Smart and Sustainable Oskarshamn Harbor Area - Load and Production Optimization

David del Río García

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Abstract

This project explores the possibilities for energy cost reduction and revenue generation for industrial actors in the harbor of Oskarshamn, Sweden. First, a literature review describing the applicable renewable energy technologies, business models, and electricity markets is included. Then, an optimization problem is formulated to get the optimum sizing and an estimation of the economic and environmental gains is solved. Finally, recommendations for the implementation of an energy system that would achieve these gains are given.

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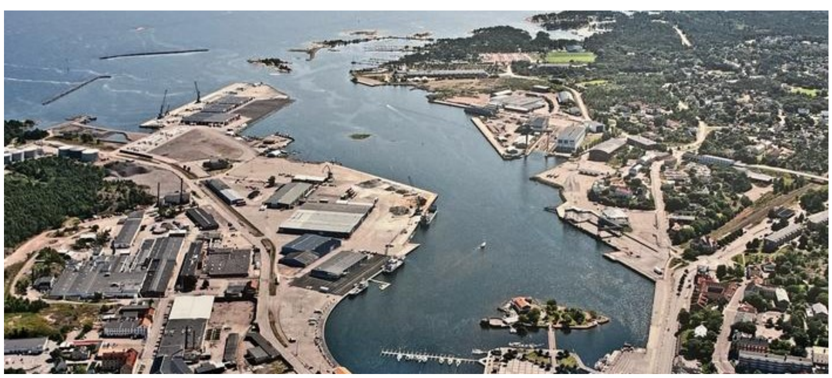

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1 Introduction

1.1 Background

We live at a turning point for the energy industry. Forced by climate change, our energy system is rapidly pivoting towards one characterized by the so-called three D's: *decarbonization*, *decentralization*, and *digitalization*. This revolution is enabled by a diverse mix of solutions, in which renewable energy integration in the energy system belongs to.

Thus, many countries around the world have released, to some extent, targets of renewable energy adoption in their electricity mix. For example, at its National Energy and Climate Plan (NECP), the Swedish government has stated its intention to completely switching to renewable-generated electricity by 2040 [1].

What this mainly implies is that renewable energy is a requirement flowing down from the policy level. However, this imposed necessity is not exactly a bitter one, as adequate planning in renewable infrastructure has been widely proven as a path to dispatch cheaper electricity and reduce carbon emissions.

This project originates from the initiative of a group of industrial actors in search of the most advantageous options for their renewable energy adoption. Solar Photovoltaics (PV) systems are one of the most extended out of these options and have been getting more and more affordable in the last decade [2]. However, simply installing standalone PV systems - or any other intermittent renewable sources -, would not totally displace conventional energy sources, posing problems related to non-dispatchability, voltage control, and frequency disturbances [3]. Thus, to totally displace traditional sources, combining different clean energy technologies in so-called hybrid systems is then required [4].

In this project, the combination of Behind-the-Meter (BTM) PV and Battery Energy Storage Systems (BESS) is evaluated, as per the schematic included in Figure 8. These two technologies complement each other in a very appealing way, mitigating the above-mentioned technical challenges besides offering remarkable economic benefits and enabling a wide array of operational strategies [5] [6].

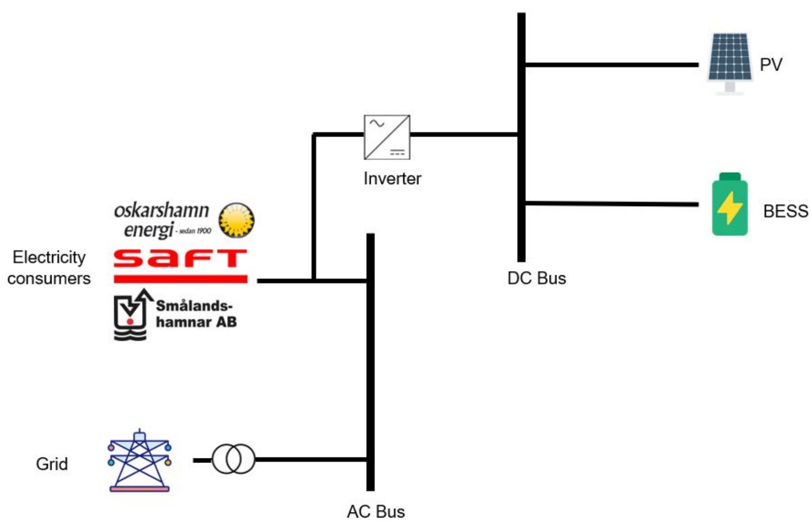

Figure 1: System schematic of the proposed layouts.

1.2 Research questions

The fact that PV and BESS are complementary technologies does not imply the nonexistence of some question marks associated. This master's thesis addresses the following research questions:

1. *What is the optimal size for a BTM PV-BESS system from an economic point of view?*

2. *How much can stakeholders in an industrial setting save on their electricity costs with a BTM PV-BESS installation?*
3. *Which are the most suitable revenue streams for a BTM PV-BESS installation?*

1.3 Objectives and Methodology

To tackle the above questions, the thesis has established the following objectives:

- Perform an optimization to find optimal PV-BESS size scenario
- Analyse and quantify the economic benefits of installing the optimal size
- Assess the possible revenue streams for a PV-BESS installation in Sweden

To build a solid foundation, the project starts with a literature review divided into four relevant main verticals: *Smart City Districts*, *Renewable Energy Technologies*, *Novel Energy Business Models*, and *Energy Optimization*. This review unveils the scarcity of studies determining the optimal sizing and operational strategies for community collective BTM PV-BESS systems in an industrial context.

With the learnings from the literature review, the list of necessary datapoints to cover the research gap was built. These were subsequently gathered from the company stakeholders. Market data was also provided by Svenska kraftnät [7] and Nordpool [8]. All these were cleaned, sorted, and analyzed to find patterns in electricity load and production and serve as input for the following steps.

To find the optimal configuration of the system, an optimization minimizing the electricity cost function for different scenarios is run. The optimization problem is solved using PuLP [9], a Python-based software. The results for the scenarios in the optimizations are then compared against economic and environmental KPIs. This comparison intends to quantify the benefits of each of them, and provides with recommendations for each of the configurations best configuration based on these benefits.

1.4 Project Scope

The thesis circles around a real case study at the harbor area of Oskarshamn, Sweden to tackle the objectives.

Figure 2: Satellite view of Oskarshamn harbor and participating stakeholders in the project.

Three companies with operations in the harbor, in conjunction with the municipality, came together to evaluate possibilities of energy infrastructure installation with potential to reduce their electricity associated costs. The companies are:

Oskarshamn Energi

Co-owned by E-On and Oskarshamn kommun, it is the local Distribution System Operator (DSO). Oskarshamn Energi also owns an entity that operates District Heating (DH) plants in the area. One of these plants, Norra Strandgatan is located in the harbor area, and besides generating heat for the local network it also has a 3.9MW electricity generation turbine, making it a cogeneration plant.

Saft AB

The company is a world leader in Ni-Cd batteries, and was acquired in 2016 by TotalEnergies. It operates a manufacturing plant in the Oskarshamn harbor area, being an important source of employment to the local economy.

Smålandshmamnar AB

It is Oskarshamn harbor operator, and it is owned by the surrounding municipalities.

Despite using a specific case study, the project findings should serve as a baseline for any industrial cluster willing to evaluate common renewable energy infrastructure investments. It can also be a beneficial exercise for DSOs, which can relieve the stress in its infrastructure caused by dramatic renewable installations expansion.

2 Literature Review

This section presents background theoretical information that serves as a foundation for the subsequent steps in the project. The review is divided in four main topics:

- Renewable Energy Technologies
- Smart City Districts and Energy Communities (ECs)
- Novel Energy Business Models
- Energy Optimization

After these topics are reviewed, a justification for the solution proposed in the thesis is provided, with an analysis of the literature gaps to be addressed.

2.1 Renewable Energy Technologies

There are few industries to which one can attribute a bigger degree of innovation during this last decade than renewable energy.

Among all the technologies that have enabled this revolution, Solar Photovoltaic (PV) and Battery Energy Storage Systems (BESS) are the ones chosen for the case study in this project. The rationale for this choice will be presented in Section 2.5, but in summary it can be attributed to their technological maturity coupled to a dramatic price decrease during the last years, which have turned them into widespread devices.

2.1.1 Solar PV

Solar PV converts light from the sun directly into electricity, being a simple, reliable, and almost maintenance free source [4].

The staggering growth in Solar PV installed capacity is represented in Figure 3. From below 1%, Solar PV has grown to represent a 12.8% of the total installed power capacity. It is also expected to be the biggest single source by 2027, with an estimated 22.2% of the total capacity by that year. This growth has been propelled not only by solar-friendly policies, but also by the significant decrease in solar cell prices. These prices are observed to follow what has been called the Swanson's Law, which states that PV modules decrease around a 20% in price for every doubling in the volume manufactured [10]. Figure 4 shows how the cost of PV cells has been dropping following an increase of manufacturing capacity, creating a powerful economies of scale example.

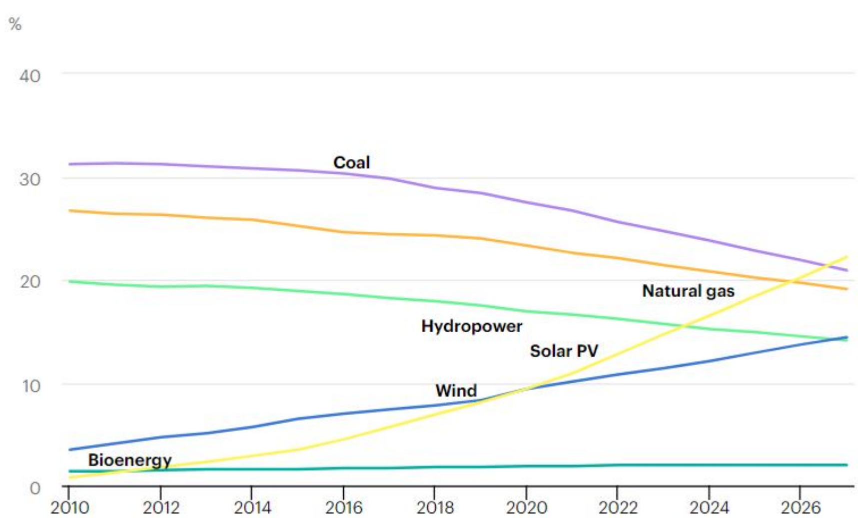

Figure 3: Share of cumulative power capacity by technology (2010-2027) [11].

