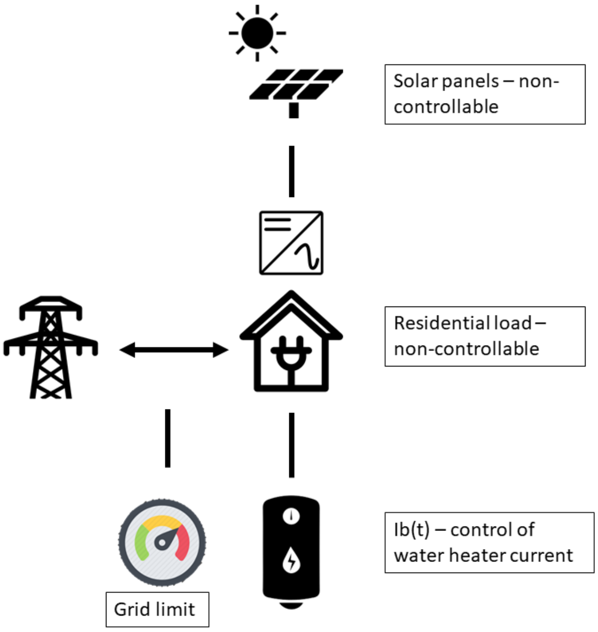

Figure 5.1: Physical system

The grid supplies 230 V AC (alternating current) to the household and receives surplus energy from the PV system. The PV system has a peak capacity of 7.36 kWp. The water heater has a capacity of 300 liters and a 2.5 kW heating element pertaining to four residents.

5.2 Water heater load modeling

This section presents the development of the water heater load model, together with its validation and aggregation to obtain load profiles of the water heating load.

To design a functional controller, a load model for the water heater is developed based on the DR(demand response)-enabled water heating load model by Shao[28]. The load model is used in the mathematical model in MatLab. The water heater temperature is calculated according to equation 5.1[28].

$$\begin{aligned} T_{outlet,i+1} = {} & \frac{T_{outlet,i}(V_{tank} - fr_i \cdot \Delta T)}{V_{tank}} + \frac{T_{inlet} \cdot fr_i \cdot \Delta t}{V_{tank}} \\ & + \frac{1gal}{8.34lb}\left[p_{WH,i} \cdot \frac{3412Btu}{kWh} - \frac{A_{tank} \cdot (T_{outlet} - T_a)}{R_{tank}}\right] \\ & \frac{\Delta t}{V_{tank}} \end{aligned} \tag{5.1}$$

T_{inlet} = Temperature of inlet water (°F)
T_a = Room temperature (°F)
fr_i = Hot water flow rate in time slot i (gpm)
A_{tank} = Surface area of the tank (ft^2)
V_{tank} = Volume of tank (gallons)
R_{tank} = Heat resistance of tank ($^\circ F \cdot ft^2 \cdot h/Btu$)
Δt = duration of each timeslot (minutes)

The power to the EWH is calculated using equation 5.2

$$p_{WH,i} = p_{WH} \cdot WWH_i \tag{5.2}$$

Where WWH_i is the control signal given to the EWH (1 or 0).

The parameters selected for the water heater model is based on assumptions referring to a typical household of 4 residents. One minute resolution is used in the implementation, which is also based on the suggestion made by[17]. Table 5.1 presents a summary of data used in the water heater model, which includes details of the water tank, water temperatures, power consumption, and water usage profile.

Table 5.1: Parameters of water heater

Parameter	Value
T_{max}	157 °F
$T_{WH,s}$	140 °F
T_{low}	120 °F
T_{inlet}	68 °F
T_a	68 °F
fr_i	Appendix
A_{tank}	14 ft^2
V_{tank}	80 *gallons*
R_{tank}	16 °F·$ft^2 \cdot h/Btu$[29]
ΔT	1 *minute*
$P_{WH,max}$	2.5 kW
η	0.80

Where,

T_{max} = Max charge-up temperature
$T_{WH,s}$ = Hot water setpoint temperature
$T_{outlet,i}$ = Outlet water temperature of the tank (Temperature inside tank)
ΔT_{WH} = Minimum temperature of the tank
$W_{WH,i}$ = Status of the water heater in time slot i (minutes)

5.3 Water draw profile

As the power demand of the water heater depends on the usage, a water draw profile for the hot water flow rate is developed. NVE estimates that around 13 % of the energy usage in a household goes to water heating[30]. The usage pattern is assumed to reflect a typical household of 4 residents and is presented in figure 5.2, where $gallons/min$ is used as a reference unit. A 1-minute resolution for the flow rate is used to coincide with the residential load demand profile. Figure 5.3 presents the effects of water draw on the temperature levels of the water heater and its effect on load demand.

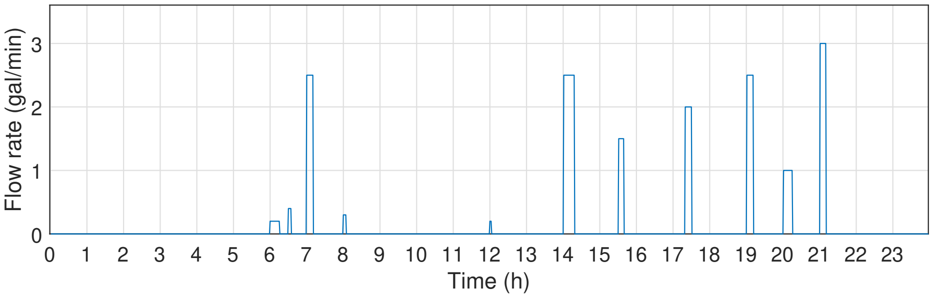

Figure 5.2: Water draw profile for household

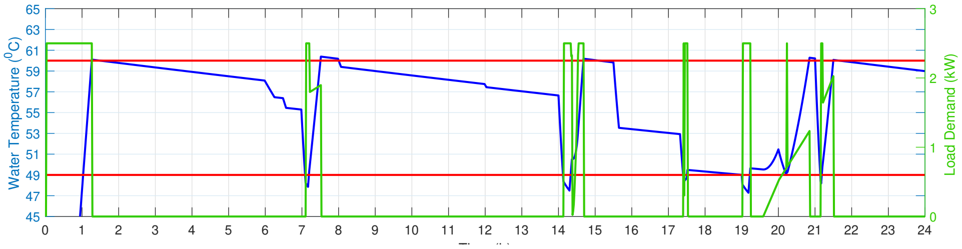

Figure 5.3: Change in temperature due to water draw

5.4 PV production and data refining

The irradiance data used for this thesis is provided by the University of Agder (UiA). Solar panels placed at the roof of UiA is processed in the MatLab environment. The data is updated every minute, but with some variance, meaning that the data may update some seconds before or after. It is therefore converted to fixed 1-minute intervals to be used in accordance with the residential load demand and water draw profile. Technical parameters for the solar panels are based on the performance assessment by Paudyal and Imenes [31]. Table 5.2 (manufactured by Sunpower SPR 230NE-BLK-I) shows the technical parameters from the performance assessment.

Table 5.2: Parameters of PV panels

Peak power Pmpp	225 W (+5%)
Cell efficiency	22.7 %
Panel efficiency	18.5 %
Rated voltage Vmp	29.6.5 V
Rated current Imp	7.61 A
Open-Circuit voltage	36.7 V
Short-Circuit current	8.15 A
Max system voltage	600 V

The yearly solar irradiance W/m^2 can be seen in figure 5.4. Location 58°20'02.0"N 8°34'38.1"E. The PV system is installed on the south-facing roof, with a tilt angle of 39°[31].

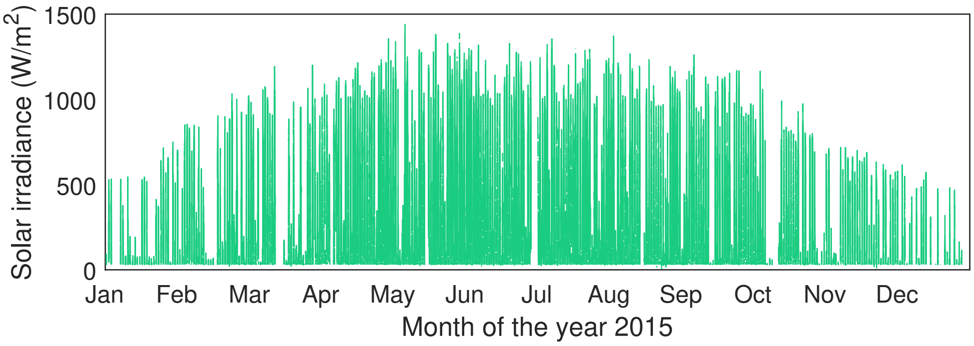

Figure 5.4: Solar irradiance W/m^2 for the year 2015

5.5 Residential load and solar panel configuration

Load data was synthesized in HOMER Grid software specifying typical load profiles included with some randomness. HOMER Grid lets the user choose among different types of load profiles, from residential and commercial to industry and community. A synthetic load based on residential was selected to create an annual load profile for a typical household in the software. An option to select peak month is used and set to January to get cyclic annual variation. To fit the application, the option for "Scaled Annual Average (kWh/day)" is used. Based on a typical Norwegian household minus load demand of the water heater, the kWh/day parameter was set to 37.26. Data from the software is interpolated for minutely values to coincide with the 1-minute resolution of the mathematical model. Figure 5.5 presents the annual load in (kW).

