ENERGY COMMUNITIES IN SWEDEN: THE CASE STUDY OF SÄTRA, VÄSTERÅS

ALAA KRAYEM

FRIDA BRÅNN

RONI BULUT

SOPHIA FISHER

PATRIC SÖDERBERG

MICHAEL ÅKERSTRÖM

FREDRIK WALLIN

School of Business, Society and Engineering

Date: 2023-05-05

Email: alaa.krayem@mdu.se

ABSTRACT

This report investigates the potential benefits, challenges, and barriers of energy communities and evaluates the solar energy potential of the Sätra area in Sweden through a method of modelling and analysis. The data collection includes weather data, building energy profiles, and PV systems, and solar irradiance modelling is conducted, followed by economic and environmental evaluations. The results show that a virtual energy community (VEC) in Sätra is technically feasible and economically viable, with potential benefits including increased local renewable energy production, reduced dependence on centralized energy systems, and enhanced energy security. Challenges such as regulatory frameworks and lack of funding must be addressed to enable the establishment of VECs in Sweden. This report provides insights into the potential of VECs as a form of energy sharing and social innovation in Sweden's energy transition, benefiting policymakers, researchers, and industry professionals interested in renewable energy and energy community development.

Keywords: energy communities, virtual energy community, solar energy potential modelling, economic evaluation, environmental evaluation.

CONTENT

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

Climate change and global warming have highlighted the urgent need for energy security and fundamental changes in our energy systems, including a transition to renewable energy. While renewable energy sources offer a sustainable alternative to fossil fuels, the nature of renewable energy poses infrastructural challenges, particularly with the power grid. The integration of renewable energy into existing energy grids requires significant investments in new infrastructure and technology to manage intermittent energy flows and ensure the grid can support and balance energy supply and demand.

Energy communities can serve as a solution to the infrastructural challenges posed by the transition to renewable energy. As previously discussed, the implementation of renewable energy sources requires fundamental changes in the energy system. Energy communities, which involve local actors such as households, businesses, and public entities working together to produce, store and distribute renewable energy, can help ensure energy security and a stable supply of energy. By pooling resources and expertise, energy communities can create more resilient and efficient energy systems that are less dependent on the traditional grid infrastructure. This can also lead to increased community engagement and empowerment in the transition to renewable energy, while helping to reduce carbon emissions and mitigate the effects of climate change.

Sweden has long been a pioneer in the transition to renewable energy sources, aiming to achieve a sustainable and environmentally friendly society. The country's commitment to reducing its carbon footprint has led to the emergence of energy communities, which are groups of citizens, local businesses, and public entities collaborating to generate, store, and distribute locally-produced renewable energy. These energy communities exemplify the decentralization of energy systems and the active involvement of citizens in the energy transition process.

This report focuses on the development and potential of energy communities in Sweden, with a particular emphasis on solar electricity production in Sätra, a district in Västerås. As Sweden experiences increasing demand for clean energy and decentralized systems, it is crucial to understand the role of local communities in contributing to the country's energy goals.

The objective of this report is to analyze the solar electricity production potential in Sätra and evaluate the feasibility of establishing a successful energy community in the area. The study will also explore the opportunities and challenges associated with the implementation of solar energy systems in the Swedish context, as well as the policy and regulatory frameworks that support or hinder the growth of energy communities.

2 ENERGY COMMUNITIES

Energy communities are a rapidly emerging concept in the global energy landscape, fostering local, decentralized energy systems and active citizen participation in the energy transition. By bringing together citizens, local businesses, and public entities, energy communities enable the generation, storage, and distribution of locally produced renewable energy. This chapter provides an overview of energy communities in general and then narrows the focus to the Swedish context. It aims to offer municipalities and energy companies a comprehensive understanding of the potential benefits, challenges, and policy frameworks associated with energy communities.

2.1 Overview of the concept of energy communities

The emergence of energy communities (EC) as a model for decentralized and community-led energy production, consumption, and distribution can be seen as a response to the growing need for more sustainable, inclusive, and locally driven approaches to energy transition. It reflects a shift towards a more democratized and participatory energy system, where communities play an active role in shaping their energy future, and where the benefits of renewable energy are shared more equitably among local stakeholders.

In Europe, the concept of energy community gained momentum with the introduction of the "Clean Energy for All Europeans" legislative package (CEP) in 2016 [1]. The package included two key legislative proposals, the Renewable Energy Directive II (REDII) (2018/2001/EU) and the revised Internal Electricity Market Directive (IEMD) (2019/944/EU). The former set the framework of Renewable Energy Communities (REC) by introducing measures to simplify administrative procedures, improve market access, and promote the participation of citizens and communities in renewable energy projects. The IEMD on the other hand, introduces new roles and responsibilities for Citizen Energy Communities (CEC). Different technologies and combinations for different contexts of EC are possible with RED II, which leave significant room for manoeuvre to the national legislators [2], [3]

Several countries worldwide have witnessed the emergence of energy communities, including Germany, the United Kingdom, the Netherlands, and Denmark [4]. Key drivers for the growth of energy communities include technological advancements in renewable energy production, government support, and increasing public awareness of environmental and climate issues [5].

However, it is important first to identify the main actors in energy communities. According to [6], the actors in an energy community can vary from natural persons to public utility companies or municipalities, and the roles that they play within the community depend on the local conditions and community goals. They are categorized into three main categories: consumer, energy service provider, and initiator. Consumers are the beneficiaries of energy services provided by other actors, while energy service providers can generate, distribute, store, supply, and aggregate energy-related commodities and services. Initiators are actors that initiate, organize, and coordinate community projects, which can be public or private, and may or may not be beneficiaries of the community energy service. Consumers can also be initiators, receiving aid from financing institutions, partnering with local companies, and forming associations or legal representatives for implementing energy efficiency measures and investing in renewable heat for self-consumption. Prosumers, who are at the intersection between consumers and energy service providers, can act as energy service providers when they generate more energy than they consume and trade it with other community members through a peer-to-peer trading platform. And this is one of the key features of energy communities, their emphasis on prosumership [2].

2.2 Configurations of energy communities

As previously mentioned, the CEP provides a lot of room for manoeuvre for member states to regulate and facilitate the establishment of ECs. For instance, researchers in Finland [7] defines three structures for ECs based on the regulatory framework for ECs in Finland: EC within a housing company, EC crossing property boundaries, and distributed energy communities. In the first structure, members of the EC, including production, are located in one housing company with one physical connection point to the distribution system operator (DSO). Electricity tax and network service cost are not required for energy produced and consumed inside the EC, and the DSO is responsible for the virtual net metering (VNM) and billing service. In the second structure, members of the EC are located in one property, but the production site is outside their property, allowing the EC to build its network and avoid paying network service and electricity tax. In the third structure, members can be distributed over the country, and a central measuring database called Datahub is required for the VNM. EC members must pay electricity tax and network service cost, as they will use the services of both transmission system operator (TSO) and DSO. In another study, the authors identified other configurations of ECs based on ownership. The authors in [8]have described different concepts that PV prosumers can be classified into. The first concept (group 1) is single direct use. This means that households residents will utilize their own generated electricity from the PV on site. The second concept is where residents share the generated electricity from the PV between each other. Thus, a collective use of PV in one building. The third concept is a district power model. This can be described as a micro grid, where PV are installed on several roofs in the community and the households/buildings share the energy between each other.