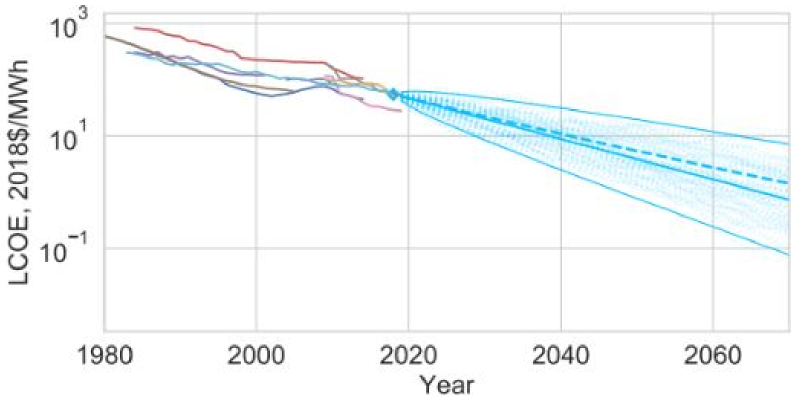

Figure 4: LCOE forecast for solar energy on a logarithmic scale [12].

This manufacturing capacity has increased notoriously in the previous years, in big part due to Chinese manufacturers exporting cells to Western economies - China represented an 84% of the world's share of solar panel manufacturing capacity in 2022 [13]. Abstaining from geopolitical concerns, these exports have turned solar panels into a household item, a remarkable trajectory considering that their main application was in the space industry and small consumer electronics until the 1980s [14].

Of course this technology has also its drawbacks. An important feature of any renewable energy source is its life-cycle emissions, as some of the processes involved in manufacturing these devices can be heavily reliant on fossil fuels, and in the worst case, they would only displace the emissions towards another stage in the energy supply chain. Despite being a great improvement with respect to fossil fuel-based generation, the embodied emissions in the materials that compose solar PV systems are higher per kWh generated than those of an existing hydropower plant, to put an example [15]. This does not invalidate the argument that PV is an environmental friendly electricity source, but serves as a reminder that an assessment of the emissions generated by new solar installations is also an important task for adequate planning.

Another rather evident disadvantage of solar generation is its heavy reliance on weather conditions. Given Sweden's northern latitude and its cold climate, it is counter-intuitive to think as solar energy as a technology to consider. In the case of Oskarshamn however, the numbers are rather favourable. The solar irradiance profile in 2022 for this city is attached in Figure 5 [16], with an aggregate value that year of 1,481.98 kWh/m2, equal to cities such as Amsterdam or Vienna, located in notably lower latitudes.

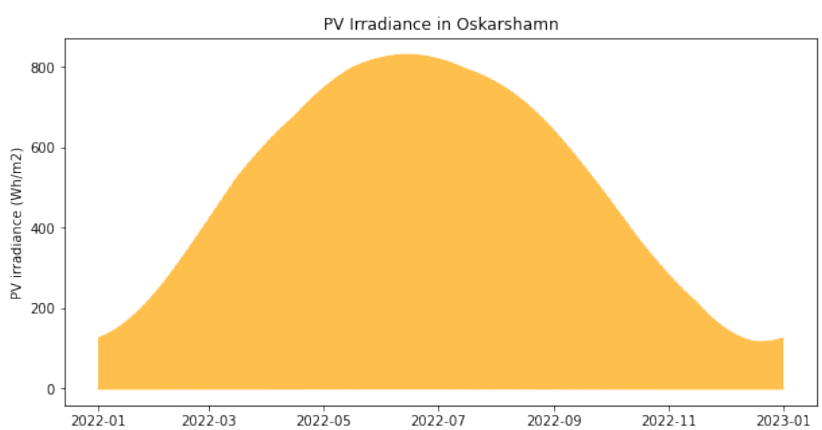

Figure 5: PV irradiance in Oksarshamn in the year 2022.

It is true that aggregate values are not that useful if most of this solar irradiance is concentrated during the summer months, leading to big volumes of curtailment, but Battery Energy Storage Systems - as described in 2.1.2 -, can help mitigate this concern.

In sum, a combination of decreasing costs, technological readiness, and acceptable weather conditions, lay the foundations of a positive case for solar energy in Oskarshamn, both in the economical and the environmental perspective.

2.1.2 Energy Storage Systems

Electricity has one key disadvantage with respect other fuels, which is that it usually needs to be consumed right after it is produced. The rising demand of this energy vector coupled to the increased variability in the production side - due to renewable energy dependence on weather conditions -, has made energy storage a key technology in the energy transition [17].

These energy storage systems are usually divided by the form of converted energy, as depicted in Table 1, which shows some of the most common examples of technologies used for electricity storage.

Form of converted energy	Technology
Electrochemical energy storage	• Battery energy storage (BESS) • Fuel Cell
Electrical energy storage	• Capacitors • Supercapacitors
Mechanical energy storage	• Flywheels • Pumped-hydro energy storage • Compressed air energy storage (CAES)

Table 1: Electricity storage technologies classification by form of converted energy [18]

Among these technologies, pumped-hydro energy storage represented an overwhelming share of over 90% of the total installed electricity storage capacity in 2020. This share is however due to decrease in the coming decades, with estimates for installed grid-scale battery storage capacity showing a 3,400% growth between 2022 and 2030 [19].

An important distinction to be made here is between long-term and short-term energy storage. Short-term energy storage is categorized as that with discharge times below few hours, with long-term presenting times of many days and even weeks. The extended commercial roll-out of long-term energy storage is one of the key missing pieces in the energy transition puzzle, being Pumped-hydro Energy Storage so far the only technology that has proven itself valuable for it [20]. This technology is based on the storage of potential energy, by pumping water into an upper reservoir and then moving that water to a lower reservoir through a turbine, generating electricity in the process[21]. Needless to say, the possibility to install one of these plants is heavily reliant on topography and societal factors, thus they are discarded from the solution set of this project.

Other options for long-term energy storage include hydrogen - which can then be reconverted into energy through fuel cells -, and Compressed Air Energy Storage (CAES). Despite the promising future some companies and scholars sponsor for the first of these, its high initial investment costs and big energy losses during hydrogen compression are still big drawbacks holding back its extended roll-out [22]. CAES, based on the storage of compressed air in subsoil reservoirs [23], has been also announced as a cheap and simple option that can support both short- and long-term energy storage; but there are still no large-scale commercial operating installations supported by this technology.

Due to their chemical properties, batteries, capacitors, and supercapacitors can not store electricity for periods longer than a few hours, at least with current state-of-the-art [24]. Evidently, this does not mean that they do not have any use cases, and short-term energy storage find useful and diverse applications such as frequency regulation, peak shifting, self-consumption maximization, and power management [25]. The business case for this kind of energy assets is further developed in Section 2.3

As its biggest drawback, batteries are still a pricey technology. Despite a dramatic decrease in their cost similar to that of Solar PV (see Section 2.1.1), the prices for lithium-ion - the most common chemistry as of today - in commercial and industrial installations is currently at around 320 EUR/kWh [12].

Another disadvantage of these is related to their degradation over time. Each time batteries are charged and discharged, they degrade in direct relation to the Depth of Discharge incurred - the percentage of total energy that has been discharged from its full capacity [26]. The costs associated to the degradation of the selected BESS in this project are calculated in Section 3.1.2.

2.1.3 District Heating (DH) and Combined Heat Power Plants (CHP)

Due to its presence in the energy system of the Oskarshamn harbor, District Heating is also briefly described in this Literature Review. District Heating (DH) is the practice of using local fuel or heat resources that would otherwise be wasted to serve local demands for heating using a distribution network of pipes [27]. This practice is very common in Scandinavia, and heat consumer get their heat services billed as another utility under this scheme.

Besides heat generation, some DH plants have the capability to generate electricity when the boiler output and the heat demand allow for it. The Norra Strandgatan DH plant - Figure 6-, in Oskarshamn is based on this principle, and has a 3.9MW tubine that generates electricity during the months between September and June. The fact that the DH turbine is operative during the winter months mitigates the drawback of solar energy being less productive at that time. Figure 7 shows the normalised curves for these generations to further reinforce this point.

Figure 6: The Norra Strandgatan DH plant. Photo from site visit on June 2023.

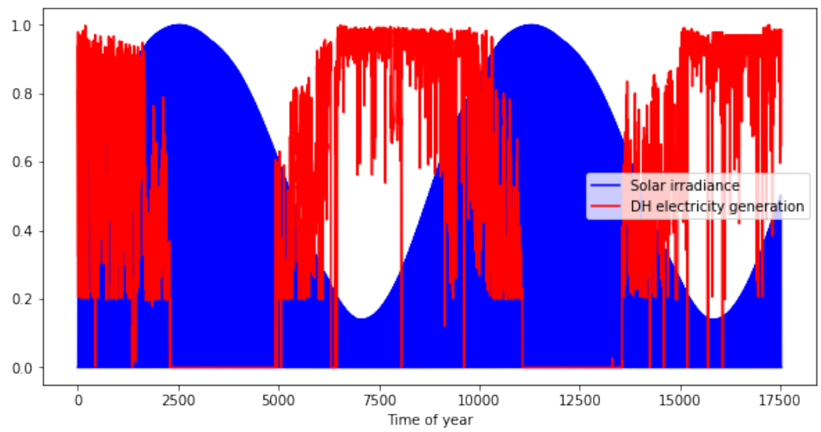

Figure 7: Comparison of normalised PV irradiance and DH turbine electricity production from March 2021 to February 2023.

2.1.4 Technology selection

Before making a choice of the renewable energy technology by which the use case system will be composed, it must be clearly stated which are the objectives to be fulfilled. The Oskarshamn harbor area is composed of few big consumers whom, citing their own words intend to minimize their electricity costs while exploring possibilities for energy revenues.

Solar PV, given its affordability and the relatively abundant solar resource found in the Oskarshamn area - per Section 2.1.1 -, is a great fit in this equation.

As described in Section 2.1.2, short-term energy storage assets are the most applicable to use cases that do not dispose of adequate topography for pumped-hydro plants. Out of the short-term energy storage supporting technologies, capacitors and supercapacitors are, despite their impressive energy density, not the most adequate for stationary uses. Thus, Battery Energy Storage systems (BESS) are the most balanced option for energy storage in the harbor, more specifically in its lithium-ion chemistry, which has a notable technological readiness compared to its alternatives.

Based on these criteria, a schematic for the system proposed is presented in Figure 8. This consists of a Behind the Meter (BTM) PV-BESS system that can help the industry actors in the harbor consume their renewable generation and open the window for new revenues as described in Section 2.3.5.

2.2 Smart City Districts and Energy Communities (ECs)

2.2.1 Smart city districts

As *smart cities* is still a novel concept, there are still many accepted definitions of it, leading in some cases to a misuse of the term. One of the most extended definitions among scholars is that smart cities are those that make use of information and communication technologies (ICT)[28]. Thus, a smart city district refers to a specific area of a city in which ICT technologies are used to improve the residents' quality of life.

