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Multi-Energy Interplay in a Planned District Community with a Large Share of PV-Produced Electricity in a Nordic Climate

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Abstract

The world's energy system faces major challenges due to transitions from fossil fuels to other alternatives. An important part of the transition is energy-efficient homes that partially produce their own electricity. This paper explores the energy interactions between heating, cooling, and electricity usage in a planned residential area in Sweden where a significant portion of the electricity is generated by solar PV systems. Conventional district heating and cooling systems and a low-temperature district heating system that uses return cascading technology were compared with heat pump systems. Electricity sharing in an energy community has a low impact on the calculated national energy efficiency metric. It is also shown that electrifying space heating with heat pumps improves the calculated energy efficiency metric, but heat pumps increase the peak power demand in the winter due to high heat demand and a lack of solar production. Using heat pumps for heating domestic hot water and compressor chillers for cooling offers a more balanced use/production of electricity since the electric cooling load is mostly met by local solar production, as shown by an increase in self-consumption of 8% and stable self-sufficiency. There is, however, a time mismatch between production and the peak electricity demand, which could be addressed by using energy storage systems.

Keywords: photovoltaic system; energy communities; district heating; heat pump; return cascading technology

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1. Introduction

The transition to sustainable energy systems is a critical challenge of the 21st century, driven by the need to mitigate climate change, enhance energy security, and promote economic development. The new European Union policies (EU) incentivize an increase in the share of renewable energy sources in their energy mix. This push is crucial because the minimum requirements of the Paris Agreement will not be met without a significant reduction in greenhouse gas emissions [1]. To mitigate the changing climate, each country within the European Union has a yearly plan to meet the region's reduction in greenhouse gas emissions. Sweden is expected to miss its carbon dioxide emission mitigation goals for 2030 [2].

A key feature of various renewable energy technologies is their low or even zero greenhouse gas emissions during operation [3]. However, many renewable energy generation technologies, such as photovoltaic (PV) and wind power generation, have variable generation patterns that depend on the availability of their primary energy sources, i.e., solar radiation, wind, etc. [4,5], adding complexity to power system management [6]. Once considered marginal, these technologies have seen exponential growth in recent decades, with, for instance, the exponential increments in global PV capacity in the past years [4]. According to IRENA, the cost of generating electricity with PV panels has dropped by 82% over the past decade [4]. Solar power is becoming more established. Of the total electric generation in Sweden, solar power constituted 1.9% in 2023 [7].

Buildings within the European Union still account for approximately 40% of the EU's energy consumption and 36% of the EU's energy-related greenhouse gas emissions. Since Europe meets most of its heating demand with fossil fuels and because energy-inefficient buildings are not renovated fast enough, the EU has launched several actions specifically aimed at the building sector [8,9]. With the Energy Performance of Buildings Directive (EPBD), the EU aims to achieve a fully decarbonized building stock by 2050 [8]. Another important directive is the Energy Efficiency Directive, aiming to use energy more efficiently and to contribute to reducing the EU's overall energy consumption [9]. Within EPBD, in 2024, the EU adopted the EU Solar Standard to enhance the amount of PV installations on buildings across the European Union [8]. The EU Solar Standard requires that all new commercial and public buildings have PV installations by 2026. The EU Solar standard also has legislation for commercial and public buildings that undergo relevant renovations (2027), new residential buildings (2029), and existing public buildings by 2030 [8]. PV systems on buildings help reduce the need to buy electricity from the grid and lower associated costs [6]. To promote local renewable energy generation and usage (self-consumption), the EU and national entities have introduced and supported Energy Communities (ECs—which comprise both Renewable Energy Communities (RECs) and Citizen Energy Communities (CECs)) in recent years, which can share locally generated energy among members at a lower cost compared to grid-imported energy [3]. This sharing is fundamental to these energy communities, providing tangible benefits to small consumers and engaging citizens in energy-related issues, including renewable generation and self-consumption. By increasing the number of ECs, member states can boost the capacity building of renewable energy resources and reduce greenhouse gas emissions in the energy sector, aligning with the EU goals [10] of mitigating climate change.

