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Master thesis

Analysis of Solar Power in Multi-residential Households

Optimal Solar Installation Size

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Renewable Energy Systems
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Abstract

This master's thesis investigates the optimal level of investment in solar power for multi-residential households in Norway, in the context of the country's upcoming solar sharing scheme. This scheme will enable localized sharing of solar energy up to 1000 kW in installed capacity, turning rooftop solar systems into joint assets for apartment buildings.

An optimization model was developed using Pyomo, a Python-based package, to identify the optimal solar investment solution that results in the greatest reduction in electricity bills. The model considers key factors such as demand profiles, weather data, grid fee structure, electricity prices, and solar installation costs.

The study also compares the benefits of solar power for residents with different electricity demand profiles, namely those who work during the day versus those who can shift their consumption to when solar power production is possible.

Additionally, the study explores the implications of current restrictions on local peer-to-peer energy trading, conducts a sensitivity analysis on various parameters, like tilt, azimuth and electricity price. The study seeks to answer guiding research questions about the willingness to install solar power in multi-residential households and the information needed by owners to decide whether solar power is a beneficial investment. The findings are expected to contribute to the body of knowledge on renewable energy optimization in residential settings, particularly in the context of Norway.

Table of Contents

List of figures

List of tables

1 Introduction

In recent years, the number of privately-owned solar power plants supplying their own energy needs has surged significantly[1]. Single-family homes and buildings that have a single measuring point towards the grid operator can operate as prosumers, reducing their grid consumption by utilizing locally produced electricity. This practice enables them to avoid paying grid fees and taxed electricity prices. However, multi-residential buildings like apartment complexes present a challenge due to each unit having its own smart meter, which prevents the application of the prosumer model where the solar system's intake and the consumption are on the same side of the smart meter.

The Norwegian Water Resources and Energy Directorate (RME) has proposed a scheme to tackle this issue[2]. The proposal allows producers of renewable energy to share their production with other grid customers on the same property, enabling localized sharing of solar energy up to 1000 kW in installed capacity.

Grid operators will register the participating customers in this sharing system in Elhub. The Elhub platform then measures the surplus electricity on a chosen smart meter, and the grid customers within the same property receive a virtual reduction on their electricity usage, similar to the principle of net metering.

These significant changes to the cost structure and the potential for shared profits between individual actors call for a thorough analysis. How do these changes affect the yearly electricity bill in a multi-residential household? What is the potential for savings? What constitutes a good solar system investment? In this master's thesis, I will try answering these questions by deriving the optimal solution for typical consumers.

1.1 Motivation

The journey to examine the potential of solar power in multi-residential households in Norway is sparked by both personal experiences and academic interests.

As an apartment owner myself, I've found that calculating the economic benefits of installing solar panels on the roof is far from straightforward. The costs of solar installation are immediate and substantial, while the benefits of reduction in electricity bills accumulate over a long period, sometimes spanning decades. Furthermore, companies selling solar systems often provide only rough estimates of energy production, with little to no information on how much of this energy can be locally consumed or will be sold to the grid at lower value.

Solar systems only generate reasonable amount of power when the sun is shining, which means that people like myself, who are out working during the day, may not reap the full benefits. This imbalance in time of supply and demand further amplifies my curiosity about the real savings potential of solar power for apartment owners.

Academically, this master thesis is a chance to apply the knowledge I gained from my courses at the University of Oslo into a practical context. During my course on Energy Markets and Regulation (TEK5410), I learned to use the General Algebraic Modeling System (GAMS) for optimization. However, I realized that continuing to use GAMS post-studies would require obtaining a license, and there were limitations in verifying data through plots and tests. Hence, I decided to switch to an open Python platform. In the python environment there is an optimization package called Pyomo, although less powerful than GAMS in computation power, is more accessible and versatile.

In addition, I've taken courses about solar power function and systems and has been intrigued by the question: why isn't everyone investing in this relatively inexpensive energy technology, especially now, with soaring electricity prices?

1.2 Scope of Work and Methodology

The primary objective of this study is to undertake a detailed analysis to identify the optimal level of investment in solar power for multi-residential households in Norway. The methodology will follow a systematic approach to construct a comprehensive optimization model aimed at minimizing electricity bills by making strategic decisions regarding the use of solar energy.

The specific steps to be taken are as follows:

1. Literature Review: A comprehensive literature review will be conducted to understand the existing mechanisms for sharing locally produced electricity, services provided by solar companies, and available solar power software tools.

2. Construction of Optimization Model: The model will be designed and implemented using Pyomo, a Python-based package, to find the optimal solar investment solution that results in the greatest reduction in electricity bills. The decision to use Python and Pyomo is due to flexible licensing, ease of result verification, and superior visualization capabilities.

3. Data Collection: Significant efforts will be devoted to gathering all necessary data, which will serve as model parameters. These parameters will include meaningful demand profiles, weather data for production predictions, grid fee structure, electricity price data, and solar installation costs.

4. Examination of Peer-to-Peer Trading Limitations: The study will explore the implications of the current restriction on local peer-to-peer energy trading among neighbors. This examination will provide insights into the potential for more advanced local energy trading policies.

5. Sensitivity Analysis: Following the model implementation, an in-depth sensitivity analysis will be conducted on various parameters to understand their impact on the optimal solution. These parameters will encompass the electricity price, daily and annual electricity consumption, grid fees, and weather data influencing solar production.

6. Analysis and Interpretation of Results: Upon completion of the optimization and sensitivity analysis, the results will be carefully analyzed and interpreted, seeking to answer the following guiding research questions:

- What is the willingness to install solar power in multi-residential households?
- What factors influence the willingness to install solar power in multi-residential households in Norway?
- What information do owners in multi-residential households need to decide whether solar power is a beneficial investment?

In summary, this study aims to provide a robust and systematic analysis leading to the optimal solution for solar power investments in multi-residential households. The findings are expected to significantly contribute to the body of knowledge on renewable energy optimization in residential settings, particularly in the context of Norway.

2 Literature Review

The shift towards sustainable energy solutions has seen increasing attention towards solar power. Apartment buildings in particular, offer unique challenges and opportunities in implementing solar solutions due to shared spaces and energy demands. This literature review delves into the current strategies and tools used for the implementation of solar power in multi-unit residential settings. Then explore innovative systems for such environments and evaluate the effectiveness and limitations of various solar power prediction tools available in the market.

2.1 Solar system for apartment building

Solar power implementation in apartment buildings is an evolving area with numerous solutions being tried. Notably, Allume Energy's SolShare system is player this space, efficiently distributing electricity generated from shared rooftop solar panels across all residents[3]. This is done by connecting the power from the solar panels trough the inverter to the solShare hub, see Figure 1. This hub monitors all residents demand and distributes current at the consumption side of the smart meter where it is needed.

While the SolShare system is financially viable with a price tag of $2000-3000 per apartment, some may find it somewhat costly. Despite this, its capacity to simplify the distribution of solar energy within a building is highly advantageous. However, potential users might question the undisclosed algorithm ensuring equitable solar electricity distribution to each resident. This obscurity can be a consideration for some.

Nevertheless, the SolShare system has proven its effectiveness in tailoring solar delivery based on demand, allowing up to 55% more solar consumption on site compared to individual systems. This highlights its potential to streamline the adoption of solar energy in apartment buildings, paving the way for a more sustainable future.

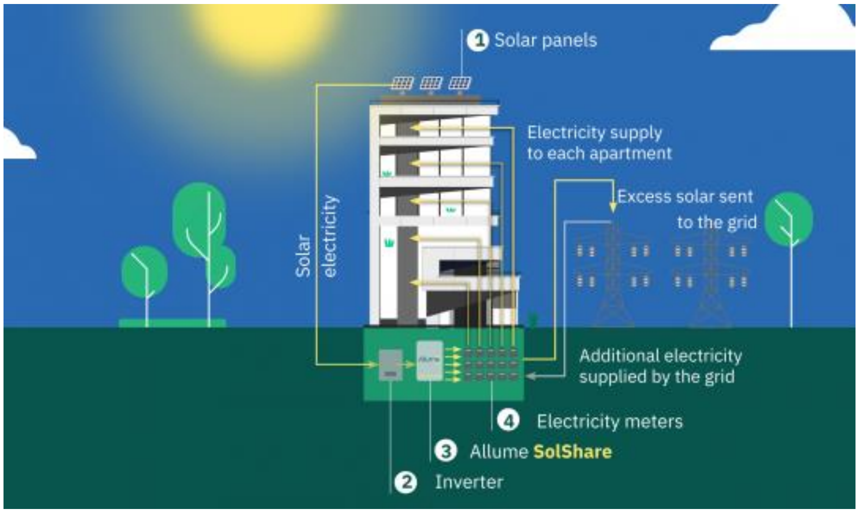


Figure 1 Solar power is divided to all smart meters[3].

2.2 Solar power programs/systems

Many software tools, including HOMER Pro, PVSyst, the System Advisor Model (SAM), PVWatts, and PVLIB, can predict the performance of photovoltaic (PV) systems, each with its own features, capabilities, and limitations. For instance, HOMER Pro designs and analyzes hybrid power systems incorporating solar PV, wind turbines, generators, among other elements, while PVSyst is more specialized for studying, sizing, simulating, and analyzing complete PV systems.

Installation companies like Otovo and Solkart offer map-based systems estimating yearly production, installation size, and price, accounting for location, roof characteristics, azimuth, and tilt. However, while these tools offer helpful estimations, they don't give a good estimation of how much how the energy produced is consumed locally and lack flexibility due to undisclosed or incompletely described integrated tools.

By investigating the existing literature on solar power systems for multi-unit buildings, including innovative systems like SolShare and various performance prediction tools, this study contributes to understanding and furthering solar power integration in multi-unit residential buildings. Nevertheless, existing tools may lack the adaptability required for a complex and tailored analysis. To address this, the study employs the open source platform Python[4], with package Pyomo[5] to develop a flexible and customizable optimization model for analyzing, and optimizing solar power investments in multi-residential households in Norway.

3 Theory

This theory chapter explores the intricacies of Norway's electricity landscape, with a specific focus on solar energy, electricity market dynamics, and grid fees. It elucidates how solar energy is captured, the determinants of solar panel efficiency, and the role of spot prices, supply, and demand in shaping the electricity market. The chapter also provides an insight into the structure of grid fees, illustrating the implications for different customer types.

The chapter further discusses the concept of 'prosumers', individuals who consume and produce electricity, alongside an introduction to the shared energy production scheme aimed at enhancing local energy production and consumption. It touches upon the challenges and solutions associated with implementing this scheme within multi-residential and commercial properties.

Finally, the chapter introduces the concepts of linear programming and the Python-based tool Pyomo, indispensable for tackling complex optimization problems. These insights pave the way for understanding the optimal deployment and utilization of renewable energy resources. This cohesive exploration offers a comprehensive view of Norway's electricity landscape, providing a robust foundation for analyzing current and future energy scenarios.

3.1 Solar resource

According to Norwich solar, the Earth surface receives about 86,000 TW of solar power at all times[6]. The current installed solar capacity in Norway is at around 483MW[7]. The primary sources for the information in this section are course materials from TEK 5330/9330 - PV systems and online resources from PVeducation.com. Solar energy can be categorized into two types: irradiance and irradiation. Irradiance, the radiant flux or power received per unit area, is measured in power per square meter (W/m2). Irradiation, on the other hand, is the accumulated irradiance over a period of time, thus constituting energy (kWh/m2).

3.1.1 Solar radiation

The solar spectrum at the atmosphere's uppermost layer resembles the Planck’s curve for black body radiation at 5778K, see Figure 2. However, atmospheric components such as O_2, H_2O, O_3, and CO_2 can absorb and influence the irradiance[8].

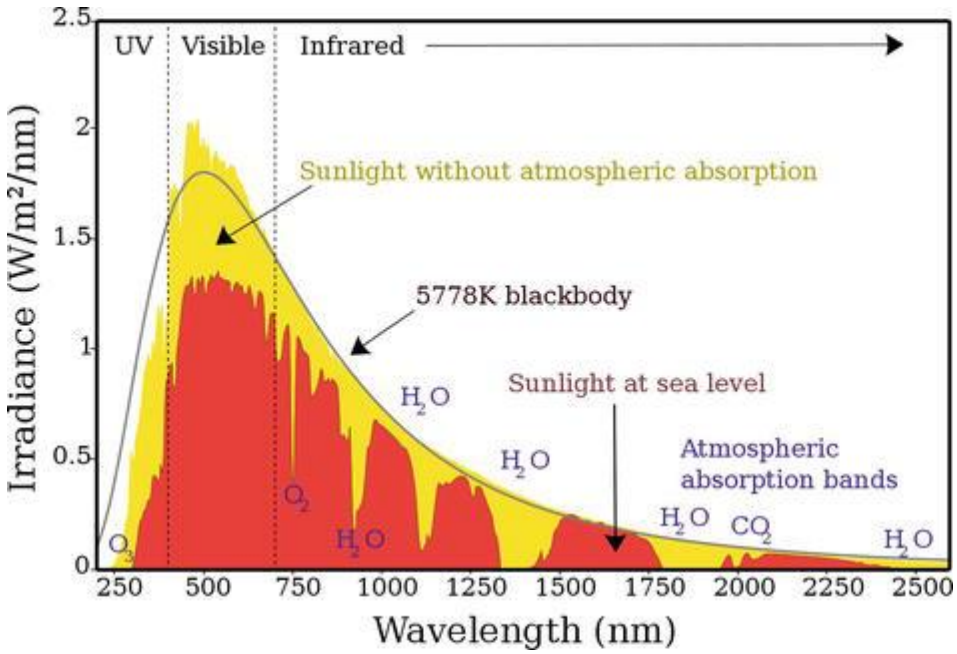


Figure 2 Shows solar spectrum from the sun where it behaves closely to a black body at 5778K and how wavelength is influenced by the atmosphere[8].

Radiation on the earth's surface varies due to factors such as:

- Atmospheric effects, including absorption and scattering.
- Local variations in the atmosphere, such as water vapor, clouds, and pollution.
- Latitude of the location.
- The season of the year and the time of day.

3.1.2 Irradiation on earth surface

Solar irradiance, the power per unit area received from the Sun, interacts with the Earth's atmosphere and reaches the Earth's surface as a combination of direct and diffuse light components, see Figure 3

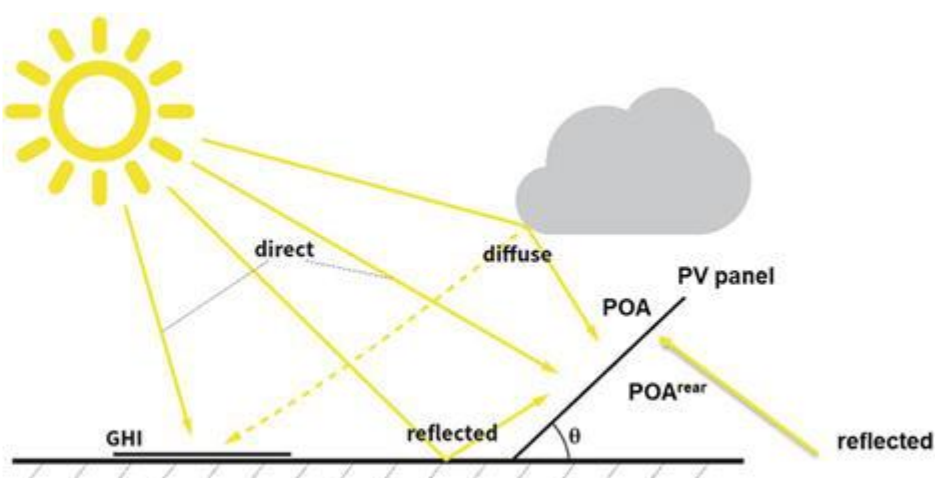


Figure 3 Show what components of the light hits a certain surface[8].

Direct Normal Irradiance (DNI): This is the solar irradiance from the direction of the sun on a surface perpendicular to the solar rays. DNI is essentially the direct beam of sunlight that is not obstructed by clouds or scattered by the atmosphere.

Diffuse Horizontal Irradiance (DHI): This is the scattered solar irradiance from the sky, excluding the direct beam from the sun, that is measured on a horizontal surface. DHI arises from sunlight scattered by molecules, aerosols, and clouds in the atmosphere.

Global Horizontal Irradiance (GHI): This is the total solar irradiance from the entire sky dome (the hemisphere above) on a horizontal surface. It includes both DNI and DHI. The GHI is particularly relevant as it represents the total amount of solar energy available on a horizontal surface like the ground.

Plane of Array (POA) or Global Tilted Irradiance (GTI): This is the total solar irradiance incident on a tilted plane, such as a solar photovoltaic (PV) panel. It includes direct and scattered radiation from the sky, as well as radiation reflected from the ground and nearby objects[8].

3.1.3 Air mass

For instance, in Oslo, with a latitude of 59.91, the Air Mass (AM) is calculated as approximately 2 by taking the reciprocal of the cosine of the latitude[9]. Typically, based on the latitude, the best tilt angle in Oslo would be around 60 degrees. However, due to the extensive diffused light traveling through the increased air mass (double the distance compared to the equator), the optimal tilt is at around 35-45 degrees[10].

3.1.4 Azimuth angle

In modern practice, the reference plane for an azimuth is typically true north, marked as a 0° azimuth when facing north[11]. Using a 360-degree circle as reference, east corresponds to an azimuth of 90°, south to 180°, and west to 270°. The azimuth angle of 180 degrees indicates a poleward orientation.

3.1.5 Earth orbit

The tilt of the Earth plays a crucial role in its interaction with the sun. At an angle of 23.45 degrees, the Earth's tilt is the primary cause of the seasons and the varying lengths of daylight throughout the year[12]. This tilt means that the sun's rays hit different parts of the Earth more directly during different times of the year. Consequently, it significantly impacts the amount of solar radiation received at any given location at various times, which directly affects solar power generation.

3.1.6 Standard test conditions

Solar energy studies often use Standard Test Conditions (STC) as a benchmark to evaluate performance across different situations[13]. These conditions usually include an ambient temperature of 25°C, an irradiance of 1000 W/m2, and a spectral distribution of AM1.5G according to IEC 60904-3.

3.2 Financial equations

In this chapter, we will delve into the fundamental financial equations that will be utilized throughout this thesis. Understanding these formulas will provide us with the necessary tools to evaluate and make decisions about investments.

3.2.1 Levelized cost of electricity (LCOE)

The LCOE is an important metric that allows us to understand the total costs (both upfront and operational) of producing electricity from a specific source[14]. It represents the average price at which the electricity produced by the system must be sold for the investment to break even, factoring in the time value of money. It can be calculated as:

$$LCOE = \frac{\sum_t (I_t + M_t + F_t)/\,(1+r)^t}{\sum_t E_t/\,(1+r)^t} \tag{1}$$

Where:

- I_t represents the capital or investment costs at time *t.*
- M_t maintenance or operational costs at time *t.*
- F_t Fuel cost (if relevant) at time *t.*
- E_t amount of electricity generated at time *t.*
- r is the discount rate, reflecting the time value of money.

3.2.2 Net Present Value (NPV)

The NPV formula is a method to calculate the present value of future cash inflows and outflows, thereby helping to assess the profitability of an investment[15]. It's calculated as follows:

$$\text{NPV} = \sum_{t=0}^{n} \frac{R_t}{(1+i)^t} - \text{initial investment} \tag{2}$$

where:

- R_t is the net cash inflow-outflows during period t.
- i is the discount rate, reflecting the time value of money.
- t equals the number of time periods.

3.2.3 Equivalent Annual Cost (EAC)

When evaluating various investments or projects with differing lifespans and costs, it's often useful to break down the NPV into a consistent annual figure. This makes comparing these investments easier. The Equivalent Annual Cost (EAC) achieves this by standardizing the present value of different investments into an annualized amount[16]. It's calculated as follows:

$$\text{EAC} = \frac{\text{NPV}}{A_{t,r}} \tag{3}$$

Where $A_{t,r}$ s the annuity factor and is calculated as:

$$A_{t,r} = \frac{1 - \frac{1}{(1+r)^t}}{r} \tag{4}$$

Where:

- r represents the cost of capital or the discount rate.
- t equals the number of time periods.

3.2.4 Payback Period (PP)

The payback period helps us understand the amount of time it takes for an investment to generate enough cash flows to recover the initial investment[17]. It's calculated as follows:

$$\text{Payback Period} = \frac{\text{Cost of Investment}}{\text{Average Annual Cash Flow}} \tag{5}$$

3.3 Electricity market

The electricity market operates as a trading platform for the buying and selling of electricity, bringing together energy producers and consumers. Central to this market is the spot price, determining the purchase and sale price for all market participants.

When purchasing electricity from the grid, consumers pay the spot price, plus an additional 25% tax. In addition to grid fees, along with an EL-certificates[18] cost of 0.01 NOK/kWh, further increasing the final cost of electricity.

The spot price is determined by the intersection point of the energy supply (dispatch) and demand curves. This point signifies the market equilibrium, the price and quantity at which the market clears. Typically, this price follows a daily curve, usually peaking around 9 AM. It then tends to flatten out before experiencing another surge around 4-5 PM. These fluctuations are driven by the varying demand for electricity throughout the day.