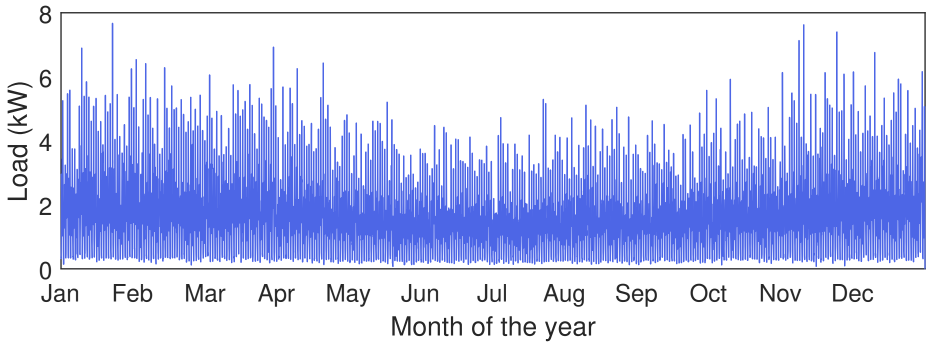

Figure 5.5: Residential load

An overview of the housing parameters are shown in Table 5.3, based on research development by Azmi [2], and Sharma et. Al[4].

Table 5.3: Overview of installed peak capacity and PV production

Usable roof (south facing)			Installed PV			
Lenght (m)	Width (m)	Area (m^2)	Strings	Modules	Module area (m^2)	Capacity (kWp)
12.2	4.7	57.43	2	16	39.9	7.36

The inverter is implemented as part of the system based on the system description in section 5.1 and will present a major factor in the economic assessment. The inverter (INVT - BG7 3-phase[Appendix]) was selected based on the characteristics of the solar panel's max capacity. The inverter[32] is of 3-phase with a maximum efficiency of 98.2%. It has a power rating of 7kW. For ideal operation, the DC voltage range should be between 180-800 for each string. The DC current per MPPT must not exceed Max. DC current.

Table 5.4: Inverter parameters

Parameter	Value
Input (DC) Max. DC voltage (V)	1000
Starting Voltage (V)	200
Min. Operating Voltage	180
MPPT operating voltage range (V) / Rated voltage (V)	(180-800)/610
Rated power voltage range	220-800
Number of MPPT/String per MPPT	2/3
Max DC power (W)	7300
Max. DC current (A) per MPPT · number of MPPT	$19 \cdot 2$
Rated power (W)	7000

The inverter will add to the capital investments when looking at the economic performance of the BIPV. Nevertheless, replacement of inverter might be necessary. In that case, the inverter price of 21500 NOK is included for economic assessment.

5.6 Grid constraints

The utility may impose a grid limit on the household due to energy tariffs based on subscribed power proposed by NVE. This grid limit may be fixed based on month or season. In this work, a proposed grid limit of month-wise fixed is evaluated to study the techno-economic performance of the BIPV. Figure 5.6 presents the monthly fixed grid constraints.

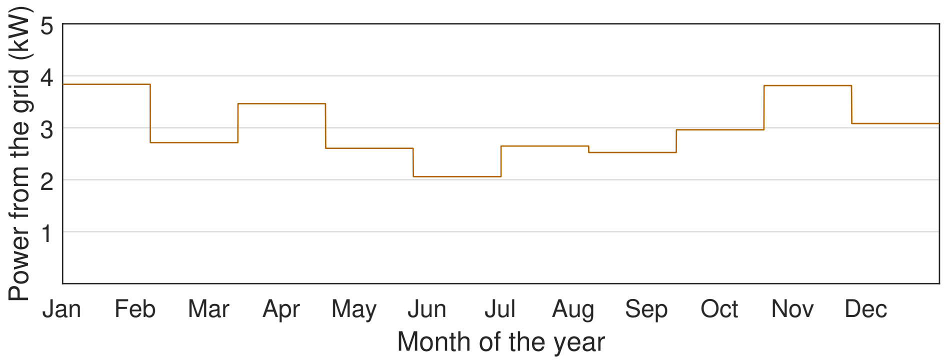

Figure 5.6: Month-wise grid constraints

The monthly-fixed limits are constructed based on the residential load profile, where the monthly values are calculated following the monthly average peak load of the household.

5.7 Energy tariffs

With the reference to the new pricing models proposed by NVE, the energy tariffs are constructed based on their proposal with some assumptions based on geographical location. Table 5.5 presents the proposed model for energy tariffs.

Table 5.5: Cost model for subscribed power

Fixed price	Subscribed power	Energy tariff	Overconsumption tariff
2640 (NOK/year)	643 (NOK/kW limit)	70 (Øre/kWh)	125 (Øre/kWh)

Where subscribed power is assumed based on geographical location of the BIPV system (e.g. Southern-Norway), the energy tariff and overconsumption tariff is based on the proposal from NVE and proposed pricings made in a pilot project by Lyse Nett[33]. The assumed energy tariffs will contribute to the economic assessment. The over-consumption tariff may play a significant factor on the Net present cost of the system over a lifetime. Furthermore, when producing solar power, some energy will be distributed back to the grid. In that regard, the feed-in tariff is assumed to be 50 RE/kWh

5.8 Mathematical model

A mathematical model was developed in a MatLab environment to obtain technical results from the proposed BIPV system with thermal storage. Conditional programming was used to develop the control of water heater. Parameters of the water heater, the residential load, PV production, and grid constraints were implemented in the model. The water heater profile is assumed to be a normal daily usage pattern throughout the year and is therefore repeated for the simulation time. Results from the simulation are presented in the results section to evaluate the techno-economic performance of the system.

5.8.1 Data handling and model validation

Parameters for the load model was set up in the mathematical model. A for loop was constructed in the model, implementing equation 5.1 based on outlet temperature of the water heater. A fixed value for the rated power of EWH is used. To test and validate the load model - simulations were ran with a randomized water draw profile. A simple control of the EWH is implemented where the turn-on signal $WWH_i = 1$ is given when temperature is below the minimum limit T_low and turn-off signal is given $WWH_i = 0$ when the temperature is above maximum limit $T_{WH,s}$.

The irradiance data from Excel was transferred to the MatLab workspace. The data contained minutely values, though not exact - so the values for date and time had to be redefined to mean values over the minute. By analysis of the irradiance data, the years 2014, and 2016-18 proved to have substantial amount of missing data scattered over large timeframes, making it difficult to obtain a realistic yearly irradiance curve without manipulating the data.

The year 2015 showed less data missing and was therefore used in the model. The data for irradiance was used in equation 5.3 to obtain minutely values of PV production of the building.

$$PV_{production} = Irradiance \cdot Area \cdot Panel_{eff} \tag{5.3}$$

Data for the residential load based on average hourly values was initially implemented in the model but proved hard to manipulate and less ideal when using a 1-minute resolution for the simulation. New data sets was then taken from the HOMER Grid software referenced in section 5.5.

As referenced in section 5.1, the thermal load is controlled based on current available from the grid and solar power. The control based on these currents will be discussed in laters sections. To get the power available from the grid - an assumption was made on the behavior of the household-, that over-consumption occurs during peak hours. Therefore, grid constraints was constructed based on the monthly maximum peak. The grid constraints for the proposed household was set to be a fraction of the monthly peak.

Furthermore, the currents for solar, grid and residence were calculated based on the system voltage V_{sys} referenced in section 5.1 and is given by equation 5.4.

$$I = \frac{P}{V} \tag{5.4}$$

Where the value for power P is determined based on the the purpose (e.g solar panels, residence, grid).

5.8.2 Current control

The system model was simulated in 1-minute intervals over a 365 day period to obtain yearly results. Figure 5.7 present a flowchart of the system with control signals and the logic used.

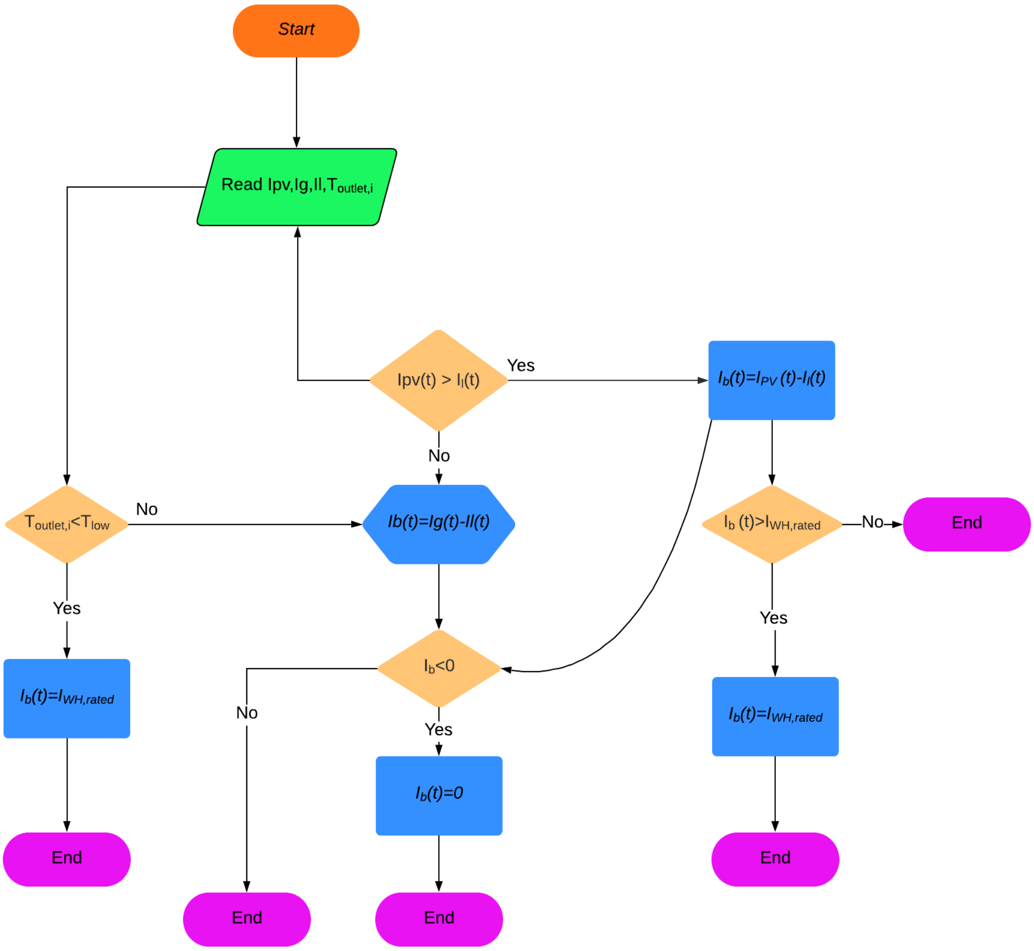

Figure 5.7: Flowchart for current control

If the water heater's outlet temperature is less than the minimum allowable temperature T_{low}, the water heater is set to rated power to maintain a comfortable temperature level. If there is available solar current, $I_{pv}(t) > I_l(t)$ (e.g. Solar supply is higher than load demand), the current available to boiler $I_b(t)$ is the delta ΔI between those currents. At high solar power production, the current available is sometimes above the rated current of the water heater. For this instance, the current is set to rated current. Else, if solar supply is below load demand, the current available to the water heater, $I_b(t)$ is ΔI between the grid constraints and load current. Furthermore, if the current calculation is below zero at any point, the current is set to zero. The current control can also be expressed, as seen in the conditions below.