Another configuration of ECs is virtual energy communities (VECs). In the traditional energy system, electricity is delivered from the energy source to the consumer and consumer covers the costs of electricity generation, network maintenance and other components in the final bill. The cost of supplied electricity is determined by electricity generation companies and transmission/distribution system operators. In an EC community, such traditional electricity supply can be replaced with a peer-to-peer system, in which the electricity produced from PV panels could be purchased directly from other households through the respective platform, introducing its own electricity tariff system. This means that electricity trade between electricity producers and consumers will be made regardless of the tariffs set by the network operators (except in cases when electricity is transmitted through these utility networks) [9]. However, such scheme is not always possible, depending on the national regulations. In this context, VECs emerge as a promising solution that leverages the existing grid infrastructure while promoting local renewable energy production.

The mix of energy resources also alter the configuration of an EC. It depends heavily on the climate and location. More and less spatially dense areas will demand different renewable energy sources. Urban centres and dense areas in general will focus on e.g., combined heat and power and district energy, solar PV and on small or no wind power generation. Rural setting can promote different technological solutions, such as combination of PVs and wind [10].

2.3 Challenges and barriers

Several barriers and solutions have been identified to help the EC establish themselves on the market. To speed the establishment, it is critical to understand the demands of actors and define what an energy community as part of a national strategy or within a legal framework [10], while still allowing actors to build energy communities that meet their individual needs [11], [12]. One frequently used mechanism to facilitate the establishment of ECs is feed-in-tariffs (FiT), which provides a stable financial basis for the project but can also pose challenges if the FiT is altered due to political decisions [11]. Another common obstacle in the development of ECs is the absence of specific regulations to accommodate them. However, the implementation of the CEP in national policies is expected to address this issue, by providing a simplified administrative process. The current regulatory and policy measures in the energy market often do not adequately support the establishment of ECs and influence consumer's willingness to get involved in ECs. Through legislation, policy imposes market restrictions, provision of various investment opportunities, support schemes etc. As for the sale of energy excess, the sharing policy is much more important than the pricing policy. Furthermore, net metering as a pricing policy does not help to form energy communities, because no savings can be made by relying on energy costs' revenue and it does not encourage demand-related activities. The most important factor to achieve zero energy community is coordinated action and communication between utilities and policymakers [9].

The existence (or not) of a support system, such as an umbrella organisation, that provides guidance and facilitates coordination between EC projects is also critical [11], [13]–[15]. For example, in the United Kingdom, the Netherlands and Germany, ECs are part of larger cooperative organisations. These intermediaries contribute with networks, a possibility for learning between ECs, and a platform for sharing the best practices [10].

In order to create an environment where ECs can thrive, a liberalized market with domestic competition is essential. A closed energy market, where rules and resources are tailored to large players, presents a disadvantage for ECs. Access to the grid is also critical for ECs, and a monopolized grid is a barrier. However, affordable grid access and cooperation with energy companies can be enabling factors for the establishment of ECs. Large energy companies and state-owned energy companies present constraining conditions for ECs, while small energy companies, consumer-owned companies, and competition and unbundling are favourable for their growth.

One of the most significant obstacles in the development of ECs is the lack of funding. ECs require subsidies and other financial support to start and overcome the initial stage. Therefore, state funding, subsidy mechanisms, and dedicated support programs are vital for the development of ECs. However, it can be challenging to secure funding in the early stages of an EC, when plans are being implemented. Thus, it is crucial to provide subsidies to encourage and facilitate the creation of ECs [10]. In addition, any system put in a place in which the consumer is expected to participate must be able to pay off itself over time. Economic and payback point of view is crucial to motivate the consumer to participate in an energy community. The payback period of the community can be positively influenced by remuneration and self-consumption [9].

As for membership of ECs, the education and awareness are often emphasized. These correlate with the willingness to participate in an EC. Especially lack of technical knowledge has been seen as a barrier for participation in ECs. The future can bring an increased complexity of the system and thus a need for more professional competence. The lack of expert knowledge will be a major barrier for newcomers. Several policy programs have been developed to educate and raise awareness among citizens about energy efficiency or renewables. These have been ineffective because it has been relying too much on the idea of rational actors and not considering a broader social context [10].

2.1 Energy communities in Sweden

Sweden has a strong tradition of community involvement in energy production, particularly through cooperative models in the hydropower and wind energy sectors [16]. Recently, the concept of energy communities has gained momentum in Sweden, driven by the government's ambitious climate and energy targets, including a 100% renewable electricity system by 2040 [17]. For Sweden, ECs provide multiple advantages, including boosting local renewable energy production, which contributes to the nation's energy and climate goals. They also enhance energy security and decrease dependence on centralized energy systems, while supporting local economic growth and creating jobs through investments in renewable energy projects. Moreover, energy communities empower citizens and encourage active participation in the energy transition process, ultimately leading to increased social cohesion.

However, several challenges need to be addressed for the successful implementation of energy communities in Sweden. When examining the potential of EC to contribute to an energy transition, Sweden presents an interesting case study. Sweden already boasts a high share of renewable energy in its energy system. However, the country's electricity market is centralized, dominated by a few utilities, and lacks direct engagement between utilities and end-users. Policies promoting community-led energy initiatives are currently lacking in Sweden. The Swedish government has not introduced specific regulations for ECs and has deemed the existing legal framework sufficient to support their development. Furthermore, there is a lack of regulatory systems to facilitate a market for energy sharing among neighbours. In fact, sharing electricity without an internal grid is currently illegal, and the construction of such a grid is subject to regulatory requirements. Moreover, the country's electricity grid is not designed for storage, so any electricity generated must be consumed. This is hindering one key aspect of ECs, which is increased citizen engagement in energy production, as these communities emphasize the importance of individual and local involvement in ensuring energy security, combating climate change, and reducing costs for consumers. In addition, limited incentives, and support measures, including financial support and technical and administrative assistance, have been a challenge for the financing and development of EC projects. Lastly, the willingness to participate in ECs is affected by a lack of technical knowledge, coordination among umbrella organizations, and the need to navigate bureaucracy, grant applications, and technical standards. A centralized umbrella organization for ECs could help to coordinate communication, provide resources, advocate for policy changes, and support the perseverance of members.

Nevertheless, despite these unfavourable conditions, the development of ECs in Sweden has gained traction, signifying the growing interest and potential of ECs in the country. An example of successful energy community is Simris. Simris is a village (about 150 households) in the Southeast of Sweden. The energy community was in operation there from 2017 to 2019. To produce electricity, wind turbine and photovoltaic power plant were used. Surplus renewable energy was stored in batteries. This energy community proofs that an entire village can run on 100% self-generated sustainable energy [18].

3 SOLAR ENERGY POTENTIAL IN SÄTRA: METHOD OF MODELLING AND ANALYSIS

The purpose of this section is to explore and investigate different solar panel configurations in Sätra that can maximize the solar potential. With the help of a provided 3D-model, the different configurations of the panels could be explored. An analysis will also be done on the integration of battery storage and how electrical vehicle will impact the community. Additionally, an economic and environmental performance will be assessed.

3.1 Data Collection

A preliminary 3D model of Sätra neighbourhood was obtained from the municipality. It provides essential information about the neighbourhood morphology, in terms of buildings density, vertical and horizontal distribution, preliminary basic design and geometries, and types. These descriptives are determinative of the total solar radiation that a surface would receive. The type on the other hand informs about the energy demand profile of the building. Table 1 shows the expected number of buildings in Sätra, their types and estimated volumes.