In some regions, different bidding zones may exist due to constraints in grid capacity. These zones are established to manage transmission congestion and ensure the stable operation of the grid. Each bidding zone can have its own electricity price depending on the balance of local supply and demand.

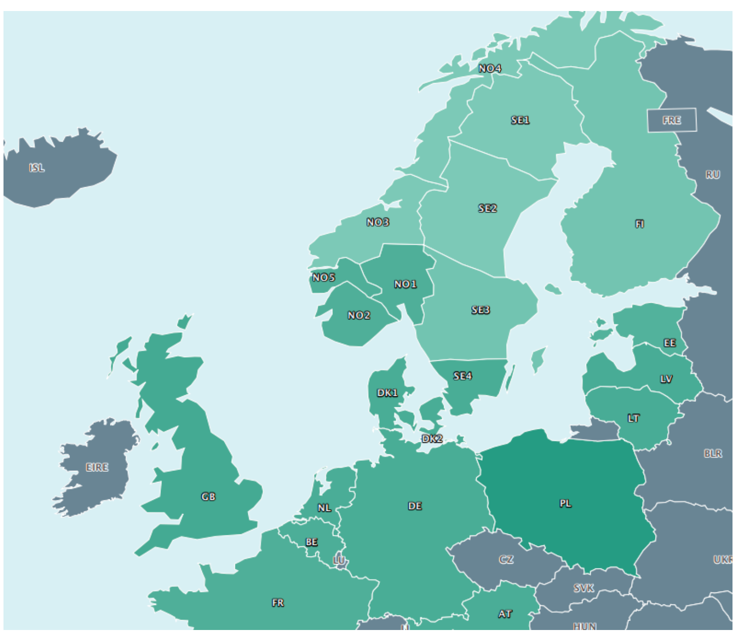


Figure 4 Different bidding zones in Europa[19].

Interconnections are vital components of the electricity market, providing a means to transport electricity across national borders. For instance, Norway has direct interconnections with several countries, including Sweden (3,695 MW), Finland (100 MW), Denmark (1,700 MW), Germany (1,400 MW), the Netherlands (700 MW), and the UK (1,400 MW)[20]. These interconnections facilitate electricity trade, improve grid reliability, and enable the integration of renewable energy sources.

This high-level overview provides a glimpse into the complexities of the electricity market. The dynamics of supply and demand, the role of spot prices, the need for bidding zones, and the significance of interconnections all shape the way electricity is traded and distributed.

3.4 Grid fees (Nettleie)

The grid fees are divided into two parts: "fixed fees" and "delivery fees". The pricing structure varies depending on whether the customer is a private individual or a company, and also on the kW demand of the customer.

3.4.1 Fixed fee

The fixed fee is calculated based on the average of the three highest daily peaks in a given month. A daily peak is defined as the hour with the highest amount of electricity consumption within a 24-hour period[21]. The average of the three highest hours of electricity consumption in a month, spread across three different days, determines the fixed fee tier applicable to the customer. The pricing applies to all consumer customers, including residential and vacation properties. This information can be viewed on the customer's account page.

Table 1 Fixed fees from Elvia for private customers[21].

Fixed fees	Max hour. kWh per hour	NOK/month	Price from 1. February NOK/month
step 1	0-2	125	110
step 2	2-5	200	170
step 3	5-10	325	270
step 4	10-15	450	370
step 5	15-20	575	470

3.4.2 Delivery fee (Energileddet)

The Delivery fee is a fee that consumers pay to grid operators for the transportation of electricity from a power plant through the grid to their homes. The fee is calculated based on hourly energy consumption (in kWh) and is multiplied by the delivery fee (øre/kWh), which varies depending on the time of day, day of week and the month.

Table 2 How cost of delivering electricity to consumers change depending on hour, day and month for private customers at Elvia[21].

Energiledd, øre/kWh	Daytime*	night/weekend*
Januar- March	35,29	29,04
April-December	43,55	37,30
(Energiledd without fees)	(18,00)	(13,00)

*The pricing periods are categorized as: Daytime: Weekdays from 06:00 to 22:00, Nighttime: Weekdays from 22:00 to 06:00, Weekend: Saturday, Sunday, and holidays.

The prices include all taxes and fees: Legal payment to the Energy Fund (Enova) of 1.0 øre/kWh and Electricity tax:

- January to March: 9.16 øre/kWh
- April to December: 15.84 øre/kWh
- 25 percent value-added tax (VAT)

The grid operator, Elvia, provides an incentive to prosumers by paying an additional 0.05 NOK/kWh for electricity sold back to the grid, as this helps in reducing grid losses[22].

3.5 Prosumer (Plusskunder)

A prosumer, as defined by the Norwegian Water Resources and Energy Directorate (NVE), is an electricity consumer who also produces electricity, typically through solar panels, micro-power plants, or wind turbines[23]. To become a prosumer with Elvia, you must produce a portion of your own electricity. The excess power you generate (up to 100 kW) can be sold back to your electricity supplier. Note that as a prosumer, you are only responsible for grid fees pertaining to the net electricity you consume from the grid, not the electricity you generate and feed back into it[24].

Becoming a prosumer requires installing your power generation system and having it approved by Elvia, after which you will enter into a grid lease agreement. There are subsidies available for electricity production, including those offered by Enova.

With the help of smart electricity meters, the process of becoming and being a prosumer is quite easy. Your unused electricity is automatically fed back into the grid, and this surplus contributes to reduced grid losses and is tariffed accordingly. If you exceed the limit of 100 kW, you are considered a separate power producer and must adhere to different terms, such as paying a feed-in tariff for the production exceeding the limit. In such cases, separate agreements are made.

3.6 Sharing local energy production scheme

From October 1, 2023, a new energy-sharing scheme allows electricity consumers on the same property to produce and use their own power. This scheme enables housing associations, multi-occupancy buildings and commercial properties to share locally produced energy, thereby reducing overall consumption from the grid[25].

Under this scheme, a producer can share surplus energy from production up to 1 MW(AC), with other customers on the same property. No grid fees apply to the locally consumed electricity, mirroring the conditions for prosumers The scheme also exempts participants from the electricity tax for self-produced electricity[26].

Despite the potential benefits, sharing schemes come with their complexities. Notably, multi-resident buildings can participate in sharing schemes within the same property up to an installed capacity of 1 MW. However, connected buildings or individual units like basements and garages often have different property unit numbers, which complicates the implementation of the scheme.

One solution to this problem is to create a virtual measuring point that balances the energy going in and out of the system. The system uses AMS readers to monitor power flow and store the data in Elhub. A new virtual value represents the net consumption or production of each customer within a common energy production unit on the same property. This arrangement ensures that a surplus production results in zero net consumption with a profit on the surplus[2].

Finally, shared production can be distributed among customers on the same property in three ways:

- Equal Distribution: All participants in the sharing system receive an equal share of the solar production. Each customer's reduction in consumption is equal to 1 divided by the total number of customers.
- Weighted Distribution: Units with higher consumption receive a larger share of the solar power distribution. Each customer's reduction is a certain percentage of the surplus production.
- Dynamic Distribution: Electricity is directed where it's needed the most at any given time. Each customer's reduction is calculated as their consumption divided by the sum of their own consumption and the consumption of their neighbors.

The choice of distribution key depends on the agreement between the producer and the grid company. These distribution models provide flexibility in managing shared energy resources, facilitating a more efficient and sustainable use of self-produced electricity.

3.7 Linear programming

Linear optimization is a powerful mathematical technique used to optimize a linear objective function subject to a series of linear inequality or equality constraints. In the context of modeling the profitability of local solar energy production, linear optimization can be used to determine the optimal configuration of solar panels to maximize energy production under varying environmental and financial constraints[27].

The formulation of a simple linear optimization problem consists of three main parts:

- Decision Variables: These are the variables it wants to find in the problem. In the context of a solar energy system, this could be the number of solar panels to install, their orientation, tilt angle, etc.
- Objective Function: This is the function that needs to be maximized or minimized. In our case, it could be the total energy production, profit, or return on investment of the solar energy system.
- Constraints: These are the limitations or restrictions that the solution must satisfy. For our problem, these could include budget constraints, space limitations for panel installation, or limitations on the total power that can be generated.

3.7.1 Pyomo and Optimization

Pyomo (Python Optimization Modeling Objects) serves as a powerful platform for the formulation and analysis of complex optimization problems. Drawing parallels to algebraic modeling languages (AMLs) like AMPL, AIMMS, and GAMS, Pyomo provides comparable capabilities but is advantageously embedded in Python, a full-featured and widely used high-level programming language[28].

At the heart of any optimization process lies the mathematical model, comprised of variables (unknown or changeable components), parameters (the unvarying data), relations (mathematical interconnections), and goals (objectives of the system under consideration). Such models, albeit simplified, effectively mimic a system or real-world scenario, facilitating prediction, analysis, and decision-making.

However, the construction and analysis of these mathematical models can often become an arduous task due to the volume of data, various formats, and the potential for human errors. Pyomo addresses these challenges by automating much of the laborious processes, making it a reliable and efficient tool in large-scale real-world applications.

The compelling reasons to choose Pyomo as a modeling and optimization tool are fourfold:

- **Open-Source Nature**: Pyomo's open-source ethos encourages transparency and facilitates community contributions to its development.

- **Customizability**: With the use of plug-ins, Pyomo users can tailor the tool's capabilities to meet specific requirements.
- **Solver Integration**: Pyomo is compatible with a multitude of solvers, both Python-based and those written in lower-level languages.
- **Built on Python**: Harnessing the power of Python, Pyomo offers extensive libraries, robust language features, comprehensive documentation, and excellent portability across platforms.

In summary, Pyomo leverages the versatility and accessibility of Python to provide a sophisticated platform for optimization modeling, making it an indispensable tool in the realm of operations research and decision science.

4 Method

This section describes the methodology used in the thesis. The main aim is to create an optimization model capable of determining the most cost-effective solar size to reduce the yearly electricity bill, ignoring the fixed fees.

4.1 Model approach

Building an effective optimization model hinges on the quality of the input data. Consequently, it is imperative to source accurate and reliable parameters for the model. The next chapter "Data Collection and Processing" to gather the most relevant input to the model.

4.2 Building an Optimization model

The objective of this chapter is to provide a detailed overview of an optimization model aimed at determining the optimal solar installation capacity and the electricity consumption for a specific residential area. The model is created using Pyomo, an open-source optimization modeling language in Python. It relies on real-world data, including spot prices, grid delivery fees, and solar capacity factors.

4.2.1 Set Definition and length

The set, in this context, comprises the hours in a year: H = {1,2,...,8760}. However, it is possible to select a slice of the set, depending on the user's preference, allowing for more specific analysis over certain periods.

4.2.2 Parameter input and Definition

The parameter input in this model that must include hourly data for a whole year are:

- Electricity demand (D_h) at each hour h. Could be a specific-, aggregated- or fabricated data containing hourly electricity consumption.
- Electricity price (P_h) at each hour h. Based on historical spot price data. Electricity market is explained in theory.
- Solar capacity factor (CF_h) at each hour h. Electricity production from each kWp solar installed, based on historical weather data.
- Electricity delivery fee (DF_h) at each hour h. Made according to Table 2 about grid fees, ignoring holydays.

4.2.3 Fixed parameters

The fixed parameters in this model are:

- Solar installation cost (IC). Equivalent annual cost for solar.
- Reducing grid losses factor (GL). Grid operator pays the prosumer for reducing grid losses.
- The Value-Added Tax (VAT). Purchasing electricity from grid is taxed.
- Certificates fee (CF). purchasing electricity includes a fee supporting renewable energy.

4.2.4 Variable Definition

The variables of this model include:

- Solar installation size (I), which is a decision variable bounded between 0 and 20. This variable represents the capacity of the solar system to be installed.
- Electricity from the grid at each hour (EG_h), bounded between 0 and 100. This variable accounts for the additional electricity needed from the grid.

4.2.5 Objective Function

The objective of the model is to minimize the total cost related to the electricity bill, which consists of the cost of solar installation, the cost of electricity from the grid, and the potential revenue from selling excess electricity. The function is expressed as:

$$\text{Minimize Total\_Cost} = Solar\_system\_cost + \sum_{h \in H} [Grid\_cost_h - Grid\_sold_h] \tag{6}$$

Or:

$$\text{Minimize Total\_Cost} = IC \cdot I + \sum_{h \in H} \left[EG_h \cdot \left((P_h \cdot \text{VAT}) + DF_h + CF\right) - (I \cdot CF_h + EG_h - D_h) \cdot (P_h + GL)\right] \tag{7}$$

4.2.6 Constraints

The model imposes a constraint ensuring that the electricity demand at each hour is met by the electricity produced by the solar installation and/or consumed from the grid:

$$D_h \leq I \times CF_h + EG_h \quad \forall h \in H \tag{8}$$

4.2.7 Equations

The model includes several equations:

- Electricity produced (produced_rule): The amount of electricity produced by solar power each hour, calculated as the product of the solar installation size and the solar capacity factor at that hour.

$$Electricity\_produced_h = I \times CF_h \tag{9}$$

- Grid cost (grid_cost_rule): The cost of electricity from the grid at a particular hour, computed as the product of the electricity taken from the grid and the sum of the adjusted electricity price including VAT, the delivery fee, and the certificate fee.

$$Grid\_cost_h = EG_h \times (P_h \times VAT + DF_h + CF) \tag{10}$$

- Grid sold (grid_sold_rule): The revenue from selling excess power back to the grid, calculated based on the surplus of produced electricity over demand, multiplied by the sum of the spot price and a factor accounting for grid losses.

$$Grid\_sold_h = (Electricity\_produced_h + EG_h - D_h) \times (P_h - GL) \tag{11}$$

4.2.8 Solver Selection

The model is solved using the GLPK solver, which is an open-source solver suitable for linear programming problems.

5 Data Collection and Processing

This chapter aims to identify the most meaningful input for the optimization model.

5.1 Electricity Demand

This section outlines the selection process for the demand parameter.

5.1.1 Data from Elhub

Elhub's database, which monitors all electricity consumption in Norway, was utilized in this study[29]. The database provides data on average household consumption from 2020 to 2022 in the bidding zone NO1, the southeast zone in Norway, see Figure 5. The data was broken down to identify average daily consumption for all households in NO1.

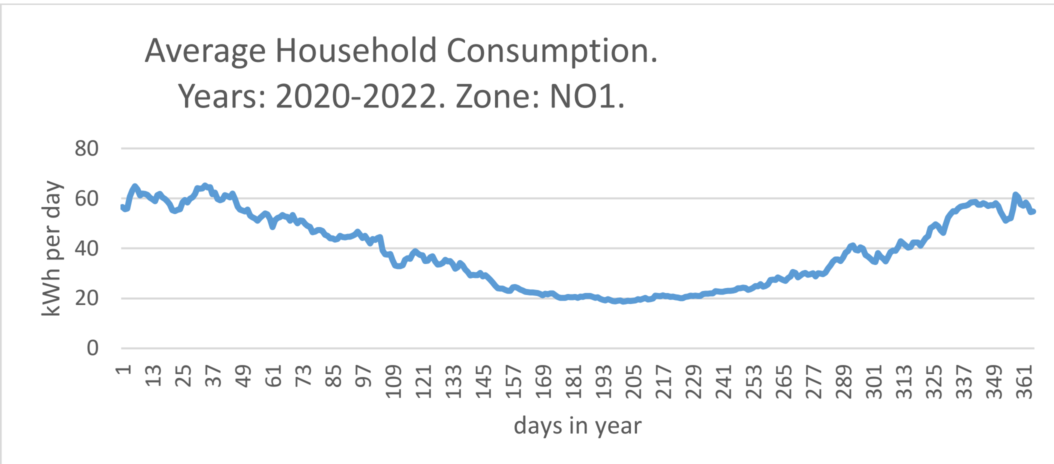


Figure 5 Average daily electricity consumption for households in year 2020-2022.

To understand the patterns of electricity consumption throughout the year, the monthly consumption was summed up for each year, see Table 3. The data reveals that an average household uses 14,058 kWh each year, with consumption in the summer months (June, July, and August) accounting for about one third of that in the winter months (December and January).

Table 3 Average electricity consumption in households each month year 2020-2022.

month_households_NO1	Average month (kWh)	Average month (%)
1	1849	13.2%
2	1628	11.6%
3	1505	10.7%
4	1201	8.5%
5	986	7.0%
6	666	4.7%
7	612	4.4%
8	661	4.7%
9	786	5.6%
10	1083	7.7%
11	1325	9.4%

12	1756	12.5%
sum	14058	100%

5.1.2 Demand in apartment building

The focus of this thesis is on multi-residential households. As such, the average yearly consumption, which is typically based on single households, needed adjustment. According to Tibber, a digital electricity supplier, the average electricity consumption for a 70m² apartment is 8,357 kWh each year[30]. In contrast, "Forbrukerguiden" suggests a significantly lower figure of 4,200 kWh per year for the same sized apartment[31].

There's a significant variance in these estimates due to factors such as heating systems for room temperature and water, and the method of electricity usage (locally or shared within the building). Such systems can include electric heaters, central heaters, heat pumps, air conditioners, and ventilation systems.

Given these factors, the base input for the model is set at 8000 kWh as a yearly consumption. This figure represents an estimate of what each resident would use if all their energy demand was accounted for in their individual electricity bill.

5.2 Demand Profile

One of the advantages of solar power is that it allows consumers to offset their electricity consumption with their solar production, thus reducing energy delivery fees and taxes. Solar production primarily occurs between 6:00 and 17:00, with peak production around 12:00. As many people are at work or school during this period, their variable consumption from 9:00-16:00 is often low, resulting in excess solar power being sold back to the grid at spot price. This section will explore how different consumer behaviors influence their electricity bills when solar is installed on their buildings, and how shifting consumption to coincide with solar generation could result in further savings.

5.2.1 Baseload

Baseload refers to the constant electricity load that is always on. This typically averages around 100 W, although a UK study found the average to be slightly higher at 112.1 W[32]. The baseload typically includes always-on devices such as refrigerators, freezers, some lights, and electronics.

Given that the demand profiles are not based on statistical data and should also represent some element of heating of water and temperature, it makes sense to choose a slightly higher baseload for the model. Therefore, the baseload for all hours is set to 20% of the daily electricity need. This represents about 0.83% of the daily electricity usage or 182.6 W, based on an average daily consumption of 22 kWh (from an annual consumption of 8,000 kWh).

5.2.2 Worker Profile

The 'Worker Profile' represents a resident who is typically absent from home from 8:00 to 15:59 due to work or studies, see Figure 6. This schedule significantly affects when they consume electricity, and thus how they might benefit from solar power.

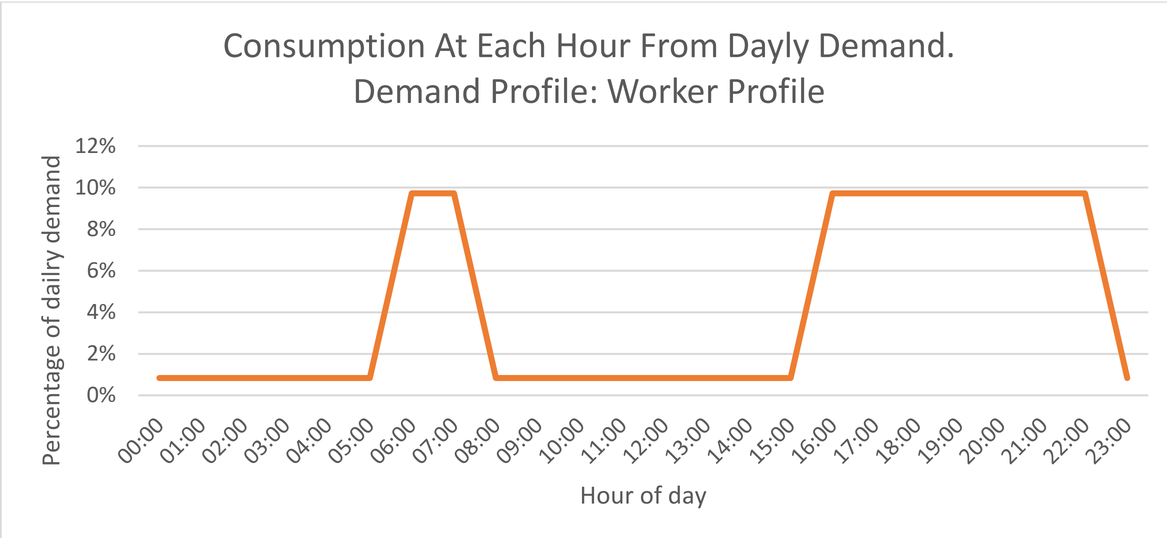


Figure 6 Daily electricity demand for every hour for a typical worker.

For the worker profile, the variable load is higher in the early morning (from 6:00 to 7:59) and in the late afternoon to evening (from 16:00 to 22:59). These periods represent times when the resident is likely home and using more electricity, such as during breakfast preparation or after returning from work. For this profile, each of these nine variable hours accounts for 9.72% of the daily load, or approximately 2.13 kW per hour, based on an average daily consumption of 22 kWh.