The energy system of a building can be considered by breaking apart two major energy forms: thermal energy and electricity. Residential buildings have three major thermal energy demands, namely, space heating to maintain comfort in cold seasons, space cooling for comfort in warm seasons, and domestic hot water use, which occurs throughout the year. Electricity demand can also be categorized as individual or household electricity demand, that is, electricity linked to the needs of the occupants within a household. Individual electricity demand includes, for example, refrigeration of food, washing clothes, and lighting indoors. Since these uses are subject to the whims of individuals and acquiring data about them can be infringing, household electricity use is often excluded from energy efficiency measures. Operational electricity is used for shared or regulated features of a building, such as ventilation systems, lighting of shared spaces, and elevators. Electricity can be used to power a direct boiler or a heat pump to meet thermal demands. Therefore, thermal and electric demands are connected. Understanding the dynamics of these energy profiles and how they relate to the availability of renewable resources will shape how climate emissions associated with meeting thermal and electrical demands are reduced.

When a new housing area is planned, it is difficult to foresee the energy use for heating and cooling, the electricity use for the operation of the building, and the electricity use by tenants. One method for estimating the energy used at a neighborhood scale was developed by the Urban Building Energy Modeling (UBEM) field. Several UBEM tools allow the energy simulation of buildings at large scales with different levels of complexity, accuracy, and usability [11]. Understanding energy demands can help decision makers apply the European EC toolset to meet the mitigation goals.

2. Aim and Novelty

This paper explores the demand and conversion of different energies: heating, cooling, and electricity usage in a planned residential area where a significant portion of the electricity is generated by PV systems in the Nordic environment. High-latitude energy systems have unique challenges, including low solar angles, high space heating demands, and unique technological systems, such as the prevalence of district heating networks [12]. This paper is unique in that it takes several of these system components into consideration simultaneously. It compares a conventional district heating (DH) and district cooling system with a low-temperature DH system, which uses return cascading technology (to use the return flow of the existing DH network as the main flow to a subdistrict), and a heat pump (HP) system, which uses electricity for heating and cooling. PV systems are modeled in different tilts and orientations to test the extent to which varied production matches electric demands. A planned housing area, "Nyhamn" in Gävle, Sweden, serves as the case study.

This study builds on a methodology from a previous paper by Ahrens Kayayan et al. [13] that used the same area to study heating technologies. In that paper, a similar systems approach was applied to a similarly situated neighborhood. There, the HP was assumed to have a static SCOP, and a single PV orientation was considered. The focus here is instead on different calculations by including more nuance for the PV system, dynamic heat pump calculations, and a new form of return heat utilization. This methodology [11] aims to bridge this gap by enabling the modeling of thermal and cooling demand, comparing two proposed building shapes, including dynamic simulations of the heat pump performance coefficients and different configurations of the PV system. The return heat system was also modeled to include returning hot water as a source for electrifying domestic hot water. This allowed for investigations into the interaction between PV system production compared to cooling demand and the impact of shading on both thermal demands and PV system production.

The novelty of this paper is a holistic discussion of the following:

1. Peak electricity import and export;
2. Orientation and tilt of the photovoltaic system;
3. Dynamic modeling of heating and cooling heat pump technologies;
4. Comparison of energy performance according to the Swedish building regulations, BBR29;
5. Technical impacts of energy sharing within the community.

These factors allow this paper to explore the nuance of dynamic energy systems, particularly how both demands and heat sources are shaped by hourly weather conditions. The energy models demonstrate the impact of technology choices and how the built environment interacts with the local weather. These are shaped by the incentives and opportunities of national and European-level legislation.

3. Background

3.1. Renewable and Community Energy Communities

Effective implementation of energy-efficient measures faces significant barriers, both technical and social [14,15]. Therefore, ECs could provide a large-scale solution to reducing carbon emissions associated with energy production by locally producing the energy needed by the community and maximizing its use. In this context, ECs emerge as an approach to achieving energy transition by integrating technological, economic, and social sustainability.

Socially, citizens worldwide are becoming increasingly interested in actively contributing to a fairer, more sustainable energy sector. A significant number of EU citizens are expected to become prosumers, generating about 50% of the system's total renewable electricity [16]. The EU legislation promotes ECs, recognizing their potential to foster social innovation by promoting an active citizen role within the EU energy sector. For that, the EU's Renewable Energy Directive II (RED II) establishes a legal framework to support the development of ECs, highlighting the significance of citizen involvement and local ownership in achieving sustainable energy goals [16]. This directive has catalyzed the growth of ECs across Europe, with numerous projects showcasing the economic, environmental, and social benefits of community-based renewable energy initiatives [17].