$$I_{b,i} = \begin{cases} I_l(t) - I_g(t) + I_{PV}(t) & I_{PV}(t) < I_l(t) \\ I_{PV}(t) - I_l(t) & I_{PV}(t) > I_l(t) \\ I_{b,max} & I_b(t) \geq I_{b,max} \\ 0 & I_b(t) < 0 \end{cases} \tag{5.5}$$

5.8.3 Water heater status

Figure 5.8 represents a flowchart for deciding the status of the water heater.

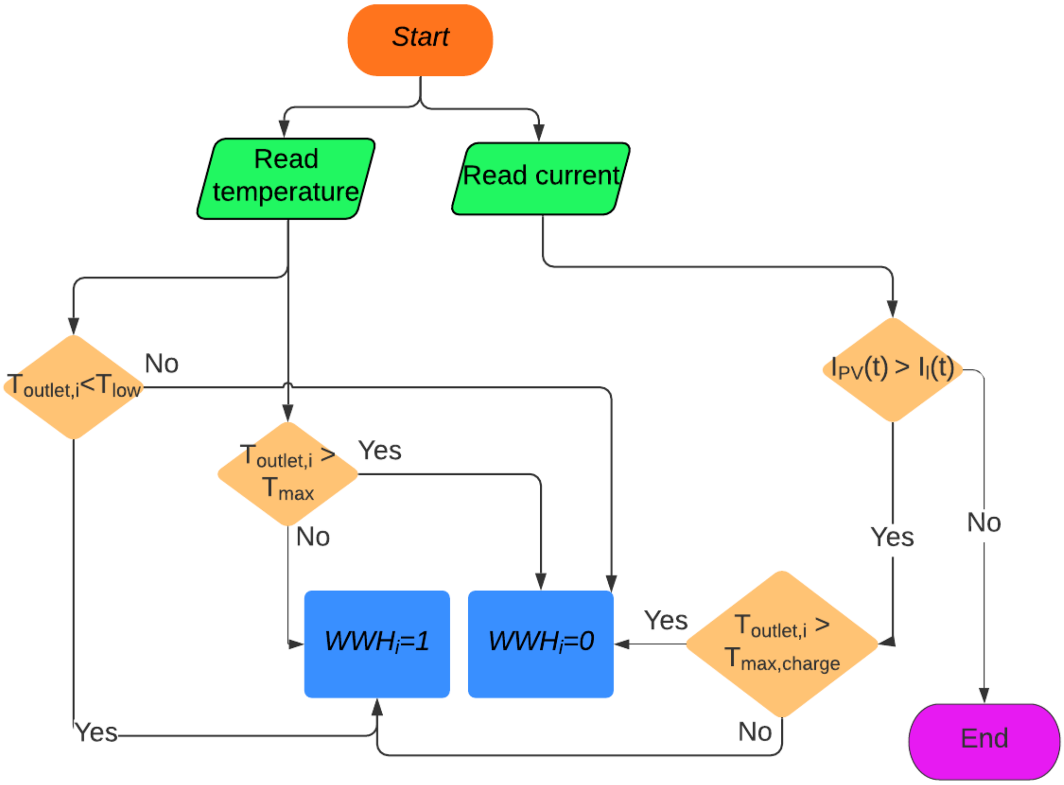

Figure 5.8: Flowchart for water heater status

In the figure, $WWHi = 0$ and $WWHi = 1$ represents the status of the water heater. 0 is off, and 1 being on. $T_{outlet,i}$, the outlet temperature is calculated. If the temperature is below the threshold, the water heater is turned on. For regular operation, if the outlet temperature is above setpoint temperature T_{max}, the water heater is turned off. For charging of water heater, the status is based on available current to the boiler. If there is available solar current after covering the load demand, the water heater is on, until reaching max point temperature for charging $T_{max,charge}$.

Based on the proposed logic in the mathematical model, the grid purchase was calculated using equation 5.6.

$$Grid_{purchase} = Total_{load} - PV_{production} \tag{5.6}$$

Where $Total_{load}$ is the combination of load from the residence added with the load from the water heater. Considering the logic used in the model, the power used by the water heater during charge-up has to be deducted from the equation. Furthermore, at times where solar production is below zero, grid purchase will be negative, therefore set to zero.

Furthermore, to obtain technical results, the power sold to the grid is calculated using equation 5.7.

$$Grid_{sale} = PV_{production} - Total_{load} \tag{5.7}$$

Again, if the value is below zero, the grid purchase is zero. To calculate the self-consumption of the building, equation 5.8

$$Self_{consumption} = \frac{PV_{consumed}}{PV_{production}} \tag{5.8}$$

5.9 Economic assessment

To make an assessment of the economic parameters, results from the technical model in MatLab is used in evaluation. Assumptions based on previous research in the field[[31],[4],[34],[35],[16]] was used and is presented in table 5.6.

Table 5.6: Assumed parameters for economic assessment

Parameter	Value
Future value discount rate (%)	5.5[4]
Electricity price inflation rate (%)	1.9[4]
Operation and maintenance rate (%)	1[34]
Operation and maintenenace cost (NOK)	717.2
Annual output degredation (%)	0.17[31]
System captital investment(NOK)	71782 [36]
Inverter replacement time (years)	15[16]
Inverter replacement cost (NOK)	21500
Operating cost rate (%)	5.5[16]

Excel was used to calculate the indicators for economic assessment based on equations presented in section 3.3. For calculating the operation and maintenance cost, equation 3.5 is used as the discount rate d and operating cost rate e_0 is equal. A lifetime of 25 years to obtain the LCOE value for the system with and without thermal storage. The spreadsheet for calculations is found in Appendix where yearly values for the NPV is found based on equation 3.8.

Chapter 6

Experimental Results

This section introduces the experimental results from the mathematical model. Results will show the technical effect on the technical parameters of the BIPV model. The mathematical model is simulated for an entire year, with minutely iteration. Economic assessment will be based on the results gathered from the system model.

6.1 Effects of charging on water heater temperature and power demand - control validation

For a typical day with PV production, the BIPV system utilizes surplus energy to charge the water heater. The daily profile for water heater charging is presented in figure 6.1. According to the methodology presented in Chapter chapter 5, to maximize the use of solar power, the tank temperature is increased during high PV production.

The figure includes start-up of the water heater occurring at 00:00 in the morning, displaying a rated power demand at this time. The water heater is fully charged to the set-point temperature at 01:15 AM. Stand-by losses are evident by the slight decrease in temperature from 01:15 to 06:00. At 06:00 the first water draw occurs based on figure 5.2, with a flow rate of 0.2 $gallons/min$ for 16 minutes. At 06:30 the next water draw occurs with a flow rate of 0.4 $gallons/min$ for a duration of 5 minutes. Two more water draws occurs resulting in a drop of water temperature below the minimum limit T_{min}. Based on the controller logic, the grid is now forced to supply the water heater with rated power, resulting in a spike in load demand. At 09:00 the solar cells are producing surplus power. The tank temperature is now increasing based on the surplus PV production, reaching a the maximum temperature T_{max} of 70 degrees at at 09:30. Additional water draws occur throughout the day, however, the surplus PV production upholds the water temperature during this period. At time 17:15, additional water draw of 2 $gallons/min$ for a duration of 12 minutes occurs.

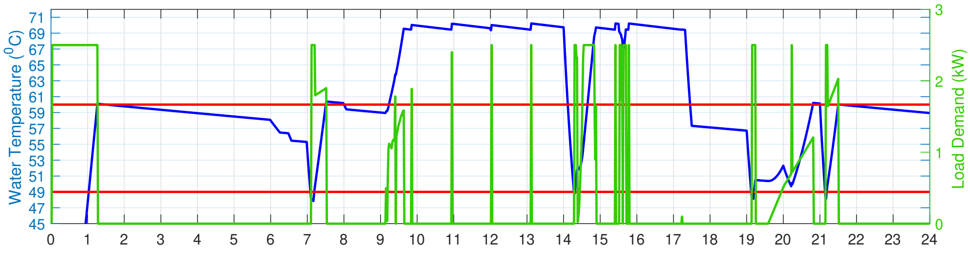

Figure 6.1: Temperature and load demand of water heater in charging mode

6.2 Effect on grid purchase

To analyze the performance of the BIPV system with thermal storage, the difference in grid purchase with and without thermal storage is evaluated. It has been assumed in this work, that the system operator is imposing a month-wise maximum grid supply limit. Therefore, it is interesting to analyse the grid contributions with month-wise limits. Figure 6.2 and figure 6.3 presents the annual electricity purchased from the grid.

