Research Centre on
ZERO EMISSION
NEIGHBOURHOODS
IN SMART CITIES

NTNU SINTEF

WHO SHOULD OWN THE PV?

Assessment of ownership structures for local energy production in zero emission neighbourhoods

ZEN REPORT No. 55 – 2024

Giulia Vergerio, Bakul Kandpal, Stian Backe | NTNU, SINTEF

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Preface

Acknowledgements

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The Research Centre on Zero Emission Neighbourhoods (ZEN) in Smart Cities

The ZEN Research Centre develops solutions for future buildings and neighbourhoods with no greenhouse gas emissions and thereby contributes to a low carbon society.

Researchers, municipalities, industry and governmental organizations work together in the ZEN Research Centre in order to plan, develop and run neighbourhoods with zero greenhouse gas emissions. The ZEN Centre has nine pilot projects spread over all of Norway that encompass an area of more than 1 million m2 and more than 30 000 inhabitants in total.

In order to achieve its high ambitions, the Centre will, together with its partners:

- Develop neighbourhood design and planning instruments while integrating science-based knowledge on greenhouse gas emissions;
- Create new business models, roles, and services that address the lack of flexibility towards markets and catalyze the development of innovations for a broader public use; This includes studies of political instruments and market design;
- Create cost effective and resource and energy efficient buildings by developing low carbon technologies and construction systems based on lifecycle design strategies;
- Develop technologies and solutions for the design and operation of energy flexible neighbourhoods;
- Develop a decision-support tool for optimizing local energy systems and their interaction with the larger system;
- Create and manage a series of neighbourhood-scale living labs, which will act as innovation hubs and a testing ground for the solutions developed in the ZEN Research Centre. The pilot projects are Furuset in Oslo, Oksenøya/Flytårnet in Bærum, Sluppen and Campus NTNU in Trondheim, Mære agricultural school in Steinkjer, Ydalir in Elverum, Campus Evenstad, NyBy-NyFlyplass Bodø, and Zero Village Bergen.

The ZEN Research Centre will last eight years (2017-2024), and the budget is approximately NOK 380 million, funded by the Research Council of Norway, the research partners NTNU and SINTEF, and the user partners from the private and public sector. The Norwegian University of Science and Technology (NTNU) is the host and leads the Centre together with SINTEF.

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Norwegian Summary

Eierstrukturer for lokal energiproduksjon i nullutslippsområder

Nyhavna, et industriområde i Trondheim, gjennomgår en transformasjon til et nullutslippsområde (ZEN) som en utvidelse av bysentrum. Dette initiativet, vedtatt i 2019 av Trondheim Kommune, involverer omtrent 300 000 m^2 med nybygg og 40 000 m^2 med bevarte bygninger, med fokus på boligstrukturer sammen med næringslokaler.

En sentral strategi for å realisere ZEN innebærer lokal produksjon av elektrisitet gjennom solcellepaneler. Imidlertid er det utfordrende å fastsette en bærekraftig eierstruktur for solcellepaneler i ZEN, og det er behov for å forstå hvordan eierstrukturen påvirker planleggingsprosessen for utviklingen av Nyhavna. I denne rapporten vurderer vi kvalitativt og kvantitativt ulike eierkonfigurasjoner og deres innvirkning på drifts- og bruksfasene i nabolaget.

Økonomiske insentiver for å tilpasse fleksible ressurser mot lokal elektrisitetsproduksjon vil avhenge av organiseringen av eierskapet.

Basert på en kartlegging av interessenter identifiserer vi flere eierkonfigurasjoner for solcellepaneler i ZEN. Forskjellige interessenter kan påta seg eierrollen, inkludert brukere, strømleverandører (både nye og eksisterende selskaper), tredjepartsenheter (tjeneste- og eiendomsleverandører) og fjernvarmeselskapet.

Hver eierkonfigurasjon har både fordeler og ulemper. For å maksimere økonomisk verdi bør eieren av solcellepanelene bruke mesteparten av strømproduksjonen selv, noe som vil være tilfelle ved eierskap hos brukere eller fjernvarmeselskapet. Ved eierskap hos strømleverandører og tredjepartsenheter er det nødvendig å forhandle priser og kontrakter med strømforbrukerne.

I alle eierkonfigurasjoner utgjør overdimensjonering av solcelleanlegget økonomiske risikoer, noe som tydeliggjør behovet for strategisk dimensjonering basert på spesifikke behov og forbruksprofiler for å maksimere lønnsomheten. Samtidig trenger Nyhavna en stor mengde lokal strømproduksjon for å nå ZEN-målene.

Resultatene i denne rapporten gir en omfattende forståelse av faktorene som påvirker beslutningsprosessen for eierskap til solcelleanlegg i et nullutslippsnabolag ved å gi eksempler og praktisk veiledning for interessenter involvert i planlegging, utvikling og drift av slike initiativer. Kravene satt av prosjekteiere og utviklere, samt designere, vil påvirke enhver eierstruktur, mens økonomiske insentiver for å tilpasse fleksible ressurser mot lokal elektrisitetsproduksjon vil variere mellom eierformer.

Beslutningen om eierskap av solceller på Nyhavna er bare én del av en bredere transformasjonsprosess. For å opprettholde ZEN-målene, er det avgjørende å knytte beslutninger som påvirker solceller og deres fremtidige eiere til de innledende planleggingsstadiene der Nyhavna befinner seg nå.

Summary

Ownership structures for local energy production in zero emission neighbourhoods

Nyhavna, an industrial area in Trondheim, Norway, is undergoing a transformation into a zero-emission neighbourhood (ZEN) as an extension of the city centre. This initiative, decided in 2019 by Trondheim Kommune, involves approximately 300,000 m^2 of new and 40,000 m^2 of preserved buildings, focusing on residential structures alongside commercial spaces.

A key strategy to realize ZEN involves locally producing electricity through solar photovoltaic panels on building surfaces. However, challenges include determining a sustainable ownership structure for photovoltaic installations and understanding how it impacts the planning process for Nyhavna's development. In this report, we qualitatively and quantitatively assess different ownership configurations and their impact on the operational and use phases of the neighbourhood.

Economic incentives for aligning flexible assets towards local electricity production will depend on the organization of the ownership.

Based on a stakeholder mapping, we identify several ownership configurations. Various stakeholders within the energy network could potentially assume the role of solar photovoltaic owners, including users, electricity suppliers (both new and existing companies), third-party entities (such as service and asset providers), and the district heating company.

Each ownership configuration has both benefits and drawbacks. For maximized economic value, the owner of the photovoltaics should also be the consumer of the photovoltaics, which will be the case for users or the district heating company. In the case of ownership by electricity suppliers and third-party entities, there is a need to negotiate prices and contracts with the electricity consumers.

In any case, oversizing photovoltaic systems poses some economic risks, which emphasizes the need for strategic sizing based on specific needs and consumption profiles to maximize profitability. Simultaneously, Nyhavna needs a large amount of photovoltaics to reach ZEN goals.

The results in this report provide a comprehensive understanding of the factors influencing the decision-making process for solar PV ownership in a zero-emission neighborhood, offering examples and practical guidance for stakeholders involved in the planning, development, and operation of such initiatives. The requirements set by the project owners and developers, as well as designers, will influence any ownership structure, while the economic incentives for aligning flexible assets towards local electricity production will vary across ownerships.

The decision on photovoltaic ownership during Nyhavna's operational phase is just one aspect of a broader transformative initiative. To uphold ZEN goals, it is crucial to link decisions impacting photovoltaics and their future owners to the initial initiative and planning stages where Nyhavna currently stands.

Innhold

1 Introduction

Nyhavna is an industrial area in central Trondheim, Norway (Figure 1) consisting of light industry and office buildings. In 2016, the municipality decided that Nyhavna will be transformed to become an extension of the city centre in Trondheim. In 2019, the municipality further decided that Nyhavna will become a zero-emission neighbourhood (ZEN). The ZEN at Nyhavna will consist of around 300 000 m^2 of new buildings and 40 000 m^2 of preserved buildings. The neighbourhood will mainly consist of residential buildings, but there will also be commercial buildings, such as offices, hotels, and shops. The transformation is planned in three construction phases, starting around 2025 and finishing in 2040-2050.

A key aspect of ZEN is the energy system in and around the neighbourhood. Nyhavna is located next to the harbour (Brattøra and Trondheim Havn), and the harbour is expected to have a highly increased power demand in the future due to electrification of maritime transport. Therefore, it is particularly important that Nyhavna plans its energy system such that its net power demand is low and flexible.

One of the critical solutions to achieve the ZEN goals at Nyhavna is to produce electricity locally with solar photovoltaic (PV) panels on the roofs and facades of the new buildings. However, it is still unclear how to realize a large amount of PV at Nyhavna. There is a need to better understand how to organise the ownership of the PV in ZEN such that the installations become socially and economically sustainable. Further, it is also unclear how a specific PV ownership structure impacts the planning process today at Nyhavna. This requires studying (qualitatively and quantitatively) the operational stage of Nyhavna considering different ownership configuration, but also, from the use phase, looking backwards to understand what can be done to steer the process in a favourable direction.

In this report, we assess different ownership structures of PV at Nyhavna. In Chapter 2, we present the context at Nyhavna and elaborate on the energy system and the key stakeholders that play a role in shaping how the use phase will be. In Chapter 3, we present different ownership structures of PV along with real world examples. In Chapter 4, we qualitatively analyse them from the perspective of the future ZEN users, including advantages and disadvantages, and from the one of each possible owner in its interplay with the other stakeholder groups. Regulatory feasibility in Norway is also discussed. In Chapter 5, we present a quantitative analysis of each ownership structure using optimization tools to assess economic viability. The report is concluded in Chapter 6 with key take-aways moving forwards.

Figure 1 The location of Nyhavna in Trondheim (Trondheim Kommune, 2021)

2 Context at Nyhavna

2.1 Energy system at Nyhavna

The energy system at Nyhavna consists mainly of two energy carriers: electricity and heat. Although there is linking between these two energy carriers, there will be one electricity system and one heat system.

The electricity system at Nyhavna will be grid connected with solar PV panels. Electricity will be used by buildings and mobility technologies, including boats, buses, and cars. It will be relevant to develop electricity storage through batteries and vehicle-to-grid solutions. Further, additional flexibility in electricity use can be developed, e.g., flexible charging of electric vehicles.

The heat system will be a local district heating network, with a heating central connected to boreholes for seasonal thermal energy storage and a large-scale seawater heat pump. The local heating central will exchange heat both ways with the main district heating network of Trondheim, which makes the Nyhavna network part of optimising the heating network for the entire city. The seasonal storage at Nyhavna can be charged by the district heating network in the summer, utilising excess heat from the waste incineration plant in Trondheim. In the colder seasons, heat from the seasonal storage and the seawater heat pump will cover Nyhavna's heating demands.

To reach ZEN goals, the greenhouse gas emissions related to building and operation of the neighbourhood at Nyhavna should be compensated for with export of locally produced electricity or heat. The annual energy use and peak power demand by the buildings can be significantly reduced through renovation of existing buildings and applying energy efficient standards to new buildings. However, according to an assessment by (Trondheim Kommune, 2021), there is still a need for as much solar PV as possible to approach ZEN, and both roofs and facades will be used.

There are several possible scenarios for how much solar PV will be at Nyhavna. If all new and existing buildings at Nyhavna will cover 50% of the roof area and 50% of the sun exposed façade area with solar PV, the estimated annual production is 14.0 GWh (Trondheim Kommune, 2021). Although this is about the same volume as the estimated electricity demand at Nyhavna with the most ambitious building standards, there will still be generally more production from solar PV than the demand at Nyhavna in the summer months. Vice versa, during winter, Nyhavna will need to import electricity from the grid.

2.2 Planning process at Nyhavna

The objective for Nyhavna to become a ZEN is extremely ambitious in terms of goals and scope and will entail a countless number of interdependent decisions. Even though PV ownership is critical in the achievement of the energy and environmental goals, the decisions related to it is a piece of a bigger effort, involving the transformation of a significant portion of urban territory, spanning over several decades, and involving different stakeholder groups.

After the approval of the *Kommunedelplan* in 2016 where Nyhavna was divided into 10 different areas with specific sequential requirements, four programs and various studies were prepared. Among them, in the context of this report it is important to mention the conceptual study prepared by Asplan Viak on the energy systems for Nyhavna (Asplan Viak, 2021). These programs and studies are now the backbone of the Quality program for Nyhavna, approved by the City Council in May 2022. The Quality program reports the illustration plan visible in Figure 1 above and defines goals and subgoals for Nyhavna, including ZEN-related goals. The area is now under development with Nyhavna Utvikling AS (established in 2021 by the municipality and Trondheim Havn) as leader. Transittkaia is the first vast area for which regulatory work is at its start-up based on the project proposed by Team COBE, winner of the architectural competition in 2023[1].

To reach ZEN goals, they must be followed up throughout the process as just delineated. However, as mentioned in a previous review study (Vergerio & Knotten, 2023), when planning for ambitious goals in a building process, one can fail in reaching them for lack of stakeholders' collaboration and commitment, and insufficient organizational processes and unsupportive development frameworks. To increase the chances for a project success in terms of goals, achievement strategies should be based, among others, on the following actions:

- Increasing knowledge across the industry.
- Engaging stakeholders.
- Adopting a collaborative perspective.

Besides increasing our knowledge about the technical aspects of the problem, mapping the stakeholders and their changing landscape is a necessary preliminary action to increase the chances of success for an ambitious project (Hamdan, Andersen, & De Boer, 2021). Furthermore, when dealing with the delivery of highly performing solutions, "integration" appears as a recurrent keyword, both in planning (i.e., integrated territorial planning), building projects (i.e., integrated design, integrated project delivery, etc.), and energy system (i.e., integrated energy system). More specifically, the highly fragmented construction industry is moving in the direction of models for integrated delivery of projects through collaborative practices in the early design stage of complex projects. Indeed, the use of collaborative contracts has already been recommended for Nyhavna (Trondheim Kommune, 2021).

Because of the importance of both, a) exploring the opportunities and needs for collaboration and integration at the district level, and b) mapping the stakeholders involved in the transformation of the area, we performed a stakeholder mapping based on network analysis. The focus of the **stakeholder mapping** is on:

- **Stakeholders' groups** (the nodes of the network) gravitating around the process of delivering the district over time, from final use (which is the focus of the rest of the report), backwards to the initiative and planning stages where Nyhavna is now.
- **Stakeholders' relationships** (the edges of the network) among stakeholders, illustrated as links in the graphical network.

The resulting stakeholder map is discussed in the rest of this chapter.

2.3 Stakeholders' groups

The main player in any transformation is its initiator, who is typically defining the strategic goals. In Nyhavna, the choice to transform the area according to ZEN principles has been made by Trondheim Kommune (also referred to as 'the municipality'), which can be considered the main **project's owner**. Trondheim Havn IKS (partially owned by the municipality itself) has also strongly participated.

Beside them, based on the general knowledge of the planning and building process in the Norwegian context and, specifically, on the situation at Nyhavna, we identified the following contextual stakeholder groups as having a role/interest in the transformation process:

- Technological actors: providers of knowledge, standards, frameworks, etc. They are NTNU, SINTEF, FME ZEN Research Centre, Asplan Viak, and possible other consultants of the project owner.

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[1] https://nyhavna.no/byutvikling/utvikling-av-transittkaia/

- Political/Regulatory actors: influencing the process according to their political and/or regulatory mandates. They are Trondheim Kommune, superordinate policymakers at County and national levels, NVE, RME.
- Economic actors: providers of financial resources. They are Enova and other potential funding agencies, banks, investors.

All these contextual stakeholders are defined as entities whose behavior, intentionally or unintentionally, sets the conditions under which the other actors must operate (Cheng, et al., 2022). Thus, in principle they include the project owner (Trondheim Kommune) and the investors who will steer the actual transformation by providing financial resources for the development.

Among the investors group, landowners, and developers within Nyhavna will play a special role, since they will be leading the realization and directly producing value for themselves and for the final users. Producers and consumers of value are defined **industry** stakeholders (Cheng, et al., 2022). The industry actors (including landowners and developers) that are the most directly relevant in the context of the energy ambitions for Nyhavna are reported in the following table (Table 1).

Table 1 Description of stakeholder groups in general and particularly at Nyhavna.

Stakeholder groups	Description	At Nyhavna
Landowners & developers	Leaders of the actual development of the area through financial investments.	Currently: Nyhavna Utvikling AS (i.e., Trondheim Kommune, Trondheim Havn) and Bane NOR as landowners. Developers are Dora AS and Koteng Eiendom AS. In future: new real estate players buying land and developing new buildings and related infrastructures.
Energy players*	Actors whose behaviour and choices are affecting the configuration of the energy systems.	Statkraft Varme, Tensio, Statnett, future energy suppliers (including aggregators) chosen by the users.
Services and asset providers – energy (potential third-party)	Providers of services (i.e., installation, consultancy) and/or assets (e.g., PV panels, batteries, etc.) that are relevant for the participation into the energy market and whose behaviour and choices are affecting the energy demand for buildings.	To be defined by future customers. Customers include investors that are interested in entering the energy market, e.g., users and energy suppliers (aggregators).
Users	Beneficiaries of the final products (buildings and infrastructures) in terms of permanent use (residential buildings) or economic exploitation (non-residential buildings).	They include future occupants of residential buildings and operators of non-residential buildings.
Mobility players	Actors whose behaviour and choices are affecting the offer of collective transportation.	Mainly AtB, which is owned by the County.
Services and asset providers – mobility	Providers of services (e.g., sharing platforms) or assets (e.g., vehicles, bikes, etc.) which are relevant for the mobility market and whose behaviour and choices are affecting mobility patterns and thus the energy demand for transportation.	To be defined by future customers. Customers include investors that are interested in entering the mobility market.