ECs unite citizens to invest in, own, and maintain renewable energy technologies [18]. However, we lack a clear consensus on the definition of the characteristics of an EC [19]. Despite this, an EC should empower individual citizens in its establishment and operation, benefit a wide range of stakeholders, be rooted in social relationships, and be tied to a specific geographic area [19,20]. In practice, ECs can take various forms, such as energy cooperatives owning wind power plants, independent market aggregators, or neighborhoods jointly owning battery storage [21], by exhibiting a diverse organizational and decision-making structure [18]. Earlier research highlights the importance of acknowledging national variations and the historically and geographically conditioned nature of energy communities [22,23].

Regulatory support is crucial for adoption, including streamlined permitting processes and consistent policy support to facilitate the integration of renewable technologies [24]. Uncertainty surrounding ECs' legal status is a major barrier in the Swedish context [25,26]. In this study, the social and economic benefits of energy communities are not assessed. The focus is instead on the impact of sharing energy in a community on the measure of energy efficiency. The regulations regarding building efficiency measures set the boundary around a singular building. Energy efficiency measures how much energy, electrical or thermal, is necessary to meet human demands. Locally used power that is produced by renewable sources is not added to the demand metrics. Conversely, power sold to outside buildings does not improve efficiency. However, some of that power might be used outside the building within the neighborhood. If the power were allowed to be shared within the neighborhood, it would increase efficiency measurements. Buildings, their demands, and their capacity to produce solar electricity are individually simulated. It is therefore possible to account for the difference if the buildings' metrics are measured on their own or as an energy-sharing EC.

3.2. Thermal and Electrical Demands in the Residential Context

European regulation is clear on prioritizing "efficiency first" [16]. The measures of efficiency are left to individual countries. In Sweden, a calculated energy performance (EP) is used. It is set forth by the Swedish building regulations. EP is an indicator of the amount of energy consumed in a year per square meter of heated area (called A_{temp}). The unit is therefore kWh/m^2. The governing body also sets forward minimum targets for which new buildings must comply, and these targets become increasingly stricter. To allow for the comparison of different technologies and solutions, EP balances different energy sources, such as district heating and electricity, by assigning weights to them (0.7 and 1.8, respectively). The latest version (BBR31) has a minimum of 75 kWh/m^2 weighted energy. In addition to those, it sets forward demands on the maximum electrical consumption and the insulation, both of which are met for all buildings herein.

Beyond the minimum requirements, the Swedish National Board of Housing, Building and Planning also sets grades from A to F depending on how well a building performs. The target is primarily concerned with meeting the comfort and hygiene requirements of a building efficiently, so to understand this measure, it is necessary to understand the energy requirements of a building. Meeting the requirement of 75 kWh/m^2 guarantees a C-grade. To obtain a B and then an A grade, a building must have a lower specific energy use than 75% or 50% of the requirement, which translates to a demand of 56.3 and 37.5 kWh/m^2, respectively.

The energy system of a building can be considered by breaking apart the two major energy forms: thermal energy and electricity. Residential buildings in Sweden have three major thermal energy demands, namely, space heating to maintain comfort during cold weather, space cooling for comfort during warm weather, and domestic hot water use, which occurs constantly throughout the year. Electricity demand can also be categorized.

Household electricity demand is linked to the needs of the occupants within a household, such as refrigerating food, washing clothes, and lighting indoors. Electricity is commonly traded in a separate agreement between the individual household and an electricity trading company. Household electricity use is often excluded from energy efficiency measures and is excluded when the primary energy number is calculated in the Swedish building regulations (BBR 31). Operational electricity (interchangeably called infrastructural electricity) for a building is used for shared or regulated features, such as ventilation systems, lighting of shared spaces, elevators, etc.