The figures shows minutely values of grid purchase. It can be seen that the grid purchase is mostly kept below the the grid constraints presented in figure 5.6. It is also noticeable that there are spikes in grid purchase extending above the grid constraints. Furthermore, analysis shows the water heater load is also contributing to electricity over-consumption.

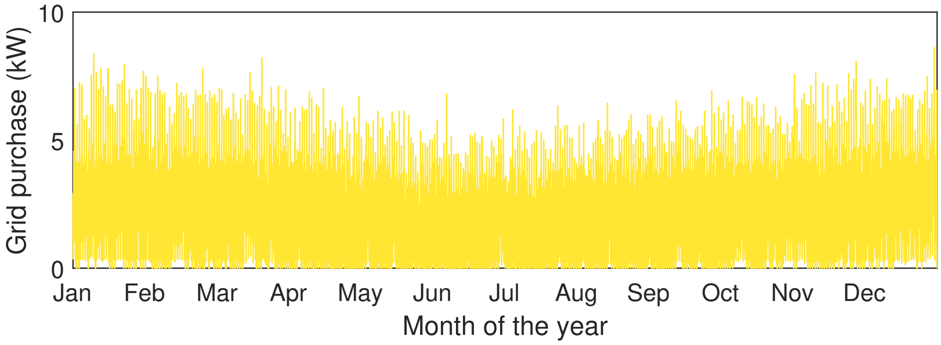

Figure 6.2: Grid purchase without thermal storage

Figure 6.3 presents the grid purchase when the system is implemented with thermal storage. Noticeable from the figure, is that there are less spikes in grid purchase during summer months due and the overall power purchased from the grid is lower.

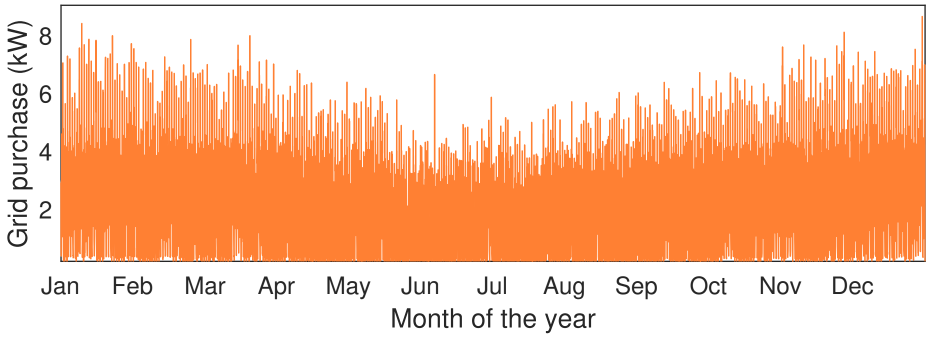

Figure 6.3: Grid purchase with thermal storage

Table 6.1 presents the technical indicators of the system. The implications of the results will be further discussed in chapter 7

Table 6.1: Resulting grid purchase and over-consumption

	Storage	No storage
Overconsumption (kWh)	613.93	692.25
Grid purchase (MWh)	10.58	10.74
Percentage overconsumption (%)	5.79	6.44

6.3 Effect on grid sale

As referenced in Background, when PV production is in surplus, the energy is transferred to the grid (grid sale). For the end-user, excess solar energy is bought by the utility, usually at a lower price, due to low power demand at these times. Therefore, storing energy becomes more beneficial both for the end-user and the utility, so it can be distributed at a later time. Therefore, impact on the feed-in electricity is important to assess.

Figure 6.4 presents the grid sale with and without energy storage for the entire year. Evident by the figure is that the grid sale is decreased using thermal storage. Analysis of the results shows that when having a storage option of water heater, 2.99 MWh is sold back to the grid. Without the storage, the grid sale is 3.27 MWh.

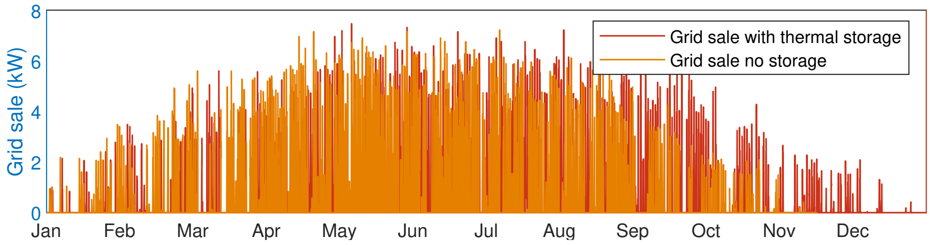

Figure 6.4: Grid sale

6.4 Effects on self-consumption and load shifting

Load shifting is referenced in section 1.1 for reducing stress on the grid during peak hours and also decrease the electricity bill. One of the main reasons for thermal storage implementation is to shift the thermal load to off-peak hours, thereby reducing the electricity bill. Results taken from the mathematical model is presented in table6.2.

Table 6.2: Self-consumption and peak overload

	With storage	Without storage
Self-consumption (%)	57.44	53.49
Peak overload(kWh)	242.6	314.5

It can be seen from the table that the self-consumption is increased by 3.95 %. The peak overload, - load comsumed above grid constraints during peak hours is decreased with 51 kWh when implementing thermal storage.

6.5 Economic assessment

For assessing the economic performance of the BIPV under grid constraints, the solar panels and inverter is assumed to be included in the capital investment. The economic assessment is based on energy pricing referenced in chapter 5 to calculate the yearly electricity bill. According to the energy tariffs the grid limit plays a major role in electricity pricing. Grid sale together will grid purchase and the overloading of grid limits will determine if the energy bill is decreased and whether or not the storage option has any effects on the yearly bill.

The Excel spreadsheet found in Appendix is used to calculate the economic parameters. Table presents the economic indicators for performance assessment.

Table 6.3: Economic indicators

	Storage	No storage
Net present cost	33541 NOK	34582 NOK
LCOE	1.136	1.207
Total annualized cost	1913 NOK	2105 NOK

Results from the mathematical model show that annually, a total of 488.5 kWh is load above the grid constraints. Comparing this results with the total grid purchase throughout the year of 10.8 MWh, the calculations show that 4.52% of grid purchase is above the grid constraints.

Analysis shows there is a slight decrease in grid purchase using the water heater. When applying the storage option, the yearly grid purchase is lowered with 300 kWh. This will contribute to lowering the energy bill for the end-user. With reference to the grid constraints, it should be noted that without storage option, the load demand peak is considerably higher which is causing the load to more frequently reach above the grid constraints.

Chapter 7

Discussion

This section presents the discussion on the techno-economic perforamance of the BIPV system with thermal storage. Results based on the difference in technical and economic indicators of the system with and without storage is evaluated in reference to the research questions presented in chapter 2.

One of the main objectives for this work was to compare the different storage options in a Nordic environment. In chapter 4, we reviewed several studies on the techno-economic analysis of BIPV systems. With reference to self-consumption in Sweden, Thygesen and Karlsson[24] saw an increase in self-consumption of 32%, up to 88%. The system studied in the present work, saw an increase of 4%. A large discrepancy is seen between the two systems. Most likely, this is due to a larger thermal load demanded by the water heater, whereas in the present case, the water heater demand was 13% of the total load. Furthermore, the maximum charge up temperature level used in the controller was 95°C, compared to 70°C, which also cause a larger increase in thermal energy potential.

Hirvonen et al.[5] used 300 litres and a temperature max limit of 70 °C, similar parameters to the present study. They saw a large increase in self-consumption from 15% to 70%. It is important to note that the water heater also distributed energy for space heating, having a load demand accounting for 54%, as opposed to the present study, where only 13% of total demand is assumed for the water heater.

According to Willams et al[22] self-consumption percentage is critically dependant on tank volume. The same study saw an increase from 55% to 65% using heat pump and storage. In comparing the tank volumes, there is a significant difference (300 litres cs 1000 litres), indicating that a larger tank size would increase the self-consumption of the system in this work.

With regards to peak overload, a 23% decrease was seen using thermal storage. According to Williams et al. [22] This value may be further decreased, when implemented with ”delayed charging” to higher prevailing irradiation months, May to September.

By reviewing the economic results, a decrease was seen for all the economic indicators, using thermal storage. The LCOE with thermal storage was lower that without storage. In comparison, Mohan et al saw an LCOE of 1.17 NOK/kWh under monthly-fixed grid limits, where capital investment of battery was considered and a system time of 10 year. In the economic analysis, the present study found a LCOE of 1.136 NOK/kWh, though a higher capital investment was assumed and a system time of 25 years.

Furthermore, the economic performance of BIPV with energy storage system mainly depends on the assumptions associated with PV and battery costs, as mentioned by Sharma et al. [3]. Moreover, Baniasadi et al.[23] studied the optimal tank size in regards to economic indicators, proving that a tank size of 1000-2000 would achieve the best results when looking at economic indicators.

In regards to feed-in tariffs, the studies reviewed varied in pricing, from twice the price of grid purchase to half the price, indicating that assumption on pricing may distort results. Although, as seen in [20], the IRR does not correlate with electricity pricing in a linear way, suggesting that assumption based on tariffs may not have a significant impact the resulting economics. On the other hard, Linssen et. Al[17] remarks that development of electricity pricing is a sensitive parameter regarding modelling, and that assumptions of a constant energy pricing increase can lead to large uncertainties.

Ultimately the goal of the thermal storage is to lower the congestion on the grid. For the end user, a decrease in grid purchase and and increased self-consumption will contribute to lowering the energy bill as seen in this study.