Table 1: Building Types and Volumes in Sätra

	Number	**Volume [m^3]**
Multi-family & commercial buildings	**121**	**455,136**
Single-family buildings	**93**	**20,610**

3.1.1 Weather data

The weather file was extracted from climate.onebuilding[1]. The climatic conditions were those of the airport station in Västerås.

3.1.2 Buildings energy profiles

Using real electricity and district heating data of buildings in Västerås, representative energy profiles of similar buildings to those in Sätra were used to estimate the energy demand in Sätra. Average daily electricity demands for the year 2020 in KWh/m^3 for villas and multifamily buildings that were built after 2008 were extracted from NRGYHUB database.

[1] https://climate.onebuilding.org

3.1.3 PV systems

Many technologies for PV systems are available, each with different advantages and disadvantages. The cost and efficiency between different PV technologies also varies. Since this project is to assist the development of the solar-based energy community in Sätra, mature solar PV technologies will be used in the assessment. Silicon-based PV modules are the first generation of PV cells and are still the most common systems to use. The efficiency for commercial use ranges from 16 -22% for single-crystalline (monocrystalline) and 15-18% for multi-crystalline (polycrystalline) silicon cells. Although polycrystalline has less efficiency, they have the added benefit of reducing the cost of the PV-module.

The characteristics of the two different types of modules, were obtained from a solar module retailer Europe-SolarStore and are summarized in Table 2. The modules were chosen arbitrarily with only their cell type and rated power output being considered. Table 2 shows that the monocrystalline module has a higher efficiency, but also a higher cost than the polycrystalline alternative. The conversion factor used to convert euro to SEK was 10.95 (2022-11-23).

Table 2: Characteristics of mono- and polycrystalline PV modules

Name [Type]	**AXITEC AXIpower AC-330P/156-72S [Polycrystalline]**	**LG MonoX Plus LG295S1C-A5 [Monocrystalline]**
Power $\boldsymbol{P_{module}}$ [W]	**330**	**325**
Cost [SEK/panel]	**1,467**	**1,905**
Efficiency $\boldsymbol{\eta_{module}}$ [%]	**17.01**	**19**
Length $\boldsymbol{L}$ [m]	**1.956**	**1.686**
Width $\boldsymbol{W}$ [m]	**0.992**	**1.016**
Datasheet	[19]	[20]

The cost of the installation of a PV system does not only consist of the modules' prices, but rather includes other additional costs shown in Table 3. The average cost for the system installation is retrieved from [21], where the prices were extracted from a direct capital subsidy programme and sale statistics data in combination with a study on Swedish grid-connected roof-mounted residential PV system. Components such as the inverter has a European efficiency of 98.3%[2]. There are additional costs associated with a fixed ground-mounted racking system for tilting PV modules which, in the USA, ranged between 0.11-0.18 USD /Wp for the first quarter of 2021 which converts to approximately 1.2 – 1.9 SEK/WP. The conversion factor used was 10.95 (2022-11-23).

[2] https://www.pvsyst.com/help/index.html?inverter_euroeff.htm

Table 3: Different cost categories for PV installation

Cost category	SEK/W_p
Mounting material	0.38
Other electronics	1.49
Inverter	2.04
Installation work	3.5
Other work-related costs excl. installation work and VAT	2.3
VAT	3.22
Total cost	12.93

3.2 Solar irradiance modelling

In order to understand the amount of solar irradiance that buildings can potentially receive in a year, an advanced light analysis tool was chosen. The tool used to gather all the data is DL-light which is an extension software for SketchUp developed by a French company called De Luminae. It is used to study and estimate the solar irradiance in urban and architecture projects. DL-light uses a ray tracing method, which is a technique that can calculate how the solar irradiance is being spread and reflected. The purpose of ray-tracing is to create a realistic three-dimensional photo on a two-dimension computer screen. It simulates light rays in three-dimensional environments [22]. It consists of launching rays into a model and analyse the absorption, reflection, refraction diffraction and scattering of each ray. One of the main advantages of DL-light is the consideration of shadings from nearby objects (buildings, trees, etc…). It also considers the climate conditions, the objects geometries and material characteristics such as reflection factor and albedo, among others. After simulating the solar irradiance, the solar energy potential can be calculated.

The objective is to maximize the generation of solar electricity in Sätra, and three distinct configurations of the distribution of solar panels are being examined for this purpose. In the first scenario (Scenario 1 S1), the placement of solar panels will be limited to flat roofs and roofs tilted towards the South (See Figure 1). Specifically, all panels will be arranged in a south-facing position using mounting structures to tilt the PV modules. In the second scenario (Scenario 2 S2), all the panels will be tilted in West and East orientation. Additional mounting structures will be utilized to tilt the PV modules on the flat roofs. In this scenario only flat roofs and rooftops tilted towards the West and East orientation will be utilized. 50% of the modules will be tilted towards east and the rest towards west direction and this fraction was chosen arbitrarily. The motive to place the panels in these directions, is the possibility to shave the peak hours. Thus, shave the first peak in the morning and the second peak in the afternoon/evening. In the last scenario (Scenario 3 S3), the solar PV panels will be placed along all available and potential surfaces without additional structures for tilting the panels further than the buildings own rooftop slope and the façades coordinal direction. In this scenario all rooftops and facades will be utilized without additional structures for tilting or orienting. The motive for this scenario is to estimate the possible electricity generation without additional tilting structures.

In addition to the previous simulations, an additional scenario (S*) was conducted where the hourly solar irradiance per m^2 was simulated using PVGIS (due to computational limitations using DL-light explained in the next paragraph) for a south facing standalone PV system. Using the estimated available surfaces for PV installations facing south in Sätra, the electrical production from PV was calculated and the self-sufficiency rate at an hourly level was estimated. This simulation allowed to estimate the potential need for storage and evaluate the viability of implementing a storage system to ensure a consistent supply of electricity throughout the day.

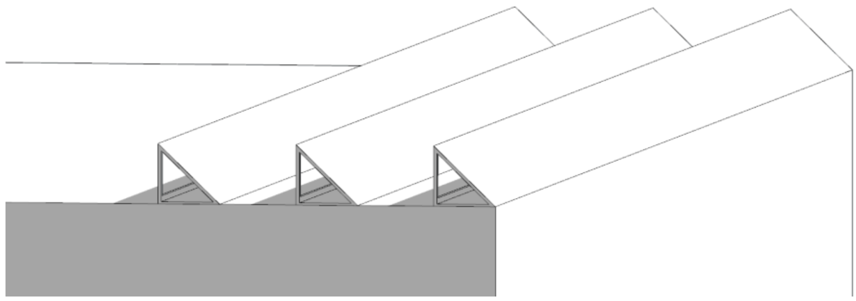

Figure 1: Visualisation of the PV panels in a south direction

Figure 2: Visualization of the PV panels in west and east direction

In the first and second scenarios, a major technical challenge was faced. Adding objects representing the tilted solar panels was a complicated task, which, given the time limit of the project, was not feasible. Therefore, the simulation of the whole neighbourhood was not possible. To overcome this challenge, one simple building was built in the Sketch-Up model. On this building, solid objects representing tilted PV modules were created as shown in Figure 2, facing south or east and west, depending on the scenario. The optimal slope for the south direction and the east-west directions, was identified using the PVGIS[3] tool. By providing the latitude and longitude to the tool, it provides the optimal slope for standalone PV systems. However, it is worth mentioning that PVGIS provided different slope values ranging from 40° to 45° when slightly moving across the longitude and latitude

[3] https://re.jrc.ec.europa.eu/pvg_tools/en/

in Sätra. It is most probably due to the topography of the area that it is not flatten for construction yet. A slope of 44° was chosen for Scenario 1, and of 40° for Scenario 2.