* Because of the scope of the report, they are further broken down when relationships are analysed (see section 2.4).

The actors mentioned in the table can be considered as the main industry stakeholders who, by producing and exploiting value, will define how well the district will be able to meet ZEN ambitious regarding the energy aspects. However, following up and alignment on such a goal is needed also from other industry stakeholder groups, including:

- Design teams: to be appointed in future by Landowners & developers. E.g., COBE for Transittkaia. As Designers in charge of defining the architectural expression at the district level, including masterplans and sketch projects of the buildings, their work will affect the results in terms of energy demands of the district.
- Project Delivery Teams: to be appointed in future by Landowners & developers. E.g., potentially COBE for Transittkaia. As designers, main contractors, and consultants in charge of the development of the final projects and construction of single (or group of) buildings, their work will affect the results in terms of energy demands of the district.
- Contractors and various suppliers: to be chosen in future by owners, project delivery teams, or users, depending on the projects' stage. As providers of materials, labour, machinery, etc., their work will affect energy consumption in a life-cycle perspective.

These industry actors are also participating (more indirectly) in the process of realizing ZEN-related goals. Thus, all the groups here identified were considered while drawing the mutual relationships, as discussed in the following section 2.4.

2.4 Stakeholders' relationships

Based on the general knowledge of the planning and building process in the Norwegian context, and specifically at Nyhavna, we draw the relationships among stakeholders gravitating around the process of delivering the district over time, from the final use (which is when the focus our following quantitative analysis), backwards to the initiative and planning stages where Nyhavna is now (Figure 2). The process entails a temporal and spatial (area/s versus individual buildings or group of buildings) dimension, which we represent in the graphical network below as well. There, relationships are represented as links suggesting that actors' behaviour/decisions can influence each other and, thus, highlighting the need for goals alignment and collaboration to achieve ZEN goals. Such influence can be indirect (dashed lines), or direct (full lines) if we expect there will be formal relationships in place (i.e., contracts for exchange of services or goods, ownerships hierarchies, etc.). The full lines are purple when the relationship is based on regulatory mandates, for instance in the case of authority bodies (e.g., Trondheim Kommune, NVE, RME). Relationships can be unidirectional (subordinance or supply) or bidirectional (mutual influence, negotiation).

Trondheim Kommune[2] (the municipality), as **project owner**, is influenced by technological (e.g., NTNU, SINTEF, FME ZEN Research Centre) and economic actors (e.g., ENOVA) that are providing finances and knowledge as resources. As a political body, Trondheim Kommune is influenced by the superordinate authorities, and, as one of its owners, it influences the choices of Trondheim Havn IKS.

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[2] Because of the energy focus of this report, we will assume that Trondheim Kommune is moving as a single actor with harmonized goals, despite potential differences across the council and the various departments.

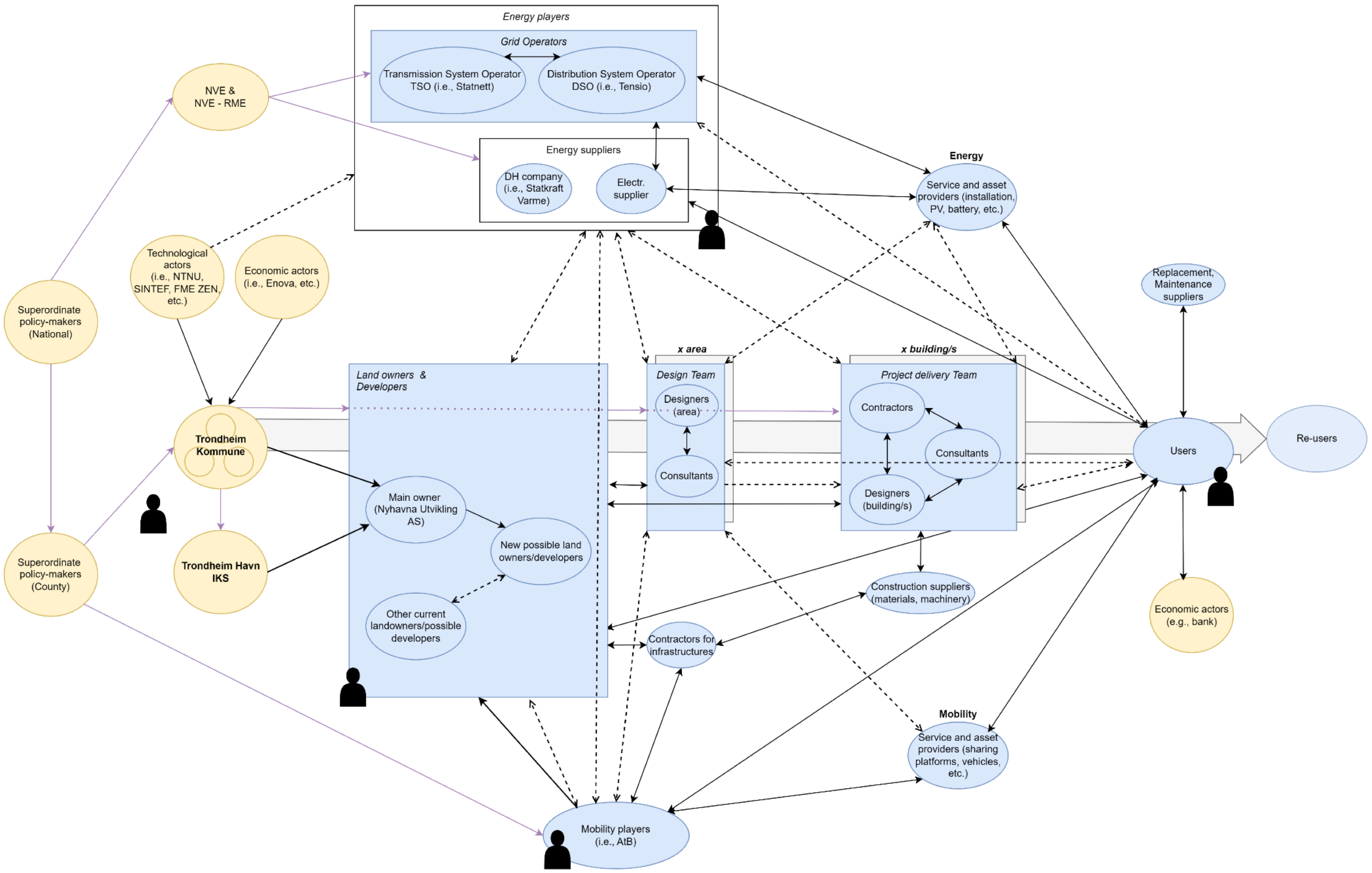

Figure 2 Illustration of the stakeholder map as a network. NB: contextual stakeholders (yellow) and industry stakeholders (blue). Actors within a coloured square are treated an individual groups in the analysis of the network (section 2.5).

As mentioned before, the delivery to the final users of such a project, with the ambitions set by Trondheim Kommune, will happen throughout a complex process lead by **landowners & developers** in two stages of design and future implementation, namely at the area (or group of plots) level and at the building level. In these two implementation stages, **design teams** (defining the architectural expression of the different areas, including outdoor spaces) and **project delivery teams** (further designing and constructing, after regulatory work at the plots level) will come to the scene. They are all influenced by Trondheim Kommune as a regulatory body and, in the case of Nyhavna Utvikling AS, as an owner together with Trondheim Havn IKS. For implementation, landowners & developers should consider collaborative models, where designers, contractors, and related consultants will work together to deliver the projects. Their work is not, or should not be, independent from the one of the suppliers that are relevant in the construction stage, whose early involvement should be considered.

Future **users** will not have a formal (direct) relationship with the actors responsible for design and construction (unless they are early owners), but hopefully their expectations will be advocated by, for example, owners or designers, and addressed. However, it is hard to foresee users' choices and behaviour, which will ultimately be impacting the actual operation of Nyhavna. They are expected to be influenced by economic actors (e.g., because of loans) and suppliers of materials and services relevant in the operation phase (replacement and maintenance). Also, at that point, users will have a direct relationship with energy players (i.e., contracts with energy suppliers) and mobility players (e.g., subscriptions), causing a mutual influence in their behaviour/choices. This relationship could be mediated and/or influenced by other players. They are those providing services (installation, consultancy, sharing platforms, etc.) and/or assets (PV panels, batteries, vehicles, etc.) relevant in the related markets. In fact, the strategies of these players should also be considered in the design and implementation of areas and buildings.

In transforming Nyhavna, even if they are not directly/contractually connected to them, landowners & developers, as well as contracted design and delivery teams, will influence and be influenced by the strategies and choices of **mobility** and **energy players** present in the area.

Because of the scope of this report, in drawing relationships, energy players are further specified. They are:

- Energy suppliers (electricity and district heating company), and
- Grid operators (Transmission and Distribution System Operators, namely TSO and DSO).

The district heating company in Nyhavna is Statkraft Varme. Tensio AS is the DSO, while Statnett is the TSO. The electricity suppliers present in the area will be diverse, depending on final users' choices in the energy market, but they will be in direct relationship with the grid operators, especially when it comes to agreements on potential infrastructure reinforcements. NVE had the role of giving concession for the distribution of heat and electricity to Statkraft Varme and Tensio AS, respectively. Statkraft Varme, Tensio AS, and the electricity suppliers are all under the influence of RME (an independent part of NVE), since it is the authority that, among other things, decide for the annual revenue framework for the electricity grid business and give concession/permission to participate in the electricity market.

2.5 Stakeholders' selection

A quantitative **analysis of the stakeholder map** shows that, if we only consider direct relationships, the network is characterized by low density[3], meaning that there is potentially low rate of interactions throughout the implementation process, with consequences in terms of possible lower trust and information exchange (but also less chances for conflicts, depending on type of interactions and other variables). By considering also indirect relationships, the density increases significantly (from 16% to 28%), the landowners & developers stand out as slightly more central than other actors, and the role of

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[3] density defined as the count of existing links over the maximum number possible.

designers and project delivery teams becomes more important. However, the overall centrality[4] of the network slightly decreases, meaning the learning process triggered by new interactions between actors does not significantly affect the capacity of the network to have a strong director in the decision-making process. It is then interesting to look at the characteristics of the individual players to identify the key ones, who are likely to, or should, give such direction.

If only formal relationships are considered (filled lines), users are the most central (i.e., high rate of links), followed by Trondheim Kommune and the group of landowners & developers. If we include the relationship between the municipality and landowner & developers under the Planning and Building Act (i.e., regulatory mandates of the municipality), then the centrality of the three actors is the same. According to this analysis, their behaviour has the potential to influence the process outputs the most. They are immediately followed by mobility players and electricity suppliers (with the related authority, namely RME). Given the centrality of the users, the stakeholders acting as a possible bridge between users and electricity suppliers are particularly important. They are the so-called 'service and assets providers' (i.e., providers of those assets and services that are relevant for the participation in the electricity market), which can play as a third party if they stay involved over time in the relationship between users and electricity suppliers (see chapter 3). If we narrow the analysis to the network of the actors that are directly and indirectly connected to one or more of the energy players (showed in the figure below), we find that service and assets providers, grid operators (i.e., TSO and DSO) and related authority (NVE-RME), have a relatively high centrality (i.e., high rate of links), followed by district heating company ad mobility players. They are proceeded by users, landowners & developers, and electricity suppliers, which stand out as the most central actors.

The network that results from this narrowing down of the scope (Figure 3) has higher density and centrality than the whole, making it a potential ground to overcome decisional impasse around the energy systems. In fact, much of the future development depends on the course of actions decided here, under the frame set by, among others, the municipality as owner and main authority.

In the next chapter we focus on the stakeholder groups defined as:

- Users,
- Electricity suppliers,
- Service and asset providers,
- Grid operators (TSO and DSO),
- District Heating (DH) company.

Given their role around the energy players network, they could all decide to take the role of PV owners, expect for the grid operators (it is not permitted in Norway). Thus, we identified the following ownership options:

- Users,
- Electricity suppliers (new or existing utility companies),
- Third party (i.e., services and assets providers).
- District heating company.

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[4] centrality of an actor defined as the ratio between its links and the total existing ones. The centrality of the network is the maximum among the actors' centralities.

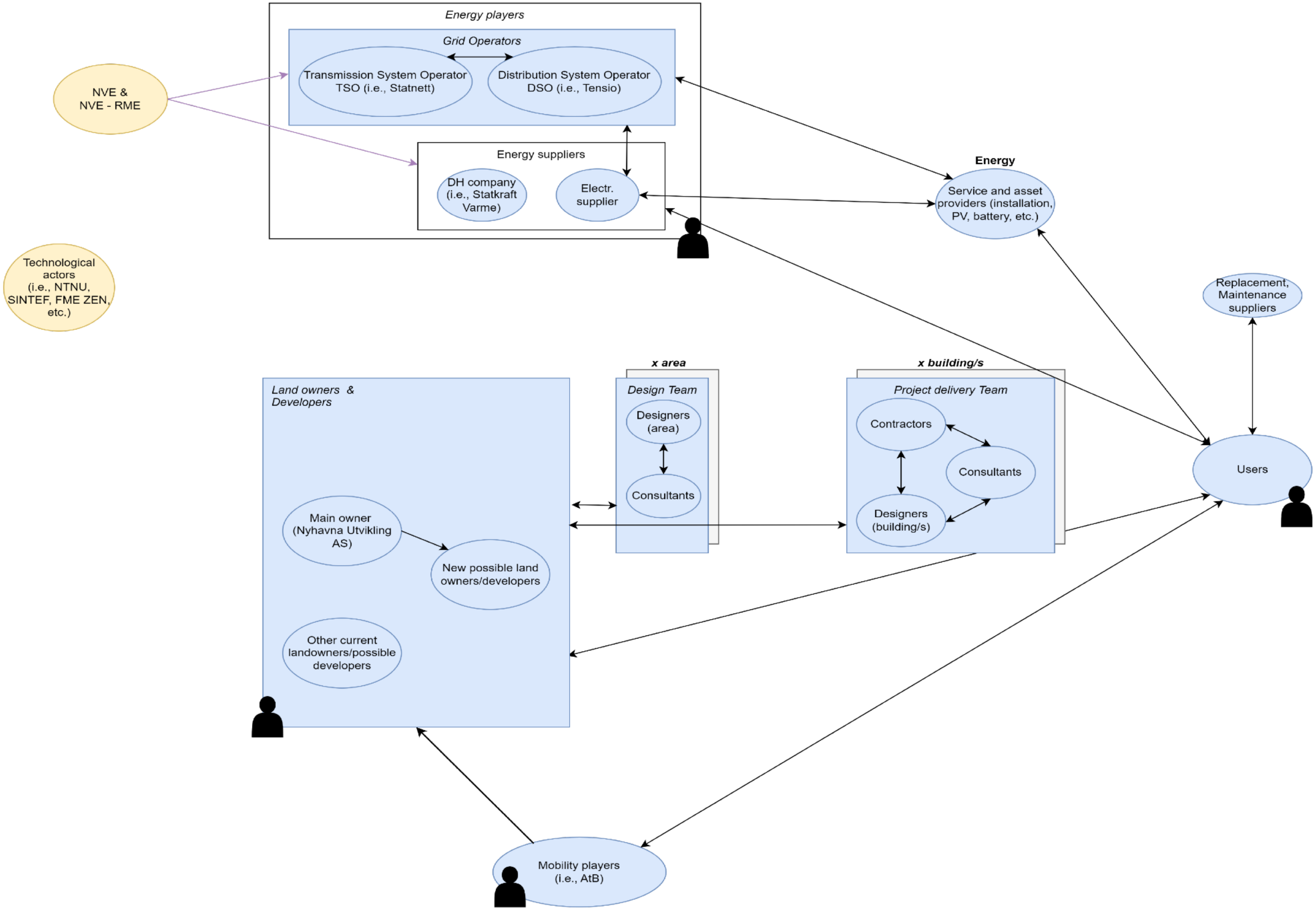

Figure 3 Illustration of selected stakeholders connected to one or more energy players.

While proceeding in the report, the reader should note the following:

- The mobility players are also central at shaping the operational status of Nyhavna. Their role is commented on along the way.
- The stakeholders' panorama between initiation and operation of the project is complex, and this chapter is only a simplified representation of how it is likely to be. The process that will shape how Nyhavna will be in operation should be taken care of. In this regard, the centrality of the landowners & developers is a reason to reflect on their role as well.
- Excluded or not-mapped stakeholders can also be affected. Stakeholders have been described and selected based on their relevance in the context of the question that we are trying to respond to with this report. A responsible decision-making cannot disregard how costs and benefits will be distributed, also beyond the boundaries identified here.

3 Ownership structures

The transition to renewable energy sources, such as PV, is not just a technological shift but also a transformation in how energy systems are owned and operated. Across the globe, diverse ownership models have emerged, each with its unique advantages, challenges, and socio-economic implications. This chapter delves into various ownership models, including user, third-party, district heating. Through a series of global examples, we will explore how these models function, their impact, and the strategies employed by different entities to use renewable energy for a sustainable future.

3.1 User ownership model

The user ownership is characterized by the fact that those paying the electricity bills are the same who are (directly, through dedicated investment, or indirectly, through increase in rental cost or buildings' purchase price) having the burden for the upfront cost of the PV panels, purchased from another party (i.e., asset provider). In the user ownership model, the generated electricity from PV systems allows building owners to lessen their dependence on the grid and decrease their electricity bills through self-consumption. Several financing options are available for installing PV systems. Building owners can purchase the system outright or secure a loan. Additionally, various government incentives, including tax credits and rebates, are available to encourage the adoption of PV systems for individual investors such as building owners. The configuration is represented by the following figure, depending on whether the upfront cost for PV is covered by developers or users. In both cases the ownership (or ownership rights, in case of renting) is transferred to the users, who are exploiting the benefits in terms of self-consumption and surplus. Users pay bills and sell surplus to the electricity supplier, who in turn provides for the remaining electricity demand and pay the credit for the received surplus.