Chapter 8

Conclusion

For penetration of renewable energy, there are still issues facing a massive takeover, namely the need for quick, efficient balancing generators running on fossil fuels. A key component to reduce the need for these balancing units are efficient storage options. Large battery storage options and smart grids can contribute to less cycling of coal plants, but by making households less reliant on grid supply through efficient use of storage, the grid supply may also be reduced during peak load periods. Therefore, the research on finding the appropriate energy storage for buildings is of importance. By utilizing already existing components for storage, such as water heaters, the self-consumption may increase, and reliance on the grid reduced.

This study investigated the techno-economic effects of implementing thermal storage. Future grid tariffs based on subscribed power was also considered. Based on technical parameters, a decrease in power purchased from the grid and grid sale was seen. The system self-consumption was also increased when implemented with thermal storage. Furthermore, the economic indicators show that the Levelized cost of energy decreased with 7 ØRE/kWh. In regards to the electricity bill, the net present cost of the system was lower when the electricity bill was based on subscribed power.

There is research done on the effectiveness of thermal storage, but geographical conditions will vary in regards to the appropriate storage option. Therefore it is essential to investigate the effects of thermal storage considering grid constraints and battery storage in Nordic areas. Although the thermal storage will charge during high PV production, the issue becomes how well it distributes across the day compared to a battery with dispatchable demand. Tough, the study showed that load shifting is possible using thermal storage, observing a 23% decrease in peak overload compared to no storage.

The system developed in this work assumed that the hot water load demand is 13%. Based on previous research reviewed, a more significant load demand and an increase in tank volume and temperature can further enhance the self-consumption of BIPV systems. In regards to a typical household integrated with solar panels, a small retrofit by opting for a change-up of electric water heater can contribute to lowering the energy bill, and in return, reduce the LCOE.

The overall intermittency of the load and the PV production can be overcome through efficient energy storage of BIPV systems. Energy storage can also assist in demand-side management and help in strengthening the system stability.

Chapter 9

Future work

BIPV systems with thermal storage should be further researched for Nordic areas. Researchers should look to increase the self-consumption and decrease the LCOE. Studies focused on a typical household should look at increasing tank temperature further above the max limit in combination with space heating. A combination system using thermal and battery storage should also be investigated to further increase the economic attractiveness of BIPV systems and to reduce LCOE.

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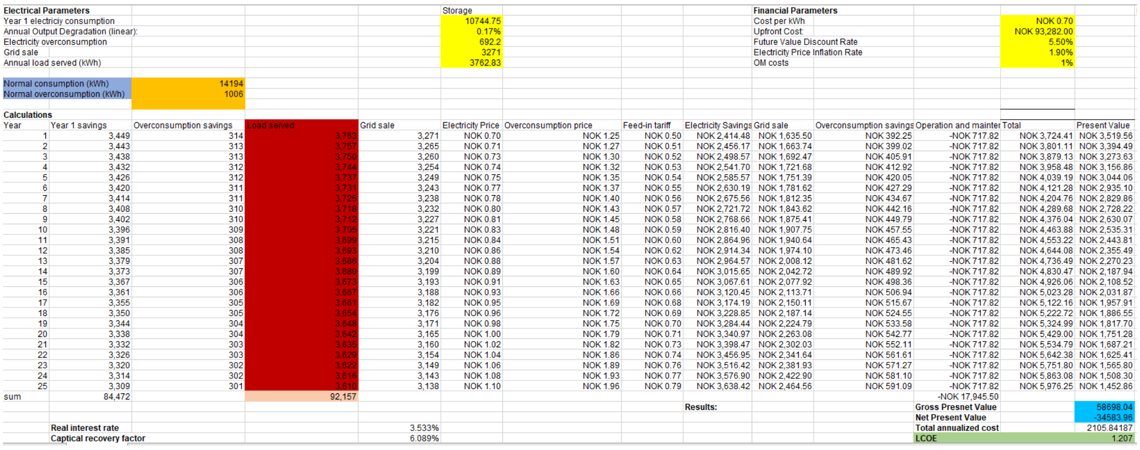
Appendix A

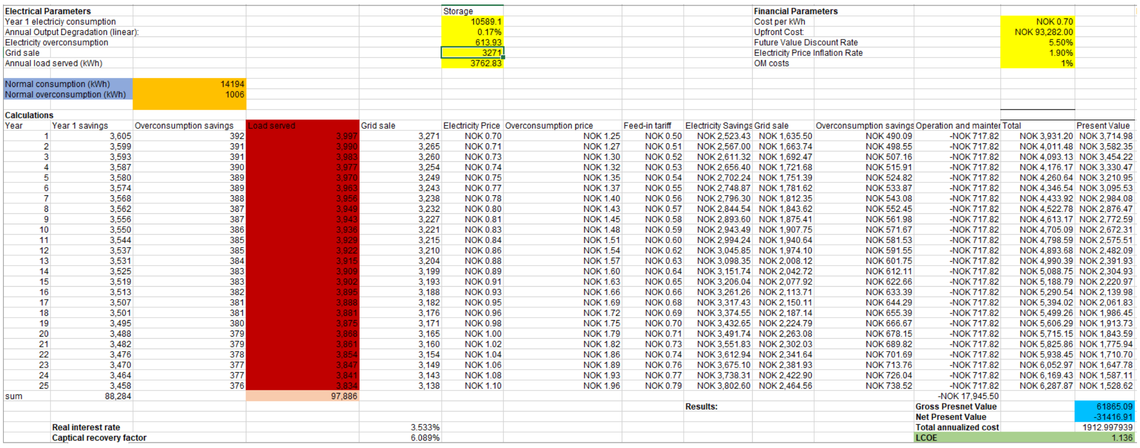
Appendix A

A.1 Excel worksheet



Electrical Parameters					Storage				**Financial Parameters**				
Year 1 electriciy consumption					10744.75				Cost per kWh			NOK 0.70	
Annual Output Degradation (linear):					0.17%				Upfront Cost:			NOK 93,282.00	
Electricity overconsumption					692.2				Future Value Discount Rate			5.50%	
Grid sale					3271				Electricity Price Inflation Rate			1.90%	
Annual load served (kWh)					3762.83				OM costs			1%	
Normal consumption (kWh)		14194											
Normal overconsumption (kWh)		1006											
Calculations													
Year	Year 1 savings	Overconsumption savings	Load served	Grid sale	Electricity Price	Overconsumption price	Feed-in tariff	Electricity Savings	Grid sale	Overconsumption savings	Operation and mainter	Total	Present Value
1	3,449	314	3,763	3,271	NOK 0.70	NOK 1.25	NOK 0.50	NOK 2,414.48	NOK 1,635.50	NOK 392.25	-NOK 717.82	NOK 3,724.41	NOK 3,519.56
2	3,443	313	3,757	3,265	NOK 0.71	NOK 1.27	NOK 0.51	NOK 2,456.17	NOK 1,663.74	NOK 399.02	-NOK 717.82	NOK 3,801.11	NOK 3,394.49
3	3,438	313	3,750	3,260	NOK 0.73	NOK 1.30	NOK 0.52	NOK 2,498.57	NOK 1,692.47	NOK 405.91	-NOK 717.82	NOK 3,879.13	NOK 3,273.63
4	3,432	312	3,744	3,254	NOK 0.74	NOK 1.32	NOK 0.53	NOK 2,541.70	NOK 1,721.68	NOK 412.92	-NOK 717.82	NOK 3,958.48	NOK 3,156.86
5	3,426	312	3,737	3,249	NOK 0.75	NOK 1.35	NOK 0.54	NOK 2,585.57	NOK 1,751.39	NOK 420.05	-NOK 717.82	NOK 4,039.19	NOK 3,044.06
6	3,420	311	3,731	3,243	NOK 0.77	NOK 1.37	NOK 0.55	NOK 2,630.19	NOK 1,781.62	NOK 427.29	-NOK 717.82	NOK 4,121.28	NOK 2,935.10
7	3,414	311	3,725	3,238	NOK 0.78	NOK 1.40	NOK 0.56	NOK 2,675.56	NOK 1,812.35	NOK 434.67	-NOK 717.82	NOK 4,204.76	NOK 2,829.86
8	3,408	310	3,718	3,232	NOK 0.80	NOK 1.43	NOK 0.57	NOK 2,721.72	NOK 1,843.62	NOK 442.16	-NOK 717.82	NOK 4,289.68	NOK 2,728.22
9	3,402	310	3,712	3,227	NOK 0.81	NOK 1.45	NOK 0.58	NOK 2,768.66	NOK 1,875.41	NOK 449.79	-NOK 717.82	NOK 4,376.04	NOK 2,630.07
10	3,396	309	3,705	3,221	NOK 0.83	NOK 1.48	NOK 0.59	NOK 2,816.40	NOK 1,907.75	NOK 457.55	-NOK 717.82	NOK 4,463.88	NOK 2,535.31
11	3,391	308	3,699	3,215	NOK 0.84	NOK 1.51	NOK 0.60	NOK 2,864.96	NOK 1,940.64	NOK 465.43	-NOK 717.82	NOK 4,553.22	NOK 2,443.81
12	3,385	308	3,693	3,210	NOK 0.86	NOK 1.54	NOK 0.62	NOK 2,914.34	NOK 1,974.10	NOK 473.46	-NOK 717.82	NOK 4,644.08	NOK 2,355.49
13	3,379	307	3,686	3,204	NOK 0.88	NOK 1.57	NOK 0.63	NOK 2,964.57	NOK 2,008.12	NOK 481.62	-NOK 717.82	NOK 4,736.49	NOK 2,270.23
14	3,373	307	3,680	3,199	NOK 0.89	NOK 1.60	NOK 0.64	NOK 3,015.65	NOK 2,042.72	NOK 489.92	-NOK 717.82	NOK 4,830.47	NOK 2,187.94
15	3,367	306	3,673	3,193	NOK 0.91	NOK 1.63	NOK 0.65	NOK 3,067.61	NOK 2,077.92	NOK 498.36	-NOK 717.82	NOK 4,926.06	NOK 2,108.52
16	3,361	306	3,667	3,188	NOK 0.93	NOK 1.66	NOK 0.66	NOK 3,120.45	NOK 2,113.71	NOK 506.94	-NOK 717.82	NOK 5,023.28	NOK 2,031.87
17	3,355	305	3,661	3,182	NOK 0.95	NOK 1.69	NOK 0.68	NOK 3,174.19	NOK 2,150.11	NOK 515.67	-NOK 717.82	NOK 5,122.16	NOK 1,957.91
18	3,350	305	3,654	3,176	NOK 0.96	NOK 1.72	NOK 0.69	NOK 3,228.85	NOK 2,187.14	NOK 524.55	-NOK 717.82	NOK 5,222.72	NOK 1,886.55
19	3,344	304	3,648	3,171	NOK 0.98	NOK 1.75	NOK 0.70	NOK 3,284.44	NOK 2,224.79	NOK 533.58	-NOK 717.82	NOK 5,324.99	NOK 1,817.70
20	3,338	304	3,642	3,165	NOK 1.00	NOK 1.79	NOK 0.71	NOK 3,340.97	NOK 2,263.08	NOK 542.77	-NOK 717.82	NOK 5,429.00	NOK 1,751.28
21	3,332	303	3,635	3,160	NOK 1.02	NOK 1.82	NOK 0.73	NOK 3,398.47	NOK 2,302.03	NOK 552.11	-NOK 717.82	NOK 5,534.79	NOK 1,687.21
22	3,326	303	3,629	3,154	NOK 1.04	NOK 1.86	NOK 0.74	NOK 3,456.95	NOK 2,341.64	NOK 561.61	-NOK 717.82	NOK 5,642.38	NOK 1,625.41
23	3,320	302	3,622	3,149	NOK 1.06	NOK 1.89	NOK 0.76	NOK 3,516.42	NOK 2,381.93	NOK 571.27	-NOK 717.82	NOK 5,751.80	NOK 1,565.80
24	3,314	302	3,616	3,143	NOK 1.08	NOK 1.93	NOK 0.77	NOK 3,576.90	NOK 2,422.90	NOK 581.10	-NOK 717.82	NOK 5,863.08	NOK 1,508.30
25	3,309	301	3,610	3,138	NOK 1.10	NOK 1.96	NOK 0.79	NOK 3,638.42	NOK 2,464.56	NOK 591.09	-NOK 717.82	NOK 5,976.25	NOK 1,452.86
sum	84,472		92,157								-NOK 17,945.50		
								Results:			**Gross Presnet Value**		58698.04
											Net Present Value		-34583.96
	Real interest rate			3.533%							**Total annualized cost**		2105.84187
	Captical recovery factor			6.089%							**LCOE**		1.207