The solar irradiance was then simulated, and the potential solar electricity production was calculated. Given the total available surfaces for the tilted structures, the results were multiplied to estimate the total solar electricity generation in the district. More details on the calculations are provided in the following sections.

In addition to the solar potential in the different configurations, each scenario will be evaluated based on economic and environmental factors, as well as the potential for the scenario to establish a net positive energy community in the area. The use of electric vehicles and batteries will also be studied in all three scenarios.

3.3 Solar electricity generation

The daily average solar irradiance (G per area in Wh/m^2 per day for a month) and area (A) in m^2 are retrieved from DL-light for the simulated objects (the tilted panels in scenarios 1 and 2 and the total surfaces in scenario 3). The area retrieved from DL-light is the total available area $A_{surfaces}$, which needs to be recalculated to the available area for PV-installation with Equation 1, were F is the reduction factor.

$$A_{avai.} = A_{surfaces} * (1 - F) \quad [m^2] \tag{1}$$

Once the available area is calculated, the number of modules that can fit on the area is calculated with Equation 2.

$$N_{module} = Round\ down\left(\frac{A_{avai.}}{A_{Module}}\right) \quad [pcs] \tag{2}$$

The total area of the PV modules and the total installed capacity are calculated with Equation 3 and Equation 4 respectively.

$$A_{tot} = N_{module} * L * W \quad [m^2] \tag{3}$$

$$P_{tot} = N_{module} * P_{module} \quad [W] \tag{4}$$

The electrical power output can now be calculated with equation 5, were d is the number of days in a specific month and η_{module} the efficiency of the module (Table 2), $\eta_{inverter}$ is the inverter efficiency which is 98.3%, and $\eta_{performance}$ is the system performance given 14% of system losses as per the experts who developed PVGIS. The system losses are from cables, and other balance-of-system components. They also include the mismatch losses that occur when the electrical characteristics of the modules in a system are not matched properly.

$$E_{tot} = G * d * A_{tot} * \eta_{module} * \eta_{inverter} * \ \eta_{performance} \quad [Wh] \tag{5}$$

To measure if a building/community has the possibility to become net zero energy, meaning it is in a balance state between energy taken from and supplied back to the energy grid over a period, the self-sufficiency ratio and self-consumption ratio (SSR) and (SSC) are computed [23]. The former is a measure of how much of the energy demand is covered from their own production whilst the latter is the share of produced energy that is consumed by the user. The SSR is calculated with Equation 6 by dividing the total power from the grid with the electric load. The average electricity consumption for a multifamily building and a villa was multiplied with the total volume of the Sätra’s villas and multifamily buildings.

$$SSR = \left(1 - \frac{E_{grid}}{E_{load}}\right) * 100 \quad [\%] \tag{6}$$

3.4 Impact of electrical vehicles

An electrical vehicle has different degrees of influence on the power demand depending on its charging time. The charging time can be categorized into normal charging, semi-fast charging, and fast charging. Normal charging is the same as the usual home charging stations that charges during a long time, the power demand for this type of charging varies between 2.3 to 3.7 kW. The semi-fast charging takes place during a couple of hours since it has a three-phase contact. It is usually available in public parking lots and has a power demand up to 43 kW. The fast charging is also a three-phase contact that is located at public rest areas and only requires 20 to 60 minutes of charging. The power demand is hence 50 kw for 1 hour charging and 150 kW for 20 minutes charging [24].

The charging profiles for electric vehicles was studied by [25]to estimate its effect on the power system. This study was carried on in Denmark where they studied the electric profile of 14 cars. The average power demand in their study can be seen in Table 4.

Table 4: Average power demand for charging 14 electricity vehicles [25]

	Average power demand for home charging for 14 electric vehicles [KWh]
January	**31.16**
February	**32.76**
March	**32.26**
April	**23.43**
May	**20.63**
June	**21.03**
July	**14.43**
August	**22.73**
September	**22.33**
October	**23.34**
November	**24.67**

December	**25.18**

The impact of electricity vehicles in Sätra was estimated by assuming that every household will own one electric car, which leads to 2000 cars (N_{cars}). The energy demand for the car charging is given by Equation 7.

$$E_{car\ charging} = E_{average\ month} * N_{cars} \quad [Wh] \tag{7}$$

3.5 Economic evaluation

An economic evaluation has been performed to compare the economic feasibility of the different scenarios and for different solar panel types. In this study, two different solar panel types have been used which are monocrystalline and polycrystalline. Equation 10 represents how to the total cost can be calculated.

$$C_{total} = C_{tot,modules} + C_{other} \quad [SEK] \tag{8}$$

Where the cost of all solar panels for each surface can be seen in equation 11. The cost of one module is multiplied with the number of modules that can be placed on the roof and the Value-Added Tax (VAT) which is 25% in Sweden [26].

$$C_{tot,modules} = N_{modules} \cdot C_{module} \cdot (1 + VAT) \quad [SEK] \tag{9}$$

The final step is the calculation of other expenses, which is represented by equation 12. Where 12.93 is the average cost in SEK for other expenses per installed power in kW.

$$C_{other} = 12.93 \cdot 1000 \cdot P_{installed} \quad [SEK] \tag{10}$$

For the first and second scenario, additional cost will come from the structure used to tilt the PV modules which is between 1.1 - 1.9 SEK/Wp meaning an average of 1.55 SEK/Wp. Therefore, equation 12 will be slightly modified to equation 13.

$$C_{other} = (12.93 + 1.55) \cdot 1000 \cdot P_{installed} \quad [SEK] \tag{11}$$

3.6 Environmental evaluation

To evaluate the reduction of CO_2 emissions achieved by producing electricity from PV panels in Sätra, it is of interest to know how much CO_2 Mälarenergi’s CHP plant emits. The CHP plant in Västerås provides both electricity to the power grid and heat to the district heating network. With the help of recycled and renewable fuels, Mälarenergi provides sustainable energy to their customers. The generated electricity and heat are up to 700 GWh and 1800 GWh respectively[4]. The carbon emission intensity, according to Mälarenergi[5], was estimated to 74,9 g CO_2/kWh 2021. Therefore, the amount of CO_2 is given by equation 14.

$$m_{CO_2} = CO_2 \cdot PV\ Generation \qquad [g\ CO_2] \tag{12}$$

4 Retrieved October 26, 2022, from https://www.malarenergi.se/om-malarenergi/framtidens-samhalle/vara-anlaggningar/kraftvarmeverket-vasteras/

5 https://www.malarenergi.se

4 MODELLING RESULTS AND DISCUSSION

The line graph in Figure 3 illustrates the relationship between the estimated electricity consumption (with and without EVs) and the simulated solar PV production under three different scenarios (S1, S2, and S3) over the course of a year. The electricity consumption lines show a clear seasonal pattern, with higher consumption during winter months like December and January, and lower consumption during summer months such as June and July. This can be attributed to higher heating demands and reduced daylight hours, leading to increased lighting usage in winter. Both S1 and S2 lines (in both mono and poly cases) are close to each other but do not match the electricity consumption line, indicating that installing PV panels only on south-facing roofs or a combination of east and west-facing roofs may not be sufficient to meet the electricity consumption demands throughout the year. The third line, S3, represents an unrealistic scenario where PV panels are installed on all available surfaces. This line shows significantly higher PV production, exceeding the electricity consumption needs.