5.2.3 Solar Profile

The 'Solar Profile' represents a hypothetical optimal scenario where a resident's electricity consumption is better synchronized with solar power production, see Figure 7. This would maximize the potential savings from solar by ensuring that most electricity consumption occurs when solar power is being produced, thus reducing the need to buy electricity from the grid in sunny hours.

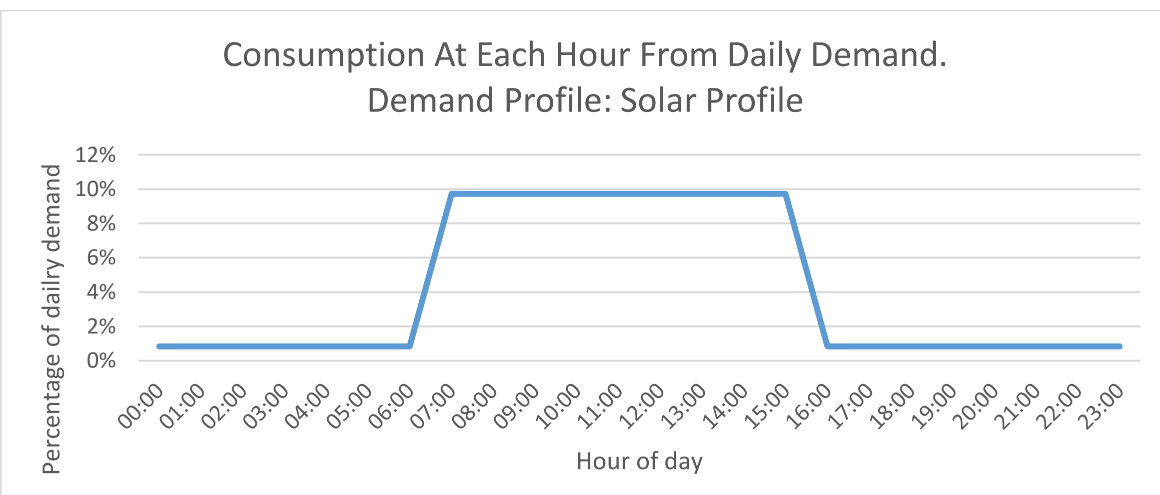


Figure 7 Daily electricity demand based around the hours solar panels produce most electricity.

For the solar profile, the variable load is higher from 7:00 to 15:59, the nine-hour period of highest solar production. As with the worker profile, each of these variable hour's accounts for 9.72% of the daily load, or approximately 2.13 kW per hour.

5.2.4 Middle Ground/Whole System

The Middle Ground/Whole System profile is a composite profile created by averaging the 'Worker' and 'Solar' profiles, see Figure 8. It assumes a scenario where residents exhibit a mix of the patterns described in these two profiles, thus representing a more accurate overall picture of a multi-residential building's energy consumption behavior.

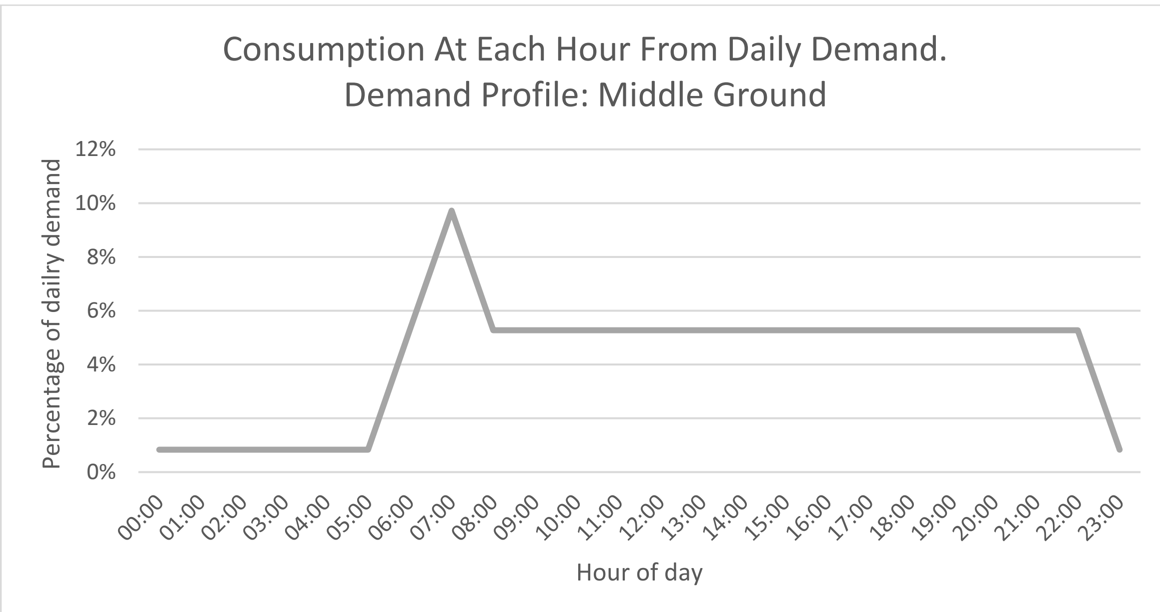


Figure 8 Electricity demand made up from the average from worker- and solar profile.

To create this profile, the energy consumption of the Worker and Solar profiles for each hour has been summed up and then divide by two. This profile thereby encompasses diverse consumption patterns - those who are away at work during the day (as characterized in the Worker profile), and those who are more home-based and align their power usage with solar power generation hours (as characterized in the Solar profile).

The purpose of the Middle Ground/Whole System profile is to compare the potential savings realized from an individual apartment perspective versus a whole-building perspective. It also serves to illustrate the benefits and potential savings of peer-to-peer energy trading between apartments within the same building - an optimal solution might be more achievable at the building level rather than the individual apartment level, and this could result in significant cost savings.

5.2.5 Seasonal Demand Shift

Given the notable variation in energy consumption across different months, it is crucial to integrate this fluctuation into the synthetic data generated for the demand profiles. In winter months, the consumption can be up to three times higher than in the summer months, as shown in Table 3.

To capture this variation, the annual electricity consumption of 8000 kWh was broken down to a monthly and daily basis, as shown in the Table 4.

Table 4 How a household with 8000kWh demand yearly would be distributed to each month and each day, based on table 3.

Month	kWh each month	days in month	Average Daily Consumption (kWh)
January	1052	31	33.9
February	926	28	33.1
March	857	31	27.6
April	683	30	22.8
May	561	31	18.1
June	379	30	12.6
July	348	31	11.2
August	376	31	12.1
September	447	30	14.9
October	616	31	19.9
November	754	30	25.1
Descember	999	31	32.2
SUM	8000	365	

As a result, the model's baseload and variable load are adjusted each month to reflect these seasonal shifts. For instance, the baseload in July is 93.6 Wh with variable load hours reaching 1092 Wh. In contrast, January sees a baseload of 280Wh and variable load hours as high as 3300 Wh. The shift in these demand profiles for both the solar and worker profiles can be visualized in the Figure 9 and Figure 10. This adjustment to demand profiles ensures a more realistic representation of the actual energy consumption patterns over the year.

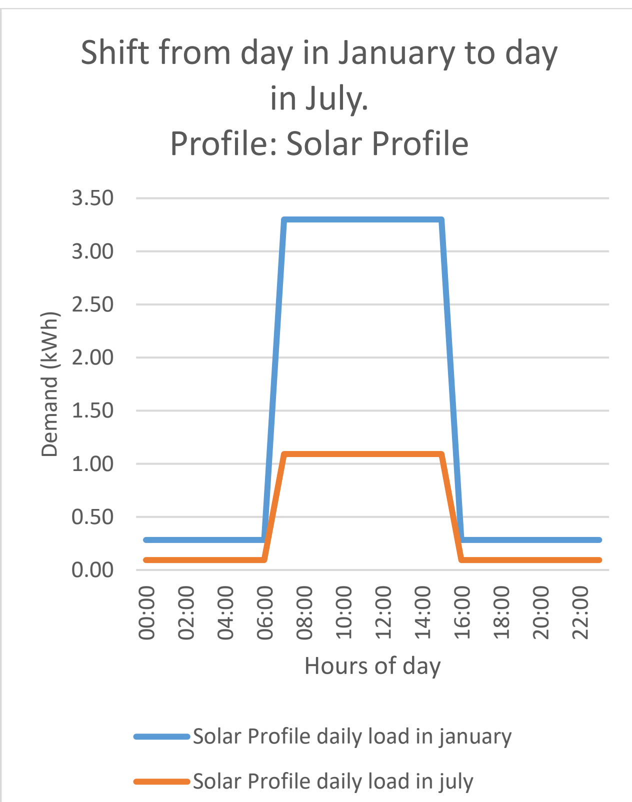


Figure 10 Comparing daily electricity demand in January to July.

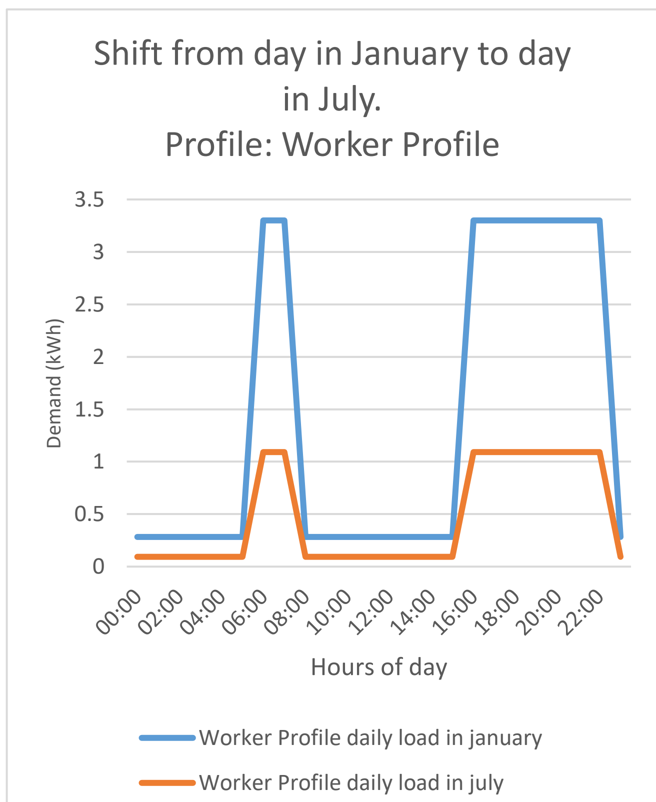


Figure 9 Comparing daily electricity demand in January to July.

5.3 Electricity price

Forecasting future electricity prices is a specialized field. As the energy production becomes more dependent on renewable, yet intermittent, energy sources, accurate forecasts are often reliant on precise weather predictions. However, the farther one tries to predict into the future, the more complex this task becomes. Adding another layer of complexity, our energy grids are increasingly interconnected with those of other countries. This interconnectedness often means that the bidding zones with the most substantial energy production influences their neighbor zones a lot, particularly those with high levels of intermittent renewable sources like wind and solar.

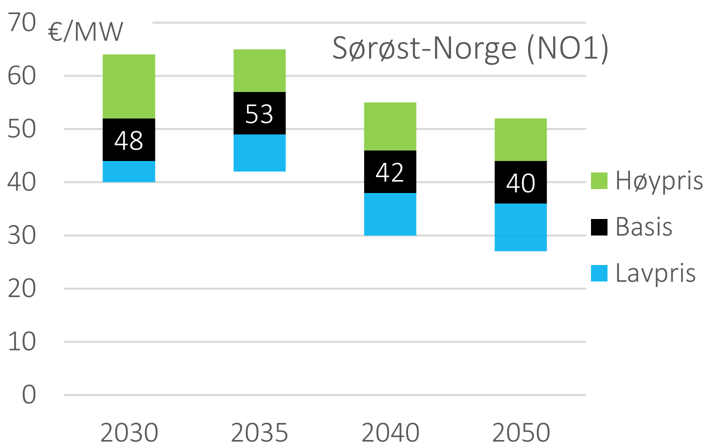


Figure 11 Statnett prediction of electricity price from 2030-2050[33].

Statnett's predictions for future electricity prices suggest a price of 48 EUR/MWh in 2030, rising to 53 EUR/MWh, and then falling to 40 EUR/MWh by 2050, see Figure 11[33]. The market analysis also estimates the electricity prices for the other bidding zones in Norway to be around 35-50 EUR/MWh in 2030, while almost all predictions for 2050 hover around 40EUR/MWh. Given the difficulty in predicting future electricity prices, the 2030 prediction of 48 EUR/MWh seems the most reasonable.

In 2022, when the report was written, the average EUR to NOK exchange rate was at 10,104[34]. Using Statnett's 2030 estimate of 48 EUR/MWh in NO1, this translates to 0.485 NOK/kWh.

5.3.1 Historical electricity prices

Historical electricity prices are gathered from Entso-E transparency platform[35]. They are then converted to NOK/kWh using historical exchange rates from Norwegian bank[34].

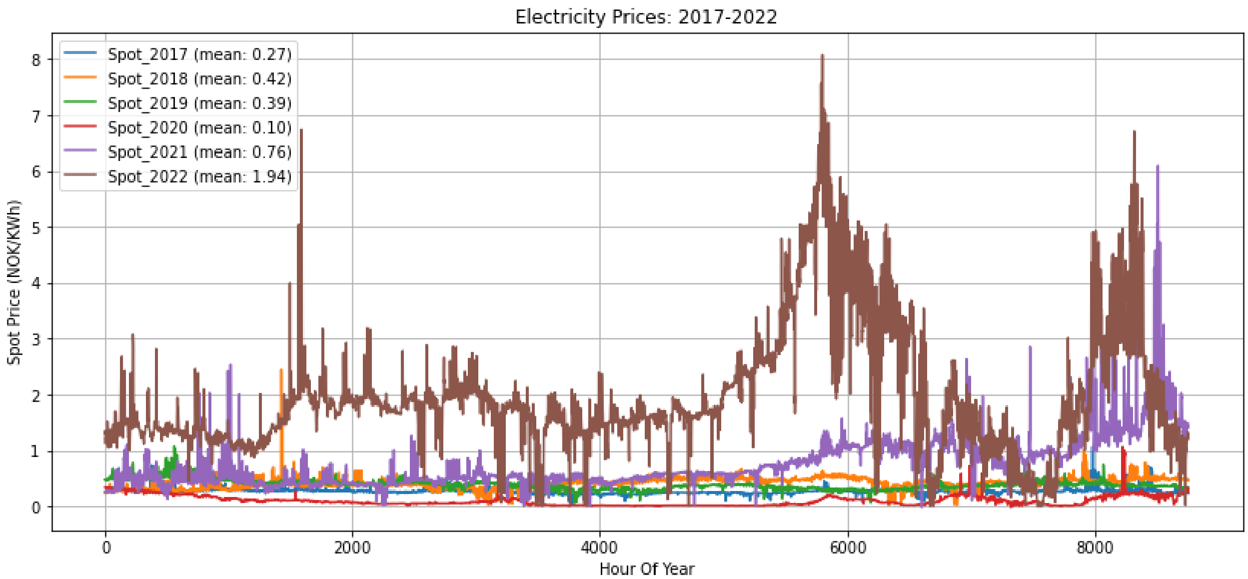


Figure 12 Historical electricity price at bidding zone NO1 from 2017-2022(NOK/kWh).

Looking at the plot showing six full years of hourly electricity prices, there are significant variations in the shape and spot prices, see Figure 12. The years 2017-2019 were relatively stable before more interconnectors were installed and the COVID-19 pandemic began in 2020, leading to plummeting spot prices during the lockdown. Prices have since gradually increased due to a combination of factors, including the decommissioning of power plants in Germany, an energy crisis brought on by insufficient investment in oil, and the war in Ukraine. These factors, coupled with additional interconnectors, have led to rising electricity prices in Norway, even though most of the power there is generated from inexpensive sources like hydroelectric power, wind, and waste incineration.

5.3.2 Normalizing Historical electricity prices

Among the possible base inputs, the year 2018 seems the best candidate as its average electricity price of 0.42 NOK/kWh is closest to the projected 0.485 NOK/kWh. To align with Statnett's prediction, it's necessary to normalize the data from different years for more accurate comparison of results. Normalizing adjusts all values within a year to achieve a desired average. For instance, if there's a need to normalize a year with an average electricity price of 1 NOK/kWh to 0.5, every number in the series should be divided by two.

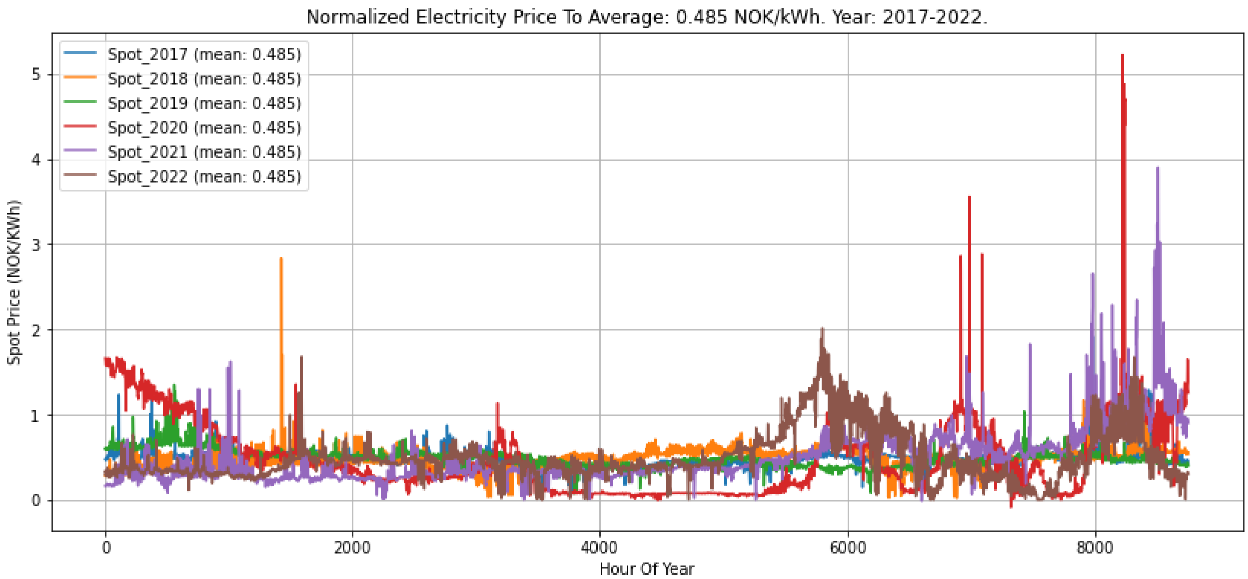


Figure 13 Historical electricity price at bidding zone NO1 from 2017-2022 normalized to 0.485 NOK/kWh.

In the Figure 13, all six years are normalized to 0.485 NOK/kWh, reflecting Statnett's prediction. This normalization allows for an additional input for the electricity price parameter in the model. Since 2018 was the closest to the pre-normalization average, its normalized version has been selected as the base input.

5.3.3 Electricity price in workdays and weekends

Figure 14 represents the average electricity prices for workdays and weekends. The blue lines, which denote workdays, exhibit a higher peak earlier in the morning around 09:00, which then falls towards 15:00 and rises again at 19:00. Upon reviewing the data from 2017 through 2022, we find a similar pattern and a variation in the mean price of around 10%. Thus, workdays are generally 10% more expensive than weekends.