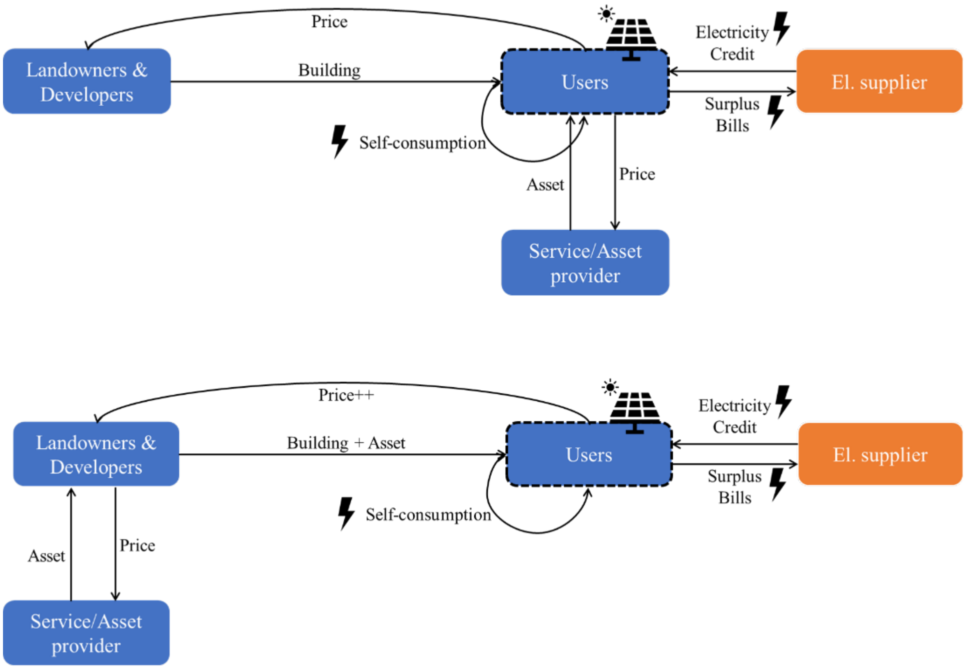

Figure 4 Illustration of the user ownership model.

Municipalities can significantly contribute to this model. As noted in a report (SolarPower Europe, 2023), they can either mandate the installation of solar panels on existing and new private buildings or incorporate PV panels on municipally owned new constructions, such as social housing. Some real-world examples are discussed below.

Norway: Powerhouse Brattørkaia

Located in Trondheim, Norway, this is an office building of around 18 000 m^2 area. Its skewed, pentagonal rooftop and the upper part of the facade is covered with almost 3 000 m^2 of solar panels, strategically placed to harvest as much solar energy as possible. The building's own energy generation is approximately 485,000 kWh per year with clean, renewable energy. On average, Powerhouse Brattørkaia produces more than twice as much electricity as it consumes daily, and will supply renewable energy to itself, its neighbouring buildings, electric buses, cars, and boats through a local microgrid. For the future, there are plans to include energy storage, allowing it to store surplus energy, especially in the summer months.

Denmark: Community ownership of solar PV

Hvidovrebo Section 6 (Roberts, Bodman, & Rybski, 2014) is a social housing estate located in a municipality on the outside suburbs of Copenhagen. The project will be owned by the housing estate, but the tenants will contribute financially to the project through additions on top of rent or mortgage payments. The project will span 10 roofs throughout the estate, producing between 120-160 MWh per year. The electricity produced will contribute towards self-sufficiency within the estate. The aim is that each dwelling will have its own part of the system, which will be operated through a common grid. The project is being implemented in cooperation with the local district heating company, Hvidovre South A.m.b.A.

3.2 Third party ownership model

In this section, we explore the third-party ownership models for PV systems. The third-party ownership is characterized by the fact that users are still the ones directly benefitting from the exploitation of the PV production in their relationship with the electricity suppliers, but they are neither owning the PV nor paying for the upfront cost for the PV installation. The party providing for the asset plays as a third-party by owning, and operating it, in return for a rental/fee, thus staying involved in the relationship between users and electricity suppliers, but not directly trading electricity. Each model offers a unique approach to installation, financing, and operation of the PV generation plant, for different community needs and market conditions. Whether it is leveraging community resources, focusing on social benefits, or optimizing for economic efficiency, these models provide a variety of pathways for the adoption of renewable energy.

The roles and responsibilities of each stakeholder in this model is illustrated in Figure 5 and briefly described below.

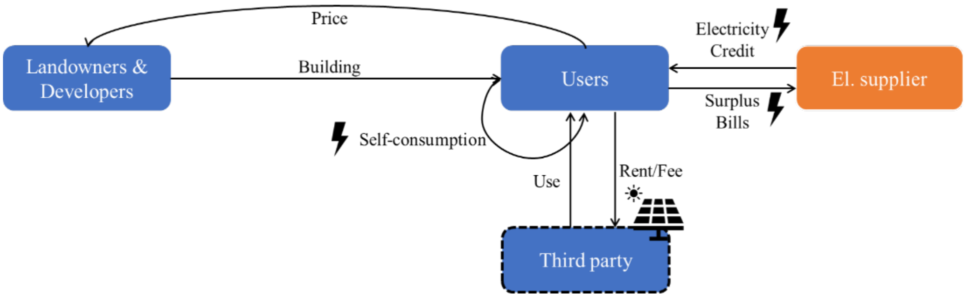

Figure 5 Illustration of third party ownership model.

The electricity supplier keeps providing electricity to the solar plant subscribers/users, who will pay bills for it. The subscribers/users receive credits for the output of their (community) solar plant on their utility bills. The community solar subscriptions are either integrated into their utility bills or are administered by the third party.

Examples are reported in the followings.

Norway: Leasing agreement

One company that offers a good choice in this model is Otovo[5] When a person chooses to lease from Otovo (at a monthly price of NOK 699/ month), the PV setup is installed on their roof. Otovo takes care of the system's maintenance and repairs for 20 years at no extra cost. Moreover, there is no cash investment or down payment needed to rent the solar cells. Otovo also provides these services for several countries throughout Europe. Additionally, building owners have the option of buying the system later if they want to, and thereby obtain user ownership (see Section 3.1). Building owners can also get investment support from Enova between NOK 7,500 and NOK 25,000.

United Kingdom: Co-ownership with electricity suppliers

Examples from literature refers also to other RES than PV. The electricity supplier Ripple Energy[6] acts as a third party (i.e., having the burden of the upfront cost, constructing, and operating the assets) when offering individual users/customers to invest in and become co-owners of the wind farms that supply their energy. Once a customer chooses to receive their energy through Ripple, they will co-own the wind farm, or an alternative renewable source of power, through a community benefit society. Customers will be charged an upfront fee, which will be dependent on how much energy they use and the size of the project. Customers could save around GBP 85 to 175 each year on their electricity bill throughout the wind farm’s 25-year lifespan.

3.3 Electricity supplier ownership model

In the electricity supplier ownership model, the electricity supplier administers and owns the solar project and sells the renewable (PV) generation to the community. As in the third party ownership, users do not have the burden of the upfront investment, which is covered by the electricity supplier buying the asset from another party (i.e., asset provider). Differently than in the previous model, the PV owner, which in this case is an electricity supplier, exploit the PV production to participate into the electricity market itself. This model can be a good option for communities because utilities are likely to have the legal, financial, and program management infrastructure to implement a community solar project. These projects are often financed by the utility, grants, and/or ratepayer subscriptions. The model is represented in Figure 6.

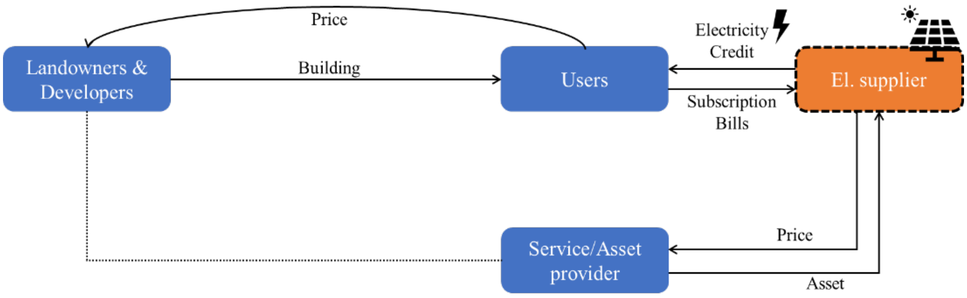

Figure 6 Illustration of electricity supplier ownership model.

As illustrated in Figure 6, the electricity supplier first identifies the project and then buys the solar plant from a party who is providing for the asset as part of a project development. The electricity supplier then works with the developer to construct the project. Once the project is built, the electricity supplier owns and operates the solar plant. Throughout the lifetime of the system, the supplier provides electricity and, in some cases, provides renewable energy certificates (RECs) to the users who are subscribers of the system. Subscribers/users pay their regular utility bill plus a community solar subscription payment and,

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[5] https://www.otovo.no/

[6] https://rippleenergy.com/

in return, receive bill credits for their share of solar production. The credit on their electric bills is proportional to the amount of the project they are subscribed to on either a kilowatt (kW) or kilowatt-hour (kWh) basis. The electricity supplier could be either an existing one or a new company operating at the district level.

In principle, a new company could trade energy wherever in the world after investing in PV plants. Users could be shareholders of such company, and benefit from the revenue. In that case the model can be revised as shown in the following figure, where other users come into play and physical boundaries are no longer relevant[7].

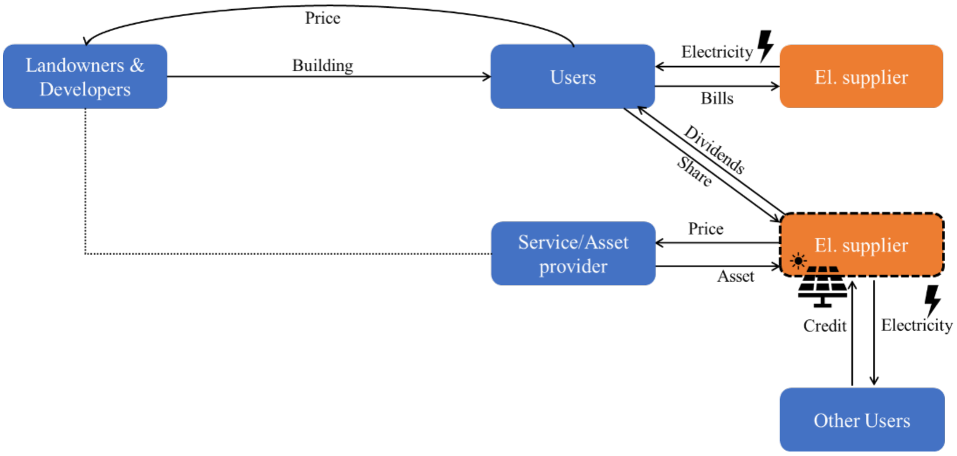

Figure 7 Illustration of shareholder model

Examples are reported in the followings.

United Kingdom: Community-owned renewables
Wiltshire Wildlife Community Energy (WWCE) is a community benefit society set up by Wiltshire Wildlife Trust for the development of community-owned renewable energy projects (IRENA, 2020). This is illustrated in Figure 7. WWCE has implemented two solar PV projects of 1 MW and 9.1 MW. The projects were funded by the sale of shares in WWCE, allowing people to invest anywhere between USD 670 and USD 134 000. The projects earn revenue through feed-in tariff payments, and after payment to its members, 80% of the remaining money is allocated to WWCE's community benefit fund, with 20% being directly allocated to Wiltshire Wildlife Trust. WWCE has paid 7% dividends to its members, and the remaining profits are spent on local community development.

Denmark: Partnership between electricity supplier and co-operative
In this example, a hybrid structure is implemented in a partnership between an electricity supplier and a co-operative. A wind farm of 20 wind turbines of 2 MW capacity each is situated offshore, near Copenhagen harbour in Denmark. This wind farm is a 50:50 joint venture between Copenhagen Energy (the local utility) and Middlegrunden co-operative. It is the largest community-owned wind project in the world, and the joint venture was encouraged by Denmark's decentralisation of energy targets and flexible planning arrangements.

Scotland: Renewable portfolio single island utility
Eigg Electric provides electricity for all island residents on the isle of Eigg from renewable sources (Clean Energy for EU Islands, 2020). 110 kW hydro projects, 24 kW wind turbines and a 20 kW solar PV plant, totalling 184 kW. Renewable sources have provided around 95% of the island's electricity.

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[7] According to ZEN definition, physical boundaires are relevant. However, we include this case as general knowledge on existing business models, since we found some examples for it.

3.4 District heating company ownership model

The last model we explore is the one where it is the district heating (DH) company that is investing in the PV panels and who is owning and operating them. As in the previous two models, the upfront cost in not on the users' shoulders. Differently from in the case above, the PV owner will not participate in the electricity market but will use the electricity from PV to feed Heat Pumps (HPs) and produce heat at a lower cost for them, which they will supply to the buildings. Indeed, modern district energy systems combine district heating and cooling with elements such as combined heat and power (CHP), thermal storage, heat pumps, and/or decentralized energy. Through economies of scale and the use of thermal storage, district energy systems are one of the most effective means for integrating renewable energy sources into the heating and cooling sectors. The presence of district energy makes it possible to integrate greater amounts of variable electricity generation into an electricity grid system, which is key to decarbonizing the power sector. The role of the stakeholders in this model is represented in Figure 8.

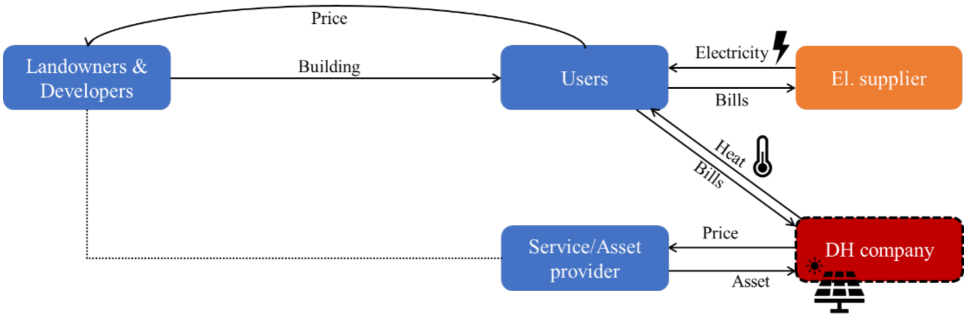

Figure 8 Illustration of the district heating company ownership model.

Examples are provided in the followings.

Norway: Seasonal storage of solar energy

The GeoTermos project (Ramstad, Holmberg, Bugge, & Riise, 2017) led by Drammen Eiendom KF aims to revolutionize seasonal storage of solar energy. The project is a key part of a larger R&D initiative called RockStore, which is partially funded by the Research Council of Norway. In this proposed project, the surplus PV generation would be given to a CO2 heat pump which would then supply energy to the seasonal thermal storage for later use.[8]

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[8] https://heatpumpingtechnologies.org/wp-content/uploads/2022/05/06-randi-kalskin-ramstad-high-temperature-borehole-thermal-energy-storage-ht-btes.pdf

Table 2 Overview of the GeoTermos project (Ramstad, Holmberg, Bugge, & Riise, 2017).

Aspect	Details
Project Owner	Drammen Eiendom KF (DEKF)
Partners & Contributors	NTNU/SINTEF, CMR, Enova, NVE, Asplan Viak, among others
Technological Innovation	Renewable energy production (solar energy), Seasonal storage of solar energy.
Components	100 wells with a depth of approx. 50 meters each, Solar collectors (150 m^2), Solar cells on the roof (900 m2) and facade (100 m^2), CO2 heat pump
Capacity	Charge: 7-800,000 kWh/year, Return: Approx. 350,000 kWh/year
Power Output	Base load: 80 kW, Peak load: Up to 300 kW
Challenges	Designing and managing the system to minimize heat leakage, Controlling the system based on various parameters like temperature, power, and market conditions
Innovation	Increased technical complexity compared to standard energy wells/heat pump systems
Area Efficiency	960 m^2 ground area

Example 2: Ramplaankwartier District, Overveen, North Holland:
A consortium led by Delft University of Technology demonstrated a solar heating network based on photovoltaic-thermal (PVT) solar systems in the district of Ramplaankwartier in Overveen[9]. This system, which can generate both heat and electricity, was linked to a very-low-temperature heat network with heat or cold storage under the ground, alongside the use of heat pumps. The network stored surplus heat from the PVT array in underground storage during summer, utilized the heat from PVT panels and heat-cold storage during intermediate seasons, and relied mainly on the heat-cold storage during winter.

Example 3: Cranbrook, United Kingdom:
A project co-pioneered by E.ON, the University of Exeter, and technology provider SK Solar in Cranbrook (Appleyard, 2016), east of Exeter, utilized solar photovoltaic technology alongside large-scale heat pumps and solar thermal panels to provide renewable heating and hot water to the community. The project aimed at reducing carbon emissions and lowering heating costs by integrating solar PV and heat pump technology in a large-scale district heating network. Cranbrook also has a 250 kWp solar photovoltaic (PV) array installed on the roof, which is capable of powering the heat pump.

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[9] https://www.districtenergy.org/blogs/district-energy/2020/12/15/photovoltaic-thermal-district-heating-networks-are

4 Qualitative analysis of ownership structures

In this chapter we analyse in a qualitative manner the different ownership paths exemplified in chapter 3, from a users' perspective first (section 4.1), and from owners and connected stakeholders later (section 4.2).