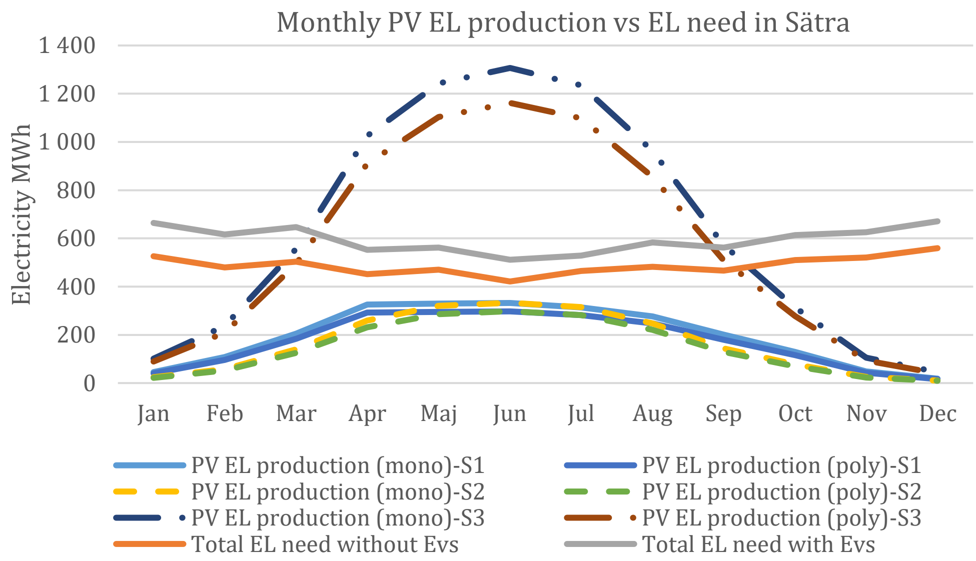

Figure 3: PV electricity production from mono and polycrystalline modules, compared to the electricity need without and with electrical vehicles.

In the graph in Figure 4, the self-sufficiency rate of solar PV systems for the different installation scenarios (S1, S2, and S3) and panel types (monocrystalline and polycrystalline) is analysed over a year (the electricity need does not include EVs). The analysis reveals that the self-sufficiency rate for South facing PV (S1 scenario) with monocrystalline panels peaks at 78.8% in June, while for polycrystalline panels, it peaks at 70.6% in the same month. For the West and East facing PV (S2 scenario), the self-sufficiency rate for monocrystalline panels reaches its highest value of 79.0% in June, and for polycrystalline panels, the peak value is 70.7% in the same month. A similar trend is observed for All Surfaces PV (S3 scenario) with both panel types, where the self-sufficiency rate peaks between May and July, reaching its highest values of 146.7% for monocrystalline panels and 129.9% for polycrystalline panels in June. Across all installation scenarios, the S3 scenario, which includes PV installations on all available surfaces, demonstrates the highest self-sufficiency rate throughout the year for both monocrystalline and polycrystalline panels. It is important to note that the self-sufficiency rate for all scenarios and panel types is lowest during the winter months, particularly November, December, and January. For instance, in December, the self-sufficiency rate drops to as low as 3.3% for monocrystalline panels and 2.9% for polycrystalline panels in the S1 scenario.

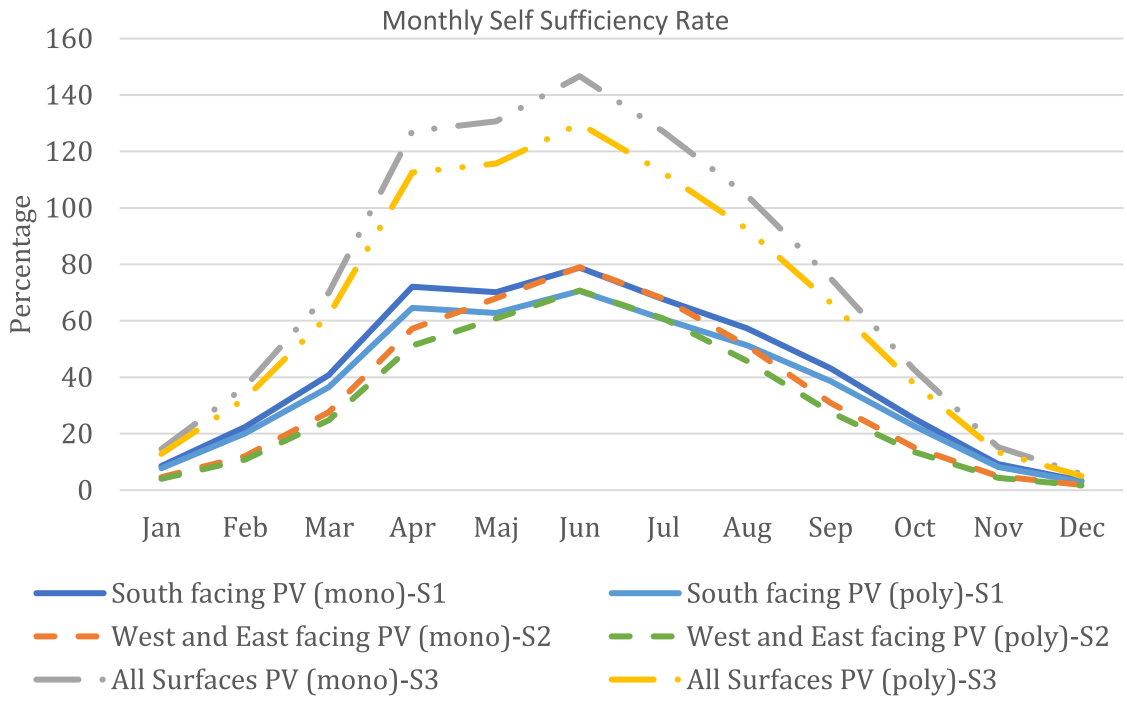

Figure 4: Monthly Self-Sufficiency Rate of Solar PV Systems for Different Installation Scenarios and Panel Types

Table 5 outlines the yearly PV generation and self-sufficiency rates (SSR) for different installation scenarios (S1, S2, and S3) and panel types (monocrystalline and polycrystalline). The table demonstrates that the yearly PV generation for monocrystalline panels is higher than that of polycrystalline panels across all installation scenarios. In the S1 scenario, monocrystalline panels generate 2,334 MWh/year, while polycrystalline panels generate 2,089 MWh/year. Similarly, in the S2 scenario, monocrystalline panels generate 1,950 MWh/year compared to 1,747 MWh/year for polycrystalline panels. The largest difference in generation is observed in the S3 scenario, where monocrystalline panels produce 7,702 MWh/year, and polycrystalline panels produce 6,842 MWh/year. The self-sufficiency rates in the table follow a consistent pattern, with monocrystalline panels having higher SSR values than polycrystalline panels in all scenarios, both with and without electric vehicles (EV). For instance, in the S1 scenario, the SSR with EV is 33% for monocrystalline panels and 29% for polycrystalline panels. Without EV, the SSR increases to 40% for monocrystalline panels and 36% for polycrystalline panels. In the S3 scenario, the SSR values are significantly higher than those in S1 and S2, with monocrystalline panels achieving an SSR of 108% with EV and 131% without EV, while polycrystalline panels reach SSR values of 96% with EV and 117% without EV.