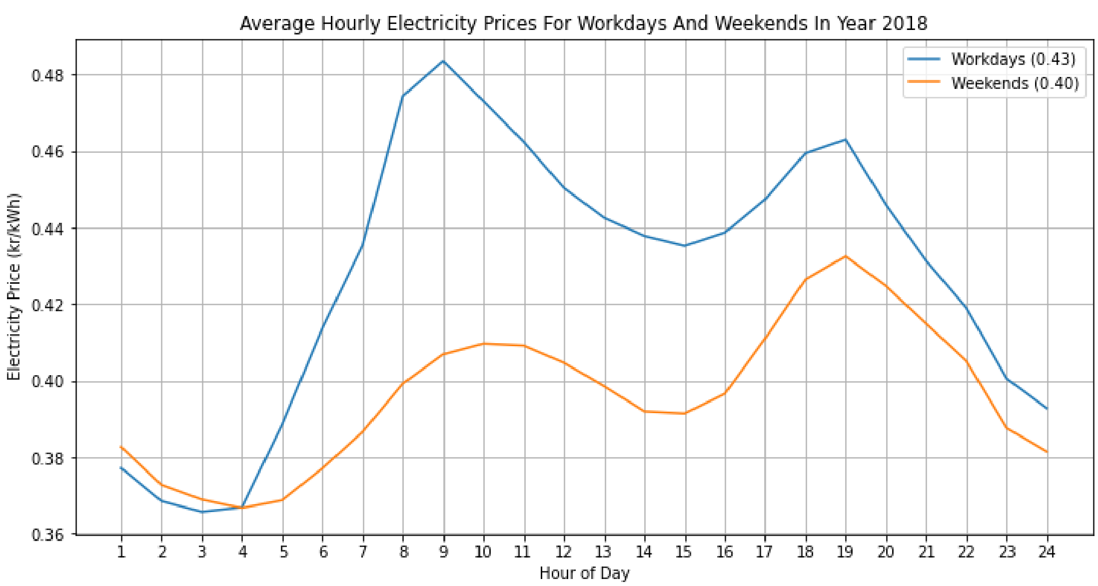
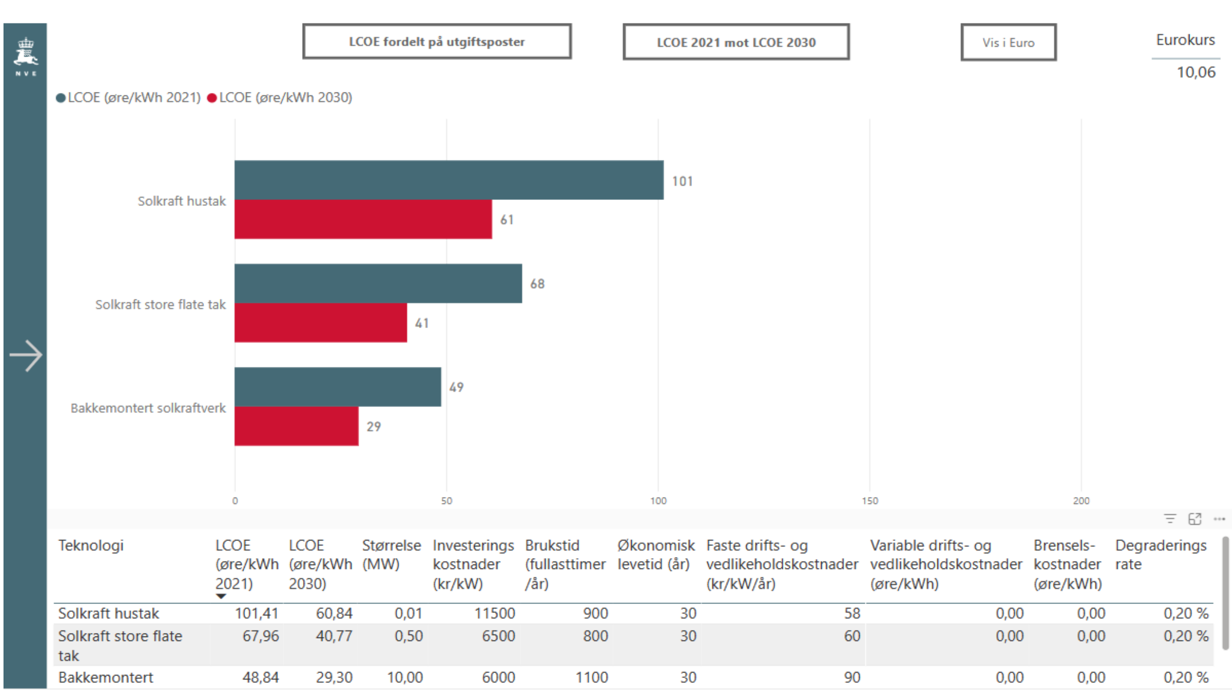


Figure 14 Shape of electricity price comparing workdays to weekend.

5.4 Solar cost

This chapter explores the cost per kWp associated with a dataset spanning one year. Analyzing NVE's LCOE calculation Figure 15, we can find the probable costs for homeowners interested in acquiring a solar system. The figure details the LCOE cost for solar power in an average single household at 11 500 NOK/kWp. With additional costs, the LCOE totals 1.01 NOK/kWh. For a structure with a large, flat roof, the cost is nearly halved to 6500 NOK/kWp, primarily due to lower installation costs and a larger system size. This results in an LCOE cost of 68 NOK/kWh. The data also covers the cost of ground-mounted solar parks at 6000 NOK/kWp, with an LCOE cost of 49 NOK/kWh. Furthermore, NVE's report includes a forecast for LCOE costs in 2030 rapidly falling, nine years from the date the data was gathered[36].



Teknologi	LCOE (øre/kWh 2021)	LCOE (øre/kWh 2030)	Størrelse (MW)	Investerings kostnader (kr/kW)	Brukstid (fullasttimer /år)	Økonomisk levetid (år)	Faste drifts- og vedlikeholdskostnader (kr/kW/år)	Variable drifts- og vedlikeholdskostnader (øre/kWh)	Brensels- kostnader (øre/kWh)	Degraderings rate
Solkraft hustak	101,41	60,84	0,01	11500	900	30	58	0,00	0,00	0,20 %
Solkraft store flate tak	67,96	40,77	0,50	6500	800	30	60	0,00	0,00	0,20 %
Bakkemontert	48,84	29,30	10,00	6000	1100	30	90	0,00	0,00	0,20 %

Figure 15 NVE's calculation for LCOE for different solar installation types[36].

To validate these figures, I consulted with an employee from Sol-Spesialisten and a solar expert at the Institute for Energy Systems (IFE). The Sol-Spesialisten representative quoted the cost of a small system to be in the range of 11 000 - 15 000 NOK/kW, while larger projects would typically cost about 7 000-10 000 NOK/kW. They also estimated the lifespan of the systems to be between 30-40 years. The IFE solar expert found the numbers from both NVE and the Sol-Spesialisten employee to be reasonable. Based on these insights, the base value for solar cost is set at 10 000 NOK/kW.

5.4.1 Enova support

Installation of a solar system receives support from Enova, providing a base support of 7500 NOK, plus 2000 NOK for each kWp installed, up to 20kW. Thus, the maximum support granted totals 47 500 NOK for a 20 kWp + installation[37].

5.4.2 Calculating annual cost

Given that the optimization model spans one year in length and the expected lifespan of a solar system is around 30 years, it's critical to calculate the EAC (Equivalent Annual Cost). Otherwise, the initial cost for solar can appear disproportionately high. It's easier to conceive that we're simply calculating the cost of leasing a solar power system for the same duration as the optimized dataset, notwithstanding the fact that dividing the installation cost by 30 might seem unusual.

With a solar cost of 10 000 NOK/kWp, operations and maintenance fees at 1.5% of the investment (150 NOK), a lifetime of 30 years, a discount rate of 4%, and annual degradation at 0.5%, the EAC is calculated to be 763.92 NOK/kWp for one year, using equation(3).

5.5 Weather data (Capacity factor)

The installation of solar panels on apartment buildings presents some advantages, as the elevated positioning of the roof decreases the likelihood of shading. However, obtaining accurate weather data can be a challenge. The orientation of a building's roof may not always align with the optimal azimuth angle for solar power generation. The color plot at Figure 17 illustrates the power output per installed kW with an azimuth of 180 degrees and a tilt of 35 degrees, while Figure 16 shows average hourly capacity factor (CF) each month in year 2018. An azimuth of 180 degrees indicates that the panels are facing directly south, which provides the highest electricity production.

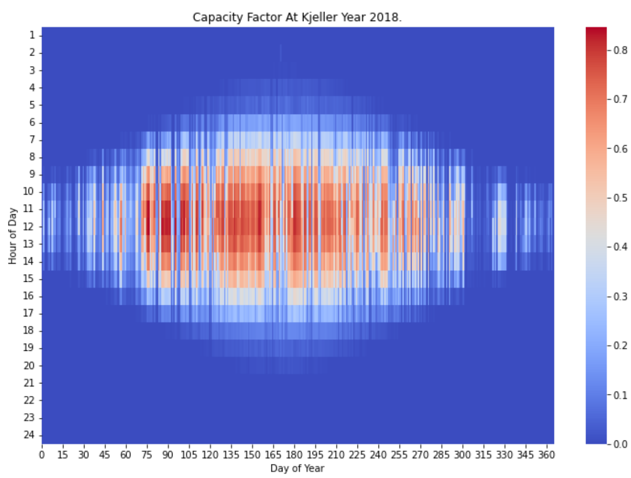


Figure 17 Showing when the solar system produces electricity.

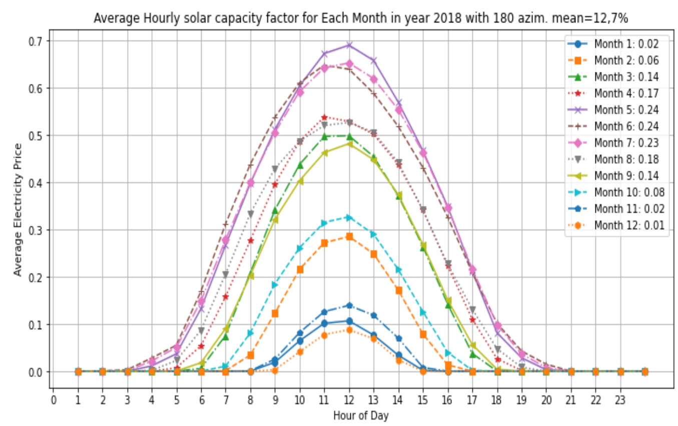


Figure 16 Hourly capacity factor with panels facing south.

Modifying the azimuth to 90 or 270 degrees means that the panels are facing east or west, respectively, as shown in Figure 18 and Figure 19. It's interesting to note the shift in peak production times; panels pointing east peak around 9.00-10.00, while panels facing west peak at 13.00-14.00.

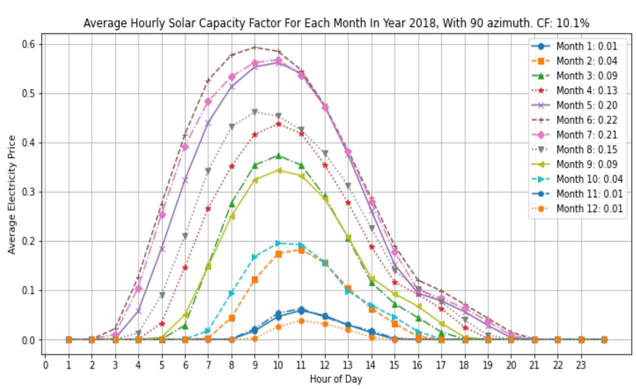


Figure 19 Hourly capacity factor with panels facing east.

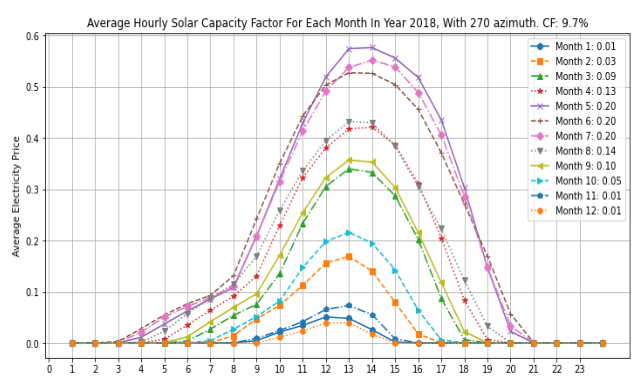


Figure 18 Hourly capacity factor with panels facing west.

5.5.1 Data source

The weather data used for calculating solar production is sourced from Modern-Era Retrospective analysis for Research[38] and Applications[39], Version 2 (MERRA2)[40], and is obtained through the Renewables Ninja homepage[41]. The platform allows users to download production data from previous years. When acquiring data for solar power generation, users must input specifications such as latitude, longitude, start and end dates, dataset, capacity, system loss, tracking, tilt, and azimuth. This data can be imported directly into Python using the site's API, allowing for convenient customization of settings.

5.5.2 Base data input

As there are no direct partners or customers for this thesis, the location has been set to the University of Oslo, section Kjeller in Lillestrøm. Here is a list of the base inputs for the optimization model:

- Coordinates: Latitude: 59.9751, Longitude: 11.0449
- Date range: 2018-01-01 to 2018-12-31. The year 2018 was selected to align with the input year for electricity prices.
- Dataset: merra2
- Capacity: 1.0 kWp. The capacity is set to 1 to facilitate multiplication of the data column to match the solar size of interest.
- System Loss: 0.1 (indicating a 10% system loss).
- Tracking: Off. No sun tracking has been incorporated.
- Tilt: 35 degrees. 0 degrees implies flat on the surface, 90 degrees means standing up.
- Azimuth: 180 degrees. This indicates panels pointing directly south.

5.6 Model assumption

The primary objective of this model is to minimize the annual electricity bill. However, since the demand profiles are constructed based on various narratives and not actual data, it may be somewhat redundant to include the costs from fixed fees. These fees could potentially obscure the results as they don't directly correspond to energy consumption, which is the central focus of the demand profiles. Moreover, installing solar power systems likely won't lead to reductions in fixed fees, as these are usually determined by the average consumption during the three highest-use hours. To influence these peak periods, it would likely be necessary to install a battery storage system in addition to the solar power system.

6 Result

This chapter presents the results of the study. It's crucial to comprehend that the annuitized cost of solar power is incorporated in the annual electricity bill answer, when the optimization model is used. For instance, if the yearly bill decreases from 10,000 NOK to 8,000 NOK, it could mean 5,000 NOK was spent on a 5 kWp solar installation if cost is 1,000 NOK/kWp. This results in a final cost of 8,000 NOK because utilizing solar power reduces the amount of electricity that needs to be purchased and enables the selling of surplus power back to the grid.

6.1 Base Parameter values

- **Demand Model**: Worker_Profile/Middle_Ground/Solar_Profile
- **Price Model**: Spot_2018_Normalized
- **Capacity Factor Model**: CF_2018
- **Delivery Fee Model**: Delivery_fee_year_2018

Additionally, the model takes into account the following key assumptions and parameters:

- Yearly electricity consumption is set at 8000 kWh.
- The model is run on a dataset sliced to include 8760 hours in a year, covering a full year without skipping any months.
- The spot prices can be scaled but is set a factor of 1 (No change).

Fixed Parameters:

- **Solar Installation Cost**: 763.915 NOK/kWp. The equivalent annual cost of chosen solar system.
- **Reducing Grid Losses**: Grid operator pays 0.05 NOK/kWh sold to the grid as it helps in reducing grid losses.
- **Value Added Tax (VAT)**: Buying electricity from the grid is taxed at a rate of 25% higher but selling only gives the regular spot price.
- **Certificates Fee**: A fee of 0.01 NOK/kWh is required for each kWh bought from the grid as part of paying for electricity certificates.

The specific results, including the optimized solar installation size, total cost reduction, and comparative scenarios, will be discussed in the following sections of this chapter. These results are based on the base parameters and the optimization model developed in this study.

Other base values:

- Solar system cost: 10 000 NOK/kWp
- Operation and maintenance cost: 1.5% of solar system cost (150 NOK/year)
- CF: 0.1275% (2018 weather data with 35° tilt and 180° azimuth)
- LCOE: 0.684 NOK/kWh (30 years lifetime, 4% discount rate and 0.05% annual degradation.

6.2 Base Case Demand Profiles

The optimizer program provides optimal solutions for both the Solar Profile and Worker Profile, suggesting solar installations of 4.3 kWp and 0.75 kWp respectively, as shown in Table 5. With these installations, the yearly cost related to the electricity bill is reduced to 88.3% for the Solar Profile and 98.6% for the Worker Profile. These results imply that, given the same base inputs, the solar capacity for the Solar Profile is nearly six times larger than that for the Worker Profile.

In terms of the percentage of produced energy used locally, the Worker Profile uses 52.22% while the Solar profile even more at 66.05%, despite producing only one-sixth of the energy. If the Worker Profile had the same solar capacity as the Solar Profile, the percentage of energy sold to the grid would be significantly higher. This shows the impact of consumption patterns on the efficiency of solar energy use.

Additionally, a rough estimation of roof space needed for these solar installations is calculated based on a solar panel efficiency of 22%. With an additional 20% of dead space taken into account for irregularities due to panel dimensions, roof shapes, and obstructions like chimneys. As such, each 1 kWp of solar capacity would roughly require approximately 5.5 m² of roof space. It was calculated as follows:

$$\text{Space needed each kWp} = \left(\frac{1\text{kWp}}{22\%\ \text{solar efficiency}}\right) \times (1 + 20\%\ \text{dead space}) = 5.5\text{m}^2 \tag{12}$$

Table 5 Base results for the solar- and worker profiles.

Demand profile	Unit	Solar Profile	Worker Profile
Yearly electricity demand	kWh	8000	8000
Total cost	NOK	7160	7858
Total cost without solar	NOK	8113	7968
Percentage of original bill	%	88.3	98.6
Solar capacity installed	kWp	4.30	0.75
Solar energy produced	kWh	4799	841
Solar energy sold	kWh	1629	402
Produced energy used locally	%	66.05	52.22
Space on roof needed	m²	23.5	4.1
Mean Solar kWh Value	NOK/kWh	0.5113	0.5113

The mean solar kWh value sheds light on how the electricity price inputs correlate with the production data. In this case, the result is a higher value of 0.5113 NOK/kWh, exceeding the average spot price of 0.485NOK/kWh.

6.2.1 Iterating with different solar sizes

By iterating the optimization program and adjusting the solar size, with a aim to identify the maximum solar installation capacity before the net total cost surpasses the original yearly electricity bill without solar, see Figure 20 and Figure 21. When the solar size is set to 0 kWp, the yearly electricity bill corresponds to the cost without solar, also represented by the red line. Both the left and right y-axes represent the same data, but in different units: the right y-axis shows the total cost in NOK, while the left y-axis represents the cost as a percentage of the original electricity bill.

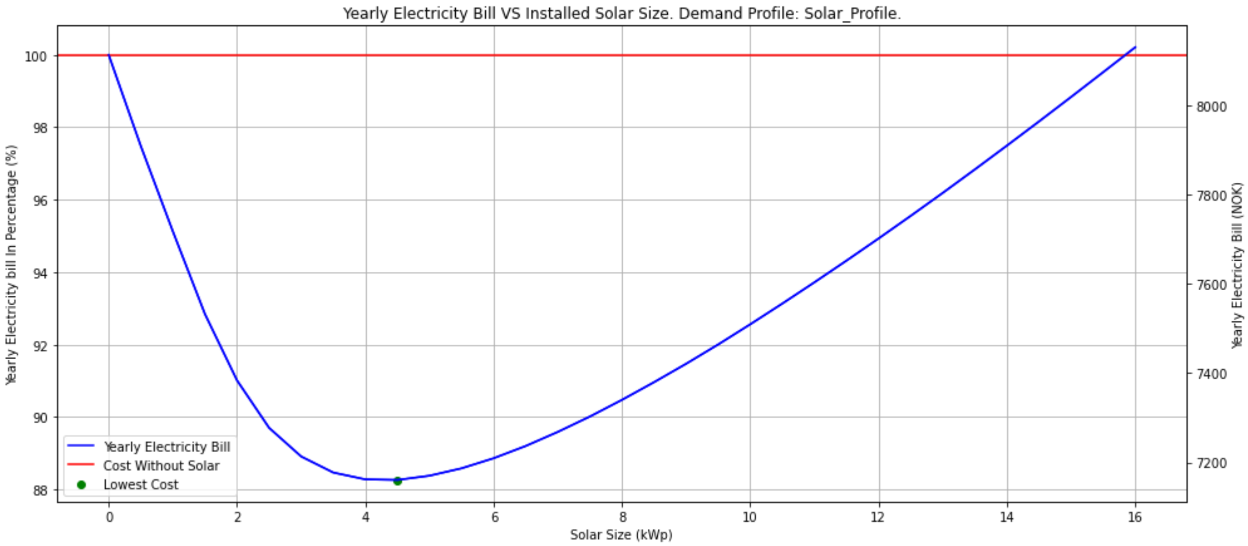


Figure 20 How the solar size installed influences the annual cost for the solar profile with base inputs.

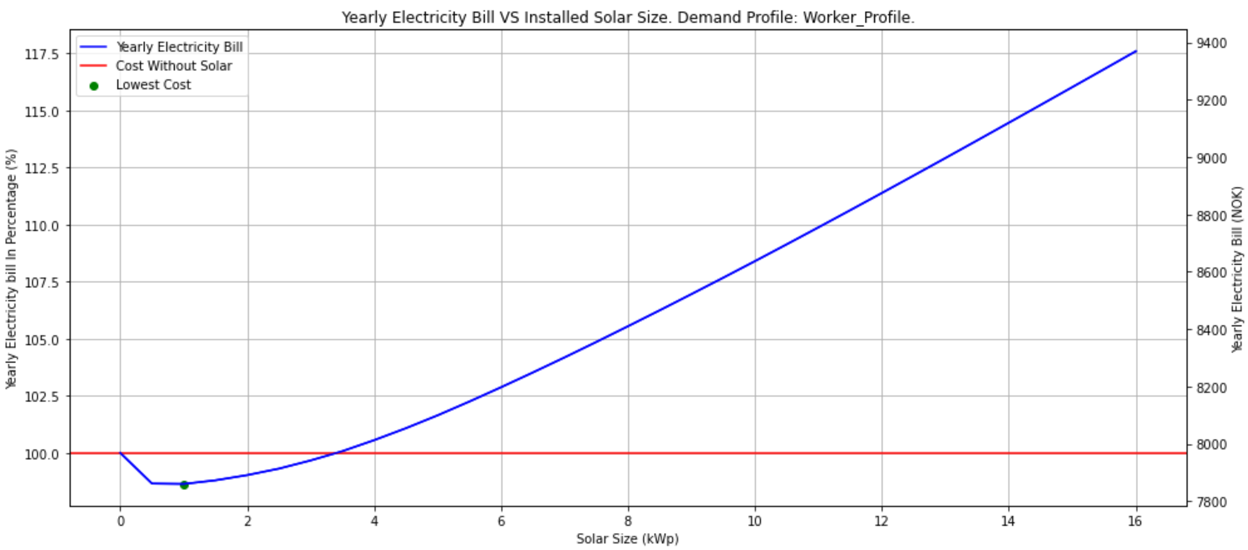


Figure 21 How the solar size installed influences the annual cost for the worker profile with base inputs.