One of many ways of improving this life quality is by making a more intelligent use of energy resources. The renewable energy technologies mentioned in Section 2.1 present better opportunities for synergies with ICT than traditional energy resources, opening the window to developments such as the integration of distributed energy storage resources into the electricity network or advanced metering schemes [29]. This integration allows for a shift towards a more decentralized and renewable energy production, which in turn helps reduce carbon emissions.

On the other hand, there are still some barriers to energy planning in smart city districts. A careful study is required, as these systems can easily fall into oversizings, which usually translate into wasted surpluses [30]. There are also barriers related to governance and financing, given the strong dependence of this kind of projects on the political support [31]

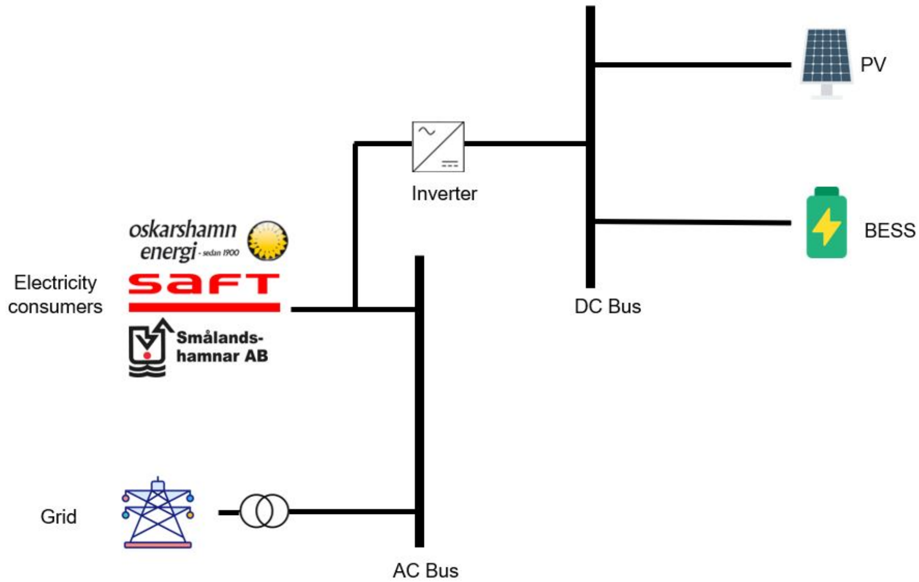

Figure 8: System schematic of the proposed architecture.

Case studies of smart city technology applied to energy management can be found in many places around the planet, such as Aarhus (Denmark) [32], Graz (Austria) [33], and Cape Town (South Africa) [34].

2.2.2 Energy Communities (ECs)

The emerging energy technologies, coupled with the connectivity enabled by them, has spurred new schemes for the sharing of energy resources. The so-called concept of Energy Communities (ECs) is one of these schemes. This concept can be useful for harbor areas such as the one in Oskarshamn, with some good case studies already in place around the world [35].

According to the European Commission, ECs englobe different collective energy actions that involve citizens' participation in the energy system, which can show different degrees of involvement in decision-making and benefit-sharing [36]. During the last years there has been no shortage of new proposals for business models suitable to ECs. Some of these business models are attached in Table 2.

This concept is obviously not short of its associated problems though. Following game theory principles, a subset of participants in a scheme like this may find it profitable to exit the community and create another one of their one. That is why, for effective planning of shared energy infrastructure installations, elaborate sharing rules need to be established, which would enable communities to share their gains in a fair and measurable way [38].

2.2.3 Sharing Scheme

From the sharing perspective, out of the models mentioned in Table 2, the community collective generation seems to be the most suitable for a potential new energy system in Oskarshamn harbor. This system would be installed in the harbor itself, and the power output would be shared among the three main consumers. A schematic of how such a business model would work is included in Figure 9.

In this model, the renewable energy system could be used for self-consumption directly, but also the DSO Oskarshamn Energi could act as the connection point between the prosumers and the TSO and balancing and wholesale market. That way, the opportunity is open for more revenue streams, as it is shown in Section 2.3.

Model	Short description
Energy cooperatives	energy end-users which join to raise the funding for owning generation systems
Community prosumerism	collective acquisition of energy infrastructure and establishment of long-term PPAs
Local energy markets	promote P2P energy exchanges locally
Community collective generation	Shared infrastructure for shared power output
Third-party-sponsored communities	external entities finance and maintain asset ownership, but cooperate closely with local communities for customized solutions
Community flexibility aggregation	pooling of flexibility from multiple members to achieve required volumes to make offers in balancing, reserve and ancillary markets
Community energy services company	partnerships between external companies and ECs to operate energy services companies

Table 2: Business models for ECs (adapted from [37])

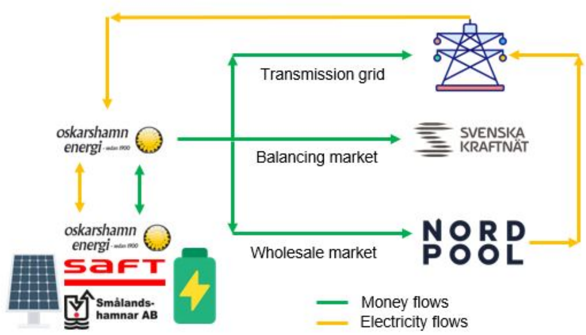

Figure 9: Proposed business model schematics. Adapted from [37].

2.3 Novel Energy Business Models

The main idea behind this section is to explore the various ways by which stakeholders in a Smart City District, an Energy Community, or similar entities can generate additional revenues with their renewable and connected energy technologies.

2.3.1 Swedish Power Markets

After the process of deregulation started in the early 1990s, power price in Sweden has been determined by the balance of supply and demand. This power is traded in two markets, operated by Nord Pool [8]:

1. Day-ahead market *(Elspot)* - in which customers sell or buy energy for the next day in a closed auction. The balanced price posted by Nord Pool represents these two prices:
    - The marginal cost of producing a kWh of power from the most expensive source required to balance the system
    - The price consumers are willing to pay for the last kWh needed to satisfy the overall demand
2. Intraday market *(Elbas)* - at which power is traded closer in time to physical delivery and thus

helps in securing the balance between supply and demand. Interest in intraday markets is growing due to growing renewable adoption, which has led to more difficulties in balancing the market just with the day-ahead market mechanisms.

Sweden was divided into four bidding areas with respect to these markets in 2011, as depicted in Figure 10. The area to which Oskarshamn belongs is SE-4, thus the market data used in this project corresponds to it.

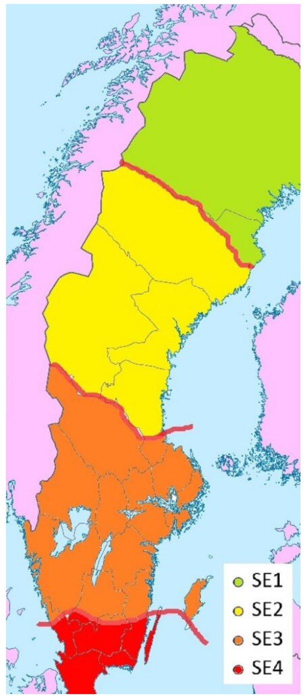

Figure 10: Map of Sweden's four electricity bidding areas [39].

2.3.2 Electricity Arbitrage

Electricity arbitrage refers to the storage of energy at low-priced moments for it to be sold on the markets when its price is bigger. The dynamic nature of electricity prices in the wholesale markets - due to the supply and demand forces described in Section 2.3.1 - enables this practice [40].

The underlying principle behind this activity when performed by batteries is simple, consisting of charging the device at low-priced hours - or at negligible marginal cost with self-consumed renewable electricity - and discharging it during the highest-priced moments of the day. A proper optimization model is key to effectively harness these price differences, considering at the same time the costs incurred by battery degradation at each charge and discharge cycle. Numerous strategies have been defined for this, showing favorable results when focused on short-term trades of less than 24 hours time frame [41].

2.3.3 Electricity Reserves

An issue that the regular power markets can not totally address is that of grid balancing. For the electricity system to appropriately work, there must be a constant balance of production and consumption, but given the constant fluctuations in the consumption, imbalances between these two magnitudes often occur [25].

Markets enabling energy asset operators to trade their reserves exist on a distribution level - known as *flexibility markets* (such as Sthlmflx in Stockholm or CoordiNet in Uppsala [42]) -, however these are still mostly in pilot phases, being very dependent on each local electricity system idiosyncrasy.

However, the market for these reserves on a transmission level is more developed in many countries, being Sweden one of them. Svenska kraftnät, as the national Transmission System Operator (TSO) operates its reserve market in order to keep the grid operating frequency at the default 50 Hz. This poses an interesting potential source of revenue for adequate energy infrastructure. There are currently six different reserves in the Swedish power system [43]:

1. Fast Frequency Reserve (FFR) - handles frequency changes occurring at low levels of rotational energy.
2. Frequency Containment Reserve (FCR) - handles frequency changes in the event of operational disturbances, being traded for each moment of the day in advance. There are three types of FCR:
    - FCR-D upp *(up)*, used in case of upward frequency disturbances
    - FCR-D ned *(down)*, used in case of downward frequency disturbances
    - FCR-N, used in normal operation disturbances
3. Automatic Frequency Restoration Reserve (aFRR) - which automatically restores the frequency to the default 50 Hz via a control signal.
4. Manual Frequency Restoration Reserve (mFRR) - which relieves the aFFR and is activated upon Svenska kraftnät's request.
5. Power reserve - used in cases of power shortage when the rest of balancing resources are not enough.
6. Disturbance reserve - which must be always able to be activated in a 15 minute window to handle disturbances. It is largely composed by gas turbines.

The frequency restoration process is further visualized in Figure 11, which shows the timing and frequencies at which each of the reserves are activated to balance the electricity system. The x-axis represents the time that it takes for each of the reserves to be activated, while the y-axis shows the frequencies that trigger their activation. For example, if the electricity consumption in the grid experiments an unexpected increase, the frequency will drop. If it drops to a value above 49.9 Hz, the FFR will be activated first, followed by the FCR-N, with no need of further reserves.

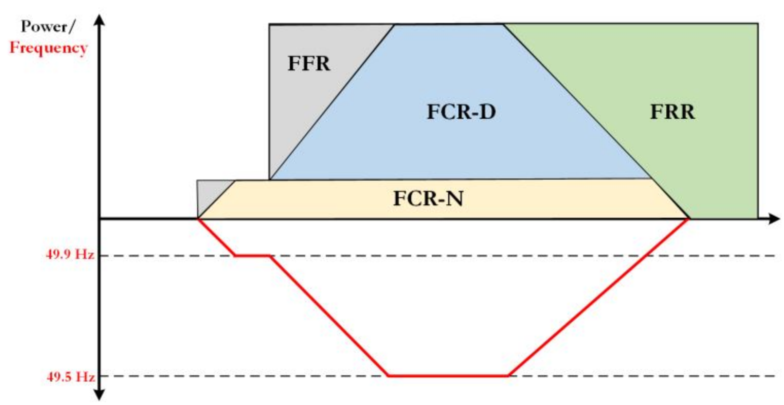

Figure 11: Timing and frequency for each of the electricity reserves [44].