When the energy performance for a building is calculated according to BBR31, only the amount of energy bought is considered. PV installations on buildings are commonly connected "behind the electricity meter" to obtain part or all of the energy produced for consumption in the building rather than exported. Since the primary energy number uses the bought amount of electricity, which is only affected by the amount of grid-consumed electricity and ignores self-consumed electricity, the calculated energy efficiency is improved by the installation of PV systems. But the only advantage is the reduction in buying grid electricity. As such, the surplus electricity exported (out of the building) provides no value for the EP calculation. So, there are diminishing returns for a larger PV system. The share of self-consumed electricity can be increased if the building electrifies its thermal demands (i.e., installs a heat pump system instead of using district heating). Then, the amount of electricity used for operations increases, and the share of surplus electricity decreases. This process, however, is dependent on the dynamics of when electricity demand occurs as well as when the PV system produces electricity. A model is needed to carry out these calculations.

3.3. Urban Energy Modeling

To determine the energy status of a neighborhood [27], it is crucial to understand its thermal and electrical energy flows, including both demand and production. In existing areas, this typically involves analyzing monitored data, if good-quality data are available. For new or planned areas, energy modeling is deemed essential to predict energy requirements and to inform decisions regarding the building facade, choice of heating technology, and sizing transformers. To address this gap, analytical methods, such as Urban Building Energy Modeling (UBEM), have been developed. UBEM is a key field for district-scale analysis [28–30].

The UBEM model by Johari [31], as applied in this paper, can utilize data from existing buildings [32] or 3D sketches of planned constructions [33]. It employs EnergyPlus, an open-source engine, and the model is calibrated for Swedish building archetypes and validated in other Swedish cities [11,34]. Space heating (SH) and cooling demands can be well understood using energy balances. Unlike space heating and cooling, which can be estimated with a physics-based approach, domestic hot water (DHW) depends mostly on the habits of its users. The model uses an occupancy-based approach to estimate DHW, i.e., the demand occurs when people are expected to be awake and occupying the buildings in the mornings and evenings. This data-driven method is used to estimate operative and household electricity demand.

4. Methods

4.1. Electricity, Heating, and Cooling Model

Datasets of monitored household electricity consumption of existing buildings were applied to estimate the same for the planned buildings, as detailed in [13]. This method was applied as an improvement to the original simplified occupancy model. The dataset was provided as two databases by Gävle Energi AB [35]. The first contained monitored data from 566 apartments with hourly household electricity consumption. These are not the apartments in the modeled area since it is not currently built. However, since they are also in newly built buildings in the same city, they functioned as data sources to estimate household electricity use. Seven apartments with no electricity demand (i.e., 0 kWh for all 8760 h) were excluded since it was impossible to estimate the number of rooms and their area. The variation due to ignoring empty apartments is small; however, there is uncertainty in the size and energy use of the buildings if they were in use. This could mean that the number of apartments with a certain number of rooms is underrepresented. The dataset of 566 apartments included all the apartments recently built by the municipal company. This leads to a small overestimate of the household demand in the planned area since some apartments there will probably also be empty. The second database provided aggregated data for the number of bedrooms (e.g., 1 bedroom, 2 bedrooms, etc.), the area of the apartments, the number of apartments with that many bedrooms in the dataset, and the average yearly household electricity consumption. Due to anonymity concerns, although the two files described the same set of apartments, they did not specify the area or the number of bedrooms for a given apartment. A simple linear estimation based on the sum across the year of the 559 apartments was performed to estimate the number of bedrooms and the area of the apartments.

Using these datasets, the size and number of rooms were approximated with a linear analysis comparing the yearly sum of the electricity consumption of the apartments with known hourly data and the known size and number of rooms. These results were fed into a Python (version 3.11) script to simulate the diversity of household electricity use in the future district. The electrical demand of a random apartment was then added to a building, and its area was subtracted from the same until no area was left to fill one apartment [13]. This random selection ensured a stochastic element in aggregating household consumption, representing consumption patterns of the new buildings in Gävle.

Operational electricity data, which does not have the same anonymity concerns as household electricity, was available along with building areas (A_{temp}) for four buildings. Operational energy was calculated hourly by selecting the existing buildings' operational profiles per square meter and multiplying them by the area of the simulated building. Both household and operational electricity demands for the buildings were then applied in the next step of estimating the thermal demands. A part of the losses from electricity use becomes heat within the building.