The results indicate that the Solar Profile achieves its lowest price with a capacity of approximately 4.5 kWp, resulting in a total cost reduction of almost 12%. This profile can accommodate a solar installation of nearly 16 kWp before the total cost becomes negative. Conversely, the Worker Profile can't even install a 4 kWp system without the total cost exceeding the original bill. If the Worker Profile were to install a 16 kWp system, it's estimated that the total cost would increase by around 17.5%.

6.2.2 Payback period with different solar sizes

To understand how long it will take to fully recoup the investment without accounting for inflation or changes in discount rates, it is essential to consider the payback period (PP). This is a particularly important indicator for investments with long lifespans, such as solar panels, which typically last 30 years. Figure 22 and Figure 23 illustrate that for both demand profiles, the PP begins just below 10 years. For the solar profile, the PP gradually increases, eventually reaching around 16 years with a solar size of 16 kWp. On the other hand, the worker profile maintains the lowest PP until about 200 Wp is installed, after which the PP rapidly increases to over 18 years, indicating a longer time is required to recoup the initial investment.

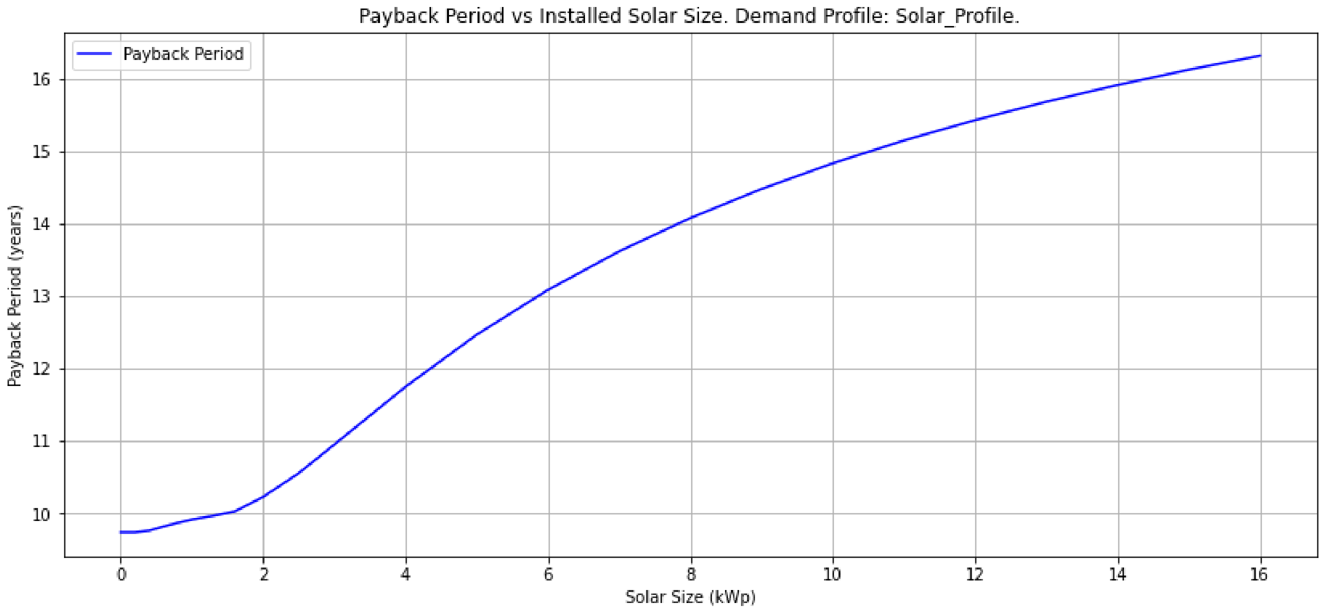


Figure 22 Payback period with different installed solar size, Solar profile.

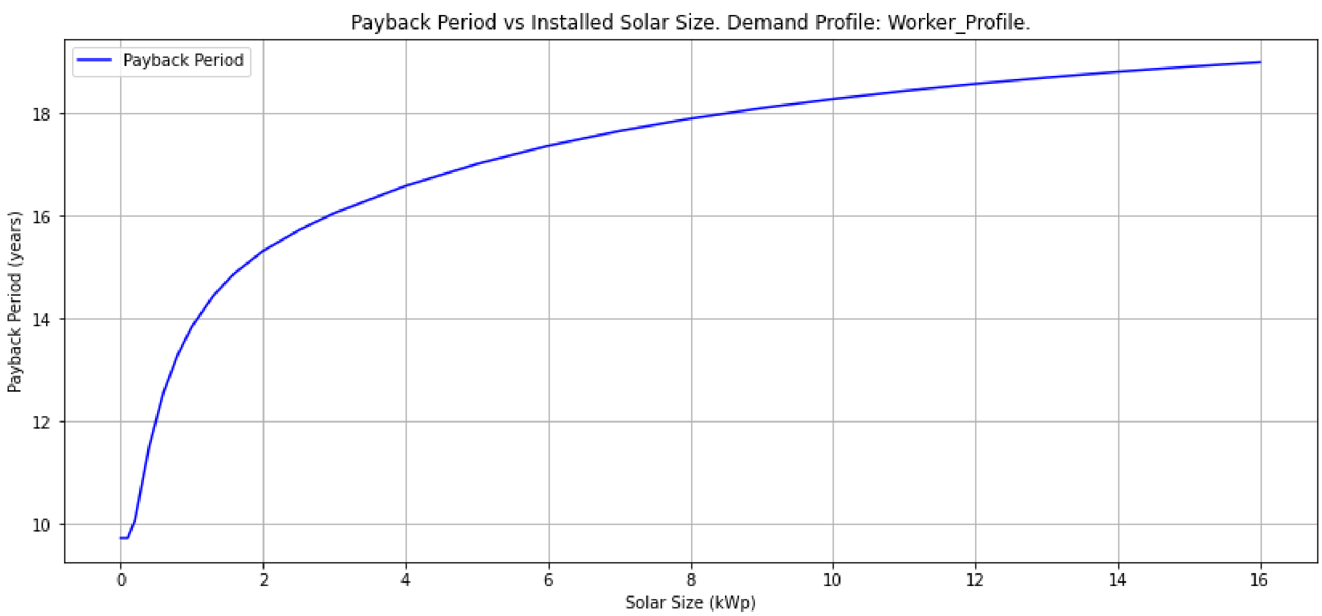


Figure 23 Payback period with different installed solar size, Solar profile.

6.2.3 Overview of energy distribution

This plot aims to visualize how the installation of different solar sizes impacts the amount of energy bought and sold from/to the grid, see Figure 24 and Figure 25. The orange line indicates the amount of energy that must be purchased from the grid. In the Solar Profile, the demand from the grid begins to plateau at 10kWp when it reaches 4000 kWh. On the other hand, in the Worker Profile, the orange line remains relatively flat at all stages, demonstrating a consistent need to purchase energy from the grid regardless of the solar size.

The green line represents the amount of energy sold to the grid. In the case of the Solar Profile, as much as 8000 kWh is sold back to the grid when the solar size is at 10 kWp. Interestingly, the Worker Profile sells even more, over 10,000 kWh, back to the grid. Lastly, the blue line shows the net demand from the grid. This line is identical for both profiles, meaning Solar and Worker Profiles could achieve self-sufficiency in a ideal world with a solar sizes above 7 kWp. But in this result, a solar system producing enough electricity to have a net demand of zero, still purchase 54% of demand with solar profile and 83.7% for the worker profile. With a solar size half of that at 3.5 kWp, the solar profile uses 74.22% of electricity produced locally while worker profile uses 24.78%.

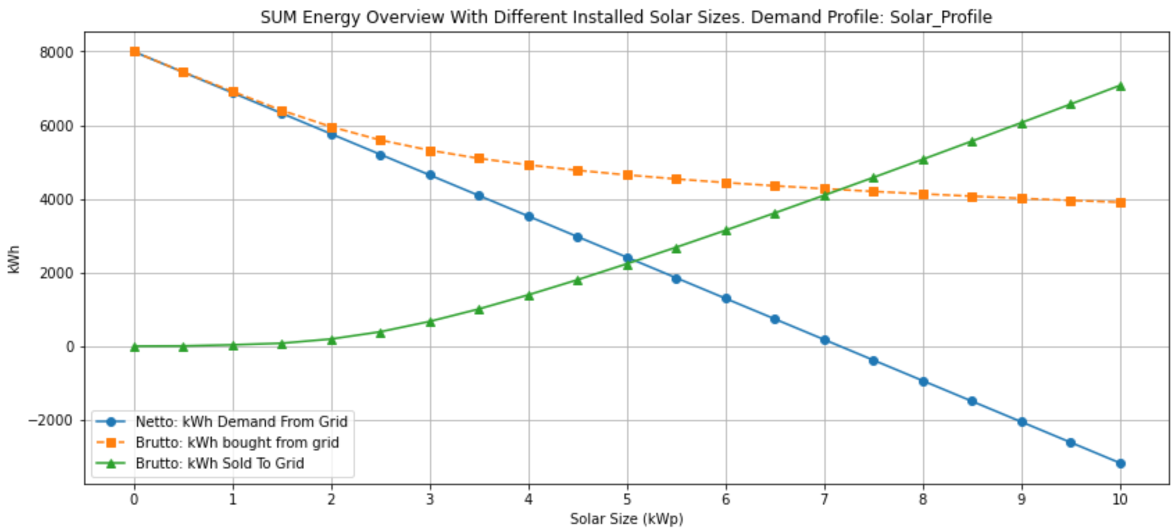


Figure 24 How different installed solar sizes influences the energy balance, for solar profile.

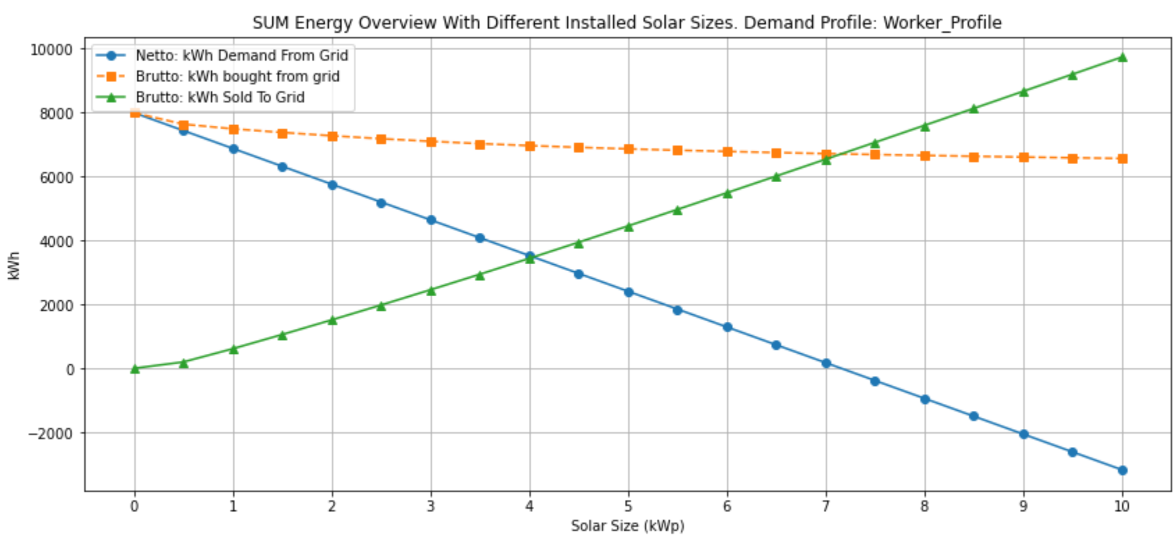


Figure 25 How different installed solar sizes influences the energy balance, for worker profile.

6.2.4 Optimizing with different solar system cost

The objective of this optimization section is to identify the optimal solar size given variable costs for annual solar cost. This analysis was conducted using the optimizer strategy as illustrated in Figure 26 and Figure 27. The blue line is the optimal size, which is constrained from 0 to 20 kWp, indicating that the optimization program cannot purchase more than 20 kWp. The red line represents the total net cost and shows that the model will not invest in solar when the annual cost approaches 1200 NOK/kWp. However, when the annual solar cost decreases to 600 NOK/kWp, the model maximizes solar investment.

When comparing the two figures, it becomes apparent that the worker profile does not show significant interest in purchasing solar until the annual price of solar drops to around 700 NOK/kWh, while the 'solar' profile shows a gradual increase in willingness to invest as solar costs decrease.

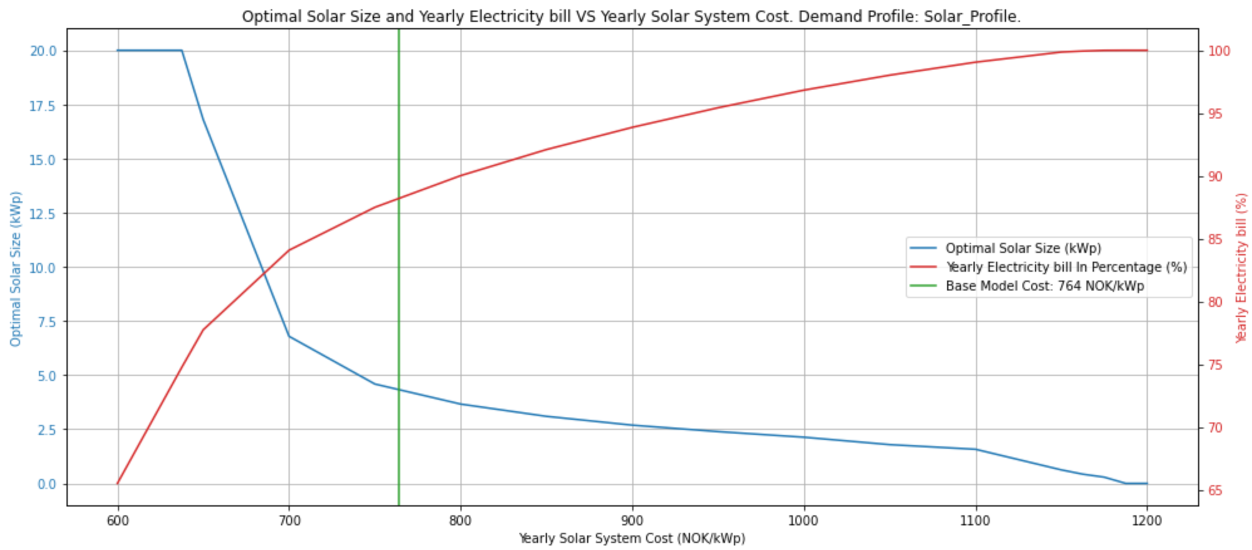


Figure 26 Optimized investment in solar size with different annual solar system cost for solar profile.

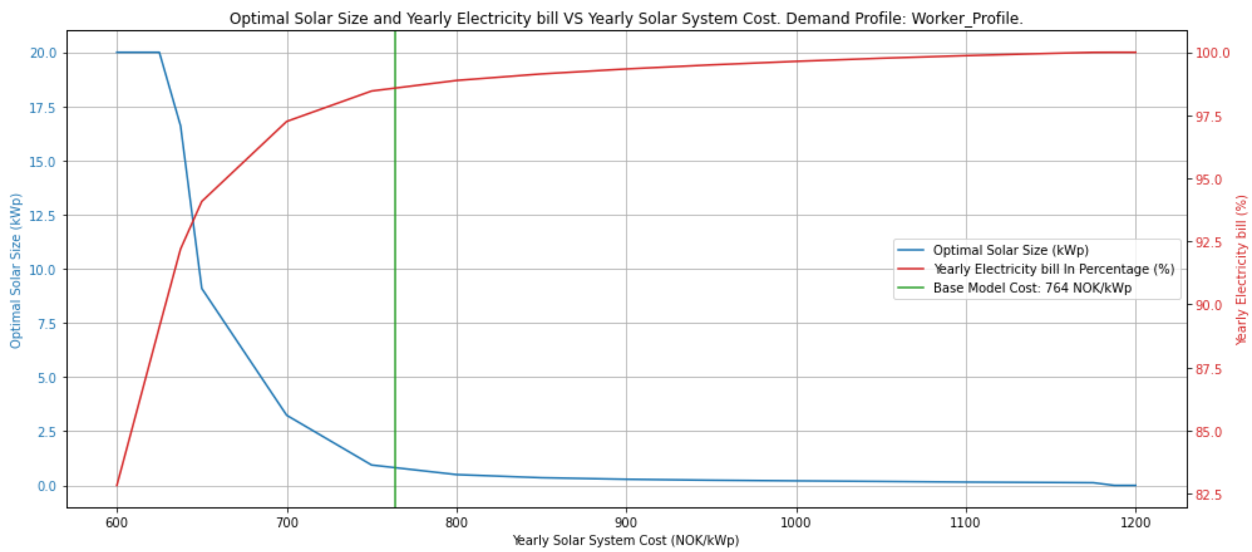


Figure 27 Optimized investment in solar size with different annual solar system cost for worker profile.

6.2.5 Optimization Decisions

To understand when the model opts for maximum solar investment, the Levelized Cost of Electricity (LCOE) is a key factor. Using a solar system cost per kWp set at 8200, coupled with yearly operation & maintenance costs at 1.5% of the solar system cost and a capacity factor of 12.75% (from the 2018 weather data). Discount rate is set to 4% with an annual degradation for solar panels at 0.05%. Using all these factors and LCOE formula (1), the LCOE is calculated to 0.5608 NOK/kWh. Equivalent annual cost is 626.4 NOK/kWp with formula (3). By using the normalized electricity price from 2018 at 0.485 NOK/kWh, where the mean value of each kWh produced is 0.5113 NOK/kWh. Additionally, there's a compensation of 0.05 NOK/kWh from the grid operator for loss reduction.

Given this data, the following relationship explains the model's decision to maximize solar investment:

$$LCOE < Mean\ sale\ price\ to\ grid(mean\ value\ each\ kWh\ produced + reducing\ grid\ losses)$$
$$0.5608 < 0.5113 + 0.05 \quad (13)$$

Meaning:

$$Difference = 0.5613(Mean\ sale\ price\ to\ grid) - 0.5608(\mathrm{LCOE}) = 0.0005\ \mathrm{NOK/kWh} \quad (14)$$

Because LCOE is lower than the mean sale price to the grid, the model then understands that every increase in kWh produced means 0.0005 NOK/kWh more money made. Essentially, the cost of producing an average kWh is lower than the average selling price.

Conversely, if the solar system cost is set to 15600 NOK/kWp, the resulting LCOE becomes 1.067 NOK/kWh, and the annual cost of each kWp rises to 1192 NOK. Assuming mean grid delivery fee for when the solar system is at 0.4176 NOK/kWh, because the solar system is mostly producing electricity from April to December at daytime. In this scenario, the equation explaining when the solar system is too expensive is as follows:

$$LCOE > Buying\ electricity\ from\ grid\ (mean\ value\ each\ kWh\ produced * VAT + grid\ delivery\ fee + certificate\ fee)$$
$$1.067 > 0.5113 * 1.25 + 0.4176 + 0.01 \quad (15)$$

Meaning:

$$Difference = 1.067(LCOE) - 1.0667(buying\ electricity\ form\ grid) = 0.0003\ NOK/kWh \quad (16)$$

A LCOE in this case is higher than the cost of purchasing electricity from the grid including all fees, meaning the model wants zero investment in a solar system. In other words, it's more economical to buy electricity from the grid than to spend 1192 NOK/kWp per year, which is derived from a discounted upfront cost of 15600 NOK/kWp. Therefore, the model will choose not to invest in solar under these circumstances.

For instances where the LCOE lies between the grid's selling and buying prices (in this case, a LCOE between 0.5608 and 1.067 NOK/kWh), the model's investment decisions are swayed by the proportion of locally consumed electricity and the solar system's cost.

In summary, the model maximizes investment in solar if upfront cost is less than 8200 NOK/kWp. From 8200-15600 NOK/kWp, the model invests in solar based on how much electricity is consumed locally and where in the span the solar system cost is. If the solar cost is higher than 15600 NOK/kWp, the model will simply not buy any solar system, since this is the point where only buying electricity form the grid is cheaper.

6.3 Comparing demand profiles and peer to peer limitation

Consider a multi-unit building composed of two distinct entities, one with a solar profile and the other with a worker demand profile. This section delves into the implications of their merger on the optimal solar solution and the propensity to invest in solar power.

The analysis begins with solar- and worker profile being individually optimized, each having an annual electricity consumption of 8000 kWh, look

Table 6. These profiles are then combined in the worker + solar column. Subsequently, the combined system, termed as Middle Ground, is optimized with a total annual consumption of 16000 kWh, which is essentially the cumulative of the two individual profiles.

Table 6 Comparing optimal solution from worker- and solar profile against whole system.