2.3.4 Service Stacking

Service stacking consists of the practice of letting a BESS provide multiple services during its cycling, thus increasing its value with a near-zero marginal cost [45]. This has already proven itself valuable in the Swedish electricity market, by adding a secondary service during the year [46].

The most interesting part of stacking revenue streams on an already existing BESS is that every new stream involves almost negligible marginal costs, thus providing with a powerful way of making the business case for energy storage a more compelling one.

2.3.5 Electricity market selection

The PV-BESS system proposed for the harbor in Figure 8 can stack different services as described in Section 2.3.4. First of all, it would be able to take advantage of the price differences in the Swedish electricity prices by doing arbitrage. On top of that, the battery system could provide the TSO with different reserves.

A description of the response times and minimum volume requisites for each of the reserves introduced in Section 2.3.3 is presented in Table 3. Based on this classification, the most adequate revenue streams for the system proposed in the project can be chosen.

	FFR	FCR-D	FCR-N	aFFR	mFFR
Minimum volume	0.1MW	0.1MW	0.1MW	1MW	5MW (SE-4)
Activation time	Steps of 0.7, 1.0, and 1.3 sec	50% within 5 sec, 100% within 30 sec	63% within 60 sec, 100% within 3 min	100% within 5 min	100% within 15 min

Table 3: Technical requirements of the Swedish electricity reserves [43]

Response times for FFR are very fast, thus making them non-suitable for BESS to provide them. Also, as it will be seen later in the thesis, the power rating of the battery would not excess 1MW in any of the scenarios, which discards also the provision of aFFR and mFFR. This leaves the system with the possibility to participate in the FCR-D and FCR-N reserves.

2.4 Energy optimization

Optimizing, in mathematical terms, is determining the inputs that maximize or minimize the value of a function, which is usually subjected to a set of constraints [47].

Optimization helps with the allocation of energy resources and services in renewable energy systems. In a scenario with large penetration of renewable electricity production, it is required to account for the effects of variability and randomness of the renewable sources, a task at which optimization is useful for [48]. Many optimization techniques have been applied to hybrid renewable systems similar to the one proposed in this project for the Oskarshamn harbor area, such as fuzzy logic [49], genetic algorithms (GA) [50], or linear programming (LP) [51].

There are different sizing objectives possible for hybrid energy systems, such as cost minimization, self-consumption maximization, power quality improvement, or carbon emissions reduction. Any of these objective function choices will be subjected to a set of constraints related to the system rated power and capacity and the electricity balance [52].

Finally, the basic process of constructing an energy optimization problem is presented in Figure 12. This flowchart will be used as a baseline to build the methodology introduced in Section 3.3.

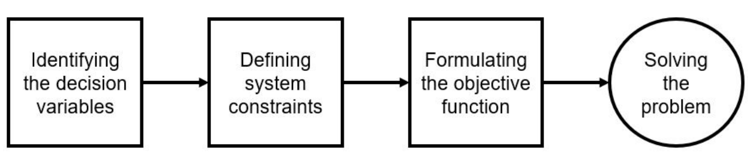

Figure 12: Optimization process flowchart. Adapted from [52].

2.5 Literature Review Findings

The following bullet points summarize the findings from the literature review chapter and serve as a baseline for the remaining of the project:

- The most suitable technologies for a renewable energy system in the Oskarshamn harbor are Solar PV and Battery Energy Storage - more specifically in its lithium-ion chemistry - due to its technological readiness and current cost-effectiveness.
- Community collective generation can provide with a business model in the interest of all the harbor stakeholders.
- The PV-BESS system should perform revenue stacking, for which the most adequate markets would be energy arbitrage and the different FCR reserves.
- An electricity load and production optimization exercise is required to allocate the energy resources in the most efficient manner.

3 Methodology

This section presents the methodology followed during the thesis to find and compare the best energy investments under a mix of assumptions and scenarios.

First, an Exploratory Data Analysis preceded by its required data collection and cleaning process was performed to find relevant observations and patterns in the electricity flows of the Oskarshamn harbor. The decision variables, constraints, and objective function of the optimization problem is then presented. Then, the logic for the different solving scenarios is presented, and finally the indicators to be used to compare the financial and environmental benefits in each of these scenarios are introduced.

A visual representation of this methodology is presented in the flowchart at Figure 13.

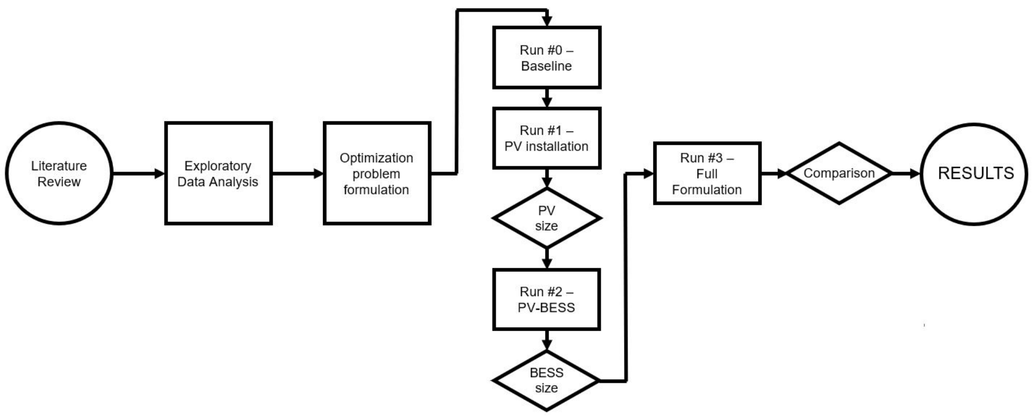

Figure 13: Methodology flowchart.

The tools used in this methodology include the Python libraries Pandas [53], NumPy [54] and Matplotlib [55] for data analysis and visualization, and PuLP [9] for LP optimization.

3.1 Data Collection and Cleaning

The first step in the project methodology involves gathering and doing an initial processing of the required data. This data is divided into two main categories: time series and pricing data.

3.1.1 Time series

A table of the data series gathered to complete this project is included in Table 4, alongside its units and the entity that provided with it. All these data series include hourly values ranging from March 1st 2021 to February 28th 2023.

Magnitude	Symbol	Units	Provider
Power consumption Saft	$E_{saft}(t)$	kWh/h	Oskarshamn Energi
Power consumption Smålandshamnar	$E_{små}(t)$	kWh/h	Oskarshamn Energi
Power consumption Norra Strandgatan	$E_{nor}(t)$	kWh/h	Oskarshamn Energi
Power production Norra Strandgatan	$\text{prod}_{turb}(t)$	kWh/h	Oskarshamn Energi
Solar irradiance	I(t)	W/m^2	pvlib [16]
Elspot price (day-ahead market)	price(t)	€/MW	Nord Pool [8]
FCR-N, FCR-D up, FCR-D down prices	$\text{price}_{FCRx}(t)$	€/MW	Svenska kraftnät [7]
FCR-N, FCR-D up, FCR-D down volumes	$E_{FCR-x}(t)$	MW/h	Svenska kraftnät [7]

Table 4: List of data series collected

Electricity consumption for the three main consumers in the harbor alongside the production in the Norra Strandgatan cogeneration turbine was received from the DSO Oskarshamn Energi. An important observation here is that the electricity demand was multiplied by 5% for Saft and Norra Strandgatan and by 20% for Smålandshamnar to account for the future increase in electricity demand expected by the harbor stakeholders.

It is important to remark that the electricity production is dependant on the heat demand in the local heat network, considering the condition of electricity as a byproduct in these type of generating units, as mentioned in Section 2.1.3.

Solar irradiance was collected from pvlib [16], an open-source tool that enables retrieval of this magnitude from any coordinates. PV production can be computed by multiplying this irradiance by the installed PV surface and the conversion efficiency of the installed solar panels, as per the equation below:

$$prod_{PV}(t) = I(t) * surf_{PV} * \eta_{PV}$$

The PV installed surface is one of the parameters that the thesis intends to advice the stakeholders about, so various scenarios assuming different values of this are run in the optimizations. Regarding the conversion efficiency η_{PV}, this is assumed to be of around 20% as per the average values in the solar industry during the latest years.

Finally, the prices of the day-ahead electricity market - Elspot in Sweden - for Oskarshamn's bidding area (SE-4), and the prices and volumes of the different FCR markets were collected from the market operator Nord Pool and the TSO Svenska kraftnät respectively. It is worth noting that these prices have been converted to euro (€) given Nord Pool's preference for this currency, and its more prominence in relevant literature than the local currency (SEK). The exchange rate used is the one as of July 13th 2023 (1 SEK = 0.08688 EUR) [56].

All these data series are then cleaned and merged into a single Pandas dataframe for easier manipulation in the following sections.

3.1.2 Pricing data

In addition to the time series, pricing data for the usage of the DSO infrastructure and for the different energy technologies to be included in the system is collected. A list of this pricing data is included in Table 5.

Pricing	Symbol	Value	Units	Source
PV panels price	price_{PV}	120	EUR/m^2	[57]
Lithium-ion batteries price	price_{BESS}	320	EUR/kWh	[12]
Battery degradation price	price_{deg}	0.011	EUR/kWh	[26]
Distribution fee	price_{DSO}	0.04257	EUR/kWh	[58]
Norra Strandgatan turbine OPEX	OPEX_{turb}	0.03583	EUR/kWh	[59]

Table 5: List of pricing data collected

PV panels and lithium batteries prices, for ease of comparison represent an average value per square meter and kWh of capacity respectively.

The degradation price represents the cost in terms of capacity loss in the battery for each cycle of charge and discharge [26]. For easier implementation in the optimization, this price has been estimated in EUR/kWh assuming a battery lifespan of 20 years - with 50% capacity at End of Life - and 2 cycles per day during this lifespan.

The distribution rates have been compiled from Oskarshamn Energi's web page, [58]. All these rates are included of taxes. The OPEX incurred by generating electricity with the cogeneration unit in

Norra Strandgatan have been compiled from a recent Flexible Sector Coupling study sponsored by Oskarshamn Energi [59], with a predicted value of 412.42 SEK/MWh for the year 2030.

Once again, both these rates has been converted to EUR with the same rates from Section 4 [56]. The prices for PV panels and lithium-ion batteries are used as a reference to compare the most beneficial scenario from the economic point of view as described in Section 3.5.

3.2 Exploratory Data Analysis (EDA)

Once the data has been cleaned, an initial data analysis is performed. The main objectives for this is to verify the collected data quality and find potential outliers that may compromise the results of the subsequent optimization. Table 6 presents the maximum, minimum, average, and standard deviation values of the different power consumption series in the analysis.