Two alternative constructions for the same area were provided by the municipality [36]. The 3D files were used in the UBEM and the PVsyst model to calculate shading. This paper presents the results for 2 different building areas, i.e., 1 and 2, within Nyhamn (Gävle), as shown in Figures 1 and 2. The two proposed areas had different roof areas (50,325 m^2 and

39,376 m^2) as well as heated floor areas (232,319 m^2 and 151,620 m^2). Weighted for area, these also had a different average number of floors: 4.6 and 3.9 floors. Notably, there was less variation in the floor heights in the second building area.

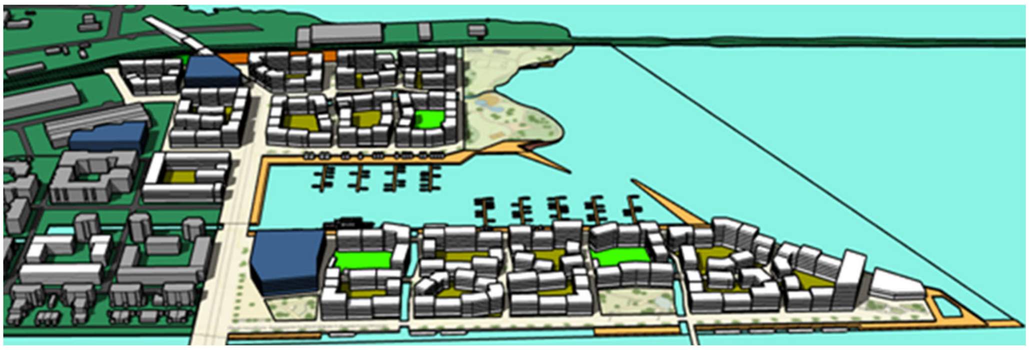


Figure 1. Building area 1 block layout. White buildings are planned apartment buildings, whereas the blue buildings are transport hubs (shade other buildings, roof area available for PV, but have no electricity or thermal loads). The grey buildings are existing buildings (which can shade but are not available for solar, nor are their energy requirements considered).

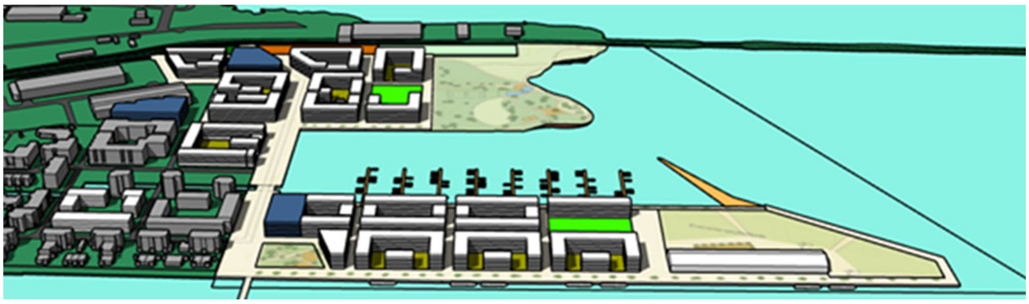


Figure 2. Building area 2 block layout. White buildings are planned apartment buildings, whereas the blue buildings are transport hubs (shade other buildings, roof area available for PV, but have no electricity or thermal loads). The grey buildings are existing buildings (which can shade but are not available for solar, nor are their energy requirements considered).

Thermal and cooling demands were simulated using physics-based UBEM [11]. This model prepared the relevant building and shading information and passed it to EnergyPlus [34] to calculate building-level demands. Thermal insulation was assumed to comply with the latest National Building Code 31 (BBR31) [37] standards. Thermal heating demand was divided into SH and DHW. Cooling is novel to this iteration of UBEM. As opposed to the previously published model, more attention is given to the windows. Earlier iterations had very high cooling loads, which were attributed to the simplified windows model. Energy from the sun enters a building primarily through the windows. In the summer, occupants can also ventilate the well-insulated building for cooling and use shading to reduce incoming solar radiation. To model this behavior, the windows can be shaded with a fixed slat interior shade. This shading was applied automatically under two conditions: the indoor temperature was higher than 25 degrees Celsius, and there was 250 W of solar radiation on the window. Furthermore, the proposed cooling model was validated by running a similar simulation through IDA ICE 5.1 [38] for selected buildings.

Thermal demand for SH is influenced by the building's interaction with its environment, making physics-based tools suitable. However, modeling occupancy is more complex due to social factors affecting how and when buildings are occupied. Occupancy, in turn, affects DHW usage and window opening conditions, impacting thermal comfort.