From a users' perspective, the ownership paths are grouped in two cases:

- User ownership: users have upfront costs on their shoulders,
- Electricity suppliers, third party, or DH company ownership: users do not have the burden of the upfront costs.

From the perspective of the PV owners in an interplay with other stakeholders, we make three cases:

- User ownership,
- Electricity supplier ownership
- DH company ownership.

These ownership structures will be quantitatively analysed in the next chapter (chapter 5). Third party ownership is not considered as a separate case because the role of a third party as an investor in the asset who is not exploiting the PV production to participate in the energy market is of a lesser impact *per se*, but relevant as a mechanism to lower the upfront costs for the users (user ownership). Its role, together with the one of all actors contributing to the process from planning to operation, is also mentioned in this chapter (section 4.2).

4.1 Users' perspective

User ownership

Regulatory Feasibility and Barriers:
Regulatory provisions, like mandates on solar installations for new constructions or major renovations, provide a legal framework favouring user ownership of PV systems. Regulatory barriers might include strict permitting processes, zoning restrictions, or lack of clear guidelines on solar installations which could discourage building owner from adopting PV systems.

Support Schemes:
Government incentives such as tax credits, rebates, and grants can significantly lower the upfront costs of installing PV systems, making them more accessible to building owners.

Advantages:

1. Users own the PV system, which can increase the property value.
2. Offers a level of energy independence and protection from rising utility costs.
3. Users can directly benefit from government incentives like tax credits, rebates, and feed-in tariffs.
4. Users have full control over the system, allowing for personal preferences and needs.
5. All financial benefits such as energy savings or earnings from energy sales go directly to the user.
6. User ownership allows for self-consumption and sometimes uses the electricity grid to balance excess production or additional consumption.
7. Energy sharing regimes can allow PV owners to sell unneeded electricity to neighbours (using P2P methods) above wholesale market prices but below supplier rates.

Disadvantages:

1. One of the biggest challenges may be the limited area to deploy solar panels.
2. The initial investment required for installing solar panels can be a barrier for some users.
3. Owners are responsible for maintenance, repairs, and operation of the system.
4. Users need to navigate permitting, installation, and incentive application processes which can be complex.
5. The financial risks as in unexpected maintenance costs etc. are borne by the building owner.
6. Depending on the size of the PV system, there will likely be some mismatch between production and user consumption. Surplus production fed back into the electricity grid can be less economical for users.

Third party, electricity supplier or DH company ownership

Regulatory Feasibility and Barriers: Regulatory frameworks can hinder the third-party ownership model. In regions where utilities or third-party entities are permitted to own and operate solar PV systems on behalf of customers, the legal and regulatory environment can significantly enhance third party ownership of PV. However, regulatory barriers could include restrictive policies on third-party electricity sales, or absence of clear guidelines on third-party solar PV operations.

Economic Driver: The ability to provide solar energy with low or no upfront costs to a broader range of customers (in a ZEN) is a strong economic benefit to this model. Moreover, the option of professional management of solar systems can ensure optimized operation and reduction in costs for subscribers.

Advantages (users):

1. Third party and suppliers ownership models often require low or no upfront investment, making renewable clean energy more accessible. An example is of Otovo (leasing company) in Norway, where users can lease solar setups with no cash investment or down payment.
2. Usually, the utility or some identified third party owns the solar system itself. For instance, when leasing from Otovo, the company takes care of the system's maintenance and repairs for 20 years at no extra cost, ensuring professional management of the system.
3. Simplified processes for subscribing or leasing, making solar energy accessible to a broader audience.
4. Offers various contract options like leases, power purchase agreements (PPAs), or subscription-based models that can cater to different financial preferences of subscribers.
5. Third Party and suppliers ownership models, especially community projects, may foster community engagement and collective participation in renewable energy adoption.

Disadvantages:

1. Since customers only buy the energy and do not own the PV, they may receive fewer financial benefits compared to owning the system (as in Enova subsidy).
2. Subscribers (and the ZEN) have less control over the overall energy system, with limited ability to customize or make decisions regarding the PV generation.
3. Over the long term, the cost of a third party and suppliers ownership arrangement can potentially exceed the cost of user ownership for the consumer.

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4.2 Owners' perspective and interplay with other stakeholders

In this section we qualitatively look at which are costs and main financial benefits for the PV owners in three configurations and discuss the interplays with other actors along the process. The main goal is to increase decisional success (i.e., the chances of the ownership paths being chosen), regardless which of the paths is the most favorable.

The decision-making by the possible PV owners is simplified as a problem where the main influencing variables are assessed. Thus, we identify such variables in each case. Through tables (Table 3, Table 4, and Table 5) we respond to the questions *when*, (planning, implementation, and operation phase), and *how* each variable is affected. A color code is also used in the tables to represent the level of influence on, and certainty of, the variables. Yellow means low-medium influence and high uncertainty (i.e., variables can only be estimated, assumed); orange is decision-making point and medium uncertainty (i.e., variables are more predictable because some critical decisions are made); grey means no more influence and medium-high certainty (i.e., variables will be stable or not change). The tables can be used to determine what the different actors can do throughout the ZEN project's life to increase the chances of a successful implementation of this ownership model.

The reader should note that the analysis is developed by considering the energy strategy for Nyhavna, where electricity demand is not used for space heating and domestic hot water, which are covered by district heating.

User ownership

In a user ownership configuration, the costs and benefits balance can be described as follows and quantitatively specified as done in chapter 5.

Costs for the users are related to the investment in PV or in extra price for the purchase (in case they buy the ready building) or cost for development (in case they are early owners) of the building with integrated PV. The recovery from the investment would happen by collecting **benefits** over time in the operational phase in the form of savings on energy bills thanks to self-consumption and of the selling of the electricity surplus. Thus, the variables that can influence their choice to go for such ownership are PV investment (related to PV cost and PV capacity installed), electricity demand and production (which determine to which extent they can self-consume and have surplus), and the economic value of self-consumption and surplus (determined by the energy market and discussed in section 5.1).

Table 3 Variables affecting profitability in user ownership and interplay with other stakeholders across the planning and building process.

User ownership			
What variables influence profitability?	*When are they influenced? How?*		
	Planning	*Implementation*	*Operation*
PV investment	The requirements set by the **project owner/s** and **developers** (e.g., intended uses, sustainability goals), determine how much PV will be needed and installed. **Design** choices (e.g., orientation, shading, etc.) and restrictions (from **authorities** or **grid operators**) affect how much PV will be installed.	**Design** choices (e.g., types of plants, equipment, exploitable surfaces, etc.) affect how much PV will be needed and installed. **Suppliers** of the PV panels affect how much they cost. **Economic players** can offer lever to tailor this variable to the users' financial capacity.	Investment has been made. It can only change if bonded to a loan with variable conditions.
Electricity demand (*buildings*)	The requirements set by the **project owner/s** and **developers** (e.g., intended uses, sustainability goals) determine what will be the electricity demand of the buildings.	**Design** choices (e.g., types of plants, equipment, etc.) determine what will be the electricity demand of the buildings. **Suppliers** of plants/equipment will affect their efficiency level.	**Users**' behaviour and actual efficiencies in operation of plants and equipment guaranteed by the **suppliers** will affect the electricity demand.
Electricity production	The requirements set by the **project owner/s** and **developers** (e.g., intended uses, sustainability goals), **design** choices (e.g., orientation, shading, etc.) and restrictions (from **authorities** or **grid operators**) affect how much PV will be installed.	**Design** choices (e.g., types of PV, exploitable surfaces, orientation) affect what will be the electricity production. **Suppliers** of the PV panels affect their efficiency level.	Weather condition, maintenance and actual efficiency in operation guaranteed by the **suppliers** will affect the electricity production.
Self-consumption value	Political discussion and market dialogues can affect this variable.	Political discussion and market dialogues can affect this variable.	Taxes, levies, and grid tariffs determine the value of self-consumption. They are defined by grid **operators** and **authorities**.
Surplus value	Political discussion and market dialogues can affect this variable.	Political discussion and market dialogues can affect this variable.	**Electricity suppliers**, based on market dynamics, will affect the price paid for feed-in.

Users who are early **owners & developers**, leading the development project, can influence most of the variables, controlling the profitability of the investment since the planning and implementation stage. If the business model involves selling buildings with integrated PV, developers should be aware that the choices affecting the variable mentioned in the table above will influence the profitability for the future users to own the PV, and matching between electricity demand and production loads should be carefully evaluated in PV sizing (section 5.6).

In general, mixing uses increases the chances of profitability of this model by increasing the potential for self-consumption. To increase the success of such ownership model, the focus on PV and electricity demands should be followed-up by **designers** both from design teams at the district level and the project delivery teams at the building/s level (see stakeholder map in Figure 2).

Suppliers' information on their services and products should be integrated in the process as early as possible to guarantee optimized solutions for the building, ensure quality in installation, and provision of information at hand-over for an effective maintenance of all components, from the demand (e.g., plants and equipment) and supply (i.e., PV panels) side.

Users should be aware of their role in shaping the actual electricity load of the buildings, as a potential lever to increase profitability for them, mostly by increasing self-consumption (more details in chapter 5). This can be done in a passive (changes of consumption habits) or active (e.g., battery installation) form, looking for **suppliers** of technology assets, services, and competences in the market. External financial levers can also be explored (e.g., loans, incentives) looking to what the **economic actors** offer. Other players, such as **grid operators**, **authorities**, and **electricity suppliers** influence the feasibility of such a model, posing some restrictions on the capacity installed or influencing the price for the electricity feed-in. Discussion over these topics should be encouraged from the planning stage.

In this report, assumptions regarding all these variables had to be made for the purpose of assessing the probable profitability (chapter 5). Most of the variables will still be subject to potential changes in the use phase, affecting the level of certainty of quantitative analysis over the capability for the users to recover from such investment. However, other benefits can be mentioned, such as those listed in section 4.1.

As the variables are affected by, among others, owners and developers, designers, regulatory bodies, authorities, grid operators, and electricity suppliers, continuous updated input are important from all of them to increase the knowledge of this configuration option and ensure that it can be pursued by the users.

Electricity supplier ownership

In an electricity supplier ownership configuration, the costs and benefits balance can be described as follows and quantitatively specified as done in chapter 5.

Costs for the electricity suppliers are related to the investment in PV. The recovery from the investment would happen by collecting **benefits** over time in the operational phase in the form of revenue from the subscription fees paid by the subscribers. If the electricity supplier can offer a competitive price for electricity when there is PV production, and if, at the same time, there are users willing to pay for it, then the model can guarantee revenues for PV owner to recover and gain from the investment. Thus, the variables that can influence its choice to go for such ownership are PV investment (related to PV cost and PV capacity installed), electricity production (which determine how much and when they can sell electricity), and the subscription revenues. The latter is particularly critical as it depends on both the price the electricity supplier itself can offer (i.e., subscription price/fee) and whether there will be demand for it from the users. Such users should be those who have high consumption during the day and in summer, when PV is producing and electricity is normally expensive, so that the subscription-based price is convenient for users/buyers compared to the average electricity market price.

Table 4 Variables affecting profitability in electricity supplier ownership and interplay with other stakeholders across the planning and building process.

Electricity supplier ownership			
What variables influence profitability?	*When? How?*		
	Planning	*Implementation*	*Operation*
PV investment	The requirements set by the **project owner/s** and **developers** (e.g., PV allowed), the **design** choices (e.g., orientation, shading, etc.), and restrictions (from **authorities** or **grid operators**) put boundaries to how much PV will be installed.	**Design** choices (e.g., exploitable surface) affect how much PV will be installed. **Suppliers** of the PV panels affect how much they cost. **Economic players** can offer a financial lever.	Investment has been made. It can only change if bonded to a loan with variable conditions.
Electricity production	The requirements set by the **project owner/s** and **developers** (e.g., PV allowed), **design** choices (e.g., orientation, shading, etc.) and restrictions (from **authorities** or **grid operators**) put boundaries to how much PV will be installed.	Design **choices** (e.g., types of PV, exploitable surfaces, orientation) affect what will be the electricity production. **Suppliers** of the PV panels affect their efficiency level.	Weather condition, maintenance and actual efficiency in operation guaranteed by the **suppliers** will affect the electricity production.
Number/ volume of subscribers (*not only buildings*)	The requirements set by the **project owner/s** and **developers** (e.g., intended uses, sustainability goals) and all **design** choices affecting future electricity demand within and in the surrounding of the district will affect the number/volume of subscribers (not necessarily buildings' users).	**Design** choices (e.g., types of plants, equipment, electric mobility solutions, etc.) determine what will be the electricity demand of the district, thus the possible number/volume of subscribers. **Suppliers** of plants/equipment/e-vehicles/etc. will affect their efficiency level.	**Users**' behaviour and actual efficiencies in operation of plants/ equipment/e-vehicles/etc. guaranteed by the **suppliers** will affect the electricity demand and thus, the possible number/volume of subscribers.
Subscription price/fee	Political discussion and market dialogues can affect this variable.	Political discussion and market dialogues can affect this variable.	**Electricity suppliers**, based on market dynamics, PV production, and level of risk they can take, will decide for it.

The **electricity suppliers** have an advantage as they can decide for the volume of the PV investment and for the subscription price/fee that will build up their revenues to recover and gain from the investment. However, this can be done only within the boundaries posed by projects' owner/s, developers, and designers, in terms of how much PV capacity that can be installed, and given that there will be demand for the subscription-based contracts.

Unlike in the previous model, PV demand could also come from other sectors or neighboring areas, because electricity suppliers can sell to other users. This also means that the sizing of the PV plant is not bonded to the demand of the building/s that hosts them. Thus, it is important that **project owners, developers,** and **designers** are aware, already in the planning phase, that the configuration of the electric uses (loads) in the district (not only buildings) and in its vicinity can affect the profitability of this business model for the electricity suppliers, as they will need to have customers interested in buying electricity at the subscription-based price when there is PV production.

In general, the presence of energy-intense uses in summer and daytime increases the chances of profitability of this model. Designers in both design teams at the district level and project delivery team at the building level should follow-up properly on choices affecting electricity loads (volume and schedule, not only at building level) and exploitable surface for PV, and dialogues between project owners, developers, and **users** on one side, and the electricity supplier on the other side should be encouraged as early as possible. Examples of users are mobility players or, in the case of Nyhavna, Trondheim Havn IKS or industries.

Suppliers' information on their services and products should be integrated in the process as early as possible to guarantee optimized solutions, hand-over and maintenance of all relevant components. **Economic players** can play a role in alleviating the upfront costs, even though it is less likely that there would be schemes like incentives or grants supporting electricity suppliers owning PV plants, as PV is already normally part of their asset.

From a regulatory perspective, **authorities** and **grid operators** are also playing a role in terms of provision of trading concessions (in case the electricity supplier is a new company) and of limitations to the power installed. Discussion over these topics should be encouraged from the planning stage.

In this report, assumptions regarding all these variables had to be made for the purpose of assessing the probable profitability (chapter 5). Most of the variables will still be subject to potential changes in the use phase, affecting the level of certainty of quantitative analysis over the capability for the electricity supplier to recover from such investment. However, it is important to remember that, from a long-term perspective, by owning more PV, the electricity supplier would also reduce its operational costs, which, strategically speaking, can be an additional benefit.

As the variables are affected by, among others, owners and developers, designers, regulatory bodies, authorities, grid operators, and users, continuous updated inputs are important from all of them to increase the knowledge over this configuration option and ensure that it can be pursued by the electricity suppliers.

Distict heating company ownership

In a district heating (DH) ownership configuration, the costs and benefits balance can be described as follows and quantitatively specified as done in chapter 5.

Costs for the DH company are related to the investment in PV, whose electricity production would be converted into thermal energy through Heat Pumps (HPs) and stored in the seasonal thermal heat storage (STES) to increase the (thermal) flexibility of the system. HP and STES as investments are already foreseen and would be there regardless the DH is going for PV ownership or not.

The recovery from the extra investment in PV panels would happen by collecting **benefits** over time in the operational phase of ZEN in the form of operational savings for the DH company. Indeed, DH uses electric boilers to meet peak thermal demands in winter (Kauko, Manrique Delgado, Sartori, & Backe, 2023). By discharging the STES instead, resulting in a reduction of the peak in winter thermal loads, the DH would save in their electricity bills (spot prices and additional tariff, taxes and levies). Thus, the variables that can influence the choice of the DH company to go for such ownership are PV investment (related to PV cost and PV capacity installed), actual thermal peak reduction, and electricity price for them as electricity buyers.

The **DH company** has an advantage in having a high degree of control over both cost, which is PV investment, and benefits, namely potential for thermal peak reduction. Indeed, the latter is mostly dependent on the efficiency (COP) and capacity of the HPs and efficiency and capacity of the STES that the DH company itself is planning for and investing into. They will however need to know what is the thermal peak that there is a potential to smoothen in the district and whether the PV production will be enough to do so. Both elements depend on the choices of the **project owner** and **developers** (e.g., intended uses, sustainability goals, allowed PV), the **design** teams and project delivery teams (e.g., buildings compactness, buildings thermal properties, exploitable surfaces) and to a certain extent also on future **users** (i.e., special uses, occupants behaviour affecting thermal demands in operation).

Dialogues between project owners, developers, and future users on one side, and the DH company on the other side should be encouraged as early as possible. It is also important that designers in both design teams at the district level and project delivery team at the building level are aware that they can influence the profitability of this model, so that choices on thermal performance and PV are followed-up properly.

Table 5 Variables affecting profitability in district heating (DH) company ownership and interplay with other stakeholders across the planning and building process.