Time series	Max	Min	Mean	Std	Units
Saft consumption	3080.94	524.43	2270.94	466.68	kWh/h
Smålandshamnar consumption	522.85	37.19	145.17	66.99	kWh/h
Norra Strandgatan consumption	699.57	15.06	354.23	198.72	kWh/h

Table 6: Time series metrics

An initial observation from Table 6 is the ratio between the standard deviation (std) and the average value (mean). This ratio is of just a 20.6% for Saft, while it is of 46.1% and 56.1% for Smålandshamnar and Norra Strandgatan respectively, a figure that indicates towards a higher variability for these last two.

Figure 14 further supports these observations. The black lines represent the power consumption for each of the days in the two years included in the time series, and the red line represents the average of all those days. The difference in the above-mentioned ratios and the nature of the variability that originates this difference are explained in the bullet points below:

- Saft presents a typical industrial load profile, with a very constant baseline consumption close to its 2.2MW mean value. The few days deviating from this pattern can be explained by maintenance periods and holiday seasons, during which the machinery of the manufacturing lines stop their operation.
- Smålandshamnar presents a bell-shaped profile during most of the days, which can be explained by its high daily variability typical of a commercial consumer. Most of the activities performed by the port operator, such as ship unloading, are done during the daytime, which explains the higher power consumption during those hours.
- The Norra Strandgatan district heating plant also presents a flat profile characteristic of industrial consumers, but with a significant seasonal variability. This is explained by the summer days, during which the demand for heat is low or non-existent and consequently Norra Strandgatan's baseline consumption stays below 100kW for most of the time.

A plot with the electricity consumption for the three companies during the year 2022 is included in Figure 15. The values have been resampled to the average daily figures for easier visualization of weekly and seasonal trends. Saft's maintenance period during the month of August and its holiday period in Christmas, which explained the lower consumption days can be seen. Another observation is the long summer stretch with low consumption in Norra Strandgatan, from June to September. Also, Smålandshamnar seems to present the lowest seasonal difference, but weekdays have a significantly higher power consumption than weekends.

Finally, it is important to highlight the significance of Saft's power demand in the harbor. As shown in the cumulative chart in Figure 16, this demand is on average higher than the combined demand of the two other big consumers at every hour. The implications this could have in the future energy system investment and ownership schemes will be further discussed in Section 5.

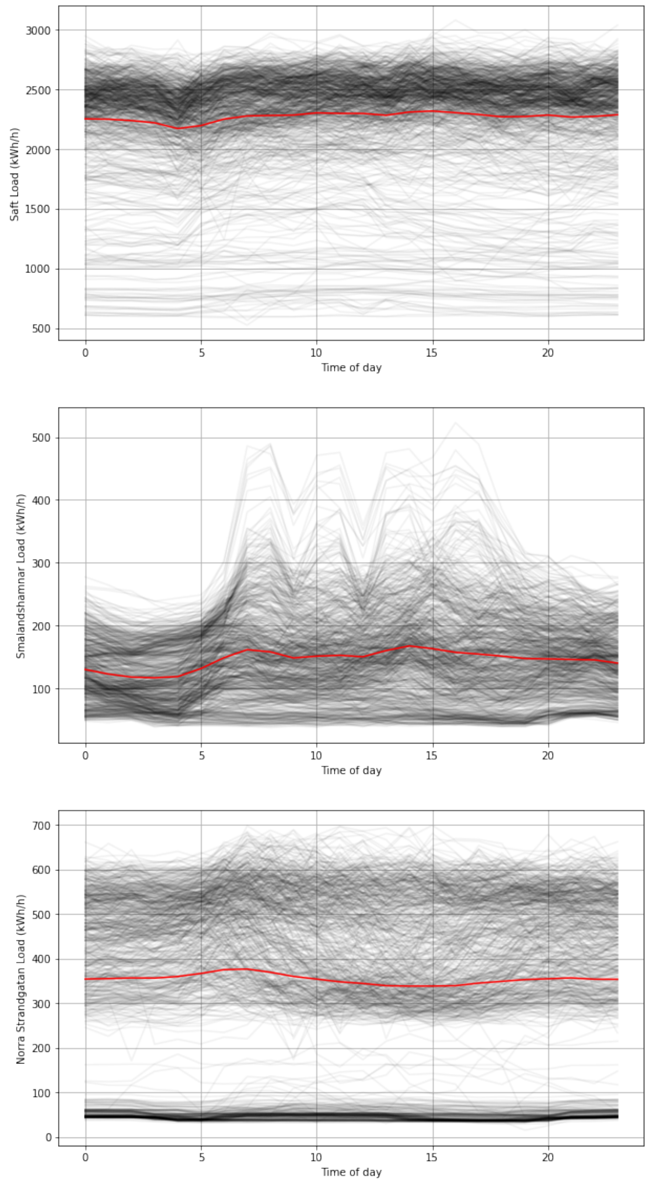

Figure 14: Power consumption for every day between March 2021 and February 2023 (black), and average value along these days (red).

3.3 Optimization Problem Formulation

The core of the methodology is in the optimization problem. As defined in Section 2.4, there can be different objectives possible for these kind of problems, but in this case the objective function will minimize the electricity costs in the system in order to find the optimal configurations for the hybrid PV-BESS system.

A full formulation including the objective function and all the decision variables and constraints is presented below, and in Section 3.4 the partial formulations used in the different scenarios are presented. These are solved then with the PuLP Python library [9], which solves the linear programming problem formulated.

3.3.1 Decision variables

To present the optimization exercises in an orderly fashion, a map of the existing electricity flows in the presented solution is included in Figure **??**. Table 7 describes all the decision variables for the

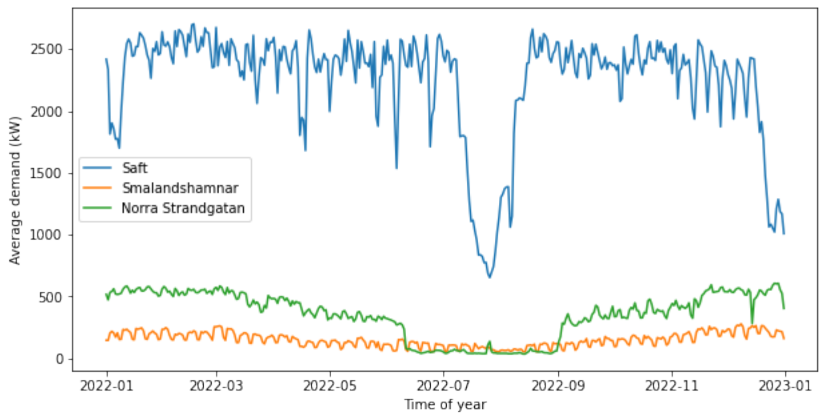

Figure 15: Daily average power consumption during the year 2022.

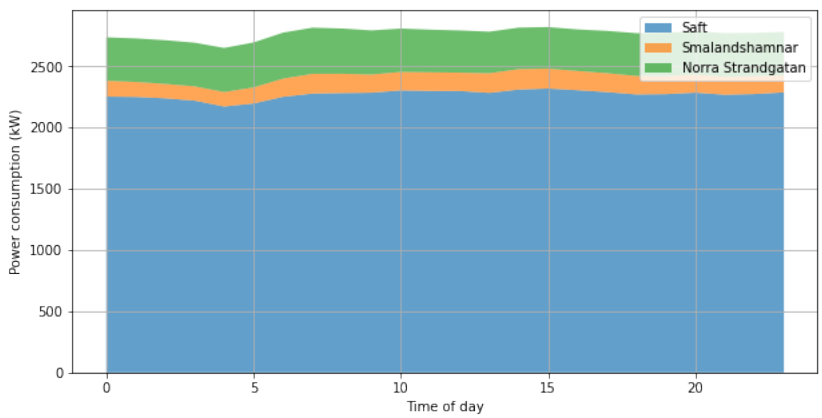

Figure 16: Cumulative average daily power demand by consumer.

optimization problem, which consist of all the electricity flows plus the current state of charge (SOC) of the battery system measured in kWh, and a "status" binary variable that prevents electricity charges and discharges to happen during the same time step in the battery. The unit for all the electricity flows is kW.

3.3.2 Input parameters

On top of the decision variables, there are some parameters that must be given as an input to the model. These are detailed in Table 8.

To indicate the size of the PV-BESS installation, the PV surface to be installed and the capacity and rated power of the BESS are inputted. The battery system is assumed to have a maximum of 2h storage, thus being its rated power half of its installed capacity. This is the current status quo in the lithium-ion grid-scale battery storage industry, proving the best returns over investment for this technology [60].

The turbine proportion indicates the maximum share of the Norra Strandgatan electricity generation that could be allocated to serve the harbor consumers. The system proposed here includes in one of its iterations a model under which Oskarshamn Energi would reserve a 5% of this electricity production as an easy dispatchable source for the harbor area, under the condition that the heat demand in the local network would allow for it. More details on the implications this would have on the financial and ownership model of the system are discussed in Section 5.

Finally, a $FCR_{\%}$ represents the maximum proportion of the total FCR volumes in the bidding area SE-4 the Oskarshamn harbor PV-BESS system would serve. Given that the maximum FCR hourly

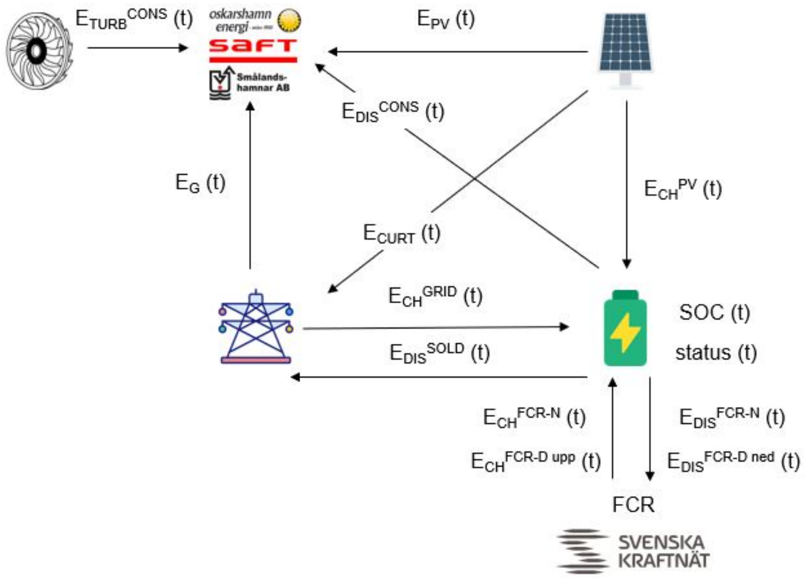

Figure 17: Existing electricity flows in the proposed system.