As a baseline, the DH network meets the buildings' thermal needs [39]. Furthermore, three technologies were selected and tested in this paper to meet the thermal demand:

district heating and cooling (DHC), CCs, and HPs. The different scenarios are summarized in Table 1. All scenarios included the PV power production that was available based on the roof footprint.

Table 1. Analyzed scenarios and their descriptions.

Scenario	Description
DH	The thermal demands for SH and DHW are met by supplying hot water from the conventional district heating network.
Return	The thermal demand for space heating is covered by using returning district heating and, when needed, primary district heating. Similarly, DHW is preheated by returning water, and the temperature is raised by a WSHP, which uses the returning water as a source.
HP	The heating demand is supplied by either an ASHP or a GSHP.
DC	The cooling demand is met by the district cooling network.
CC	The cooling demand is supplied by an ASHP.

In an earlier model [13], a static SCOP of 2.57 was applied throughout the year to consider the ratio between electricity consumption relative to thermal demand. In this paper, a change was implemented since the updated COP values reflect a more nuanced hourly method, which leads to a more precise assessment of energy efficiency and peak powers (as HPs are less efficient when source temperatures are lower) [40]. To provide a better assessment of the importance of a more precise SCOP, a dynamic SCOP analysis was introduced, as presented in the following section. Dynamic COP is based on the weather profile of the year. The When2Heat method was applied, which links dry bulb temperature (of the air for air sourced and of the ground for ground sourced) to the COP of a heat pump with a validated data-driven approach [41]. Measured data were applied to the outdoor temperature. For the ground temperature, the ERA5 dataset from Copernicus [42] was applied. Although it is the same source as the When2Heat method, and it is well validated, the variation in data sources could be a new source of error for the method. It does not provide an equivalent for cooling. The relationship between wet bulb temperature and the COP of a heat pump used for cooling was adapted from [43]. The paper from which the relationship was taken explicitly advises against disregarding the internal mechanism of a heat pump to predict its COP. But without sizing the components of the different buildings' heat pumps and then accounting for mass flows and mechanical systems, it is not possible to apply other recommended methods. A simpler approach was taken. The wet bulb temperature depends on the dry bulb temperature of the air, as well as its relative humidity and pressure. Ground source heat pumps can provide “free cooling” simply by using the lower ground temperature in the summer. Thus, electricity consumption is only the circuit pumping power, leading to a high COP. Furthermore, since heat is added to the ground, it could potentially improve the heating COP later [44,45]. The exact mechanism for this was difficult to replicate without simulating boreholes. Therefore, only air-based heat pump cooling was considered.

Although cooling systems are not widely implemented in multi-family buildings in Sweden, due to the country's relatively cold climate and low cooling demand [46,47], there is a growing interest in these technologies due to future climate change and the possibility of warmer summers with longer and more intense heat waves [48]. As an example, a multi-family building in Gävle is already connected to the DC system. However, it is worth noting that the monitored energy consumption for cooling in the Gävle building areas, which are connected to the DC system, is higher than what was simulated in this manuscript, as the acquired data focused solely on 2022 data and tended to be higher than the normalized data.

4.2. Return Heat Utilization

One method to reduce the temperature in the district heating network is to make use of the heat that is returned to the combined heat and power plant. This is referred to as district heating return heat reutilization, which has been applied, for example, in the Swedish city of Falun [49]. A few buildings have been tested to determine if the returning heat can be used to cover the space heating loads, as well as to preheat domestic hot water, and as a heat source for a domestic hot water heat pump. The system is configured in the following way. Primary district heating is only connected with a heat exchanger to the domestic hot water loop. The returning pipe takes water that returns from the rest of the city and uses the remaining heat in the lower-temperature water for SH and to preheat DHW. It comes into the system and immediately splits. In parallel, the returning water first covers the space heating demand and preheats cold water for the domestic hot water system. Then, the two flows are combined. The combined flow is then used as a heat source for a water-to-water heat pump, which increases the temperature of the preheated water to the required 60 degrees Celsius for domestic hot water use. These uses require heat, and the return leaves the system at a lower temperature than when it entered. The reutilized return then continues to the return of the city. Lowering the temperature of the returning water reduces losses on the way to the combined heat and power plant and potentially increases the efficiency of thermodynamic processes there.