District heating (DH) company ownership			
What variables influence profitability?	*When? How?*		
	Planning	*Implementation*	*Operation*
PV investment	The requirements set by the **project owner/s** and **developers** (e.g., PV allowed) and the **design** choices (e.g., orientation, shading, etc.) put boundaries to how much PV will be installed.	**Design** choices (e.g., exploitable surface) affect how much PV will be installed. **Suppliers** of the PV panels affect how much they cost. **Economic players** can offer a financial lever.	Investment has been made. It can only change if bonded to a loan with variable conditions.
Potential for thermal peak reduction (*buildings*)	The requirements set by the **project owner/s** and **developers** (e.g., intended uses, sustainability goals), as well as how the requirements are followed up by **designers,** determine what will be the thermal peaks. Potential of peaks reduction depends on efficiency (COP) and capacity of the HPs and efficiency and capacity of the STES, which are selected by the **DH company** itself. It also depends on how much PV will be installed, which is affected by choices of projects owner/s, developers, authorities, grid operators (i.e., allowed PV), and designers (e.g., orientation, shading, etc.).	**Design** choices (e.g., physical properties of building envelopes, types of PV, orientation) affect what will be the thermal peak and what will be the electricity production providing for thermal flexibility via the STES. **Suppliers** of HP and technologies for STES will affect their efficiency and, thus, how much thermal energy will be stored and used.	Weather conditions, **users**' behaviour and actual efficiencies in operation of plants guaranteed by the **suppliers** will affect the peak thermal demand and its potential reduction.
Electricity price (spot price, grid tariff, taxes and levies, as buyer)	Political discussion and market dialogues can affect this variable.	Political discussion and market dialogues can affect this variable.	**Electricity suppliers**, based on market dynamics.

Suppliers' information on their services and products should be integrated in the process as early as possible to guarantee optimized solutions, hand-over, and maintenance of all relevant components.

Economic players can play a role in alleviating the upfront costs. This can be in the form of support schemes like incentives or grants for companies owning PV plans. For example, the RockStore initiative's partial funding by the Research Council of Norway indicates a supportive scheme for such projects.

From a regulatory perspective, it is harder to foresee what the influence could be because of lack of examples. For instance, Drammen Eiendom KF (DEKF) in the GeoTermos project (section 3.4) might have found it easier to get approvals for their integrated system since it was part of a larger R&D initiative supported by the Research Council of Norway. In regions where there is a push for renewable integration, owning both the heating system and PV plant might be encouraged through regulations. The Ramplaankwartier District's project in North Holland (section 3.4) could have benefited from Netherlands' progressive policies on sustainable energy. In some jurisdictions, regulations might be separate for electricity generation and district heating. Navigating such a landscape can be challenging for companies. Owning and operating a PV plant might come with additional compliance requirements, such as environmental assessments, which can be cumbersome.

In this report, assumptions regarding all these variables had to be made for the purpose of assessing the probable profitability (chapter 5). Most of the variables will be still changing throughout the design, implementation, and use phases, affecting the level of certainty of quantitative analysis. However, other drivers/advantages than profitability for a DH company to own PV can be mentioned, such as:

- *Enhanced Control:* Having control over both energy production (from the PV plant) and distribution (through the district heating system) allows for better synchronization and optimization.
- *Consumer Demand:* As consumers become more environmentally conscious, there's a growing demand for green energy solutions. Meeting this demand could be a driver for district heating companies to own and integrate PV plants.

As the variables listed in Table 5 are affected by, among others, projects' owners and developers, designers, users, and electricity suppliers, continuous updated input are important from all of them to increase the knowledge over this configuration option and ensure that it can be pursued by the DH company.

5 Quantitative economic assessment of ownership structures

In this chapter, we aim to quantify the economic implications of different ownership structures, namely of a) user ownership, b) electricity supplier ownership and c) district heating (DH) company ownership models.

For the user ownership, we study the single building property of Transittgata 16, with rooftop PV panels shared to meet the electrical load demand of the entire year (section 5.2). Moreover, the economic viability of electricity trade between two buildings (of Transittgata 12) is also explored, seeking to understand the aggregated benefits of centralized placement of PV panels within one property (section 5.3).

For the electricity supplier ownership, we study the viability of long-term subscription-based contract between the users (of Transittgata 16) and the electricity supplier which bears the capital costs PV panels (section 5.4). For the DH company, the financial prospects of owning PV and storing surplus energy in summer for heating use in the winter is explored (section 5.5).

Finally, this chapter also comments on the need of strategizing asset sizing (of PV and battery energy storage) based on the electrical loads of Transittgata 16, for optimized reduction of import and export of PV generation from the property (section 5.6).

5.1 Economic value of self-consumption versus surplus

With the solar PV mounted behind the meter of an electricity consumer, electricity production will be either:

- **Self-consumption**—the consumer is using more or as much electricity as the solar PV is producing.
- **Surplus**—the consumer is using less electricity than the solar PV is producing.

This is an important distinction because the economic value of self-consumption and surplus is different. The electricity bill of a user consists of three parts:

- Electricity price
- Grid tariff
- Taxes and levies

Figure 9 shows the national average price of each part on the total electricity bill for Norwegian households from 2015-2022. Note that the electricity price in 2021 and 2022 are given including the government subsidy (strømstøtteordningen).

Figure 10 shows the share of each part on the total electricity bill for Norwegian households from 2015-2022. Generally, the electricity price makes up the largest share of the bill, followed by taxes and levies and grid tariff. Simultaneously, the share of the electricity price as part of the total electricity bill is most volatile, but normally varying between 35-40% of the total electricity bill.

All the three parts (electricity price, grid tariff, and taxes and levies) of the electricity bill depend on the net electricity consumption of the user. When the user is self-consuming, the net electricity consumption of the user is reduced. Therefore, self-consumption means that the user gets reduced electricity price, reduced grid tariff, and reduced taxes and levies.

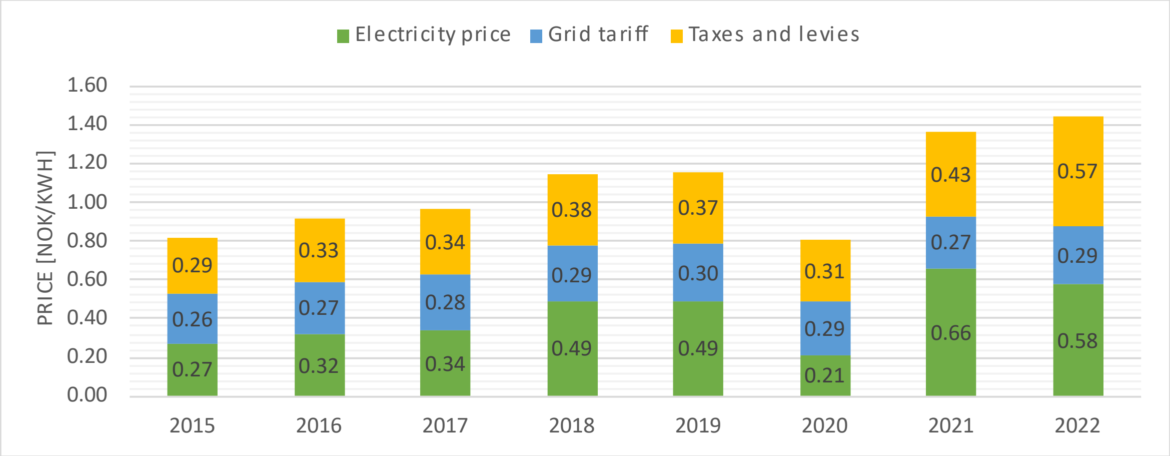

Figure 9 The total electricity bill for Norwegian households from 2015-2022 grouped by electricity price (incl government subsidy), grid tariff, and taxes and levies. Source: SSB.

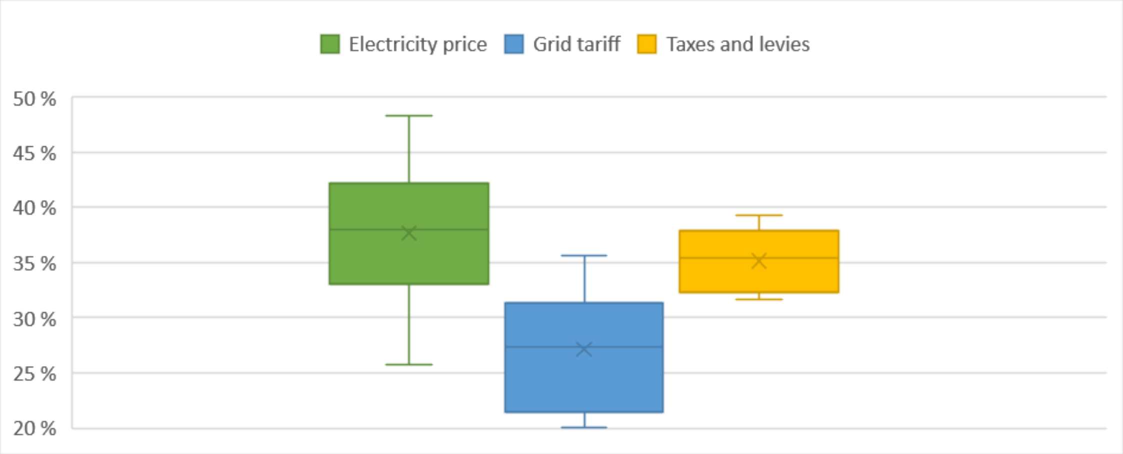

Figure 10 Box plot illustrating the share of electricity price (incl government subsidy), grid tariff, and taxes and levies as part of the total electricity bill for Norwegian households from 2015-2022. Source: SSB.

When the user has surplus, the surplus needs to be sold to generate economic value. In this situation, the user becomes a seller of electricity and will therefore receive an electricity payment for the surplus. However, the surplus selling price is usually close to or equal to the wholesale electricity price, as discussed in chapter 3. Note that the selling price excludes government subsidy because that is given to the buyer, not the seller. Therefore, surplus electricity is generally worth less than self-consumption.

Assuming that surplus electricity is worth exactly the electricity price excluding the government subsidy, Table 6 shows the economic value of self-consumption and surplus for a Norwegian household between 2015-2022. Before 2021, self-consumption was worth between 1.36-2.88 more than surplus. The largest difference in economic value was in 2020, where self-consumption was worth almost three times (2.88) more than surplus, mainly because electricity market prices were low.

After 2021, the difference in value between self-consumption and surplus was reduced because of the government subsidy. The smallest difference was in 2022, where surplus was worth slightly more (0.04 NOK/kWh) than self-consumption. This is because the value of self-consumption includes the government subsidy, whereas the value of surplus is the electricity price excluding the government subsidy. Surplus was worth more than self-consumption in 2022 because the government subsidy exceeded the grid tariff plus the taxes and levies.

Table 6 The economic value per production quantity from solar PV for Norwegian households from 2015-2022.

Year	Value of self-consumption [NOK/kWh]	Value of surplus [NOK/kWh]	Value of self-consumption versus surplus [-]
2015	0.82	0.27	2.07
2016	0.92	0.32	1.91
2017	0.97	0.34	1.81
2018	1.15	0.49	1.36
2019	1.16	0.49	1.38
2020	0.80	0.21	2.88
2021	1.36	0.72	0.90
2022	1.44	1.50	-0.04

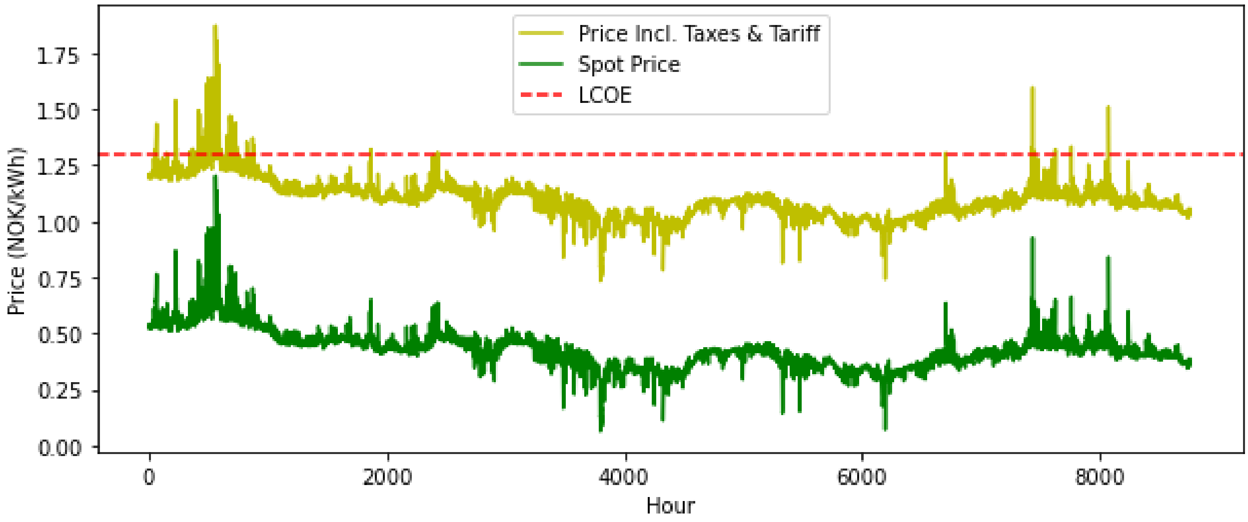

Figure 11 Electricity tariff of 2019 including taxes and grid fee compared with LCOE.

Figure 11 illustrates the hourly spot electricity price for 2019 alongside the consumer price, which includes VAT and grid fees. These additional charges constitute a major component of the final electricity tariff. The Levelized Cost of Electricity (LCOE) represents the break-even price per kWh for solar PV energy, ensuring the initial investment is recovered over the 25-year lifespan (n) of the system. With a capital cost (C_0) of 16 666 NOK/kWp, maintenance cost (C_t) as 1% of capital cost and a 3% discount rate (r), the LCOE is calculated to be 1.3 NOK/kWh.

$$LCOE = \frac{C_0 + \sum_{t=1}^{n} {C_t}/{(1+r)^t}}{\sum_{t=1}^{n} {E_t}/{(1+r)^t}}$$

where, E_t is annual energy production by solar panels in kWh estimated based on the hourly production profile from 2019, see Appendix.

The data from 2019 indicates that the spot price rarely exceeded the LCOE, suggesting potential losses for PV owners selling at spot prices. In contrast, the cost of importing electricity, inclusive of taxes and grid fees, surpasses the LCOE during several hours, which highlights the economic advantage of self-consuming PV energy generated on-site.

5.2 Economics of user ownership at Transittgata 16 (with and without battery)

To calculate the profitability of user ownership at Nyhavna, we need to estimate how much self-consumption and surplus that is produced on an hourly basis for one user-owned solar PV installation. Since Oct 1st, 2023, users on the same property address ("same gårds- og bruksnummer") can share self-consumption.

Figure 12 Transittgata 16 (yellow) at Nyhavna could have one shared PV installation. Source: Norgeskart.

We use Transittgata 16 (Figure 12) as a case study for individual user ownership structure of PV panels. Out of the total property area of ~ 5 000 m^2, we assume 35%[10] building area (1 750 m^2), which is the building footprint. Therefore, the total rooftop area available for solar PV would be 1 750 m^2, which can hold about 350 kWp[11] capacity of solar. We can estimate the hourly production from this solar PV installation by linearly scaling the profile presented in the Appendix.

Moreover, considering five floors, the total floor area of the building would be 8 750 m^2 which allows a rough estimate using PROFet on the electrical load consumption Figure 13. See Appendix for more details.

Figure 13 presents the solar PV production and the electrical load consumption on an hourly basis. We observe that a 350 kWp PV system generates more than the electrical demand for most of the year, with a particularly notable surplus during the summer months. Consequently, the redistribution of PV energy within the property results in an overproduction during numerous hours throughout the year.

Figure 14 shows an example for a day in May with a disparity between PV output and building load profiles. The residential apartments have a consumption peak in the evening (orange line in Figure 14), precisely when PV generation (blue line in Figure 14) declines towards zero. This temporal discrepancy between electricity generation and its utilization highlights the potential necessity for implementing energy storage solutions.

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[10] According to the recent architectural proposal for Transittkaia, outdoor area at the ground floor level is 57%, meaning 43% of covered surface. As the proposal is under regulatory work, we assume a conservative 35% to avoid overestimating PV surface.

[11] One 400 Wp solar PV panel is approximately 2 m^2, so we assume 200 Wp/m^2

Figure 15 shows the monthly average hourly production by the solar panels and the electricity used by the building, indicating that the annual PV production is about the same as the annual electricity use. This situation strongly suggests the use of an energy storage system because the main issue is the difference in timing between when energy is available and when it is needed.

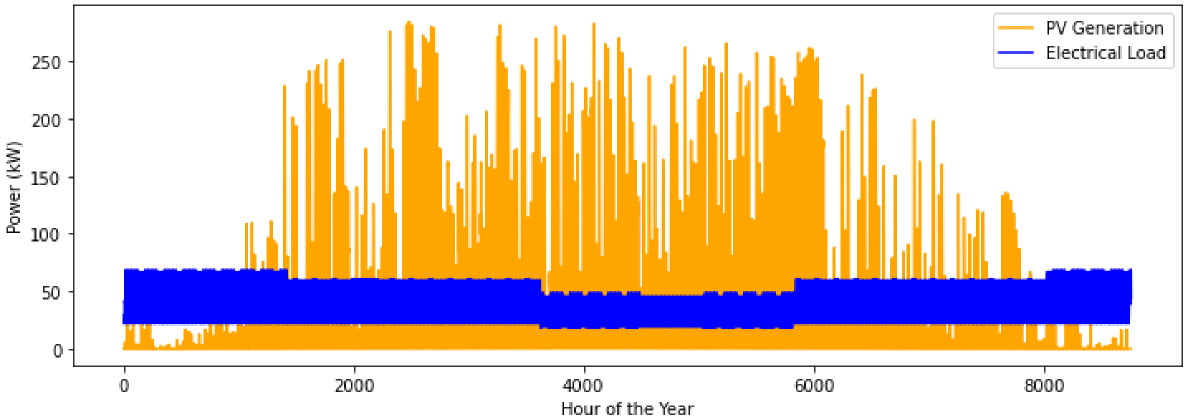

Figure 13 Hourly PV generation (orange) and electrical (blue) load profile for the building from January (left) to December (right).