Table 5: Solar PV generation and self-sufficiency rate under different installation scenarios

Parameter	S1	S2	S3	Unit

Yearly PV generation mono	2,334	1,950	7,702	MWh/year
Yearly PV generation poly	2,089	1,747	6,842	MWh/year
Yearly SSR mono with EV	33	27	108	%
Yearly SSR mono without EV	40	33	131	%
Yearly SSR poly with EV	29	25	96	%
Yearly SSR poly without EV	36	30	117	%

Table 6 presents an economic and environmental comparative analysis of the monocrystalline and polycrystalline solar modules under three different installation scenarios (S1, S2, and S3). The table reveals that the total cost for monocrystalline modules is consistently higher than that of polycrystalline modules across all installation scenarios. This finding suggests that while monocrystalline panels might offer higher efficiency, they come at a greater financial investment. The monocrystalline modules also demonstrate a higher installed power capacity than polycrystalline modules in each scenario. This difference indicates that monocrystalline panels may have a higher power generation potential, contributing to their increased cost compared to polycrystalline alternatives. Although the electricity production per installed power is relatively similar between monocrystalline and polycrystalline modules in each scenario, the table shows a significant decrease in produced electricity per installed power for both module types in scenario S3 compared to S1 and S2. This finding might suggest that the installation configuration in S3 is less efficient in converting the installed power capacity into electricity. The cost per installed kWp is consistently higher for monocrystalline modules than for polycrystalline modules across all scenarios. The difference in cost per installed kWp ranges from SEK 1,770 to SEK 2,320, further emphasizing the higher installation cost of monocrystalline panels. In terms of CO_2 emissions, the table shows that monocrystalline modules save more CO_2 emissions per year than polycrystalline modules in all scenarios. This finding implies that the higher efficiency and power generation potential of monocrystalline panels lead to a greater environmental benefit.

Table 6: Comparison of Costs and Environmental Benefits for Monocrystalline and Polycrystalline Solar Modules in Different Installation Scenarios

Mono and poly crystalline modules cost and emissions						
	S1		**S2**		**S3**	
	Mono	**Poly**	**Mono**	**Poly**	**Mono**	**Poly**
Total cost [MSEK]	44.7	36.8	44.3	36.3	229	185
Total installed power [kWp]	2,052	1,838	2,032	1,814	11,304	10,045
Produced electricity per installed power [KWh/KWp]	1,137	1,137	960	963	370	369
Cost per installed kWp [SEK/kWp]	21,807	20,037	21,806	20,036	20,258	18,486

Emissions saved by the PV panels [ton CO_2/year]	175	156	146	130	313	277

Based on the graph in Figure 5 representing the results for the additional scenario S* (without considering EVs due to limitation in generating hourly profiles of their charging), there are significant fluctuations in the hourly electricity production from PV. During the summer months, many hours exceed the electricity demand, while in the winter months, some of the values fall within the range of the electricity demand values. It is worth noting that there are null values for the hourly electricity production from PV, which are due to the system not working when there is insufficient sunlight. These results emphasize the importance of considering seasonal variations in solar irradiance and fluctuations in electricity demand when designing a solar PV system and highlight the potential benefits of integrating an appropriate energy storage system to ensure maximum efficiency and reduce reliance on the grid.

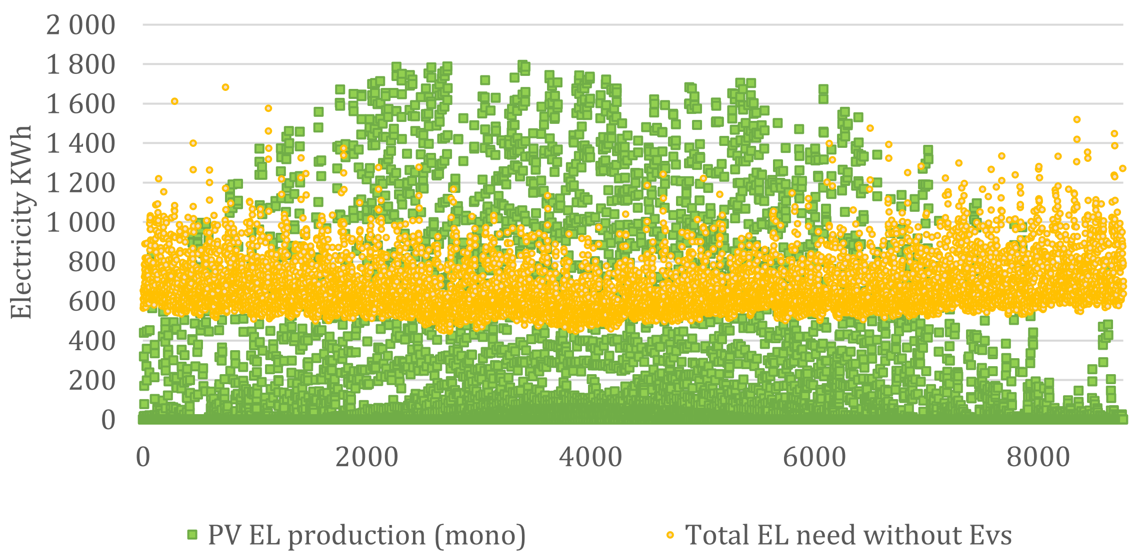

Figure 5: Hourly Electricity Production from PV vs Hourly Electricity Demand: Seasonal Fluctuations and Potential for Energy Storage.

The hourly self-sufficiency rate plot in Figure 6 shows that the highest value of the self-sufficiency rate is around 358% during the summer months suggesting that the system is capable of producing more electricity than is needed for the building's energy demands during these periods.