Demand profile	Unit	Solar Profile	Worker Profile	Worker + Solar	Middle Ground	Difference
Yearly electricity demand	kWh	8000	8000	16000	16000	0
Total cost	NOK	7160	7858	15017	14820	197
Total cost without solar	NOK	8113	7968	16081	16081	0
Percentage of original bill	%	88	99	93	92	1.22
Solar capacity installed	kWp	4.30	0.75	5.05	5.95	-0.90
Solar energy produced	kWh	4799	841	5640	6651	-1012
Solar energy sold	kWh	1629	402	2031	2390	-359
Space on roof needed	m²	23.7	4.1	27.8	32.7	-4.9

Table 6 highlights the variations in results. The difference of 197 NOK is attributed to the system's inability to sell electricity directly to the neighboring unit and the enhanced willingness to invest an additional 0.9 kWp in solar, upon merging the units.

For a more direct comparison, each profile is manually adjusted to have a solar installation size equating to half of the 5.95 kWp, as observed in the Middle Ground from

Table 6. This adjustment allows for an examination of the effects of equal solar capacities across each demand profile.

Table 7 Result when worker- and solar profile both have solar capacity installed set to half of system installation size: 2.98 kWp.

Demand profile	Unit	Solar Profile	Worker Profile	Worker + Solar	Middle Ground	Difference
Yearly electricity demand	kWh	8000	8000	16000	16000	0
Total cost	NOK	7216	7940	15156	14820	336
Total cost without solar	NOK	8113	7968	16081	16080	0
Percentage of original bill	%	89.94	99.65	94.25	92.16	2
Solar capacity installed	kWp	2.98	2.98	5.95	5.95	0
Solar energy produced	kWh	3323	3323	6646	6646	0
Solar energy sold	kWh	654	2432	3086	2390	770
Produced energy used locally	%	80.3	16.2	53.6	64.07	10.47
Space on roof needed	m²	16.4	16.4	32.7	32,7	0

As can be seen from Table 7, certain changes are noticeable. Particularly, the worker profile achieves marginal savings from the 3 kWp solar installation, accounting for 99.68% of the original cost. This can be partially attributed to the sale of 2681 kWh out of the 3323 kWh produced, rather than using it for self-consumption. The most significant finding, however, is the total cost difference of 336 NOK, indicative of the lost revenue due to the absence of intra-building electricity trading.

6.3.1 Net Demand of Worker- and Solar Profiles with Same Solar Installation Size

To visualize the variation in different demand profiles over the year, we examine Figure 28, which includes both profiles, each with 2.98 kWp of solar capacity installed. In these plots, the red line represents the solar profile, and the blue line represents the worker profile. Each line signifies the net demand, defined as the electricity demand from the grid minus the electricity generated from the solar system. If the solar system generates more electricity than the demand, the net demand becomes negative, indicating that the prosumer is selling energy back to the grid. The overall view of the net demand appears quite blocky due to many points and daily variations into a smaller scale. Nevertheless, it offers valuable insights into the general trends: the solar profile typically clusters towards the center, while the worker profile exhibits dramatic fluctuations, painting the background blue.

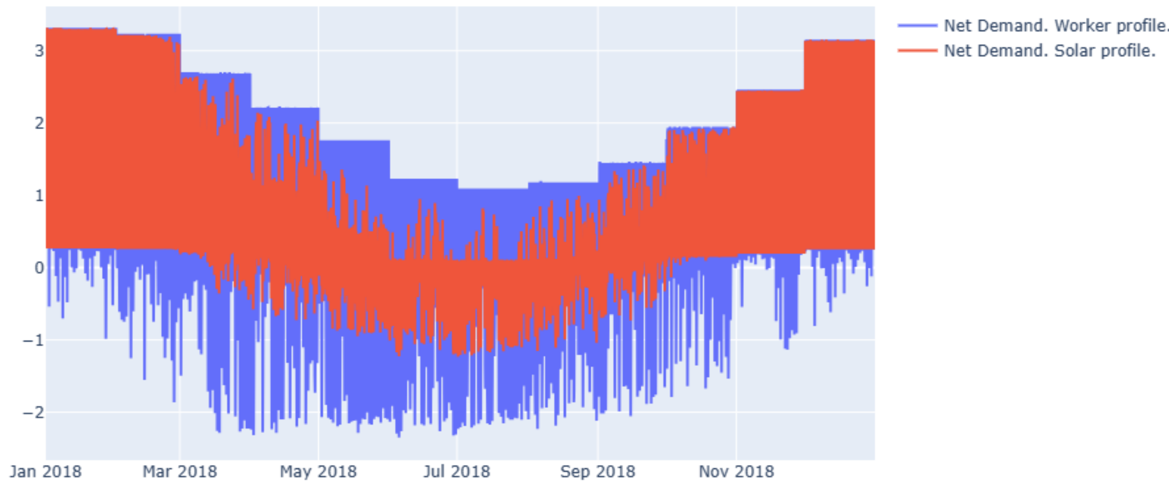


Figure 28 Net demand for worker- and solar profile with a yearly demand of 8000 kWh and 2,98 kWp installed solar system.

Taking a closer look at the first two days of the year at Figure 29, it's evident that the worker profile is compelled to sell its surplus energy production because its generation exceeds its demand. On the other hand, the solar profile still requires additional energy.

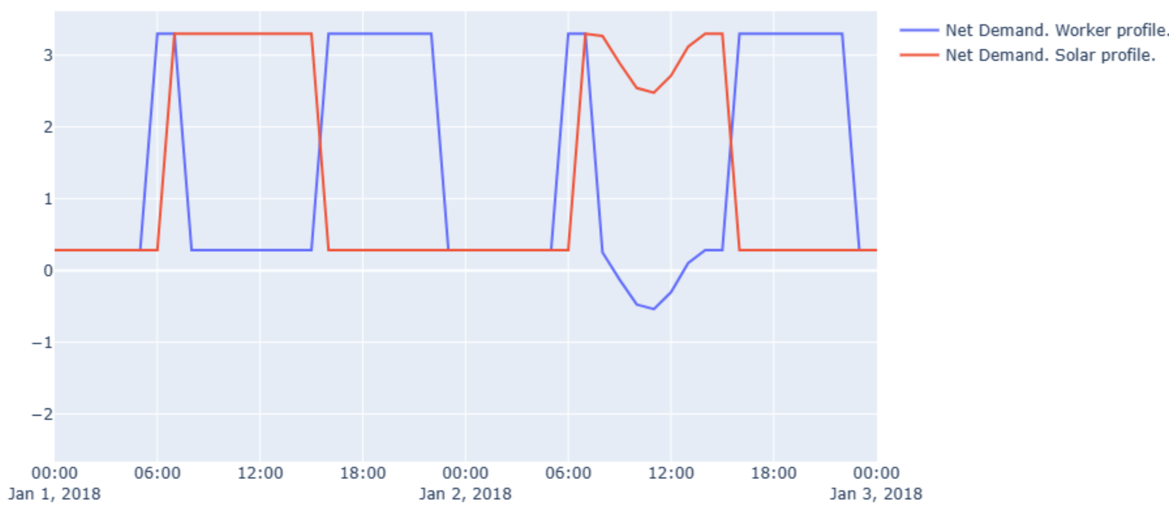


Figure 29 Net demand for worker- and solar profile at 1-2 January using 2018 data.

Observing the data for 31 March and 1 April at Figure 30, it becomes clear that the grid demand of the solar profile is lower than that of the worker profile. This is the time of a monthly shift, where the demand reduces as the summer months are closing in. Notably, the net demand line dips below zero around 11:00 on 1 April, signaling surplus generation. Meanwhile, the worker profile only covers a portion of its demand in the morning, subsequently selling nearly all the energy produced back to the grid.

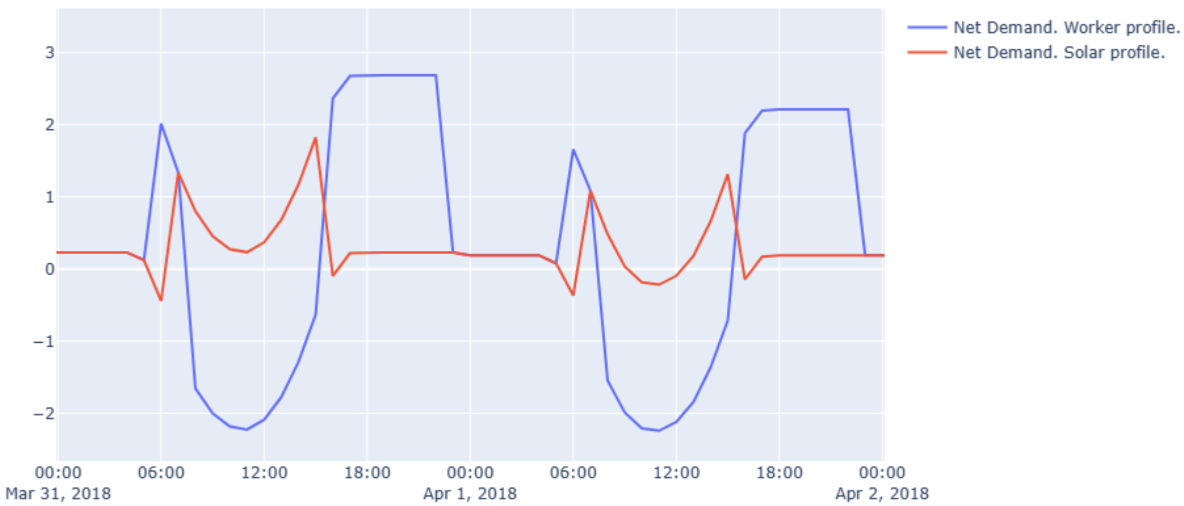


Figure 30 Net demand for worker- and solar profile at 31 March and 1 April.

The following figure, which captures a snapshot from 30 June to 1 July at Figure 31, represents a period of typically high energy production and low demand due to reduced summer consumption. During this period, the red line (solar profile) consistently exhibits a net demand below zero from around 5:00 to 18:00 on both days. While it's positive to see that the worker's demand is largely covered early in the morning and somewhat in the afternoon, the variable load post-18:00 remains largely unaffected.

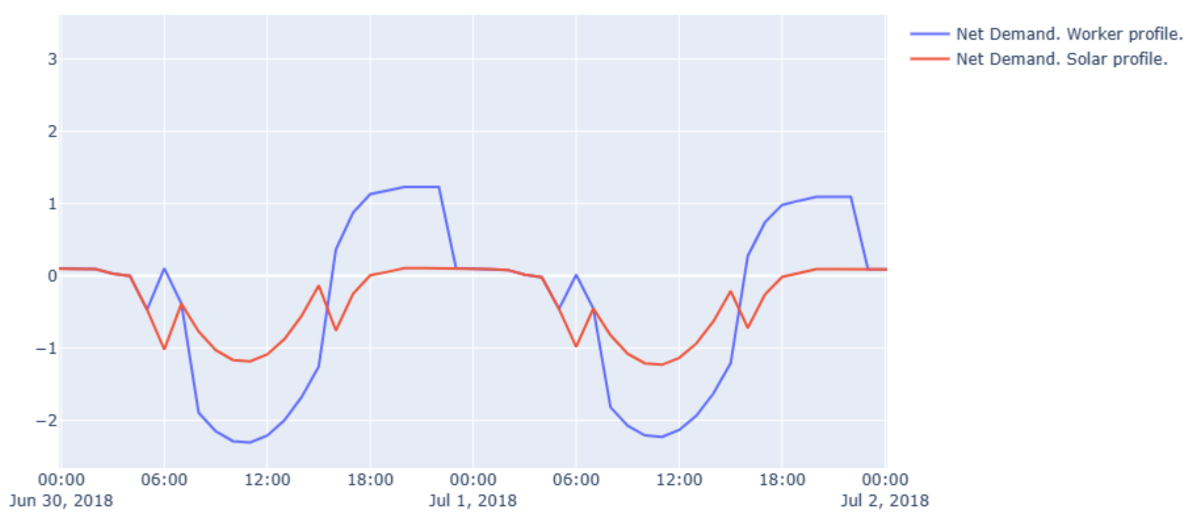


Figure 31 Net demand for worker- and solar profile at 30 June and 1 July.

6.4 Sensitivity analysis

Given that our model comprises several inputs, each of which can significantly impact the profitability of the solar investment, it is beneficial to examine the influence of different assumptions or inputs. There is focus on parameters such as tilt, azimuth, electricity price, capacity factor, and solar installation cost.

The yearly demand is directly proportional to both the optimal solar system size and the percentage reduction in electricity bills. Therefore, varying this parameter will not provide novel insights. So, if you're interested in a yearly consumption twice or half of the base input of 8000 kWh, you can simply imagine the results multiplied or halved, respectively.

6.4.1 Historic electricity price

To show the yearly potential that could be achieved using historic electricity prices from 2017 to 2022 in bidding zone NO1. On top of highlighting the difference between mean electricity price to the mean value of the energy produced by the solar system. The shapes of the electricity price can be found at Figure 12.

Presenting Figure 32 for the solar profile. This profile indicates willingness to invest in solar capacity for every price year except for 2020, which is understandable considering the mean solar value was measured at 0.06 NOK/kWh.

On the other hand, the worker profile Figure 33 shows some willingness to invest in 2018 and 2019 and a considerably larger investment in 2021 and 2022, corresponding with the significant increase in electricity prices from 2021 onwards.

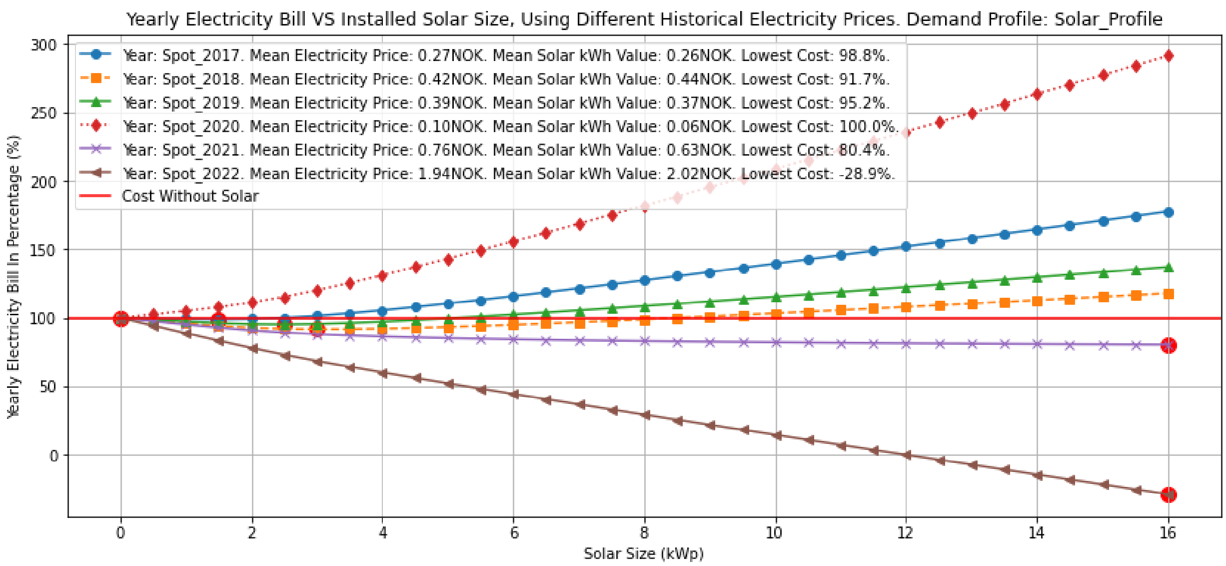


Figure 32 Yearly electricity bill with different installed solar size using differing historical electricity prices, for solar profile.

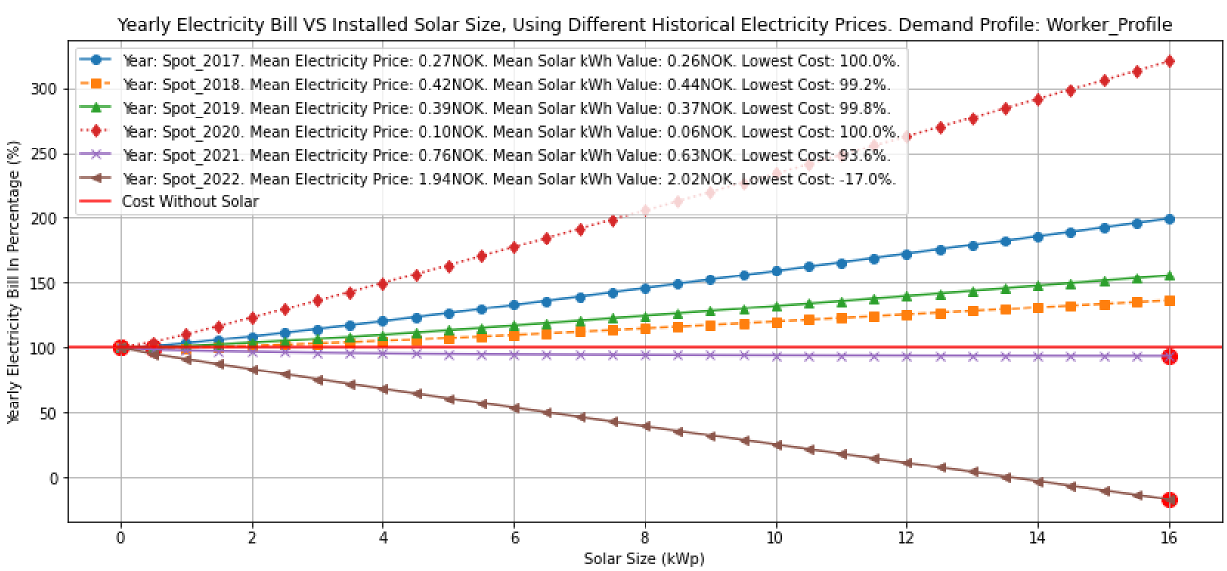


Figure 33 Yearly electricity bill with different installed solar size using differing historical electricity prices, for worker profile.

6.4.2 Normalized Historic electricity price

To enhance comparability across different years, all historic electricity prices are normalized to a constant value of 0.485 NOK/kWh, meaning all years have equal average price. To see the normalized historical electricity price shape, see Figure 13. The key difference to note in this normalized scenario lies in the mean solar kWh value, which ranges from 0.31 NOK/kWh to 0.51 NOK/kWh. If they had same mean solar value, then all the curves would be identical.

Looking at the different years in Figure 34 and Figure 35 shows just how just how much the shape of the price year matter. Since solar power produces most electricity in the summer, then having as high as possible electricity price in that period is very beneficial.

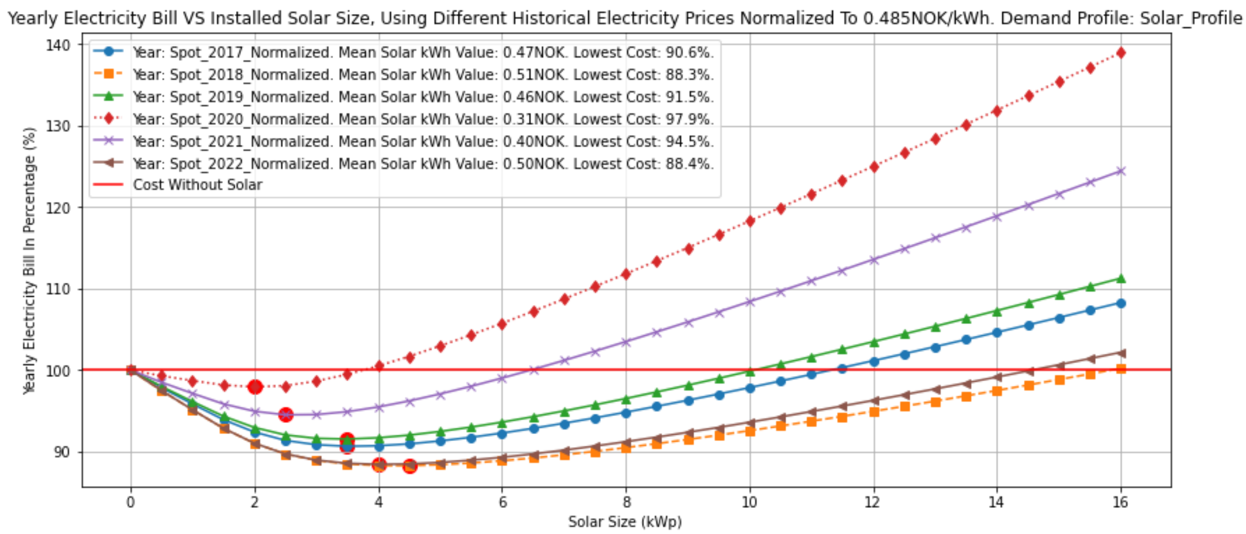


Figure 34 Yearly electricity bill with different installed solar size using differing normalized historical electricity prices, for solar profile.