Name	Description
$\mathrm{E}_{grid}(t)$	Electricity consumed directly from the grid
$\mathrm{E}_{PV}(t)$	Electricity directly self-consumed from the PV system
$\mathrm{E}_{curt}(t)$	Electricity curtailed from the PV system to the grid
$\mathrm{E}_{ch}^{PV}(t)$	Electricity charged into the battery from the PV system
$\mathrm{E}_{ch}^{grid}(t)$	Electricity charged into the battery from the grid
$\mathrm{E}_{ch}^{FCR-N}(t)$	Electricity charged into the battery replying to the FCR-N market calls
$\mathrm{E}_{ch}^{FCR-Dup}(t)$	Electricity charged into the battery replying to the FCR-D up market calls
$\mathrm{E}_{dis}^{cons}(t)$	Electricity discharged from the battery for self-consumption
$\mathrm{E}_{dis}^{sold}(t)$	Electricity discharged from the battery to be sold on the Elspot market
$\mathrm{E}_{dis}^{FCR-N}(t)$	Electricity discharged from the battery replying to the FCR-N market calls
$\mathrm{E}_{dis}^{FCR-Ddown}(t)$	Electricity discharged from the battery replying to the FCR-D down market calls
$\mathrm{E}_{turb}(t)$	Electricity consumed from the Norra Strandgatan cogeneration turbine
SOC(t)	Battery State of Charge (SOC)
$\mathrm{status}_{bess}(t)$	Binary variable that impedes charging and discharging at the same time

Table 7: List of decision variables (all energy flows are in kW)

volume traded in the 2022/2023 period in SE-4 was of 34.4 MW, and that the proposed system would have in every scenario a maximum rated power between 0.1 and 0.5 MW, it has been assumed that the maximum proportion would be of a 1%.

3.3.3 Objective function

The objective function minimizes the sum of the electricity price at all the time steps. For this purpose, an objective function including the prices of all the existing electricity flows is created. These included prices are:

1. $\mathrm{P}_{\mathrm{E}_{\mathrm{grid}}}$ - price of electricity consumed from the grid, which represents the price paid for electricity

Parameter	Symbol	Value	Units
PV installation surface	surf_{PV}	5000-50000	m^2
BESS installed capacity	cap_{BESS}	200-1000	kWh
BESS rated power	P_{BESS}	100-500	kW
Turbine proportion	$\mathrm{turb}_{\%}$	5	%
FCR share	$\mathrm{FCR}_{\%}$	1	%

Table 8: List of input parameters for the optimization.

consumed directly from the grid. This price is defined by the product of $\mathrm{E_{grid}}(t)$ and the sum of the Elspot price as per [8] and Oskarshamn Energi distribution tariffs, as described in Table 5.

$$P_{E_{grid}}(t) = E_{grid}(t) * (price(t) + price_{DSO})$$

2. $\mathrm{P_{E_{PV}}}$ - price of electricity consumed directly from PV production, which is assumed to be zero, given the negligible nature of solar PV operative expenses.

$$P_{E_{PV}}(t) = 0$$

3. $\mathrm{P_{E_{curt}}}$ - price of the electricity curtailed, which represents the price receiving for the electricity being curtailed from excess PV generation. This price is defined by the product of $\mathrm{E_{curt}}$ and the sum of the Elspot price - with a negative sign given that it represents revenues -, and the distribution tariffs.

$$P_{E_{curt}}(t) = E_{curt}(t) * (-price(t) + price_{DSO})$$

4. $\mathrm{P_{E_{ch}}}^{\mathrm{PV}}$ - price of electricity being charged to the battery from the PV system. This price is defined by the product of $\mathrm{E_{ch}}^{\mathrm{PV}}$ by the battery degradation price.

$$P_{E_{ch}^{PV}}(t) = E_{ch}^{PV}(t) * price_{deg}$$

5. $\mathrm{P_{E_{ch}}}^{\mathrm{grid}}$ - price of electricity charged to the battery from the grid. This price is defined by the product of $\mathrm{E_{ch}}^{\mathrm{grid}}$ by the sum of the battery degradation price, the DSO tariffs, and the price paid in the Elspot market.

$$P_{E_{ch}^{grid}}(t) = E_{ch}^{grid}(t) * (price_{deg} + price_{DSO} + price(t)$$

6. $\mathrm{P_{E_{ch}}}^{\mathrm{FCR\text{-}N}}$ - price getting paid for the electricity charged in the battery responding to the FCR-N market signals. This price is defined by the product of $\mathrm{E_{ch}}^{\mathrm{FCR\text{-}N}}$ by the sum of the battery degradation price and the bid price in the FCR-N market at that time step.

$$P_{E_{ch}^{FCR-N}}(t) = E_{ch}^{FCR-N}(t) * (price_{deg} - price_{FCR-N}(t)$$

7. $\mathrm{P_{E_{ch}}}^{\mathrm{FCR\text{-}D\ up}}$ - price getting paid for the electricity charged in the battery responding to the FCR-D up market signals. This price is defined equally to $\mathrm{P_{E_{ch}}}^{\mathrm{FCR\text{-}N}}$ but changing the price to its respective FCR-D up market price.

$$P_{E_{ch}^{FCR-Dup}}(t) = E_{ch}^{FCR-Dup}(t) * (price_{deg} - price_{FCR-Dup}(t)$$

8. $P_{E_{dis}}{}^{cons}$ - cost incurred by discharging the battery for self-consumption. This price is defined by the product of $E_{dis}{}^{cons}$ by the battery degradation price.

$$P_{E_{dis}^{cons}}(t) = E_{dis}^{cons}(t) * price_{deg}$$

9. $P_{E_{dis}}{}^{sold}$ - price getting paid for the electricity being sold from the battery to the market. This enables the model to reply to big spikes in the Elspot electricity price and unlocks the possibility of energy arbitrage for the system. The price is defined by the product of $E_{dis}{}^{sold}$ by the sum of the degradation price, the DSO costs, and the Elspot price with a negative sign - as it represents a revenue.

$$P_{E_{dis}^{sold}}(t) = E_{dis}^{sold}(t) * (price_{deg} + price_{DSO} - price(t))$$

10. $P_{E_{dis}}{}^{FCR\text{-}N}$ - price getting paid for the electricity discharged from the battery responding to FCR-N market signals. This price is defined the same way as $P_{E_{ch}}{}^{FCR\text{-}N}$ but changing the electricity component to $E_{dis}{}^{FCR\text{-}N}$

$$P_{E_{dis}^{FCR-N}}(t) = E_{dis}^{FCR-N}(t) * (price_{deg} - price_{FCR-N}(t))$$

11. $P_{E_{dis}}{}^{FCR\text{-}D\ down}$ - price getting paid for the electricity discharged from the battery responding to the FCR-D down market signals. This price is defined the same way as $P_{E_{dis}}{}^{FCR\text{-}N}$ but changing the price and energy to the FCR-D down ones.

$$P_{E_{dis}^{FCR-Ddown}}(t) = E_{dis}^{FCR-Ddown}(t) * (price_{deg} - price_{FCR-Ddown}(t))$$

12. $P_{E_{turbine}}$ - price being paid for the electricity consumed from the Norra Strandgatan cogeneration turbine. This price is defined by the product of $E_{turbine}$ and the sum of the turbine OPEX and the DSO tariffs. A markup of 50% has been added on the turbine OPEX to compensate for the dispatchability of this, as it will be detailed in Section 5.

$$P_{E_{turb}}(t) = E_{turb}(t) * (OPEX_{turb} * 1.5 + price_{DSO})$$

The objective function is then defined as the sum of the electricity flows multiplied by their respective prices at every time step. The solution that minimizes this sum is the desired outcome:

$$\begin{aligned} min \sum_{t=0}^{n} [P_{E_{grid}}(t) + P_{E_{PV}}(t) + P_{E_{curt}}(t) + P_{E_{ch}^{PV}}(t) + P_{E_{ch}^{grid}}(t) + P_{E_{ch}^{FCR-N}}(t) + P_{E_{ch}^{FCR-Dup}}(t) + \\ + P_{E_{dis}^{cons}}(t) + P_{E_{dis}^{sold}}(t) + P_{E_{dis}^{FCR-N}}(t) + P_{E_{dis}^{FCR-Ddown}}(t) + P_{E_{turb}}(t)] \end{aligned}$$

3.3.4 Constraints

Every combination of decision variables must meet the following constraints in order to solve the optimization problem in a satisfactory manner. These constraints must also be met at every time step.

Power flow balance

There must be a power balance in the system at every moment. This is ensured by the following constraint, which adds the electricity productions in the left side and the loads in the right side.

$$\begin{aligned} E_{grid}(t) + E_{PV}(t) + E_{dis}^{cons}(t) + E_{dis}^{sold}(t) + E_{dis}^{FCR-N}(t) + E_{dis}^{FCR-Ddown}(t) + E_{turb}(t) = \\ = E_{saft}(t) + E_{sma}(t) + E_{nor}(t) + E_{ch}^{grid}(t) + E_{ch}^{PV}(t) + E_{ch}^{FCR-N}(t) + E_{ch}^{FCR-Dup}(t) + E_{curt} \end{aligned}$$

PV constraints

The sum of all the power flows related to PV production needs to be balanced. The sum of the solar energy consumed - either directly or from the battery -, and the curtailed electricity must equal the PV generation at every moment.

$$E_{PV}(t) + E_{curt}(t) + E_{ch}^{PV}(t) = prod_{PV}(t)$$

Battery constraints

The battery SOC on each time step needs to be equal to the one in the previous time step after applying the electricity charge and discharge flows happening at the new time step:

$$\begin{aligned} SOC(t) = SOC(t-1) + E_{ch}^{grid}(t) + E_{ch}^{PV}(t) + E_{ch}^{FCR-N}(t) + E_{ch}^{FCR-Dup}(t) - \\ - E_{dis}^{cons}(t) - E_{dis}^{sold}(t) - E_{dis}^{FCR-N}(t) - E_{dis}^{FCR-Ddown}(t) \end{aligned}$$

On top of this, the charges and discharges happening at the same time step in the battery can not exceed the rated power of the system, which is enforced by the following:

$$\begin{aligned} E_{ch}^{PV}(t) + E_{ch}^{grid}(t) + E_{ch}^{FCR-N}(t) + E_{ch}^{FCR-Dup}(t) + \\ + E_{dis}^{cons}(t) + E_{dis}^{sold}(t) + E_{dis}^{FCR-N}(t) + E_{dis}^{FCR-Ddown}(t) <= P_{BESS} \end{aligned}$$

Another two battery-related constraints are needed to ensure that the system is not charging and discharging at the same time. These constraints add the charges (or discharges) at one time step and ensure they stay lower than the product of the binary variable $\mathrm{status_{bess}}$ by a large positive number M - which acts as an upper bound:

$$E_{ch}^{PV}(t) + E_{ch}^{grid}(t) + E_{ch}^{FCR-N}(t) + E_{ch}^{FCR-Dup}(t) <= M * status_{bess}(t)$$

$$E_{dis}^{cons}(t) + E_{dis}^{sold}(t) + E_{dis}^{FCR-N}(t) + E_{dis}^{FCR-Ddown}(t) <= M * (1 - status_{bess}(t))$$

FCR constraints

Given the juicy benefits the different FCR markets pay, constraints need to be enforced to avoid the system to serve it over its capacity. This is where the share $\mathrm{FCR_{\%}}$ comes into place as an upper-bound. A constraint is created for each FCR-N, FCR-D up, and FCR-D down:

$$E_{ch}^{FCR-N}(t) + E_{dis}^{FCR-N}(t) <= FCR_{\%} * E_{FCR-N}(t)$$

$$E_{ch}^{FCR-Dup}(t) <= FCR_{\%} * E_{FCR-Dup}(t)$$

$$E_{dis}^{FCR-Ddown}(t) <= FCR_{\%} * E_{FCR-Ddown}(t)$$

Turbine constraints

As discussed in Section 2.1.3, it is not possible to dispatch electricity from a cogeneration turbine such as the one in Norra Strandgatan in a loose manner. The production of electricity in these turbines is always dependent on the heat demand in the network, thus a constraint is needed to ensure electricity is dispatched only when this demand allows for it. Also, the turbine proportion $turb_{\%}$ ensures that it is only the proportion allocated to the harbor area the one that gets consumed, as was discussed in Section 8.

$$E_{turb}(t) <= prod_{turb}(t) * turb_{\%}$$

These constraints correspond to the full formulation of the optimization problem. For the previous iterations to that full formulation, some of the constraints will remain unused. This will be detailed in Section 3.4.