Figure A.1: No storage



Electrical Parameters					Storage				**Financial Parameters**				
Year 1 electriciy consumption					10589.1				Cost per kWh			NOK 0.70	
Annual Output Degradation (linear):					0.17%				Upfront Cost:			NOK 93,282.00	
Electricity overconsumption					613.93				Future Value Discount Rate			5.50%	
Grid sale					3271				Electricity Price Inflation Rate			1.90%	
Annual load served (kWh)					3762.83				OM costs			1%	
Normal consumption (kWh)		14194											
Normal overconsumption (kWh)		1006											
Calculations													
Year	Year 1 savings	Overconsumption savings	Load served	Grid sale	Electricity Price	Overconsumption price	Feed-in tariff	Electricity Savings	Grid sale	Overconsumption savings	Operation and mainter	Total	Present Value
1	3,605	392	3,997	3,271	NOK 0.70	NOK 1.25	NOK 0.50	NOK 2,523.43	NOK 1,635.50	NOK 490.09	-NOK 717.82	NOK 3,931.20	NOK 3,714.98
2	3,599	391	3,990	3,265	NOK 0.71	NOK 1.27	NOK 0.51	NOK 2,567.00	NOK 1,663.74	NOK 498.55	-NOK 717.82	NOK 4,011.48	NOK 3,582.35
3	3,593	391	3,983	3,260	NOK 0.73	NOK 1.30	NOK 0.52	NOK 2,611.32	NOK 1,692.47	NOK 507.16	-NOK 717.82	NOK 4,093.13	NOK 3,454.22
4	3,587	390	3,977	3,254	NOK 0.74	NOK 1.32	NOK 0.53	NOK 2,656.40	NOK 1,721.68	NOK 515.91	-NOK 717.82	NOK 4,176.17	NOK 3,330.47
5	3,580	389	3,970	3,249	NOK 0.75	NOK 1.35	NOK 0.54	NOK 2,702.24	NOK 1,751.39	NOK 524.82	-NOK 717.82	NOK 4,260.64	NOK 3,210.95
6	3,574	389	3,963	3,243	NOK 0.77	NOK 1.37	NOK 0.55	NOK 2,748.87	NOK 1,781.62	NOK 533.87	-NOK 717.82	NOK 4,346.54	NOK 3,095.53
7	3,568	388	3,956	3,238	NOK 0.78	NOK 1.40	NOK 0.56	NOK 2,796.30	NOK 1,812.35	NOK 543.08	-NOK 717.82	NOK 4,433.92	NOK 2,984.08
8	3,562	387	3,949	3,232	NOK 0.80	NOK 1.43	NOK 0.57	NOK 2,844.54	NOK 1,843.62	NOK 552.45	-NOK 717.82	NOK 4,522.78	NOK 2,876.47
9	3,556	387	3,943	3,227	NOK 0.81	NOK 1.45	NOK 0.58	NOK 2,893.60	NOK 1,875.41	NOK 561.98	-NOK 717.82	NOK 4,613.17	NOK 2,772.59
10	3,550	386	3,936	3,221	NOK 0.83	NOK 1.48	NOK 0.59	NOK 2,943.49	NOK 1,907.75	NOK 571.67	-NOK 717.82	NOK 4,705.09	NOK 2,672.31
11	3,544	385	3,929	3,215	NOK 0.84	NOK 1.51	NOK 0.60	NOK 2,994.24	NOK 1,940.64	NOK 581.53	-NOK 717.82	NOK 4,798.59	NOK 2,575.51
12	3,537	385	3,922	3,210	NOK 0.86	NOK 1.54	NOK 0.62	NOK 3,045.85	NOK 1,974.10	NOK 591.55	-NOK 717.82	NOK 4,893.68	NOK 2,482.09
13	3,531	384	3,915	3,204	NOK 0.88	NOK 1.57	NOK 0.63	NOK 3,098.35	NOK 2,008.12	NOK 601.75	-NOK 717.82	NOK 4,990.39	NOK 2,391.93
14	3,525	383	3,909	3,199	NOK 0.89	NOK 1.60	NOK 0.64	NOK 3,151.74	NOK 2,042.72	NOK 612.11	-NOK 717.82	NOK 5,088.75	NOK 2,304.93
15	3,519	383	3,902	3,193	NOK 0.91	NOK 1.63	NOK 0.65	NOK 3,206.04	NOK 2,077.92	NOK 622.66	-NOK 717.82	NOK 5,188.79	NOK 2,220.97
16	3,513	382	3,895	3,188	NOK 0.93	NOK 1.66	NOK 0.66	NOK 3,261.26	NOK 2,113.71	NOK 633.39	-NOK 717.82	NOK 5,290.54	NOK 2,139.98
17	3,507	381	3,888	3,182	NOK 0.95	NOK 1.69	NOK 0.68	NOK 3,317.43	NOK 2,150.11	NOK 644.29	-NOK 717.82	NOK 5,394.02	NOK 2,061.83
18	3,501	381	3,881	3,176	NOK 0.96	NOK 1.72	NOK 0.69	NOK 3,374.55	NOK 2,187.14	NOK 655.39	-NOK 717.82	NOK 5,499.26	NOK 1,986.45
19	3,495	380	3,875	3,171	NOK 0.98	NOK 1.75	NOK 0.70	NOK 3,432.65	NOK 2,224.79	NOK 666.67	-NOK 717.82	NOK 5,606.29	NOK 1,913.73
20	3,488	379	3,868	3,165	NOK 1.00	NOK 1.79	NOK 0.71	NOK 3,491.74	NOK 2,263.08	NOK 678.15	-NOK 717.82	NOK 5,715.15	NOK 1,843.59
21	3,482	379	3,861	3,160	NOK 1.02	NOK 1.82	NOK 0.73	NOK 3,551.83	NOK 2,302.03	NOK 689.82	-NOK 717.82	NOK 5,825.86	NOK 1,775.94
22	3,476	378	3,854	3,154	NOK 1.04	NOK 1.86	NOK 0.74	NOK 3,612.94	NOK 2,341.64	NOK 701.69	-NOK 717.82	NOK 5,938.45	NOK 1,710.70
23	3,470	377	3,847	3,149	NOK 1.06	NOK 1.89	NOK 0.76	NOK 3,675.10	NOK 2,381.93	NOK 713.76	-NOK 717.82	NOK 6,052.97	NOK 1,647.78
24	3,464	377	3,841	3,143	NOK 1.08	NOK 1.93	NOK 0.77	NOK 3,738.31	NOK 2,422.90	NOK 726.04	-NOK 717.82	NOK 6,169.43	NOK 1,587.11
25	3,458	376	3,834	3,138	NOK 1.10	NOK 1.96	NOK 0.79	NOK 3,802.60	NOK 2,464.56	NOK 738.52	-NOK 717.82	NOK 6,287.87	NOK 1,528.62
sum	88,284		97,886								-NOK 17,945.50		
								Results:			**Gross Presnet Value**		61865.09
											Net Present Value		-31416.91
	Real interest rate			3.533%							**Total annualized cost**		1912.997939
	Captical recovery factor			6.089%							**LCOE**		1.136

Figure A.2: With storage

When including the cost of PV system in the mortgage it was found that a annual loan price of 1631 NOK is needed for break-even investment. In this case, the inverter is also replaced after 15 years.