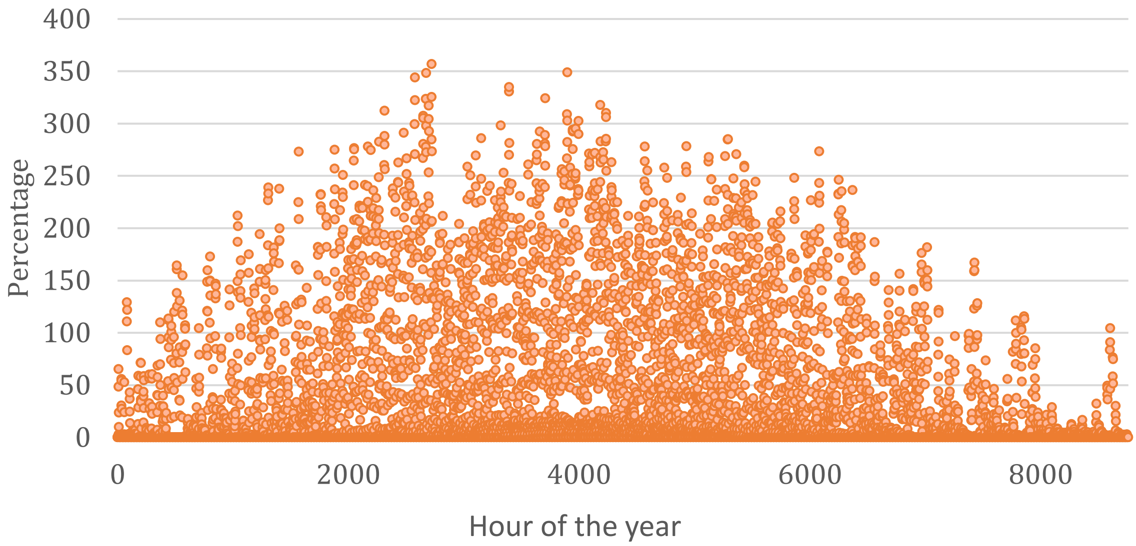

Figure 6: Self-Sufficiency Rate Based on Hourly Electricity Production from PV

The distribution plot of the hourly self-sufficiency rate in Figure 7 provides important information on the performance and potential of the solar PV system in meeting the building's energy demands. The plot is based on the data collected during hours when the solar PV system was producing electricity, excluding the hours when there was no sunlight, and the system was not producing any electricity. The majority of the data points in the distribution table fall within the range of self-sufficiency rates greater than 100%, with 1402 instances recorded. This indicates that during these hours, the system was generating more electricity than was needed to meet the building's energy demands, with the excess being available for storage or export to the grid. The remaining data points are distributed across the other ranges, with the highest frequency of 1286 instances recorded for the range of self-sufficiency rates between 1% and 17%. This suggests that during these hours, the solar PV system was not generating enough electricity to meet the building's energy needs, with a significant portion of the energy being supplied by the grid.

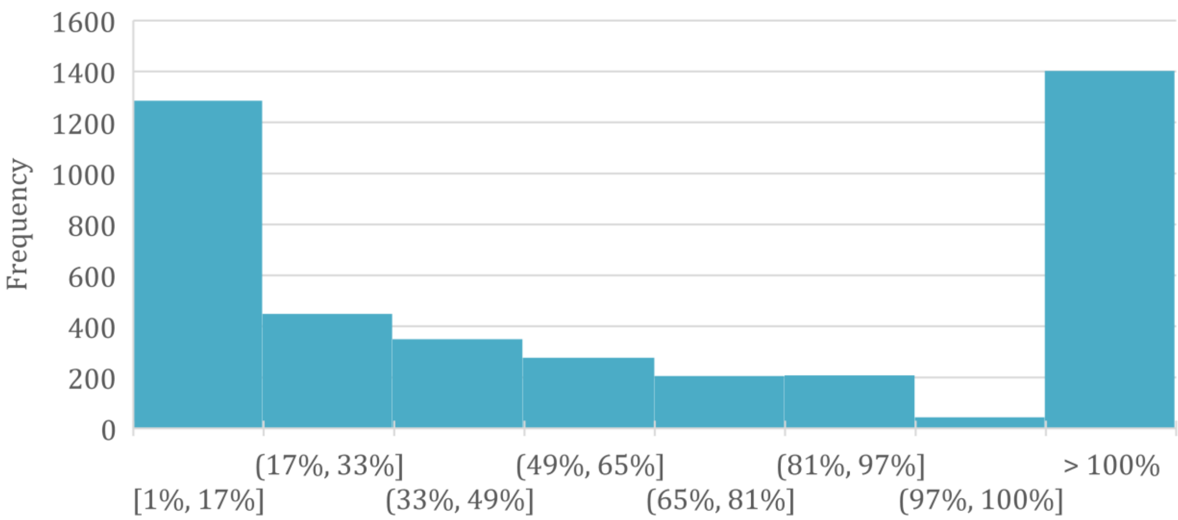

Figure 7: Distribution plot of the hourly self-sufficiency rate

The results from the three scenarios S1, S2 and S3, show that the placement and orientation of solar PV panels have a significant impact on electricity generation and investment cost. While the scenario with all panels facing south S1 generates the most electricity per installed power, the scenario with panels on every available surface S3 has the highest total installed PV power, resulting in the highest electricity generation but also the highest investment cost. However, due to its unrealistic nature, S3 may not be a feasible solution for practical implementation. The scenario with panels facing east and west direction S2 has the lowest electricity generation and investment cost. In all cases, as Figure 3 and 4 demonstrate, the contrasting seasonal patterns of electricity consumption and solar PV production under the three different scenarios are well pronounced, and the graphs highlight the challenges of relying solely on solar PV to meet electricity demands. While S1 and S2 show similar production levels that do not match electricity consumption, S3 exceeds the needs but represents an unrealistic approach, which may suggest the need for a more diverse energy generation mix or further innovations in energy storage and efficiency. Additionally, the distribution graph (Figure 7) emphasizes the importance of carefully managing and optimizing the solar PV system to ensure maximum efficiency and reliability, particularly during periods of low solar irradiance or high energy demand. The graph also highlights the potential benefits of a well-designed and operated system, including the ability to generate excess electricity for storage or export to the grid. It is important to note that the distribution table only includes the data points for the hours when the solar PV system was generating electricity, excluding the hours when there was no sunlight and the system was not producing any electricity, which is an important consideration when analysing the distribution of self-sufficiency rates.

Regarding the study limitations, one limitation is the consideration of two buildings' types, multi-family buildings and villas. Other types of buildings like schools and sport halls with different electricity profiles were neglected.

The impact of electric vehicles on the electricity consumption in Sätra was found to be less than anticipated, and there was no significant difference between the graphs with and without electric vehicles. To estimate the impact of electric vehicles, it was assumed that every household had one electric car, resulting in 2,000 cars that needed charging. The monthly power demand was estimated using average charge values per day and data from the literature. However, the estimation was based on a daily average demand and neglected people's charging patterns, which could lead to inaccurate results due to power peaks when multiple cars are charged at the same time. Furthermore, the estimation only considered normal charging devices, whereas semi-fast and fast charging could significantly increase power demand but were not considered. The total electricity consumption during a year increased by 1,279 MWh when electric vehicles were included.

In relation to the reduction of CO2 emissions that could be achieved by generating electricity from PV panels, the results align with expectations. As a result, the amount of saved CO2 emissions is greater for the third scenario, which generates more electricity compared to scenarios 1 and 2. The difference in saved CO2 emissions between monocrystalline and polycrystalline is not significant, as evidenced by the tables for all scenarios. However, it should be noted that the assumption that all residents in Sätra purchase their electricity from Mälarenergi does not take into account the CO2 emissions of other electricity suppliers. As a result, these figures may vary as the choice of electricity supplier is a personal decision.

The current carried technical analysis could not provide any recommendations regarding a trading market or peer-to-peer trading scheme in Sätra. Such scheme highly depends on the individual profiles of each building which was not analysed in the current study. Due to the resolution limitations, an accurate and complete analysis of e.g., battery integration is not possible, as the analysis for the battery would be more appropriate on an hourly basis to investigate the potential benefits of time-shifting the electricity generation to better match the electricity demand of the households. Batteries have therefore, in this study, no significant effect on the SSR in the scenarios.