3.4 Code Running Sequence

The optimization is run in a sequential bottom-up manner. The steps followed in this sequence are detailed in the bullet points below, with their respective architectures in Figure 18. The decision variables used in each of the runs are disclosed in Table 9. The usage or not of these decision variables determines which pricing components will be included in the objective function and which constraints are put in place. It is worth noting that these scenarios are run incorporating the expected electricity demand increases from the coming years mentioned in Section 4.

1. Baseline case - the baseline current case, on which all the electricity consumed comes from the distribution network.
2. PV installation - which adds a PV installation behind the meter that can serve the prosumers. The revenues generated by feeding to the grid the excess of produced electricity are calculated. An optimal PV installation size is determined here that will be used in subsequent steps.
3. PV-BESS installation - on top of the PV installation, this adds a BESS which offers a buffer to charge part of the curtailed solar energy, which can then be used for self-consumption or electricity arbitrage when appropriate. As in the previous step, an optimum BESS size is determined here to be used in the following optimizations.
4. Full Formulation - this scenario considers the possibility to stack the electricity arbitrage revenue with the selected reserves from the literature review. Besides, a proposal under which a portion of the electricity generated in Norra Strandgatan would be allocated when possible to the consumers in the harbor is included. The implications of this proposal are described in Section 5.

Run	Architecture	Decision variable additions
0	Baseline	E_{grid}
1	PV	E_{PV}, E_{curt}
2	PV-BESS	$E_{ch}^{PV}, E_{dis}^{cons}, SOC, status_{bess}, E_{ch}^{grid}, E_{dis}^{sold}$
3	Full formulation	$E_{ch}^{FCR-N}, E_{ch}^{FCR-Dup}, E_{dis}^{FCR-N}, E_{dis}^{FCR-Ddown}, E_{turb}$

Table 9: Decision variables participating in each of the runs. Each run includes all the decision variables in the runs above them plus their additions

3.5 Scenario Comparison Criteria

To quantify the impact each of the scenarios would have in the Oskarshamn harbor stakeholders, a common financial indicator needs to be applicable to all the runs. A Return on Investment (ROI) for the two studied years is used [61]:

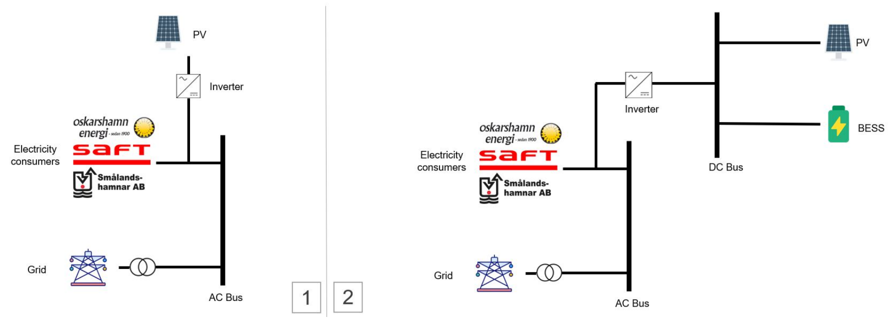

Figure 18: Architecture for PV (1) and PV-BESS (2) proposals.

$$ROI = \frac{Savings}{CAPEX}$$
$$Savings = Baseline\ cost - Scenario\ cost$$

The CAPEX are those incurred for the total cost of the installation, determined by the formula:

$$CAPEX = price_{PV} * surf_{PV} + price_{BESS} * cap_{BESS}$$

Another indicator, the avoided CO_2 emissions avoided, will be used to quantify the environmental gains from the proposed system. This amount is calculated with a formula inspired by the model in [62], which calculates the CO_2 emissions by multiplying the consumption avoided per source by the emission data. Thus, the formula adds the emissions avoided by consuming self-generated PV electricity and substracts the embodied emissions in the PV panels and the BESS. These embodied emissions have been divided by the assumed life span of each device, 30 years for PV panels and 20 years for the BESS, and multiplied by two to account for the two years of duration of the optimization.

$$CO_2^{avoided} = \sum_{t=0}^{n} [E_{PV}(t) + E_{dis}^{cons}(t)] * CO_2^{grid} - surf_{PV} * \frac{2 * CO_2^{PV}}{30} - cap_{BESS} * \frac{2 * CO_2^{BESS}}{20}$$

The emissions figures used in the formula are compiled from the latest literature and data on the topic, and they are presented alongside their sources are presented in Table 10.

Symbol	Description	Emissions	Units	Source
CO_2^{grid}	SE-4 grid carbon intensity	39	gCO_2eq/kWh	[63]
CO_2^{PV}	PV panels embodied emissions	350	$kgCO_2eq/m^2$	[15]
CO_2^{BESS}	Lithium BESS embodied emissions	89	$kgCO_2eq/kWh$	[64]

Table 10: Emissions used for calculation

4 Results

The results for the runs presented in Section 3.4 are presented here. Each of the scenarios will present graphs representative of the energy flows in them. Then, a matrix comparing the economic and environmental indicators for these scenarios is included.

4.1 Run #0 - Baseline scenario

The scenario simply calculates the baseline electricity costs incurred by the consumers in the harbor during the studied years. This baseline cost is of 8,495,985.7€. This cost is used in the next scenarios to estimate the savings in them.

4.2 Run #1 - PV installation

4.2.1 Determining PV size

The main purpose of this run is to choose an optimum size for the potential PV installation in the harbor. For this purpose, the cost of electricity was determined with PuLP for different installation sizes, ranging from 5,000 to 50,000 square meters. Then, a ratio relating this cost to the CAPEX required for the solar panels is computed. A plot illustrating this ratio compared to the square meters of the installation is attached in Figure 19.

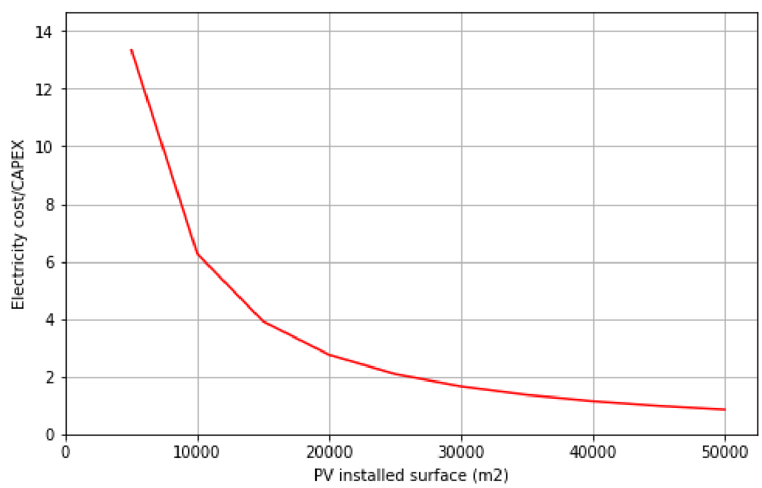

Figure 19: Ratio between electricity cost and required CAPEX for different PV installation sizes.

This electricity cost refers to the cost that would be achieved by installing the corresponding PV panel area, which is calculated by solving the optimization problem for different square meter values. For example, a value of 2 in the y-axis shows that the costs to be paid for electricity in the studied period would be twice the required CAPEX in that scenario.

It can be seen that the slope of this graph is considerably reduced after 30,000 m^2. This indicates that increasing the installation's size to the surfaces above would not give significant rewards in the shape of returns on the CAPEX to the prosumers. Thus, **a PV installation size of 30,000 square meters is chosen for the remaining project**.

4.2.2 Representative weeks visualization

Figure 20 shows a visualization of the energy flows in a representative in each of the four seasons. As expected, some PV curtailments are expected in the summer months such as June, while the long winter nights in December impede much self-consumption at that time.

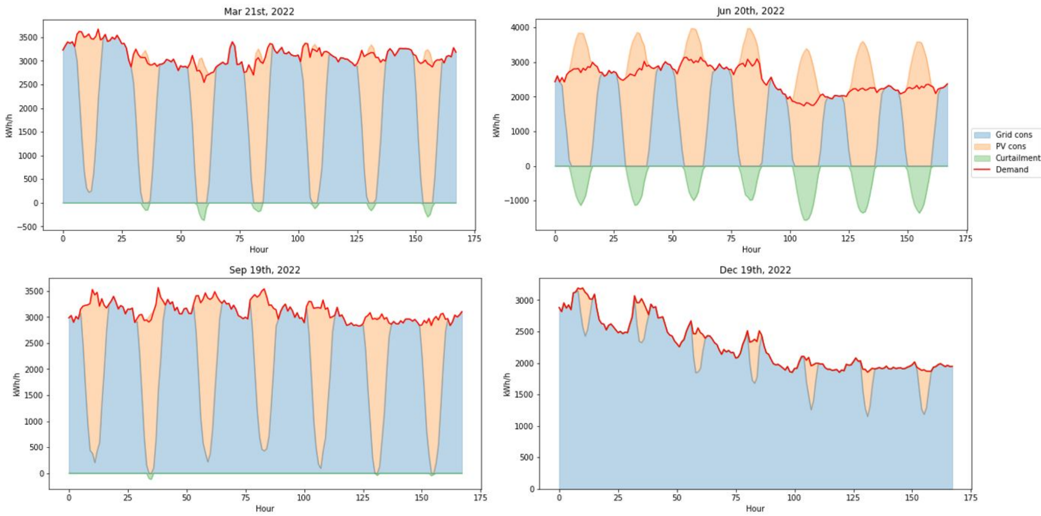

Figure 20: Energy balance at four different representative weeks for Run #1.