This process was computed as simple thermodynamic interactions. To explore the potential of return heat reutilization, the primary flow was set to zero. The heat exchangers were assumed to be a properly sized counterflow system with an 85% effectiveness for the minimum value of the thermal capacity rate [50]. The cold water was assumed to oscillate between 2 and 15 degrees Celsius from mid-winter to mid-summer, respectively, and was approximated by a sinus curve.

The warmth heat pump functioned, as the rest of the warmth heat pumps in this paper, based on the method described in [41]. This heat pump was modeled using the coefficients for the "Water-sourced heat pump." Unlike [41], the source temperatures were set by the temperature mix of the post-SH and post-cold water preheat, as opposed to the fixed 5 degrees Celsius. By knowing the temperatures of the source and sink, it is possible to estimate the COP [41]. With the COP, it is possible to know the ratio of energy that comes from the source and how much energy is electrical. With the flow rate, the CP, and then the energy, which is taken from returning water, the temperature fall at the heat pump can be calculated. Thus, it is possible to calculate the temperature at which the reutilized return would be put back into the district heating system. To reiterate, the returning water enters and simultaneously covers the SH demand and preheats the cold water using heat exchangers. Then, it is mixed back together and is used as a heat source for a heat pump. After that, it is returned to the district heating system. Reducing the temperatures of the return can lead to reduced losses to the ground and improve efficiency at a combined heat and power plant [51]. A schematic of the return heat reutilization system is presented in Figure 3.