5 CONCLUSION

The energy market structure in Sweden is currently not supportive of the development of energy communities (ECs). Despite this, many ECs are being established, indicating the growing demand for sustainable and community-based energy solutions, and the recognition of ECs as an essential component of the energy transition process in Sweden, offering a decentralized approach to renewable energy production and empowering citizens to actively participate in the shift towards a sustainable energy system. Energy communities can bring various benefits to the local community and the local economy as well. ECs can contribute to that the members save both energy and money and feel less risk to invest in different energy solutions. They can also bring welfare to low-income households and contribute to the collective distribution of benefits. Social motivations such as public acceptance, awareness, and trust in renewable energy technologies and community-based initiatives can overrule financial motivations. There are also indications that customers are prepared to pay more for locally generated power and that the locality contributes to a feeling of trust in the energy system. By integrating social science perspectives into the analysis of energy communities, municipalities, and energy companies can better understand the factors that influence the adoption and success of these initiatives, and design targeted strategies to overcome the challenges they face.

In Sätra, there is a high potential for solar energy production, which can be leveraged to foster the development of a virtual energy community. A virtual energy community can provide a solution to some of the challenges faced by traditional ECs in Sweden, such as lack of physical space, by allowing participants to share energy production and consumption data and optimize energy use. The development of a positive energy district in Sätra can serve as a model for other communities to follow, helping to achieve Sweden's climate and energy targets. By utilizing the potential of solar energy and virtual energy communities, Sätra can pave the way for a more sustainable and community-based energy future in Sweden.

6 REFERENCES

[1] T. Bauwens *et al.*, "Conceptualizing community in energy systems: A systematic review of 183 definitions," *Renewable and Sustainable Energy Reviews*, vol. 156, no. December 2021, 2022, doi: 10.1016/j.rser.2021.111999.

[2] J. Lowitzsch, C. E. Hoicka, and F. J. van Tulder, "Renewable energy communities under the 2019 European Clean Energy Package – Governance model for the energy clusters of the future?," *Renewable and Sustainable Energy Reviews*, vol. 122, no. January 2020, p. 109489, 2020, doi: 10.1016/j.rser.2019.109489.

[3] D. Frieden, J. Roberts, and A. F. Gubina, "Collective self-consumption and energy communities: Overview of emerging regulatory approaches in Europe," *COMPILE Project*, no. June, 2019.

[4] C. Morris and A. Jungjohann, *Energy democracy: Germany's energiewende to renewables*. 2016. doi: 10.1007/978-3-319-31891-2.

[5] G. Seyfang, J. J. Park, and A. Smith, "A thousand flowers blooming? An examination of community energy in the UK," *Energy Policy*, vol. 61, 2013, doi: 10.1016/j.enpol.2013.06.030.

[6] V. Z. Gjorgievski, S. Cundeva, and G. E. Georghiou, "Social arrangements , technical designs and impacts of energy communities : A review," *Renew Energy*, vol. 169, pp. 1138–1156, 2021, doi: 10.1016/j.renene.2021.01.078.

[7] P. H. Divshali, A. Kulmala, and P. Jarventausta, "Forming a Local Market using a Virtual Energy Community," in *International Conference on the European Energy Market, EEM*, 2020. doi: 10.1109/EEM49802.2020.9221985.

[8] G. Lettner, H. Auer, A. Fleischhacker, D. Schwabeneder, B. Dallinger, and F. Moisl, "Existing and future PV prosumer concepts," 2018.

[9] R. Lazdins, A. Mutule, and D. Zalostiba, "PV energy communities—challenges and barriers from a consumer perspective: A literature review," *Energies*, vol. 14, no. 16. 2021. doi: 10.3390/en14164873.

[10] J. Palm, "New Clean Energy Communities in a Changing European Energy System (NEWCOMERS)," 2020.

[11] H. Busch, S. Ruggiero, A. Isakovic, and T. Hansen, "Policy challenges to community energy in the EU: A systematic review of the scientific literature," *Renewable and Sustainable Energy Reviews*, vol. 151. 2021. doi: 10.1016/j.rser.2021.111535.

[12] European Commission, "Joint Research Center Photovoltaic Geographical Information System (PVGIS)." https://re.jrc.ec.europa.eu/pvg_tools/en/ (accessed Jan. 09, 2023).

[13] E. C. of the Regions, S. O'Brien, C. Monteiro, M. Gancheva, and N. Crook, *Models of local energy ownership and the role of local energy communities in energy transition in Europe*. Committee of the Regions, 2018. doi: doi/10.2863/603673.

[14] J. Palm, "The transposition of energy communities into swedish regulations: Overview and critique of emerging regulations," *Energies (Basel)*, vol. 14, no. 16, 2021, doi: 10.3390/en14164982.

[15] J. Kanters and M. Wall, "Experiences from the urban planning process of a solar neighbourhood in Malmö, Sweden," *Urban Plan Transp Res*, vol. 6, no. 1, pp. 54–80, 2018, doi: 10.1080/21650020.2018.1478323.

[16] D. Magnusson and J. Palm, "Come together-the development of Swedish energy communities," *Sustainability (Switzerland)*, vol. 11, no. 4, 2019, doi: 10.3390/su11041056.

[17] Ministry of Climate and Enterprise, "Sweden's draft integrated national energy and climate plan," 2019.

[18] Housing Evolutions, "SIMRIS – A 100% RENEWABLE ENERGY COMMUNITY VILLAGE." https://www.housingevolutions.eu/project/simris-a-100-renewable-energy-community-village/ (accessed May 23, 2023).

[19] Axitec, "Data sheet - Axitec AXIpower AC-330P/156-72S." https://www.europe-solarstore.com/download/axitec/Axitec-AXIpower_310-330P.156-72S-datasheet.pdf (accessed Dec. 09, 2022).

[20] LG, "Data sheet - LG Neon 2 Black LG325N1K-V5", Accessed: Dec. 09, 2022. [Online]. Available: https://www.europe-solarstore.com/download/lg/LG_Neon_2_Black_LG320-330N1K-V5_data_sheet.pdf

[21] J. Lindahl, A. Oller Westerberg, K. Vanky, and J. Berard, *National Survey Report of PV Power Applications in Sweden 2020*. 2021.

[22] Stanford University, "Ray Tracing." https://cs.stanford.edu/people/eroberts/courses/soco/projects/1997-98/ray-tracing/intro.html (accessed Sep. 20, 2022).

[23] Regalgrid, "Solar energy self-consumption and self-sufficiency." https://www.regalgrid.com/en/magazine/self-consumption-self-sufficiency/ (accessed Jan. 06, 2023).

[24] EFUEL, "Olika laddhastigheter för elbil." https://www.efuel.se/artiklar/olika-laddhastigheter-for-elbil (accessed Nov. 22, 2022).

[25] F. M. Andersen, H. K. Jacobsen, and P. A. Gunkel, "Hourly charging profiles for electric vehicles and their effect on the aggregated consumption profile in Denmark," *International Journal of Electrical Power and Energy Systems*, vol. 130, 2021, doi: 10.1016/j.ijepes.2021.106900.

[26] Skatteverket, “VAT rates on goods and services.” https://www.skatteverket.se/servicelankar/otherlanguages/inenglish/businessesandemployers/startingandrunningaswedishbusiness/declaringtaxesbusinesses/vat/vatratesongoodsandservices.4.676f4884175c97df419255d.html (accessed Dec. 09, 2022).