4.3 Run #2 - PV-BESS installationn

4.3.1 Determining BESS size

A similar exercise to the one in the previous run is performed to determine the BESS capacity to be installed. Figure 21 represents the ratio of minimum electricity cost to required CAPEX for different kWh of installed energy storage. The curve is also a descending one, but the slope does not show any inclination to decrease as in the PV panel surface one. The upper limit of 1 MWh is chosen, as the cost of the battery would still be lower than that of the PV installation.

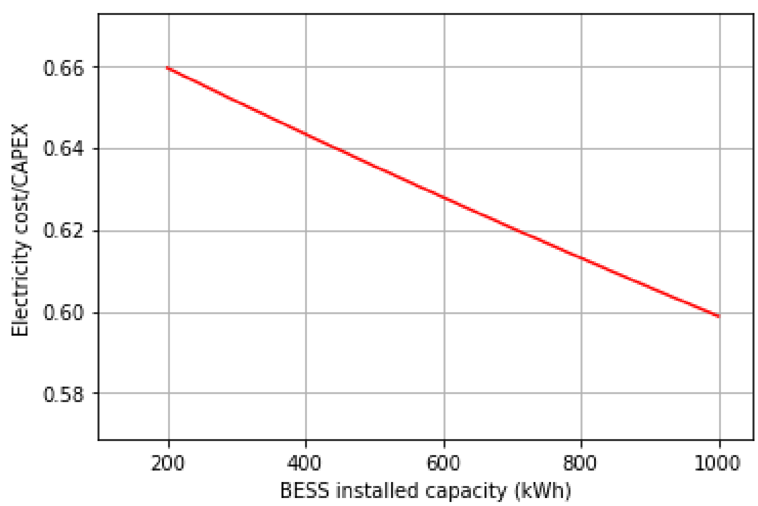

Figure 21: Ratio between minimum electricity cost and required CAPEX for different BESS installation capacities.

In this case, the minimum electricity cost refers to the cost that would be incurred had the optimum BESS charge and discharge schedule been achieved. Thus, a value of 0.66 indicates that the minimum electricity cost would be two-thirds of the CAPEX required to install the BESS.

4.3.2 Representative weeks visualization

Figure 22 represents the energy flows for the same four representative weeks for the PV-BESS installation. It can be seen how the curtailments are complemented by some eventual charges and discharges in the battery for both self-consumption and energy arbitrage.

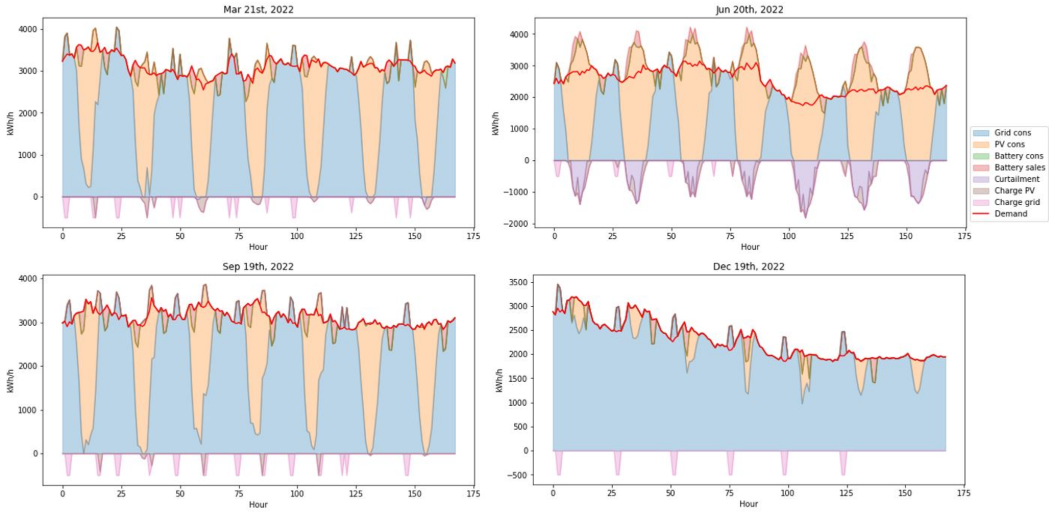

Figure 22: Energy balance at four different representative weeks for Run #2.

4.4 Run #3 - Full formulation

The full formulation of the optimization problem includes the possibility for the battery to participate in the FCR markets and also incorporates the turbine in the Norra Strandgatan turbine as a partially dispatchable source of electricity, enabling the battery to generate the maximum revenue. Figure 23 shows the four representative weeks in this full formulation. The turbine is used to cover the electricity demand at some hours when PV production is not high, and FCR market calls are more frequent than electricity arbitrage calls.

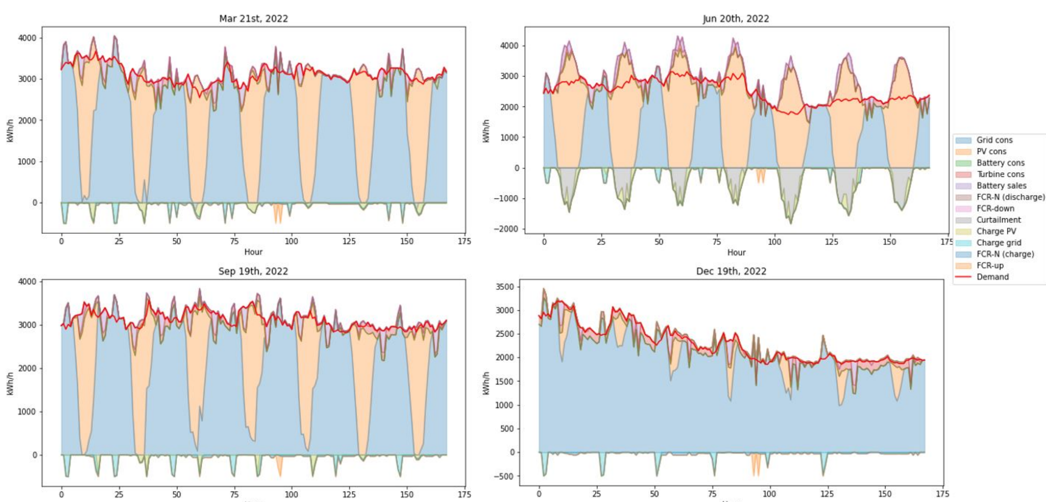

Figure 23: Energy balance at four different representative weeks for Run #3.

4.5 Results comparison

A comparative matrix of the economic and environmental gains achieved in the different scenarios is included in Table 11.

	Scenario	CAPEX (EUR)	Yearly savings (EUR)	ROI(%)	CO_2 avoided (ton)
0	Baseline	0	0	-	-
1	PV	3.60M	1.26M	35	80.2
2	PV-BESS	3.92M	1.70M	43	92.9
3	Full formulation	3.92M	1.85M	47	96.1

Table 11: Results comparison for the different scenarios

5 Discussion

5.1 Ownership scheme

As per the literature review in 2.2.2, a thought on the infrastructure sharing rules can be even more important than the system's technical specifications themselves. A joint venture for community collective generation should be established between the three industrial actors, with a recommended investment requirement of 70% for Saft, 20% for Smålandshamnar, and 10 % for Oskarshamn Energi. The proposed role of these actors in the system and their investment is explained here:

- Saft, as the biggest consumer in the harbor, would be the most interested party in decarbonizing its operations. Thus, it should invest a bigger proportion of the initial CAPEX than the two other actors.
- Smålandshamnar has a lower electricity consumption but it is expected to increase this in the coming decade at a bigger pace than its neighbors. However, considering that it is the player with more available space for solar PV installation, it would be interesting for them to host it. In exchange, they would need to invest a lower amount initially in the venture.
- Oskarshamn Energi, in the full formulation model, needs to allow the turbine to be an easily dispatchable electricity source up to some extent. As compensation for this, they would have to invest a lower proportion of the CAPEX.

5.2 Gains per stakeholder

5.3 Limitations of the study

The following assumptions need to be taken into account alongside the investment recommendations made in this project:

- Data for the periods from March 2021 to February 2023 was used to solve the optimization problem. What this means is that the system proposed is sized assuming that the trends in the electricity load and production remain similar to those of the last years.
- The limits around which the battery should cycle vary from one manufacturer to another and could influence the final savings.
- Reaching the assumed FCR market share of 2% is very dependent on market conditions. It is fair to think that the total FCR market volume is set to increase in the next years, which would open a possibility for higher revenue from there.
- The turbine OPEX in Norra Strandgatan is predicted to increase due to growing fuel costs [59]. This increase would progressively reduce the weight cogeneration would have in the harbor electricity system.
- It is worth noting that the optimizations are the best cases for the dates studies. The final cost savings achieved if such system is installed would be lower in practice, as it would be not feasible to replicate a perfect schedule in the charge and discharge of the battery.

6 Conclusion

This project was initiated with the aim of helping industrial actors in the context of a harbor in Oskarshamn, Sweden with the decision-making for new energy cost reduction strategies.

A hybrid PV-BESS installation has the potential to dramatically reduce the electricity costs in the Oskarshamn harbor by up to €1.85M on the first two-year period. This installation would be mainly composed of a 30,000 square-meter PV system alongside a 0.5MW-power and 1MWh-capacity BESS. The required CAPEX for the construction of these are estimated at €3.92M.

Besides these cost reductions, the proposed system would help lowering the CO_2 emissions in the harbor by 96.1 tons per year in the best-case scenario.

A business model based on a community collective generation scheme is proposed in which the three actors would share the renewable energy infrastructure and its subsequent electricity production. The DH turbine in Norra Strandgatan would further help reducing the costs while ensuring a predictable revenue stream for Oskarshamn Energi.

Finally, the most suitable revenue sources facilitated by these new energy assets would be electricity arbitrage and the participation in the different FCR markets operative in the Swedish grid.

7 Future works

Next steps to further evaluate the feasibility of such system are disclosed in this section.

1. The possibility to re-stack the BESS in order to maintain the capacity alongside its lifespan should be evaluated in an attempt to further decrease the degradation costs associated with it.
2. Establishing a local flexibility market in the harbor area would relieve congestions at the distribution level, while opening new sources of revenue for the proposed system. Existing use-cases in Sweden could help in the design of such a market.
3. The optimization problem could be integrated with a Machine Learning (ML) model that would incorporate predictions in the PV production and electricity price, in order to ensure a better scheduling for the battery charges and discharges.

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Appendix - Python code for the Optimization

The code developed for this master thesis has been made available openly at `https://github.com/ddriog/thesis-oskarshamn-harbor`.