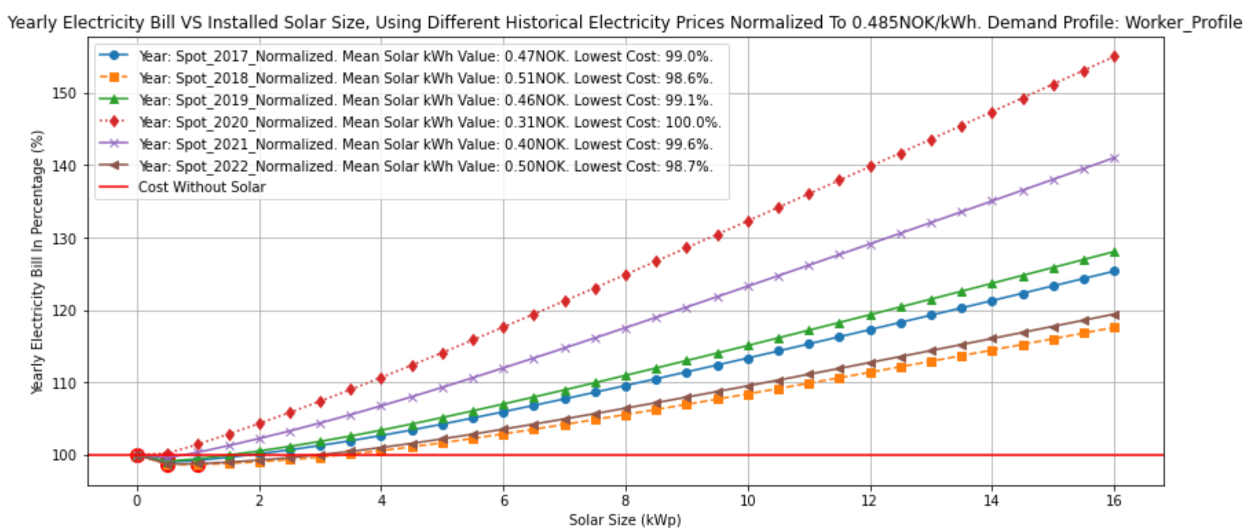


Figure 35 Yearly electricity bill with different installed solar size using differing normalized historical electricity prices, for worker profile.

6.4.3 Scaled electricity price

To better understand the influence of electricity prices on the willingness to invest in solar energy, the original electricity price input is multiplied. Looking at Figure 36 and Figure 37 the curves have a distinctly different shape when the electricity price is increased by 30%, lowered 30% and 60%. Lowering the electricity price by 60% makes it so that the total cost is higher than the original electricity bill even from the start and later doubles the cost when solar size is approaching 12-14 kWp. Having a 30% higher electricity price makes the model want to maximize investment in solar, as an average sale price of 0.66 NOK/kWh in this case high enough even selling excessive amount of electricity to the grid is profitable.

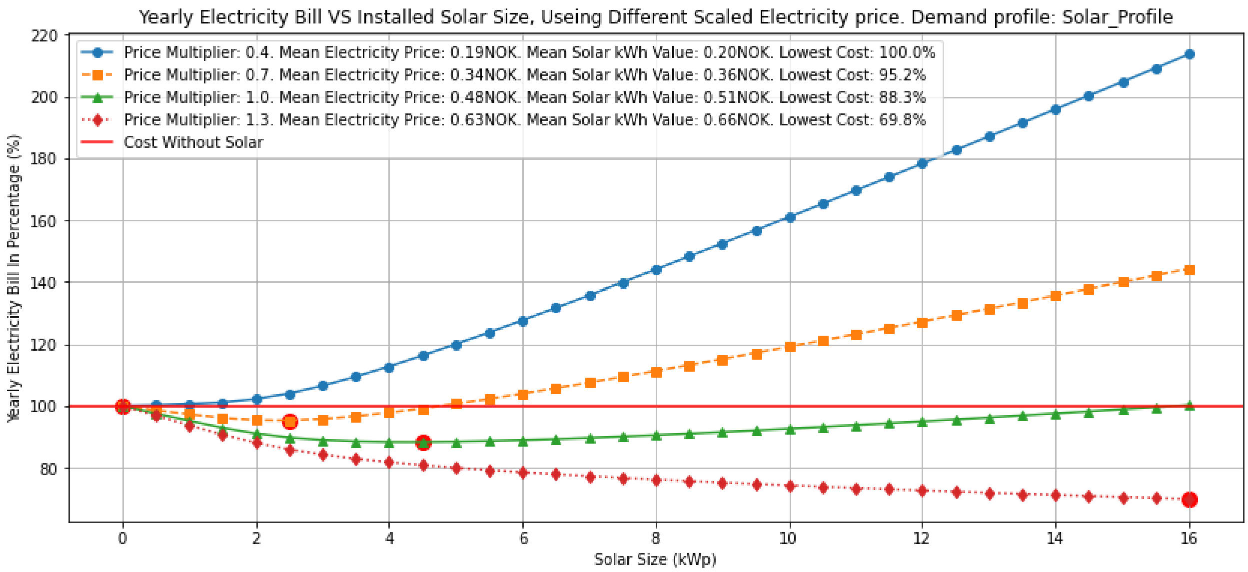


Figure 36 Yearly electricity bill with different installed solar size using differing scaled historical electricity prices, for solar profile.

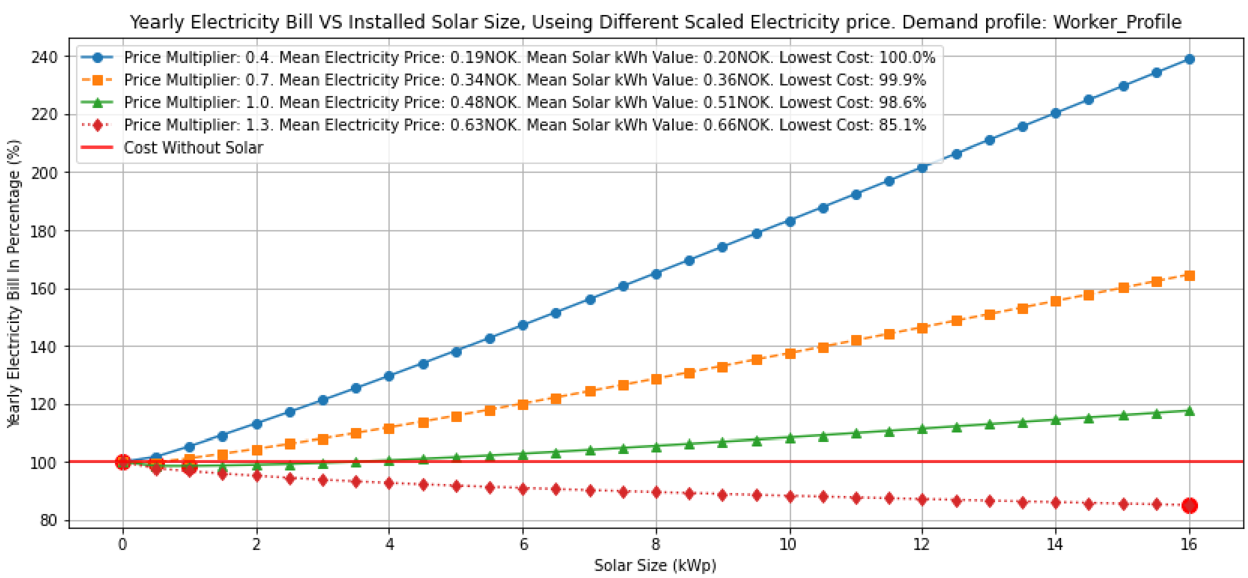


Figure 37 Yearly electricity bill with different installed solar size using differing scaled historical electricity prices, for worker profile.

6.4.4 Azimuth

To find the influence of azimuth angles on the net total cost and energy production (CF), different weather data iterations were executed using an API to the renewable ninja website. Each iteration adjusts the azimuth angle by 30°. It should be noted that 90° corresponds to east, 180° to south, and 270° to west.

For the solar profile Figure 38, it's observed that shifting the angle 30° west or east from 180° does not significantly alter the willingness to invest in solar. However, rotating the azimuth by 90 degrees in any direction reduces the profitability of investing in a solar system larger than 4 kWp. Meanwhile Figure 39 representing the worker profile barely reduction in the electricity bill with a solar size no larger than 0.5-1 kWp.

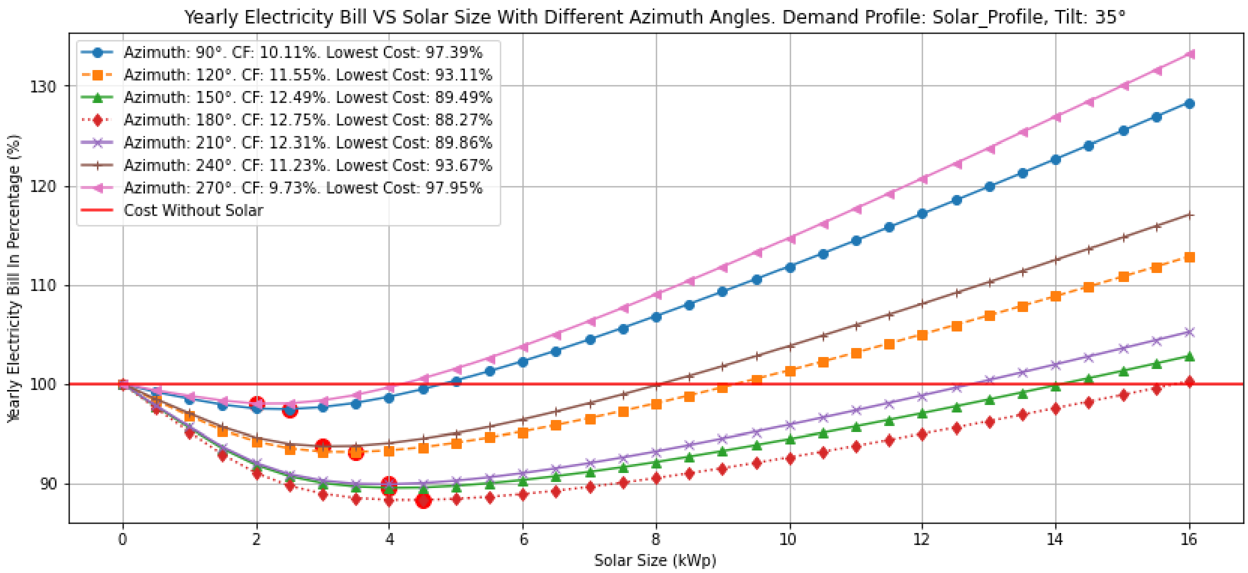


Figure 38 Yearly electricity bill with different installed solar size using differing azimuth angles, for solar profile.

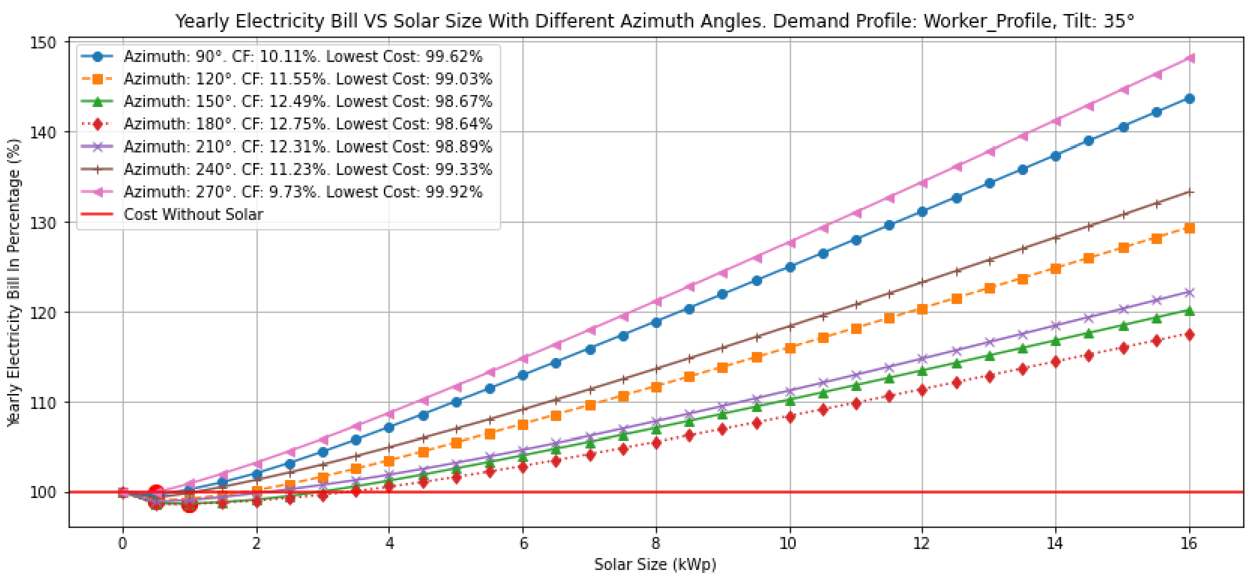


Figure 39 Yearly electricity bill with different installed solar size using differing azimuth angles, for worker profile.

6.4.5 Tilt

In order to assess how varying tilt angles, influence the energy production, different tilt angles are examined using an API. Observing Figure 40 and Figure 41 the tilt with 45° has best performance as expected while 90° and 0° has the worst.

The performance for the solar panels with 90° and 0° tilt maintain a capacity factor of around 10% compared to the optimal 12.8% with 45° tilt.

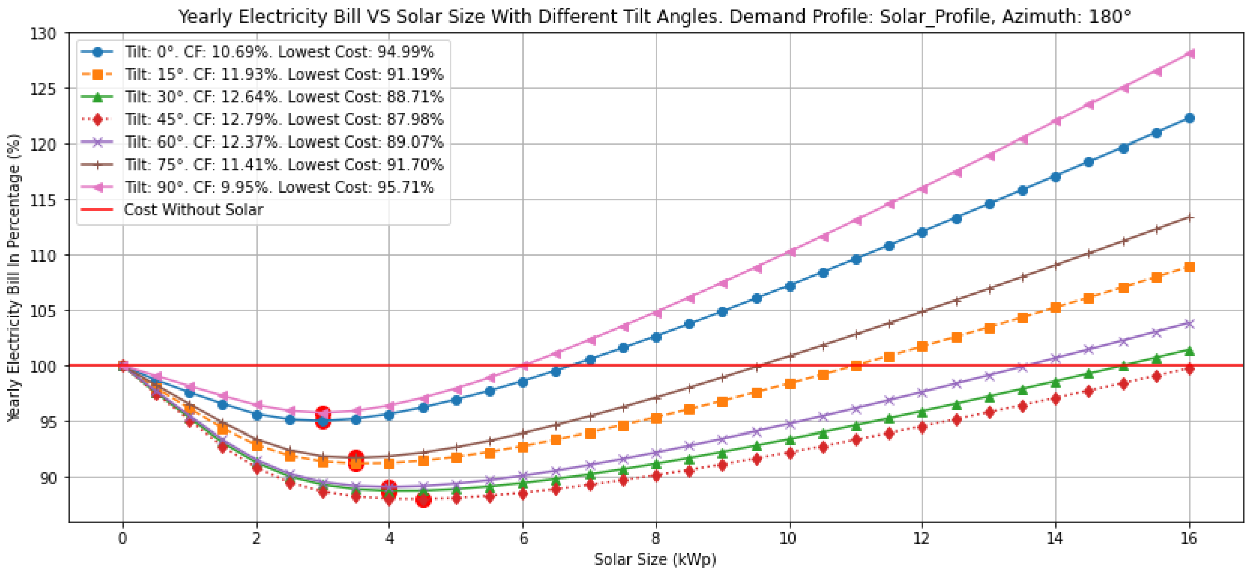


Figure 40 Yearly electricity bill with different installed solar size using differing tilt angles, for solar profile.

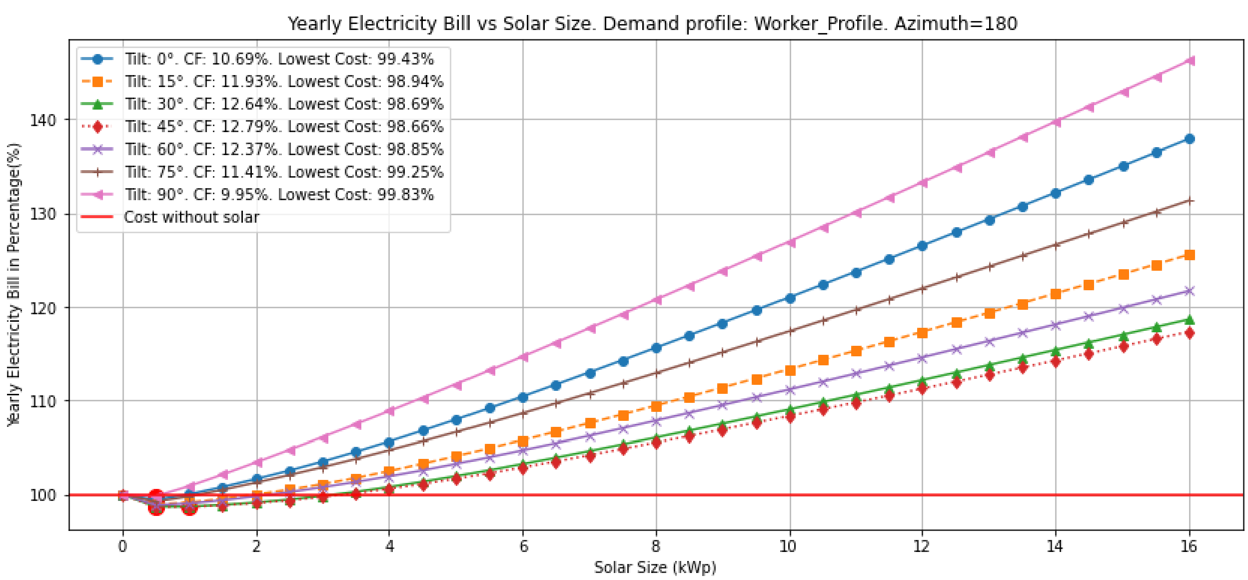


Figure 41 Yearly electricity bill with different installed solar size using differing tilt angles, for worker profile.

7 Discussion

In this chapter, I reflect upon the findings of the analysis and delve into the economic and energy efficiency implications of solar installation under different demand profiles. The results from the optimization model reaffirm that the investment in solar power can indeed yield a reduction in the yearly electricity bill.

The difference in outcomes for the Solar Profile and Worker Profile emphasizes the importance of aligning consumption patterns with solar generation hours. Figure 24 shows that having a good match between consumption and energy production can reduce more than 50% of the electricity bought from the grid with a solar system at 10 kWp. Meanwhile the worker profile could only reduce their consumption from the grid by around 17%, with a 10 kWp solar system.

Experimenting with different solar sizes showed that while the Solar Profile could handle a large solar installation, the Worker Profile struggled to maintain even a moderate-sized system for being profitable. This highlights the need for optimizing the size of the solar installation based on individual consumption patterns.

When evaluating the influence of solar system cost, it is evident that investment decisions heavily lean on the costs of the solar system and the electricity price from the grid. The model is designed to maximize solar investment when the cost per kWh of solar production is less than the mean value of electricity from the grid.

Comparing different demand profiles, the merged profile system results in a further reduction of the electricity bill, suggesting a collective approach to solar power in multi-unit buildings might be more cost-effective. However, the lack of local electricity trading reduces the potential savings, implying that changes in local energy regulations could enhance the economic benefits of solar power in such settings.

7.1 Optimization Decisions

The model's decision regarding solar investments becomes evident when considering the Levelized Cost of Electricity (LCOE) and other related costs. If the LCOE of a solar system is lower than the price from selling electricity to the grid, the model will maximize investments in solar. Because on average each kWh extra produced is more money, even when it's sold directly to the grid. Conversely, if the LCOE is higher than the price of buying electricity for the grid, the model will prefer to buy electricity from the grid.

In cases where the LCOE is between the selling and buying prices of the grid, the decision gets a bit more tricky. During these times, the model checks how much of the electricity is used locally. This when the importance of the demand profile comes in. With a higher portion of the electricity produced is utilized within the building, residents can avoid purchasing electricity from the grid at potentially higher prices, because of grid fees and VAT.

7.2 Peer to Peer Limitations

When optimizing each demand profile separately, the worker profile's ideal solution is found at 0.75 kWp, and the solar profile's is at 4.3 kWp. Combined, these profiles could result in savings of 197 NOK. This is attributed to instances where both units could mutually benefit by buying locally-produced energy from each other during periods where one resident has a excess production. If both units installed a solar capacity of 2.98 kWp, potential savings from this dataset amount to 336 NOK. Given a yearly consumption of 8000 kWh and an electricity bill ranging between 7216-7940 NOK, splitting the 336 NOK savings between two residents equates to a 2.1-2.3% reduction. While this might appear modest, over a solar systems typical 30-year lifespan, each resident stands to save approximately 5040 NOK.

7.3 Comparing Demand Profiles

For a solar system to be most beneficial, it's ideal for the net grid demand to be as close to zero as possible. Net grid demand is calculated by electricity demand from the grid subtracted by the electricity generated from the solar system. A net demand around zero means that most of the consumption is covered, or not a lot of excess electricity is sold to the grid for a lower value when net demand is just in the negative. However, finding a perfect solar size isn't easy. Trying to fit the solar size to cover the demand in summer would lead to a small solar size, as it's in the summer that solar production is highest, and the demand is lowest. A bigger solar system could cover the energy demand in months in spring and autumn, where the demand is also higher.