A.2 MatLab script

```
%% Heater model
V_tank=80; %volume of the tank in gallons
%fr=xlsread;%water usage in gallons per minute
T_inlet1=20; %inlet water temperature in Celsius
T_inlet=(T_inlet1*9/5)+32; %conversion to Fahrenheit
%P_WH=4; %power consumption of water heater
A_tank=14; %surface area of the tank
R_tank=16; %heat resistance of the tank
Ts1_WH=60; %water temperature set point_Celsius
Ts_WH=(Ts1_WH*9/5)+32; %conversion to Fahrenheit
T_outlet_i1=1; %initial temperature water_ Celsius
T_outlet_i=(T_outlet_i1*9/5)+32; %conversion to Fahrenheit
T_outlet_i2=(T_outlet_i1*9/5)+32;
eff_WH=0.8; %efficiency of the water heater
Delta_Temp_WH=11; %allowable temperature band_ Celsius
Temp_low1=Ts1_WH-Delta_Temp_WH; %lower limit of water temperature
Temp_low=(Temp_low1*9/5)+32; %conversion to Fahrenheit
Ta1=20; % Ambient temperature in Celsius
Ta=(Ta1*9/5)+32; %convert to Fahrenheit
IWH_rated=2500/230; %Rated current of water heater
%% Residential load
V_sys=230*10^-3; %System voltage
%---Interpolate for minutely values----%
g1=1:60:8760*60;
gi=1:1:8760*60;
Load1=readmatrix('37.26kWh.txt.xlsx'); % Read data for residential load
Total_Load=interp1(g1,Load1,gi); %Interpolate for minutely values
Total_Load(isnan(Total_Load))=0; % Convert NaN to 0
I_l=Total_Load/V_sys; % Load current


a1=findpeaks(I_l, 'MinPeakDistance',43200); % Find peaks interval -> monthly
d=52560;
a2=reshape(repmat(a1,d,1),1,[]);
I_g=a2/2;  %Grid limit half of monthly max
%% Solar
P_max=230; % peak power (W)
Cell_eff = 22.7; % Cell efficiency (%)
Panel_eff = 18.5; % Panel efficiency (%)
V_rated = 40.5; % Rated voltage (V) Vmpp
I_rated = 5.68; % Rated current (A) Impp
V_oc = 48.2; % Open circuit voltage (V)
I_sc = 6.05; % Short circuit current (I)
V_max = 600; % Max system voltage (V)
Area = 32.5; % Area of solar panels
```

```
%aggregate timetable data (for future)

%—————————Daily solar irradiation—————%
TT = table2timetable(Irradiance); % Timetable
output=retime(TT,'daily', 'mean'); % Daily mean irradiance
newTimes = [datetime('2015—01—01⍰00:00:00'):minutes(1):datetime('2015—⍰⍰12—
31⍰23:59:00')]; % Time interval
TT2 = retime(TT,newTimes,'mean'); % Mean irradiance over time interval
Table = timetable2table(TT2(:,1)); % Convert to table
SolarIrradiance = table2array(TT2); % Solar irradiance daily (minutely) m^2
PV_prod=SolarIrradiance*Area*Panel_eff*10^—2*10^—3;
% Solar production for household

%PV_prod = 0.5 * (fillmissing(PV_prod1, 'previous') + fillmissing(PV_prod1, 'ne
PV_prod(isnan(PV_prod))=0; % convert NaN to 0
I_PV=PV_prod/(V_sys); % PV current

%% Pricing solar
Install_cost=102309; %cost of installing (kr)
Operating_cost=102309*0.02; % Operating cost 2% of install cost
Lifetime=25; %Lifetime of solar panels in years
%% Initial values
fr=readmatrix('gpm.xlsx'); % GPM in time slot i
fr_1=fr(:,2); % read all rows column 2
fr_i=repmat(fr_1,365,1);    % Repeat matrix for 365 days


i=1;    %Initial value
charge=0; %Initial value
delta_T=1/60; % MInute
%P_WHi = zeros(1,1440);
WWHi=0; %Initial value
WWHi_1=0; %Initial value
for i = 1:1:525600 %Minutely iteration (year)


    I_b(i)=I_g(i)—I_l(i); % Current available to Water heater

    if I_PV(i)>I_l(i)             % If PV current is larger than load
       I_b(i)=I_PV(i)—I_l(i);
       % Current available to boiler — Excess current after load
    end
    if I_b(i)>IWH_rated      % If current is above rated current
       I_b(i)=IWH_rated;     % Current is rated current
    end
```

```
if T_outlet_i<Temp_low  % If Outlet temp exceeds lower temp
   I_b(i)=IWH_rated;    % WH is charged with rated current
end
if T_outlet_i2<Temp_low % If outlet temp exceeds lower temp (no charge)
   I_b(i)=IWH_rated;    % WH is charged with rated current
end
if I_b(i)<0
    % If current available to water heater is below zero
    I_b(i)=0;           % Current is zero
end



P_WH=I_b(i)*V_sys;
% Power to the water heater - current times system voltage
P_WHi=P_WH*WWHi;
% Power to water heater in time slot i - Power times WH status
P_WHi_1=P_WH*WWHi_1;
% Power to water heater in time slot i - no charging power

WH_charge(i)=P_WH*charge; %Charged power

 T_outlet=(T_outlet_i.*(V_tank-fr_i(i)*1)+(T_inlet*fr_i(i)*1))/(V_tank)
 +1/60*(P_WHi*eff_WH*3412-(A_tank*(T_outlet_i-Ta)/R_tank))/V_tank;
 T_outlet_i=T_outlet;   % Update outlet temperature


T_outlet1=(T_outlet_i2.*(V_tank-fr_i(i)*1)+(T_inlet*fr_i(i)*1))/(V_tank)
+1/60*(P_WHi_1*eff_WH*3412-(A_tank*(T_outlet_i2-Ta)/R_tank))/V_tank;
T_outlet_i2=T_outlet1;  % Update outlet temperature


%----------Deciding Status of the Water heater--------------------


if T_outlet_i<Temp_low      % If outlet temperature exceeds lower temp
    WWHi=1;                 % Water heater status on
    charge=0;
end
if T_outlet_i>=Ts_WH        %if temperature exceed max-limit
    WWHi=0;                 % Water heater status off'
    charge=0;
end

if I_PV(i)>I_l(i)  % If PV current exceeds load current
```

```
          WWHi=1;                          % Water heater status on for charging
          charge=1;
          if T_outlet_i>=Ts_WH+17 % If outlet temp exceeds max temp of heater
               WWHi=0;
               charge=0;% Water heater status off
          end
     end

     if T_outlet_i2<Temp_low         % If outlet temperature exceeds lower temp
          WWHi_1=1;                       % Water heater status on
     end
     if T_outlet_i2>=Ts_WH                 %if temperature exceed max-limit
          WWHi_1=0;                         % Water heater status off
     end



     GS(i)=(PV_prod(i)-Total_Load(i)-P_WHi); % Grid sale
     GS_no(i)=(PV_prod(i)-Total_Load(i)-P_WHi_1); %Grid sale, no storage
     if GS(i)<0                                % If grid sale is below zero
          GS(i)=0;                             %Grid sale is zero
     end
     if GS_no(i)<0                   %If grid sale is below zero (no charge)
          GS_no(i)=0;                          % GRid sale is zero
     end
     GP(i)=(Total_Load(i)+P_WHi-PV_prod(i)-WH_charge(i));     %Grid purchase
   GP_no(i)=(Total_Load(i)+P_WHi_1-PV_prod(i)); %Grid purchase (no storage)

     if GP(i)<0                               % If grid purchase is below zero
          GP(i)=0;                                     %Grid purchase is zero
     end
     if GP_no(i)<0                             % If grid purchase is below zero
          GP_no(i)=0;                                  %Grid purchase is zero
     end


     NetLoad(i)=Total_Load(i)+P_WHi;
     %Total residential load including water heater
     NetLoad_no(i)=Total_Load(i)+P_WHi_1;
     %Total residential load including water heater (no charge)
     RES_LOAD=sum(NetLoad)*delta_T;                              % In kWh
     RES_Load1=sum(NetLoad_no)*delta_T;                          % In kWh

     GP_net=sum(GP)*delta_T;              %Grid purchase storage
     GP_net1=sum(GP_no)*delta_T;          %Grid purchase no storage
```

```
    GS_net=sum(GS)*delta_T;            %Grid sale storage
    GS_net1=sum(GS_no)*delta_T;        %Grid sale no storage
    WHcharge_net=sum(WH_charge)*delta_T;     %Charge up demand in kWh
    NET(i)=Total_Load(i);          % Residential load (no water heater load)