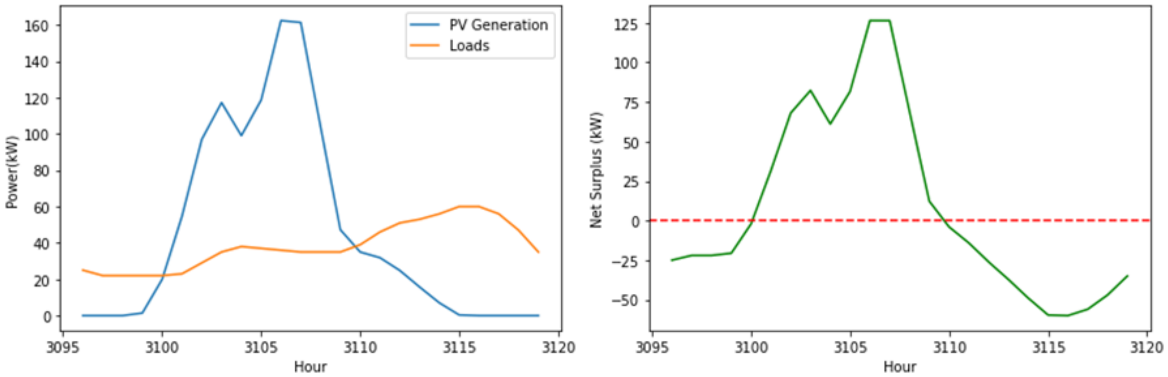

Figure 14 (a) PV generation (blue) and electrical load profiles (orange) and (b) hourly surplus (green above red line) and deficit (green below red line) for a typical day in first week of May.

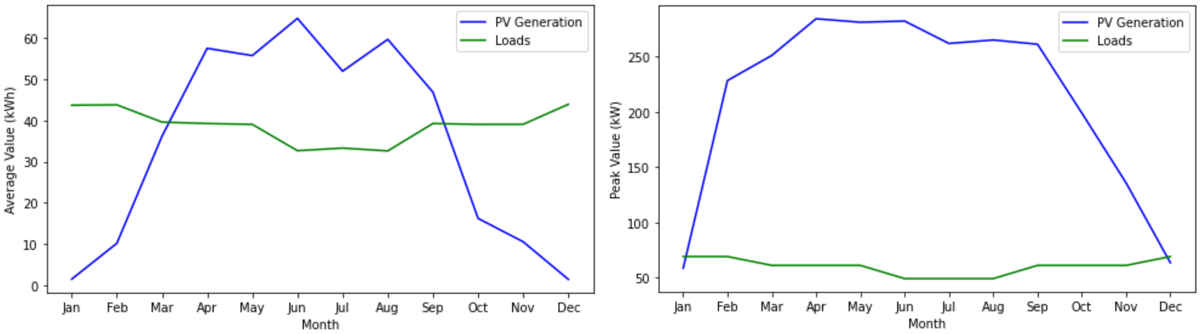

Figure 15 Monthly average and peak hourly PV generation and electricity consumption.

Figure 15 also illustrates a comparison between the highest hourly electricity demand within each month and the highest hourly solar electricity production during the same period. For most of the year, there is a significant gap between the highest electricity production and the highest electricity consumption. This gap indicates that incorporating a battery energy storage system (BESS) could enhance the building's self-consumption. However, because the difference between maximum electricity production and maximum electricity need can exceed 200 kW during spring and summer months, achieving an optimum match between excess solar energy and storage would require a very large capacity for the BESS.

We examined the daily patterns of solar energy production and building energy consumption to calculate the energy surplus during the day and the deficit at night for each day of the year. By comparing these values, we determined the potential of solar energy to meet daily energy needs.

The smaller value between each day's surplus and deficit indicates the optimal size for a daily battery energy storage system (BESS), as depicted in Figure 16. Notably, there are significant spikes in required BESS capacity around March (day 70) and October (day 300). During winter, the demand for BESS is minimal due to the low solar energy production, which eliminates the need for energy storage. During summer, the electricity demand is decreased without a large increase in PV production (Figure 13), and we therefore observe higher deficit in March and October compared to July and August.

The substantial yearly needs for battery storage could lead to significant initial investment costs for the ZEN. Furthermore, permitting energy exchange between buildings could amplify the surplus or shortfall, potentially requiring larger and more expensive battery systems.

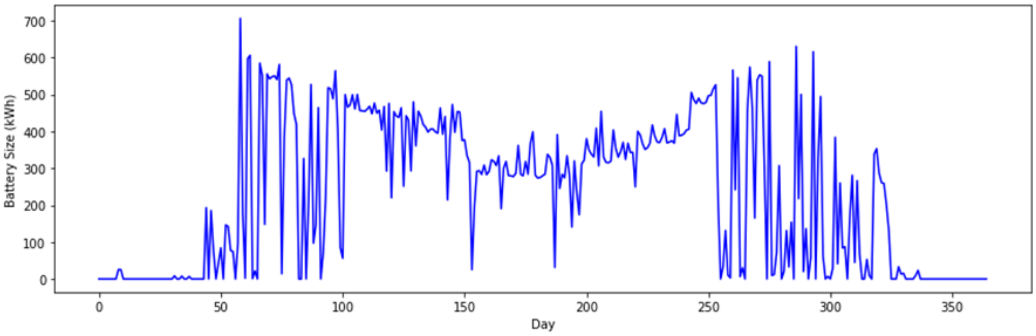

Figure 16 Energy storage requirement due to generation-demand mismatch during all days in one year.

We now assess whether battery storage can economically offset the cost of importing electricity by increasing the self-consumption.

First, we assume that there is no flexibility or energy storage resource within Transittgata 16, therefore the electricity demand is met on an hour-to-hour basis through PV and the electrical grid. The PV sold to the grid is shown in Figure 17a, which is high mostly during summer and spring as PV significantly surpasses the low electricity needs. It is to be noted that all surplus PV must be exported out of the property address due to lack of storage facilities.

Figure 17b shows the utilization of PV generation for electrical loads at the building (i.e., self-consumption). As winter months are low on PV generation, most of the electricity requirement is fulfilled from the grid as also seen in Figure 17c. In hours where PV generation falls short (typically winter months), the grid power import increases.

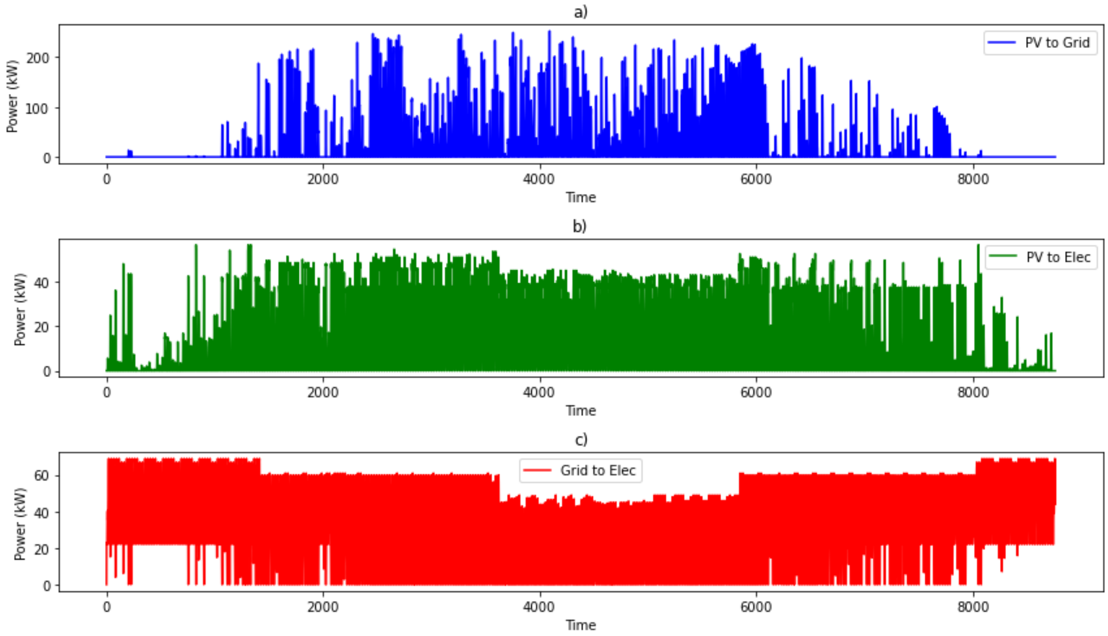

Figure 17 a) PV energy sold to the grid (surplus), b) PV generation used directly for electrical loads (self-consumption) without BESS Electricity c) grid import needed to meet electricity demand when PV generation is not sufficient.

We assume a shared 1 MWh battery storage system for the building, with a 500-kW power rating, allowing full charge or discharge in two hours. While this capacity may appear too large, typical PV production on a summer day nearly reaches 1 MWh with a 350-kW system. Additionally, with lower energy demands in summer, the net surplus, as previously seen in Figure 13, is around 650 kWh.

With this additional storage capacity, we explore the financial advantages of storing excess solar energy during the day for use during the night. Moreover, to focus solely on improving PV self-consumption, the BESS is assumed to be charged only through solar without taking electricity from the grid.

As seen in Figure 18a, the export of surplus PV to the grid is reduced compared to Figure 17a without BESS, as more of the PV is now stored in the BESS. As the import cost of electricity is 2-3 times the export benefits of selling the surplus (Section 5.1), an optimized PV-BESS scheduling process ensures a high percentage of the PV surplus is stored for later use (as at night-time). Therefore, investments in BESS saves the ZEN from grid tariffs and taxes and levies. The energy transfer from PV to the BESS is shown in Figure 18b, and the BESS's state of charge (SOC) is seen in Figure 19.

It is to be noted that this analysis considers the role of PV in solely fulfilling the electric-specific loads. Therefore, the space heating and hot water requirements of the building are not directly met through solar.

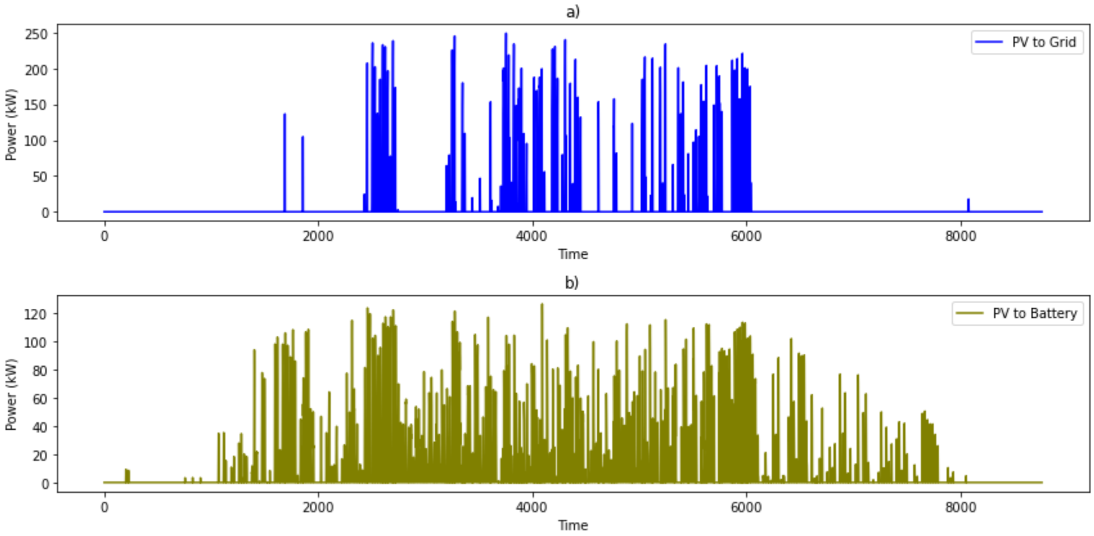

Figure 18 a) PV energy sold to the grid (surplus) with BESS. b) PV electricity stored in BESS

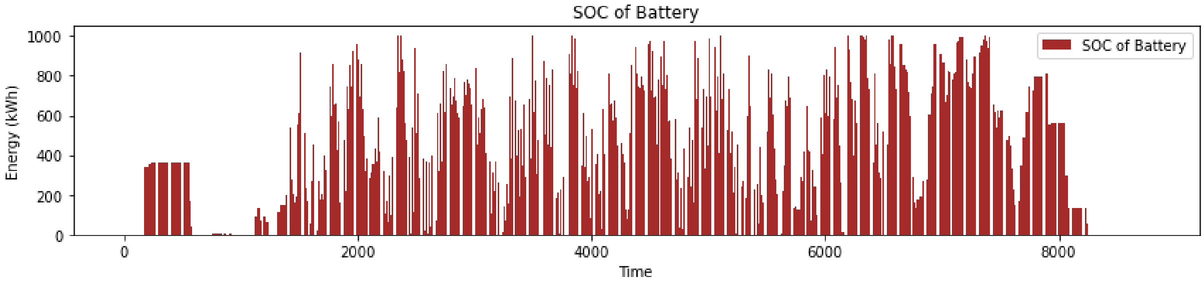

Figure 19 The state of charge (SOC) of the BESS through the year.

Table 7 shows the financial advantages of investing in PV generation and BESS for the Transittgata 16 considering that the yearly benefit of having a PV is NOK 190 977 (i.e., savings in net yearly costs of Case I compared to Case 0). Moreover, it also shows the yearly operational costs with and without using the BESS, where BESS triggers cost savings of NOK 19 460 (i.e., savings in net yearly costs of Case II compared to Case I). The savings are due to increased self-consumption, which yields lower operational costs from grid tariffs and taxes and levies. Although yearly revenue from selling surplus is decreased, the loss of revenue is more than compensated by lower operational costs.

Table 7 Resulting yearly costs for user ownership with and without BESS.

	Case 0 (without PV)	Case I (with PV but without BESS)	Case II (with PV and 1 MWh BESS)
Yearly Operational Costs (NOK)	374 152	260 090	183 870
Yearly Revenue (NOK)	-	76 915	20 155
Net Yearly Costs (NOK)	**374 152**	**183 175**	**163 715**
PV exported (MWh)	-	190	50
PV self-consumption (MWh)	-	110	250

Note that we do not assume any costs related to the BESS, so NOK 19 460 is the break-even yearly BESS costs (incl. investment costs) if the BESS is used solely to increase self-consumption from solar

PV. Considering PV cost of 350 kW to be NOK 5.8 million and BESS cost of 1 MWh to be NOK 1.2 million, we can calculate the simple payback period of the PV panel to be about 30 years and more than 50 years for the BESS. This is within the expected lifetime of the PV, but not for the BESS.

Note that this is considering the market prices from the year 2019 which were relatively stable and low. If the prices are higher, as was the case of year 2021 and 2022, the revenue of selling PV to the grid and the savings in the operational costs would be higher, resulting in lower payback period for the PV and BESS system. A detailed study on the change in net yearly revenues and costs due to market price variation is out of scope of this report.

5.3 Economics of user ownership when sharing solar between buildings

In this section, we present how sharing solar production between two buildings on the same property ("same gårds- og bruksnummer") increases the economic value of solar PV.

To do so, we considered two example buildings at Nyhavna standing within the same property boundaries (Figure 20). Table 8 shows the floor area of the two example buildings and the available rooftop area for PV exploitation.

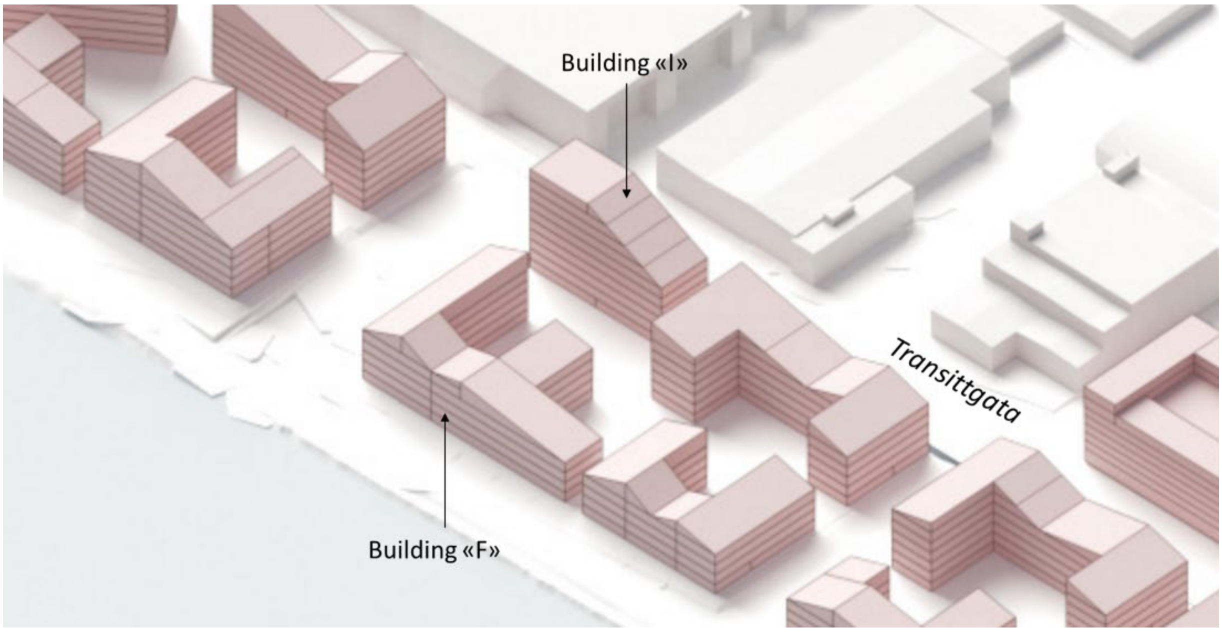

Figure 20 Illustration of two buildings at Transittgata 12 at Nyhavna. Source: Ny Havna – Nye horisonter (winner concept by team Cobe[12]).