Referring to Section 6.3.1, where both Solar and Worker Profiles are equipped with a 2.98 kWp installation, it becomes evident how important the demand profile is. The solar profile sells just 21.6% of its generated energy, in contrast to the worker profile's 80.7%. This disparity clarifies the 11% yearly cost reduction for the solar profile, as opposed to the worker profile's mere 0.35% reduction. With an 8000 kWh annual consumption, the solar profile reduces its grid dependency by 32.6%, whereas the worker profile manages only an 8% reduction.

7.4 Electricity Markets Influence on Solar Investment Decision

Making a decision to invest in solar based on analyzing and predicting the electricity market is no easy matter. Currently, only around 483 MW[7] is installed in Norway, suggesting a significant potential for expansion. However, several factors must be considered when trying to predict electricity demand, energy generation, and consequently, electricity prices. Traditionally, the demand side has been relatively inflexible, but the recent surge in electricity prices may have caused people to pay closer attention to power prices.

Looking at week 20 2023, at Attachment 1 there is a snapshot of electricity prices in Norway, while also showing Norway power generation. In a country like Norway where a lot of the power production can be regulated, it makes sense that the electricity price has a similar shape to the energy demand curve. Because higher electricity demand dispatches more powerplants with a higher sale price setting the spot price. But there are instances where the electricity price crashes down to zero or even below.

Interestingly, Norway's demand does not vary significantly throughout the day or week (Attachment 2). In the same week, it ranged from 11,000 MW to 14,000 MW, a variation of around 10% from the average demand of 12,500 MW. Despite this, there is little to no visible power generated from solar, indicating a significant opportunity for solar installation. However, the interconnectedness of Norway with neighboring countries complicates this analysis. For example, power generation in Norway sometimes drops by almost 50%, from around 15,000 MW to 8,500 MW (Attachment 4). This drop is due to the sudden export of power from Germany, the Netherlands, and Denmark to Norway, almost reaching full connection capacity.

This sudden change from Norway being an exporter to an importer of electricity can be partly explained by the overproduction of power from solar and wind from neighboring countries like Germany (Attachment 3). On some days in May, solar production in Germany may reach as high as 35,000 MW, contributing to a net generation of 55,000 MW, while the local energy demand was only around 45,000 MW. This surplus of 10,000 MW is ideally distributed to neighboring countries in need of power. However, such a large surplus can disrupt the surrounding electricity markets, resulting in negative electricity prices in most neighboring countries.

This analysis underscores the complexity of predicting the electricity market and, consequently, the challenges in making solar investment decisions. The interconnectedness of the electricity markets, the unpredictability of energy generation, and the inflexibility of demand all contribute to the difficulty in predicting electricity prices.

7.5 Practical Consideration for Solar size

When considering solar installation for apartment buildings, the available roof space per resident becomes a limiting factor. For example, a building with four 70 m^2 apartments stacked on top of each other leaves only about 17.5 m^2 per resident on the roof, when the roof is divided on four. This space can accommodate a solar installation of approximately 3 kWp, assuming each kWp requires about 5.5 m^2. Alternatively, if there are only two or three units stacked on top of each other, this would allow for a maximum divided installation of 4.5-6 kWp.

Dividing a smaller solar system for each resident will reduce the payback period of the investment, as illustrated in Figure 22 and Figure 23. This is due to the ease of minimizing electricity sold to the grid with a smaller solar system. In practice, having a divided solar size of 200 Wp power production will almost always be locally consumed in a resident, because of electronics like refrigerator, freezer, water heaters and other standby electronics.

It is also important to consider that in practice, a solar system will never produce power at 100% of the panel's rated capacity, as solar panels are rated based on standard test conditions. While Norway's colder climate provides an advantage in cooling down the panels, it is unlikely that they will operate at the low temperature of 25 °C, for which the panels are rated. Norway also has a high latitude, meaning more losses, due to solar irradiance traveling longer in earth atmosphere.

In a multi-residential building, it should be possible to designate one prioritized consumption point, depending on where the intake from the solar system is connected. This prioritized point could offset the consumption from common areas used for heating and lighting, as well as from centralized electrical loads such as central water heaters, ventilation, or other central heating systems. Electric vehicles could also benefit from this approach.

7.6 Limitations of the Study

The study has limitations, including the absence of real data from apartment buildings and data for electricity consumption in common areas in households. These limitations could impact the optimal solar installation size. Future research should consider these factors for a more accurate and comprehensive analysis.

The Solar profile shape was deliberately made simple by just consuming in the hours where the sun is producing most. It could have an even better match with a more curved shape, but then it won’t have fitted good in the sensitivity analysis where the direction the solar system is changing.

7.7 Source Credibility and Reliability

In this study there had been used sources like Elhub and Statnett, NVE and Entso-E, which are key players in the energy sector. I also had some discussions with experts in solar power to cross-verify some information. Some of the other key information sources was the renewable ninja website for weather data, and information about the grid fee system in Elvia.

8 Conclusion

The study revealed several crucial factors that influence the willingness of consumers to invest in solar power, including the payback period, Levelized Cost of Electricity (LCOE), solar system cost, grid fees and the dynamics of energy pricing, both for consumption and back-to-grid sales.

It is important to consider the broader context of interconnected countries, not just local solar installations in Norway. Countries without hydropower and nuclear generation will be compelled to install intermittent energy sources like wind and solar to meet their climate goals. This could lead to a significant increase in solar installations in Europe, at times overproducing too much electricity resulting in free electricity and causing solar owners to cannibalize their own profits.

Rising grid fees always benefit the decision of investing in solar. Because even when the electricity price drops towards zero, there is still a substantial cost getting it delivered to your building. Therefore, a LCOE for the solar system approaching the grid delivery fees helps reduces the electricity bill even with those hours where the price of electricity goes towards zero.

Investing in a solar system as a hedging strategy is also advantageous. A hedging strategy involving solar installation can minimize the risk of unexpected high electricity costs. If electricity prices reach beyond 2 NOK/kWh, a solar system will help offset that. Managing a good risk profile is important in a world full of conflict, cooperation, and individualism.

The results indicate that there are significant differences between having multiple consumers with separate power measures versus a unified system for the entire building. During hours of abundant sunshine, when electricity is being distributed to each resident, a resident with low demand cannot directly sell their surplus energy to a neighbor in need. This problem could be alleviated if all residents were combined into a single unit. For example, merging the Worker and Solar profiles into a single unit could result in savings of 197-336 NOK each year compared to separate units (as shown in Table 6). While this annual saving might not seem substantial, it accumulates over the 30-year life expectancy of a solar system. Although we do not anticipate a short-term solution to this issue, it is something that could be addressed in the future when a shared energy system is implemented.

The advantage of a solar system is tightly tied to its demand profile. A poorly aligned profile, such as that of a grid user absent from the residence between 8:00 and 16:00 (akin to the worker profile), dilutes the potential benefits. Without adding an energy storage system like batteries, a significant portion of generated electricity, produced during peak sunlight hours, is sold to the grid, often at reduced rates. When households begin to participate more in balancing markets, the economic feasibility of integrating pricier batteries with solar systems is likely to enhance, ensuring a more efficient and financially viable energy management strategy.

Overall, installing a solar system in a multi-residential household seems like a low-risk investment. If, on average, each resident gets a shared production of around 3 kWp, it would only cost around 30,000 NOK. With a payback period of 11-16 years depending on the demand profile, and if the azimuth and tilt are not too far off the optimal placement. Ideally, the panels should be facing directly south and have a tilt around 45° degrees for most electricity production, but panels pointing 45° towards east or west from south, or a tilt within 10-75° degrees, are also great. On top of having a value on the solar energy produced of at least 0.4 NOK/kWh on average.

8.1 Future research

It would be beneficial to conduct an analysis and plots with different demand data and maybe use another bidding sone as the input for the electricity price or maybe even a modified one. The model is flexible enough that all it takes is loading in other demand data, electricity price, production data or grid delivery fee and the solver and all plots will be updated.

I did create an optimization model that works with batteries, but quickly realized that market price for batteries are too expensive for the model to invest in them. There was also already so many aspects to dig deep into with just a solar system. But doing some scenarios and sensitivity analysis with batteries would be exciting.

When setting up a battery storage system in a building, several challenges arise. Having a separate battery for each apartment might be costly and could increase risks, such as potential fire hazards. On the other hand, if there's a single large battery for the entire building, a sophisticated system to distribute the power evenly among residents could be need. Additionally, determining the optimal time to draw from the battery's energy is crucial, and residents would need guidance on when best to use their devices and appliances.

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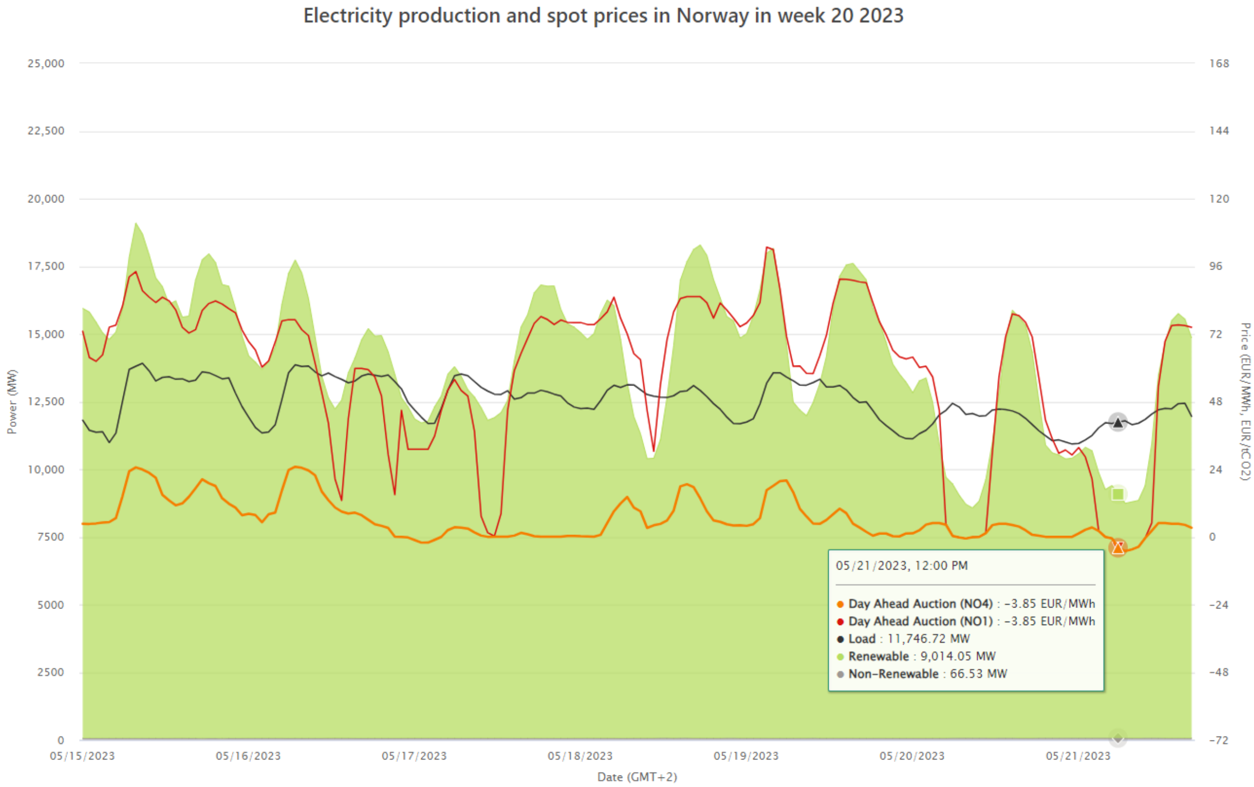
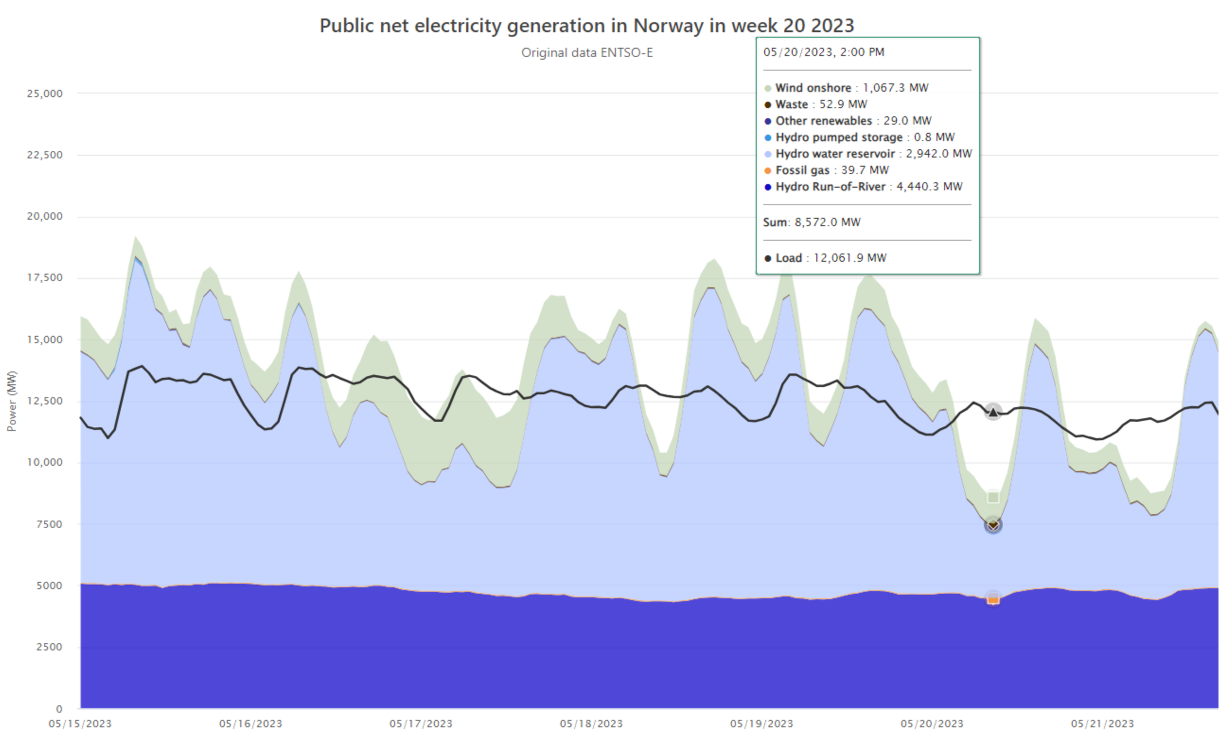
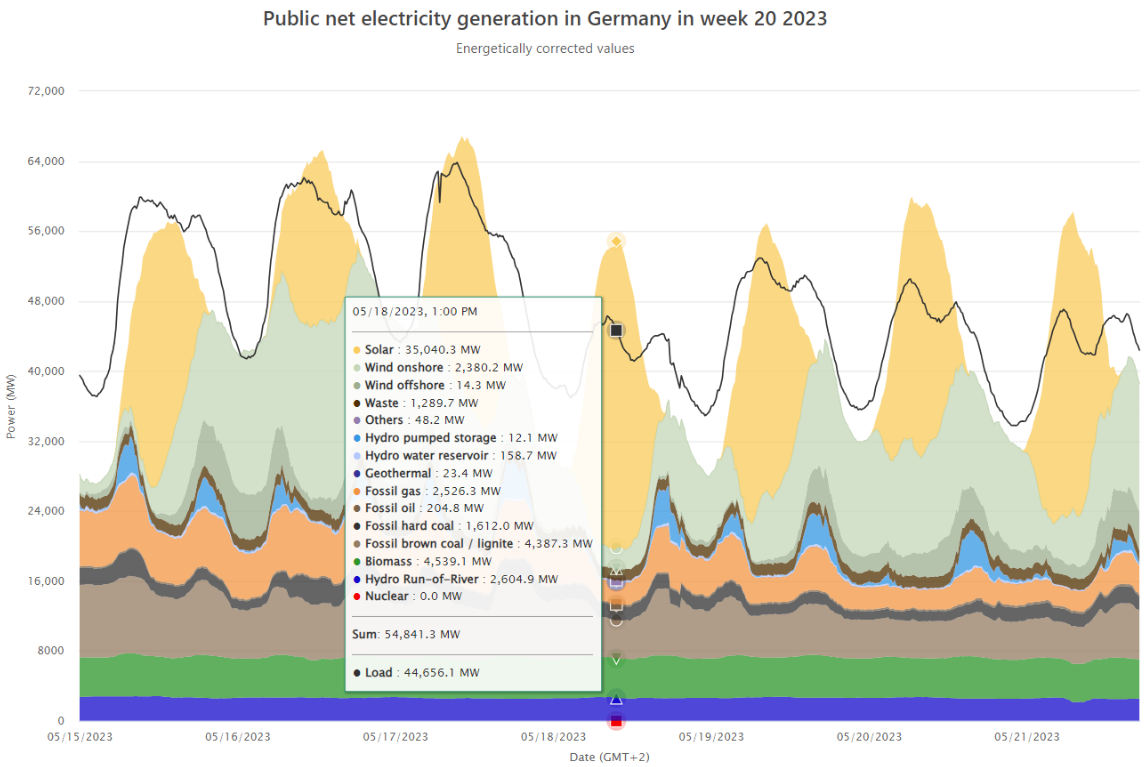
Attachments



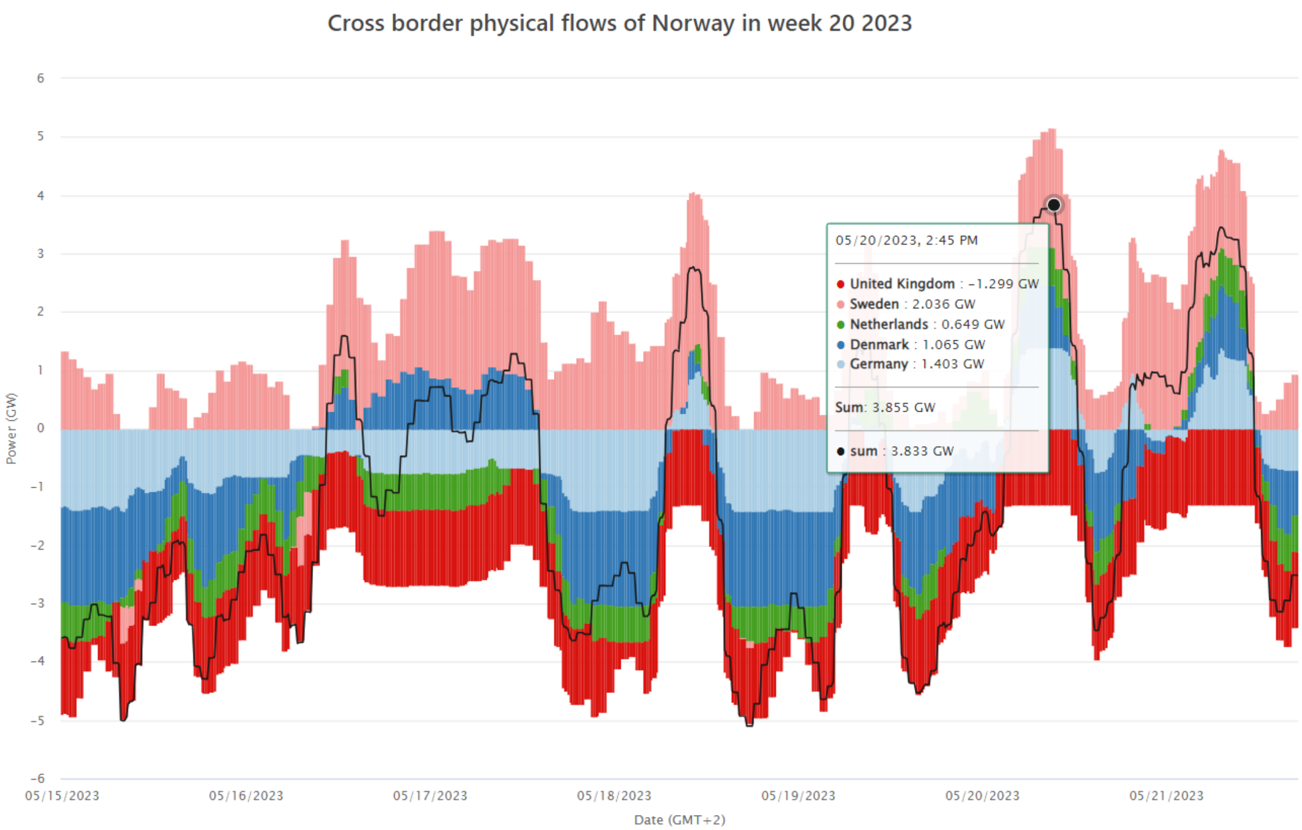
Attachment 1 Electricity price for NO1(South east) in red, NO3(north) in orange. Norway's power production and load in black[42].



Attachment 2 Electricity generation in Norway from different sources together with national load in black[42].



Attachment 3 Electricity generation in Germany from different sources together with national load in black[42].



Attachment 4 Cross boarder physical flow of power in week 20, year 2023[42].