    Net1=sum(NET)*delta_T;                   %In kWh
    P_grid(i)=I_g(i)*V_sys;                  % Grid contraints in kW

    Self(i)=PV_prod(i)-GS(i);                % Selfconsumption in kW
    Self_no(i)=PV_prod(i)-GS_no(i);     % Selfconsumption in kW (no storage)


    PVnet=sum(PV_prod);                      % PV production yearly
    SelfNet=sum(Self);                       % Self consumption yearly
    SelfNet_no=sum(Self_no);                 % Self consimption yearly (kWh)
    PVconsumption=(SelfNet/PVnet)*100;
    % Self-consumption in percentage
    PVconsumption_no=(SelfNet_no/PVnet)*100;
    % Self-consumption in percentage (no storage)



%-------Price calculations--------%

    if GP(i)>P_grid(i)  % If power purchased from grid is above constraints
        P_over(i)=GP(i)-P_grid(i);                % Overconsumption
    else P_over(i)=0;                             % Else overconsumption is
    end

    if GP_no(i)>P_grid(i)                     % No storage overconsumption
        P_over1(i)=GP_no(i)-P_grid(i);
    else P_over1(i)=0;
    end

    if NetLoad_no(i)>P_grid(i)                    % No PV overconsumption
        P_over2(i)=NetLoad_no(i)-P_grid(i);
    else P_over2(i)=0;
    end

P(i)=0.7*(GP(i)-P_over(i))*delta_T+(1.25*P_over(i))
*delta_T -0.5*GS(i)*delta_T; %daily energy bill
P1(i)=0.7*(GP_no(i)-P_over1(i))*delta_T+(1.25*P_over(i))
*delta_T -0.5*GS(i)*delta_T; %daily energy bill no storage

P2(i)=0.7*(NetLoad_no(i)-P_over2(i))
```

```
*delta_T+(1.25*P_over2(i))*delta_T; %Bill without PV

Pnet=sum(P);          %Sum of bill
Pnet1=sum(P1);         %-.-
Pnet2=sum(P2);         %-.-

 Bill=Pnet+150+2640; % Total bill
 Bill2=Pnet1+150+2640; % Total no storage

 Bill3=Pnet2+150+2640;   %Total bill no PV system
%-------------Check Kwh above limit----------%
P_over_net=sum(P_over); % Total overconsumption
P_over_net1=sum(P_over1); %Total overconsumption no storage
P_over_net2=sum(P_over2);   % Total overconsumption

 if Total_Load(i)>P_grid(i) % If the total load ( no water heater) is above grid
     GP_above(i)=(GP(i)-P_grid(i))*delta_T;  % Grid purchase above constraints i
else GP_above(i)=0;                          % Else 0
end

 if Total_Load(i)>P_grid(i)                  % Grid purchase above contraints (
     GP_above1(i)=(GP_no(i)-P_grid(i))*delta_T;  % Grid purchase above contraint
else GP_above1(i)=0;                             % Else 0
end

Loadshift=sum(GP_above);                     % Total load above grid limits in p
Loadshift1=sum(GP_above1);                   % Total load above with no storage

%----------Save plots-----------%
          Plot_T_outlet(i)=(T_outlet -32)*5/9;
          Plot_T_outlet1(i)=(T_outlet1 -32)*5/9;
          PlotWWH=WWHi;
          PlotWWH_1=WWHi_1;
          PlotP_WH(i)=P_WHi;
          PlotP_WH1(i)=P_WHi_1;
          PlotTime(i)=i;
          PlotMax_WH(i)=Ts1_WH;
          PlotMin_WH(i)=Temp_low1;
end

figure;
[haxes,hline3,hline4] = plotyy(PlotTime,Plot_T_outlet, PlotTime,PlotP_WH);
set(hline3,'Color','b','linewidth',1.5)% to change the first line
set(hline4,'Color',[0.2 0.8 0],'linewidth',1.5) % to change the second line
set(haxes(1),'ylim',[45,65]);
```

```
set(haxes(1), ’YTick’,(45:2:65));
set(haxes(2),’ylim’,[0,4.5]);
set(haxes(2), ’YTick’,(0:1:4.5));
set(haxes, ’Xlim’,[0,1440]);
set(haxes, ’XTick’,(0:60:1440));
set(haxes(2),’YColor’,[0.2 0.8 0])
set(haxes,’XTickLabel’,{’12PM’,’1AM’,’2AM’,’3AM’,’4AM’,’5AM’,’6AM’,’7AM’,’8AM
grid;
hold on;
plot(PlotTime,PlotMax_WH,’r’,’linewidth’,1.5);
hold on;
plot(PlotTime,PlotMin_WH,’r’,’linewidth’,1.5);
title(’Plot of Outlet Water Temperature over Time ’); % title
ylabel(haxes(1),’Water Temperature (^0C)’) % label left y-axis
ylabel(haxes(2),’Load Demand (kW) ’) % label right y-axis
xlabel(haxes(2),’Time (Minutes)’) % label x-axis

figure;
[haxes,hline3,hline4] = plotyy(PlotTime,Plot_T_outlet1, PlotTime,PlotP_WH1);
set(hline3,’Color’,’b’,’linewidth’,1.5)% to change the first line
set(hline4,’Color’,[0.2 0.8 0],’linewidth’,1.5) % to change the second line
set(haxes(1),’ylim’,[45,65]);
set(haxes(1), ’YTick’,(45:2:65));
set(haxes(2),’ylim’,[0,4.5]);
set(haxes(2), ’YTick’,(0:1:4.5));
set(haxes, ’Xlim’,[0,1440]);
set(haxes, ’XTick’,(0:60:1440));
set(haxes(2),’YColor’,[0.2 0.8 0])
set(haxes,’XTickLabel’,{’12PM’,’1AM’,’2AM’,’3AM’,’4AM’,’5AM’,’6AM’,’7AM’,’8AM
grid;
hold on;
plot(PlotTime,PlotMax_WH,’r’,’linewidth’,1.5);
hold on;
plot(PlotTime,PlotMin_WH,’r’,’linewidth’,1.5);
title(’Plot of Outlet Water Temperature over Time ’); % title
ylabel(haxes(1),’Water Temperature (^0C)’) % label left y-axis
ylabel(haxes(2),’Load Demand (kW) ’) % label right y-axis
xlabel(haxes(2),’Time (Minutes)’) % label x-axis

figure;
plot(PlotTime, GP, ’Color’, [1 0.5 0.2] );
xlim([1 525600]);
set(gca, ’XTick’,[1:43800:525600]);
set(gca, ’xticklabel’,{’Jan’,’Feb’,’Mar’,’Apr’,’May’,’Jun’,’Jul’,’Aug’,’Sep’,
ylim([0.18 9]);
```

```
set(gca,'TickLength',[0 0])
xlabel('Month␣of␣the␣year');
ylabel('Grid␣purchase␣(kW)');
box on
x0=50;
y0=25;
width=558;
height=178;
set(gcf,'position',[x0,y0,width,height]);
%
% figure;
% plot(PlotTime, GP_no, 'color', [1 0.9 0.2]);
% xlim([1 525600]);
% set(gca, 'XTick',[1:43800:525600]);
% set(gca, 'xticklabel',{'Jan','Feb','Mar','Apr','May','Jun','Jul','Aug','Sep',
% %ylim([0.18 9]);
% set(gca,'TickLength',[0 0])
% xlabel('Month of the year');
% ylabel('Grid purchase (kW)');
% box on
% x0=50;
% y0=25;
% width=558;
% height=178;
% set(gcf,'position',[x0,y0,width,height]);

% figure;
% plot(PlotTime, P_grid, 'Color' , [0.7 0.4 0] );
% xlim([1 525600]);
% ylim([0 5])
% set(gca, 'XTick',1:43800:525600);
% set(gca, 'YTick',1:5);
% set(gca, 'xticklabel',{'Jan','Feb','Mar','Apr','May','Jun','Jul','Aug','Sep',
% %ylim([0.18 9]);
% set(gca,'TickLength',[0 0])
% xlabel('Month of the year');
% ylabel('Power from the grid (kW)');
% box on
% x0=50;
% y0=25;
% width=558;
% height=178;
% set(gcf,'position',[x0,y0,width,height]);
%
figure;
```

```
plot(PlotTime,GS,’Color’,[0.5 0.4 0],’linewidth’,0.7);
xlim([1 525600]);
xticks([1:43800:525600]);
xticklabels({’Jan’,’Feb’,’Mar’,’Apr’,’May’,’Jun’,’Jul’,’Aug’,’Sep’,’Oct’,’Nov
set(gca,’TickLength’,[0 0])
xlabel(’Month␣of␣the␣year’);
ylabel(’Grid␣sale␣(kW’);
legend(’Grid␣sale␣with␣thermal␣storage’,’Grid␣sale␣no␣storage’)
box on
x0=50;
y0=25;
width=558;
height=178;
set(gcf,’position’,[x0,y0,width,height]);
hold on
plot(PlotTime, GS_no,’Color’,[0.5 1 0.7],’linewidth’,0.7);
%
%
% plot(1:1:1440, fr_1);
% set(gca, ’XTick’,[0:60:1440]);
% set(gca, ’xticklabel’,{’1’,’2’,’3’,’4’,’5’,’6’,’7’,’8’,’9’,’10’,’11’,’12’,’
% xlabel(’Time (h)’);
% ylabel(’GPM’);
% grid;
%
% figure;
% plot(PlotTime,Selfconsumption,’Color’,[0.1 0.1 1],’linewidth’,0.7)
% xlim([1 525600]);
% xticks([1:43800:525600]);
% xticklabels({’Jan’,’Feb’,’Mar’,’Apr’,’May’,’Jun’,’Jul’,’Aug’,’Sep’,’Oct’,’N
% %ylim([0.18 9]);
% set(gca,’TickLength’,[0 0])
% xlabel(’Month of the year’);
% ylabel(’Self consumption (%)’);
% legend(’Self consumption with thermal storage’,’Self consumption no storage
% box on
% x0=50;
% y0=25;
% width=558;
% height=178;
% set(gcf,’position’,[x0,y0,width,height]);
% hold on
% plot(PlotTime, Selfconsumption_no,’Color’,[0.1 1 0.1],’linewidth’,0.7);
```

Figure A.3: Inverter used for capital investment