The two buildings ("F" and "I") are those expected to cover the current property Transittgata 12 according to the winning proposal of the architectural competition for Transittkaia[12]. According to such proposal, it is more straightforward than for Transittgata 16 to say that two distinct buildings will stand within the same property boundaries. For this analysis, we assumed that property boundaries will not be redesigned. Furthermore, because the final architectural expression will depend on the regulatory and design stages, we assume that the buildings have flat roofs, which are considered as fully exploitable for PV. Distribution between residential and non-residential uses (which is relevant for energy demand estimation) is also assumed from the competition proposal.

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[12] Publicly available at https://nyhavna.no/byutvikling/utvikling-av-transittkaia/

Table 8 Floor and roof area in m^2 for two example buildings at Nyhavna.

Area [m^2]	Total	Residential	Non-residential	Roof
Building F	**6129**	5634	495	1271
Building I	**5154**	4897	257	601

NB: The quantities in this table have been calculated from the drawings of the architectural competition for Transittkaia that are publicly available at Nyhavna Utvikling AS website[12], including indication of residential and non-residential uses in siteplan. Given the small scale of representation of the original drawings, surfaces can only be considered as a rough estimation for the purpose of our analysis, and by no means as reference for what will be actually built in Transittgata 12.

The rooftop area of Building F is twice than that of Building I, while the total floor area is quite similar. Thus, Building F could have a higher surplus of PV generation which could be shared with Building I. The maximum capacity of PV generation in Building F and Building I would be of 250 kWp and 120 kWp, respectively, considering 200 Wp/m^2.

Figure 21 shows the surplus of two buildings. Note that both buildings have surplus because of the seasonal mismatch of load and generation.

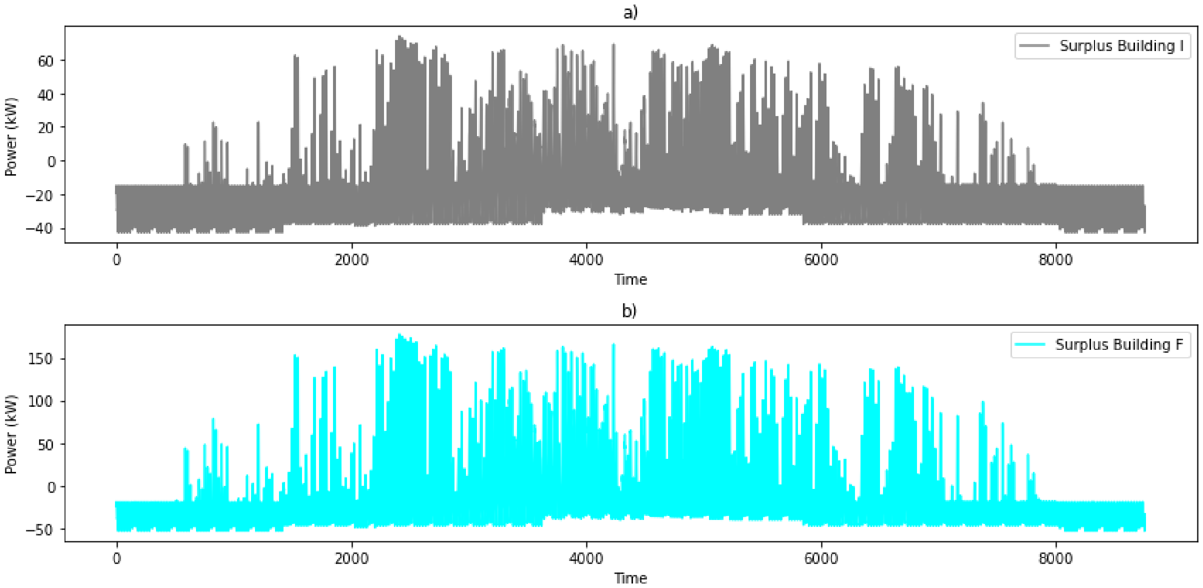

Figure 21 Hourly surplus of Building F and Building I

Figure 22 shows the surplus electricity transfer from Building F to Building I. This considers the hours where surplus is available from Building F and there is a deficit at Building I. If Building I can count this as self-consumption, it would cheaper than buying electricity from the grid. Specifically, Building I would be willing to buy the surplus electricity from Building F at a higher price than the spot price because Building I can avoid grid tariff and taxes and levies.

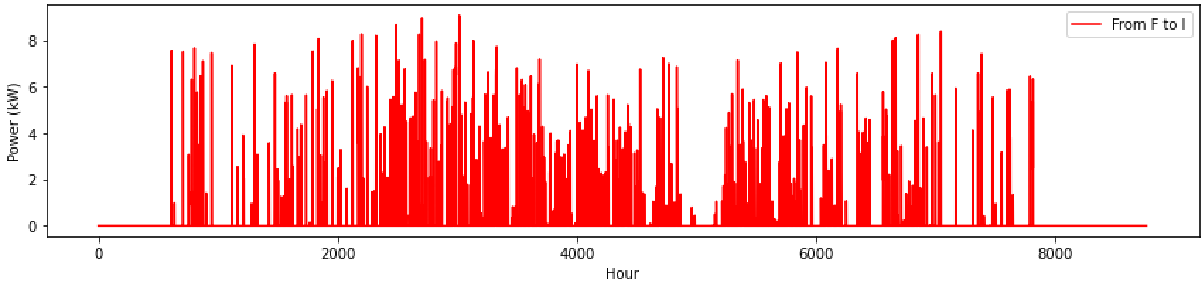

Figure 22 Hourly electricity transfer from Building F to Building I.

Table 9 shows the resulting yearly costs for Building I and Building F when they cannot share solar surplus, and the costs when they can share solar surplus (Building I & F). The sum of the net yearly costs for Building I and Building F is NOK 1 013 higher than the costs for Building I & F when they can share solar production, which is because they export a total of 1 MWh less. When these two buildings can share solar, the net yearly costs needs to be distributed between them. Because the total net yearly costs are smaller when they can share solar, it is possible to distribute the costs such that both Building I and Building F have lower costs than the alternative scenario without sharing solar.

Table 9 Resulting yearly costs for user ownership when sharing and not sharing solar between buildings.

	Building I (not sharing solar)	**Building F (not sharing solar)**	**Building I& F (not sharing solar)**	**Building I & F (sharing solar)**
Yearly Operational Costs (NOK)	182 828	217 249	400 077	398 388
Yearly Revenue (NOK)	19 002	56 302	75 304	74 628
Net Yearly Costs (NOK)	**163 826**	**160 947**	**324 773**	**323 760**
PV exported (MWh)	45	135	180	179
PV self-consumption (MWh)	63	95	158	159

Moreover, if we consider no PV generation in Building I, then the transfer of surplus PV from Building F to I increases as seen in Figure 23. Moreover, the annual PV exported from Building F to Building I now substantially increases to 45.8 MWh from the earlier 1.4 MWh (when Building I itself owned a PV). Building F now supplies almost 25% of the annual demand of Building I (225 MWh). This illustrates the potential benefits of a shared PV system among multiple buildings within the same property with the PV installation being centralized at a single location.

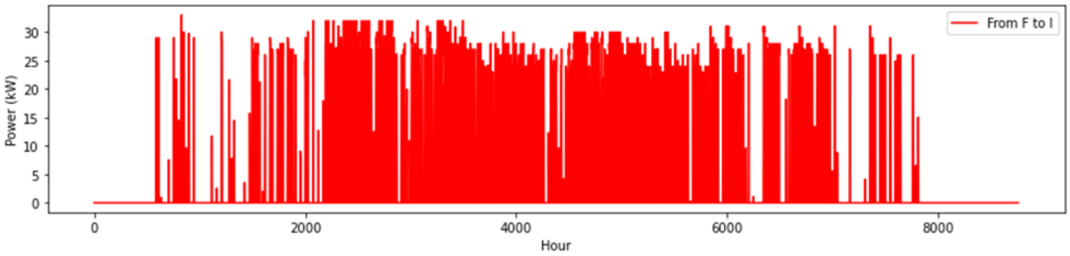

Figure 23 Hourly electricity transfer from Building F to Building I (with no PV at Building I).

5.4 Economics of electricity supplier ownership

In this case, an external entity, such as an electricity supplier, installs solar PV panels on the rooftops of ZEN buildings, as discussed in chapter 3. The primary purpose of this arrangement is to meet the electricity demands of these buildings directly through rooftop PV systems. When a building utilizes energy generated by its rooftop PV system, it reduces its dependence on grid electricity. This reduction in grid dependency translates to substantial savings in taxes and grid fees for the users. Consequently, this model presents an opportunity for electricity suppliers looking to establish power purchase agreements (PPAs) with users.

In negotiating a PPA, an electricity supplier might consider the combined costs of the spot electricity price, taxes, and grid fees as the price for the agreement to cover the initial capital investment required for the PV installation. An alternative strategy for electricity retailers, apart from establishing PPAs, could be to sell the electricity generated by the PV systems at the spot price.

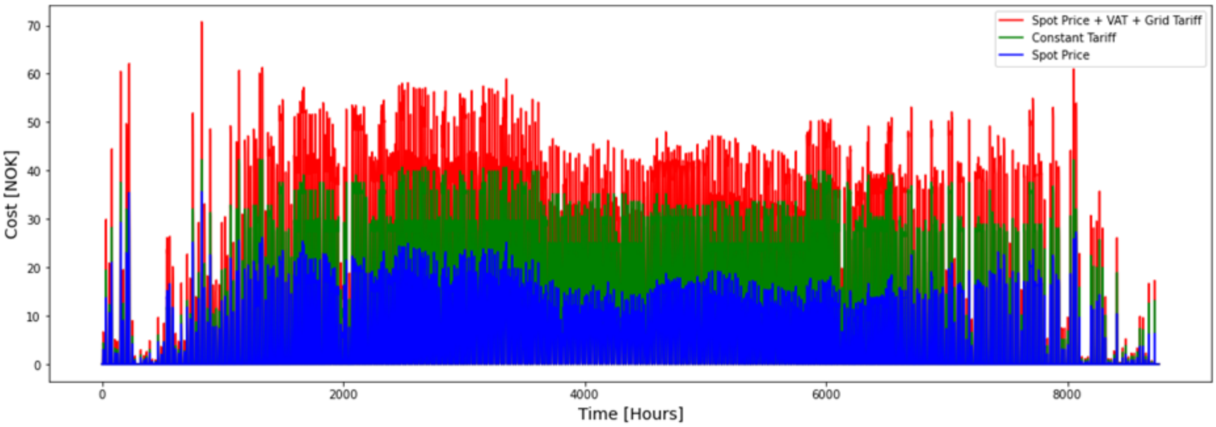

Figure 24 Hourly revenue from selling PV generation at times of electricity demand.

Figure 23 shows the hourly revenue that the supplier would generate by selling the PV generation (matching the loads) to the one-building-property (Transittgata 16). As there is significant difference between spot price and the additional costs of grid tariff and taxes, there is much potential for a middle price for a PPA between the supplier and the ZEN property. If we choose a constant (middle) tariff for the PPA (green line in Figure 24), the supplier still can get a revenue of about NOK 85 046 without counting any revenue from selling surplus PV generation that was not required within the property.

Table 10 also shows the maximum annual revenue that the supplier may get from yearly contract could be NOK 115 691. This is the maximum revenue because for any higher annual cost than NOK 115 691, there would not be any long-term (or annual) financial incentive for the users of the property. Note that the maximum revenue does not include NOK 77 985 of potential revenue from selling surplus PV at spot prices to other customers.

Table 10 Annual revenue for the electricity supplier from selling PV generation to the building (no flexibility).

	Spot Price	Constant Tariff (PPA)	Spot Price + VAT + Grid Fee
Annual Revenue[13](NOK)	45 015	85 046	115 691

However, if the property owns flexibility, as in BESS, then in an optimal scenario, they will not purchase their energy at high price hours of any typical day. Therefore, the annual energy costs[14] for the property can reduce drastically with a large BESS.

Figure 25 shows the electricity consumption cost (considering the spot prices) for each hour with and without the BESS. The electricity consumption is now concentrated at few hours (which would be cheaper, see Figure 11) rather than spread out in each hour like in the case of ‘No BESS.’ Therefore, the annual operational cost for meeting the electricity demand (considering only the demand that can be met by solar) would be lowered as we include higher flexibility in form of BESS.

Figure 26 shows that the annual operating costs reduces from NOK 45 015 (without BESS) to lower than NOK 10 000 with a large BESS capacity of 1 MWh. This is because the BESS is used to store energy in times of cheaper spot price, and thus the expensive hours can be avoided if there is sufficient flexibility within the ZEN.

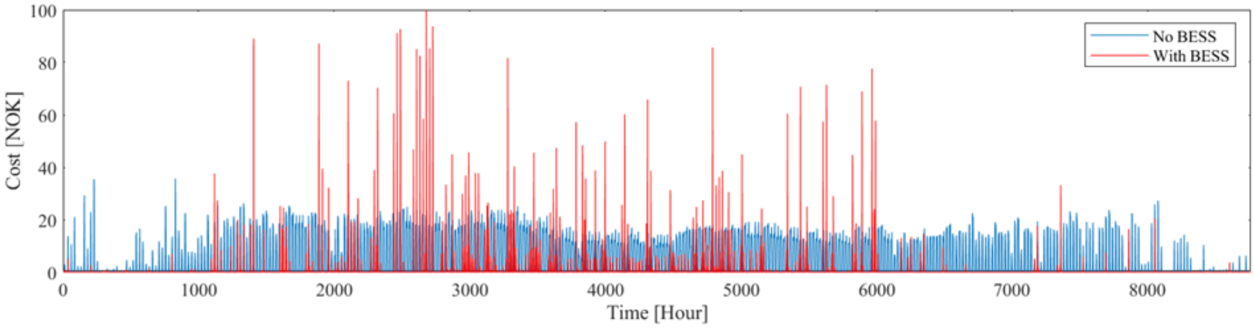

Figure 25 Comparison of hourly operational cost based on spot prices with and without BESS (of 800 kWh).

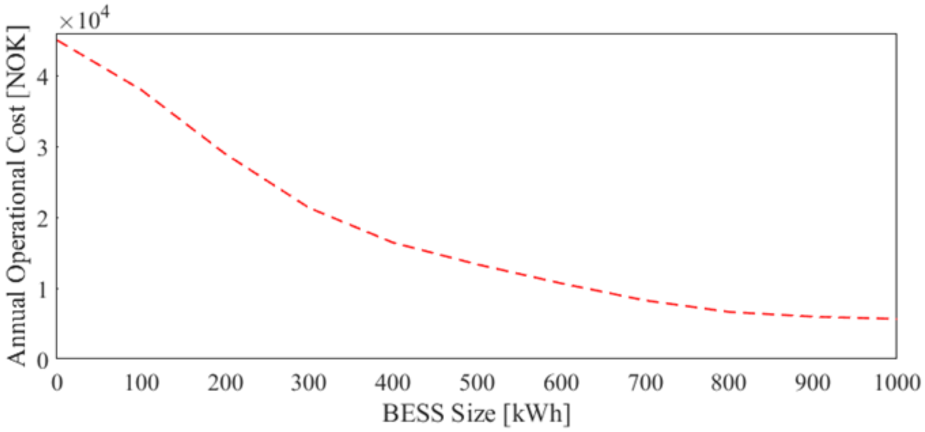

Figure 26 Annual operational cost for the property considering varied BESS size.

With ample flexibility resources available, the users (of the property, or the ZEN) would not be willing to get into a long-term fixed tariff contract which is higher than the worst-case market-based cost (of spot price + taxes + grid fee) after utilizing the BESS. Table 11 shows the range of annual revenue the

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[13] Not including the 77 985 NOK of potential revenue from selling surplus PV at spot prices.

[14] Considering the minimum of PV generation and electricity demand of each hour.

electricity supplier may possibly get from selling the PV generation, considering a 300 kWh BESS available within the property. Compared to Table 10 (without BESS) we see the revenue reduction is almost half as the buyer (the ZEN users) with flexibility would encounter lower electricity costs in the market alternative by utilizing flexibility.

Table 11 Annual revenue for the electricity supplier from selling PV generation to the building having BESS of 300 kWh capacity.

	Spot Price	Constant Tariff	Spot Price + VAT + Grid Fee
Annual Revenue (NOK)	21 347	39 136	56 926

Thus, if the ZEN has more flexibility (in the form of BESS or otherwise), they can bargain lower prices for the PPA contract that reflect their actual cost of electricity purchase from the market.

5.5 Economics of district heating company ownership

In this section, we consider the case where the district heating company at Nyhavna (Statkraft Varme), owns both the heat pumps, the seasonal thermal energy storage (STES) system, and the solar panels. We show the potential economic benefits that could be obtained if the heat pump, STES, and the solar PV electricity are managed together.

We explore the value of the district heating company using electricity from the PV to power the heat pumps. Heat from heat pumps could then be stored in the STES for later use (Figure 27). By coordinating the PV, heat pumps, and STES, the district heating company could cut its operating costs by reducing electricity imports in winter when the spot prices are high. Instead, parts of the heating demand in the winter could be supplied from the STES, where the STES has been charged with surplus PV electricity in the summer. Efficiently managing solar energy production with STES could mean that the district heating company relies less on more expensive heat sources during winter.

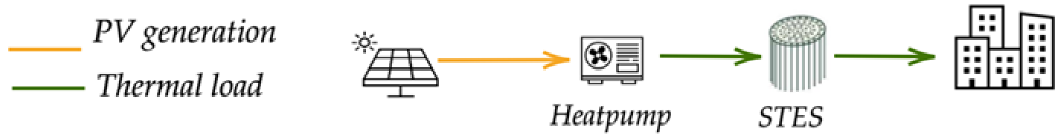

Figure 27 Seasonal thermal storage of surplus PV generation through heat pumps.

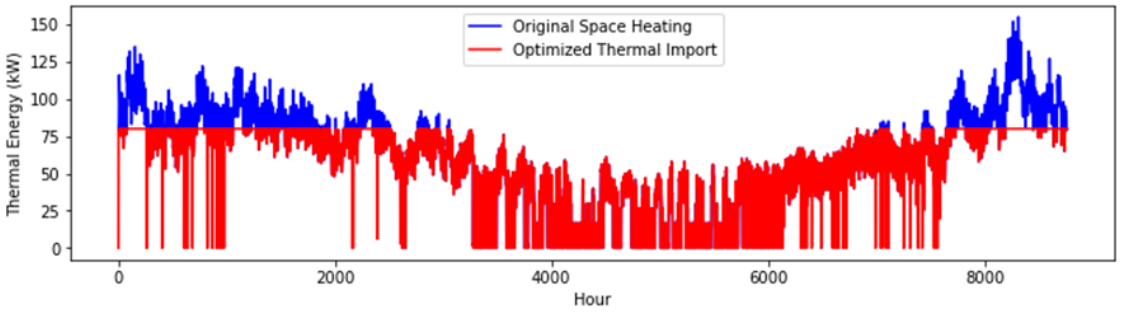

Figure 28 Thermal peak reduction during winter using seasonal storage.

We are exploring seasonal storage to address peak heating demands during winter. This can be achieved with a model that minimize the maximum of thermal import for entire year:

$$\min(\max T_{import})$$

This approach benefits district heating companies in reducing costs. District heat is largely generated through waste incineration[15]. However, in winter, the demand for heat increases, often exceeding the capacity of waste-burning facilities. One of the sources district heating companies use to meet this increased demand is electric boilers (Kauko, Manrique Delgado, Sartori, & Backe, 2023). By implementing seasonal storage, we aim to store excess heat generated in warmer months and use it during winter, thus minimizing the dependency on expensive alternatives, including electric boilers.

Figure 28 shows the peak reduction of thermal loads, where PV generated in the summer (Figure 29) powers the heat pump with assumed coefficient of performance (COP) of 3. A COP of 3 is a conservative chosen assumption where in practical settings it may go higher. This conservative approach is because we have not conducted a detailed modeling of the STES, particularly regarding its efficiency in the conversion processes, both from electricity to heat (input) and from stored thermal energy back to usable heat (output).

Due to this high efficiency from heat pumps, even low PV generation can result in substantial reduction in winter peak demands of space heating. Even a 30 kW PV is sufficient for a thermal peak reduction of around 50 kW in winters (Figure 28). Note that 30 kW PV installation will take around 150 m^2 of rooftop area.

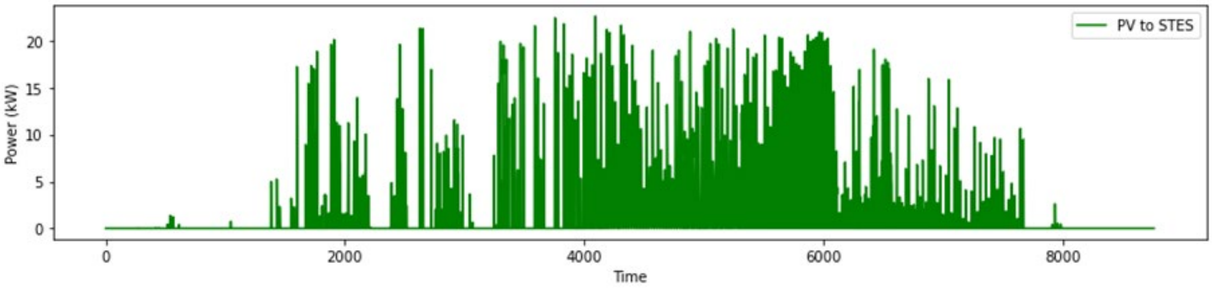

Figure 29 PV generation stored in STES through heat pumps.

If the district heating company uses electric boilers to meet peak thermal demands in winter, we can estimate the cost savings per hour for the district heating company as the supply from the STES multiplied with the spot price plus grid tariffs and taxes and levies (Figure 30).

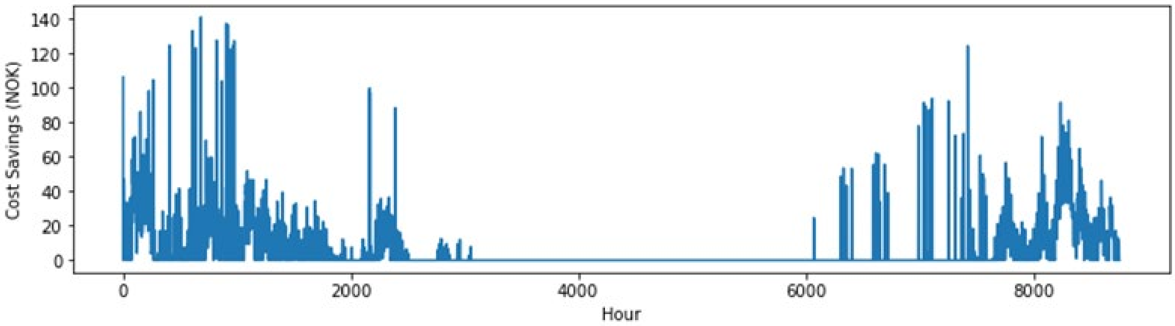

Figure 30 Hourly cost savings due to reduction in peak winter thermal loads using STES.

5.6 Sizing of PV assets

This section presents some fundamental aspects regarding sizing of solar PV. The right sizing of PV will help reducing the dependency on BESS and minimize surplus, which is less economically valuable.

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[15] https://www.fjernkontrollen.no/

If the primary objective for Nyhavna is to maximize self-consumption to ensure economic profitability, then the PV system should be adapted to meet specific energy requirements without too much excess.

Figure 31 shows how electricity import and export varies with changes in PV size with and without (w/o) battery energy storage system (BESS). A key observation is the differential change in import and export values corresponding to PV size variation.

For grid imports, we observe first a linear decrease with increasing PV size. However, when the PV is sufficiently large, the reduction in grid imports is also smaller and smaller when sizing the PV larger, leading to a stagnation of grid import reduction when the PV size is sufficiently large.

For grid exports, we observe a somewhat opposite trend: when the PV size is small, the increase in exports is larger and larger when PV size is increased. However, when the PV is sufficiently large, the increase in exports is linear (constant) with the increasing PV size.

Specifically, in Figure 31, when the PV size increases from 200 to 350 kWp, there is a reduction in grid import values from 250 MWh to 230 MWh, a decrease of approximately 20 MWh (grey line in Figure 31). Conversely, with the same variation in PV size, the export energy significantly rises from 75 to 200 MWh, an increase of 125 MWh (green dashed line in Figure 31). This substantial change in export energy, compared to the relatively smaller reduction in grid imports suggests that oversizing PV systems can occur quite easily.

However, inclusion of flexibility within ZEN, for example in the form of a BESS, can substantially enable more self-consumption of large PV installations. In Figure 31, we can notice that using a fixed capacity of 1 MWh BESS available for storing surplus PV generation, the export outside the property is reduced from 110 MWh to around 35 MWh for the entire year. This is achieved through reducing the temporal mismatch of the solar PV production during the day, and electricity demand at the night. Thus, optimal sizing of energy assets along with their coherent control strategies is crucial for maximizing the utilization of self-generated PV generation.

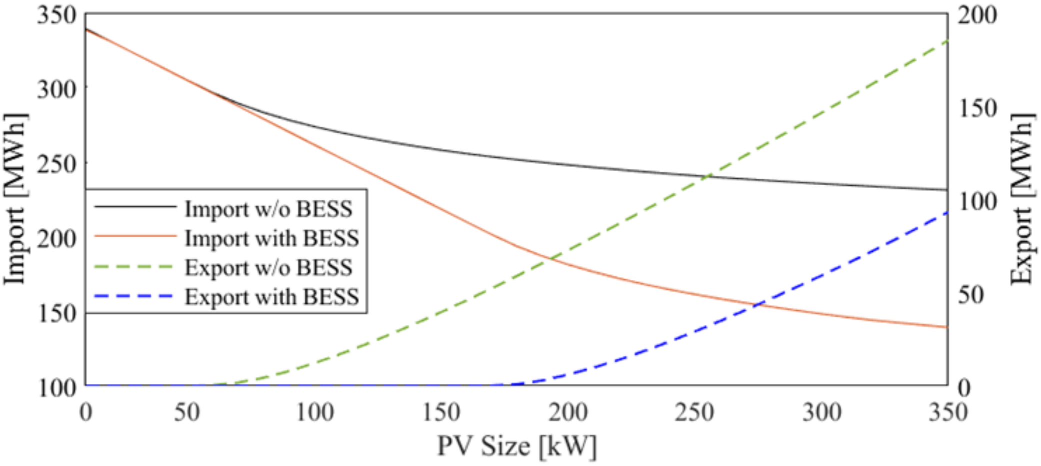

Figure 31 Comparison of yearly import vs export energy with increase in PV size with and without (w/o) BESS.

6 Conclusion and key takeaways

In this report, we focused on exploring Nyhavna in Trondheim as a case study to study challenges and opportunities of different ownership structures for solar PV generation in a zero-emission neighbourhood.

We identified relevant stakeholders at Nyhavna in Chapter 2 and assessed potential photovoltaic (PV) ownership structures with international examples in Chapter 3. Subsequently, we examined various PV ownership structures at Nyhavna, considering qualitative and quantitative factors as well as decisional and technical aspects in Chapters 4 and 5.

Regarding the mapping of stakeholders, we have the following takeaways:

- A **stakeholders' map** as a network, entailing temporal and special dimensions, is an effective tool to explore the roles of different actors, as well as the need/opportunities for collaboration and goals alignment between different actors.
- Both **contextual** and **industry actors** should be considered. Industry actors, creating and exploiting value, can both directly and indirectly affect how well the district will be able to meet ZEN ambitions regarding the energy aspects. Their roles should be made explicit.
- Users, landowners & developers, and electricity suppliers stand out as the most **central actors** in the network of stakeholders connected to one or more energy players. Users and landowners & developers are among the most central also at the whole network level. Within the scope of our analysis, their behavior has the potential to influence the process outputs the most.

We studied the **decision-making** process for a certain ownership path as a simplified problem where the main variables influencing costs and benefits are assessed in terms of when and how they can be affected in each ownership configuration:

- **Owners** and **developers** should be aware that their choices affect PV capacity potential and demand, which will influence the profitability for users, electricity suppliers, or district heating company to own the PV. The focus on PV and energy demands should also be followed up by **designers** both at the district and building/s level.
- **Authorities** and **grid operators** play a role in terms of provision of trading concessions for new electricity suppliers and of limitations to the power installed. Early dialogues are encouraged, especially in the case of users and electricity supplier ownership. Dialogue among these two is also important in case of users' ownership.
- **Users**, as PV owners, have a smaller influence on their financial benefits than other potential owners. However, they should be aware that their flexibility potential can shape the actual electricity load of the buildings and be a lever to increase profitability for them. This can be achieved through changes in consumption habits or installations such as batteries, facilitated by technology asset suppliers offering services, expertise, and financial support.
- **Electricity suppliers** have an advantage as potential PV owners because they can decide, within boundaries, for the volume of the PV investment and for the subscription price/fee that will build up their revenues, looking for consumers among other sectors than buildings (e.g. mobility) and in the vicinity of Nyhavna. However, this is not easy and involves risks, so early dialogue with future users should be encouraged.
- **District heating company** holds a strategic advantage by exerting control over both costs (PV investment) and benefits (thermal peak reduction potential). The extent of thermal peak smoothening in Nyhavna depends on the company's choices regarding heat pumps (HPs) and Seasonal Thermal Energy Storage (STES). Facilitating early dialogues with project owners, developers, and users is also crucial to determine the potential for thermal peak reduction in the area.

We also performed **quantitative studies** to determine the economic potential within different ownership structures:

- User ownership models shows that optimal control of a PV-battery system can significantly decrease the energy import for a building. Moreover, with a large enough battery, the export of surplus PV energy can be substantially reduced, indicating that batteries can effectively align production of solar with consumption patterns of end-consumers, and in turn reduce reliance on grid imports during peak demand periods.
- The economic assessment demonstrates that investing in PV will lead to significant operational cost savings for users, with a likely payback period within the lifetime of the investment.
- With the currently high capital costs of batteries, combined with a relatively short lifetime, it not likely that their payback period is shorter than their lifetime.
- The payback period of the PV and the batteries can decrease with increasing spot prices and lowering capital costs.
- The sharing of PV generation between buildings on the same property can lead to higher profitability of the PV system. Moreover, if multiple buildings within a property have unequal capacity for PV generation, optimal use of rooftop area can be achieved through a centralized PV installation.
- There can be risks associated with oversizing PV systems, where the increase in energy export does not proportionally offset reduction of grid imports. Therefore, strategic sizing of PV assets for the specific energy needs and consumption profiles of the buildings is essential to avoid unnecessary capital expenditure.

The choice of PV ownership in the operational phase of Nyhavna is only a piece of a bigger transformative effort, which requires to **look backwards** until the initiative and planning stages where Nyhavna is now to ensure that ZEN goals are preserved.

Most of the variables affecting decisions to own PV will still be subject to changes because of the choices of owners and developers, designers, regulatory bodies, authorities, grid operators, users, and electricity suppliers. Continuous inputs from all of them are important to increase the knowledge over all the configuration options towards their pursuit.

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Appendix

Input data and assumptions

For the quantitative economic assessment presented in chapter 5, we make the following assumptions about the relevant input data:

Hourly production from solar PV at Nyhavna

We simulate hourly production profiles from 2015-2022 based on the MERRA-2 (global) data set available through renewables.ninja[16]. We use the coordinates 63.4399, 10.4171 to represent Nyhavna assuming a system loss of 0.1 and no tracking. Furthermore, we assume 35° tilt from the horizontal facing south (azimuth 180°). The profile is produced for an installation of 1 kWp, and it is scaled linearly. The hourly production is illustrated for 2015 in Figure 32.

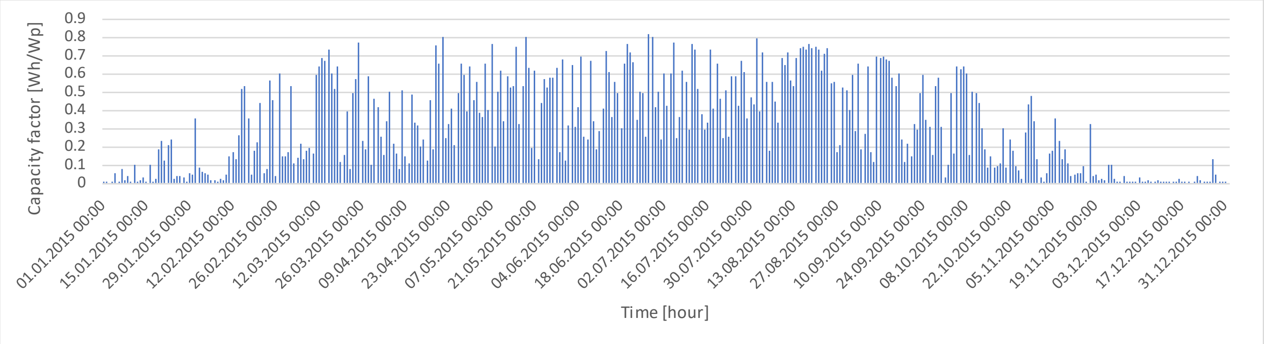

Figure 32 Illustration of hourly capacity factor for solar production at Nyhavna from January to December 2015.

Price of electricity from the grid

We use historical data for hourly wholesale electricity prices from ENTSO-E[17] for 2015-2022 for price zone NO3 where Nyhavna is located.

Electricity and heat demand at Nyhavna

To generate demand data for electricity and district heating, we use the PROFet tool developed by SINTEF Community. This tool generates hourly demand profiles for electricity and heat based on a given building mass specified by building category and total floor area (Table 12). All buildings are assumed to be "New buildings" and "Very efficient" in PROFet. The tool also needs input on hourly outdoor temperatures, which is generated for 2015-2022 based on the MERRA-2 (global) dataset available through renewables.ninja. We use the same coordinates as above (63.4399, 10.4171) to represent Nyhavna.

Table 12 building categories and their respective total floor area at Nyhavna to generate hourly demand profiles with PROFet.

Building category	Total floor area [m^2]
Apartment	313 500
Office	65 946
Shop	7 777
Hotel	37 039
Kindergarten	804
Culture_Sport	2 685

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[16] https://www.renewables.ninja/

[17] https://transparency.entsoe.eu/

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