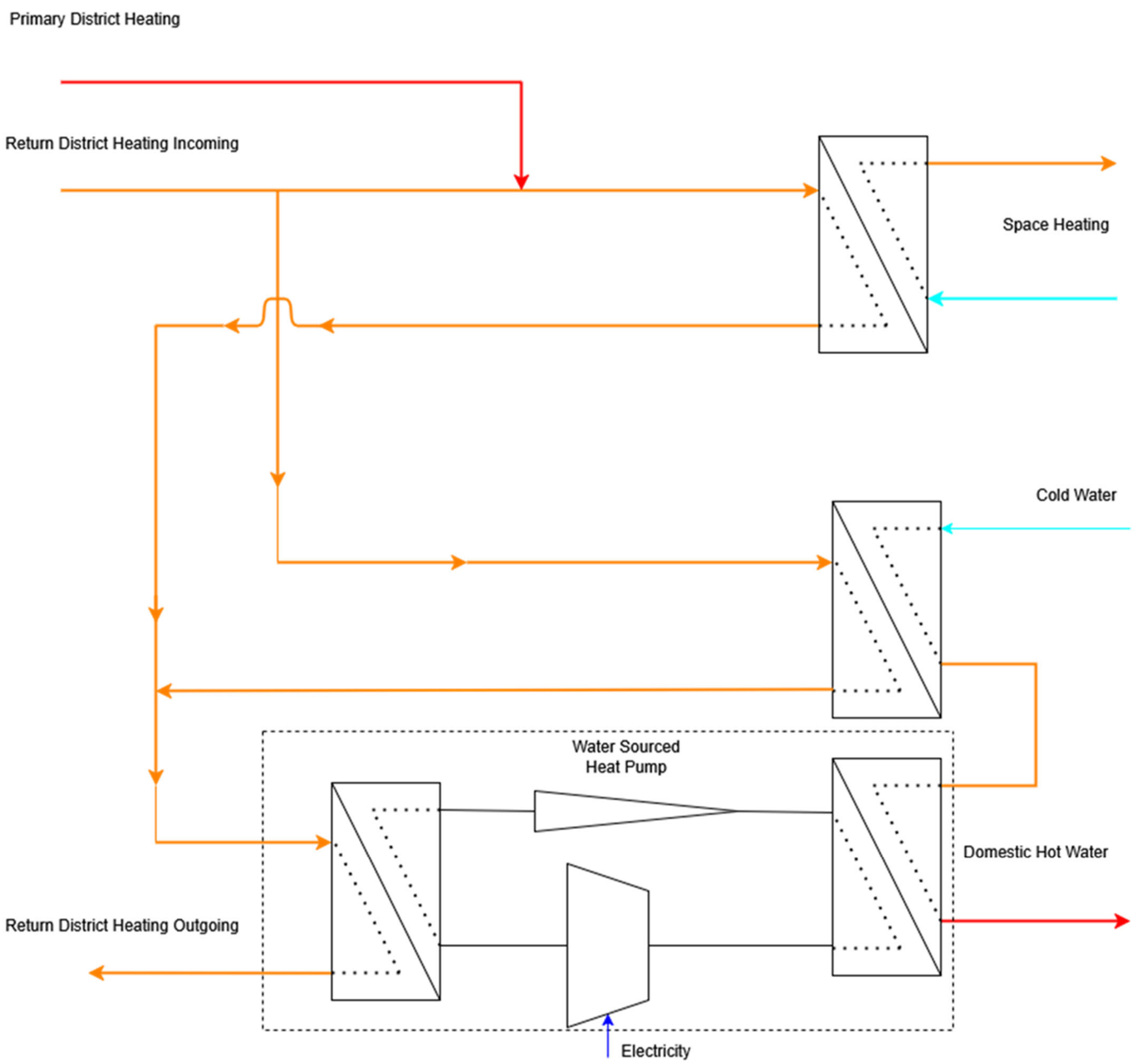


Figure 3. Overview of the return heat reutilization system. Red, orange, and light blue symbolize the flow of high, medium, and low temperature water. The dark blue arrow is the electrical input into the heat pump.

4.3. Key Performance Indicators

To assess the performance of a certain system, it is required to measure metrics that translate the real behavior of a certain energy system. Therefore, an energy performance indicator evaluation, according to the existing Swedish national standards, was used as a key performance indicator. In the Swedish context, the standard method for evaluating the energy performance of a building is the energy performance (EP) method. It measures the energy efficiency of buildings. To compare different energy carriers, weights are given to these before they are summed and divided by the heated area. The operational electricity, cooling, and heat for SH and DHW are added and depend on the energy carrier used for importing energy. The EP equation is reformulated here (Equation (1)) based on BBR31 recommendations [13,37,52].

$$EP = \frac{\left(\frac{E_{heat,el}}{F_{geo}} + E_{DHW,el} + E_{Cool,el} + E_{op,el}\right) \times PE_{el} + \left(\frac{E_{heat,dh}}{F_{geo}} + E_{DHW,dh}\right) \times PE_{dh} + (E_{Cool,dc} \times PE_{dc})}{A_{temp}}, \quad (1)$$

where E_{heat} represents the SH demand, F_{geo} is the geographical factor (1.1 for Gävle), E_{DHW} denotes the thermal demand for DHW, and E_{op} is the operative energy. Primary energy (PE) is the weighting factor. The subscript "el" refers to the demand met by electricity, while "dh" pertains to the energy needs supplied by DH, and "dc" pertains to the energy supplied by DC. A_{Temp} is an area heated above 10 °C in the building. It is important to separate the SH/cooling and DHW demands due to geographical factors. Furthermore, cooling demand is often not considered in most building assessments in Sweden, although cooling comfort is increasingly included, particularly regarding the regulations for fresh air.

The EP methodology only considers additional purchased energy, whether electric or thermal. When locally produced electricity from PV systems is consumed within a building, it reduces the amount of electricity that needs to be purchased, thereby lowering the EP. Exported electricity from PV systems is not considered in the EP calculation. For the calculation of the EP, we applied the following assumptions: when PV electricity is available, if an HP is used, it is first allocated to DHW and operational electricity use, then to SH and cooling, and any surplus is finally exported.

Since the results of the EP analysis are dependent on measured data from a specific year, the resulting heating demand can be higher for a particularly cold year. As such, it becomes difficult to compare results, and calculations based particularly on mild years can make a building seem more effective. To avoid these issues, the Swedish Meteorological and Hydrological Institute (SMHI) [53,54] developed an energy index that can be used to standardize the heating demand. The tool, however, is currently only applicable to space heating demand and lacks an equivalent for space cooling demand in residential buildings. Despite the daily level of detail, it is recommended to apply it yearly as the ratio of the sum of the actual year's index and the sum of the standard year's index. This leads to a loss of detail in dynamic processes. The normalized weather will also affect the heat pumps and their COPs, but this effect is not considered here.

PV power production influences the EP described above. Additionally, two metrics were calculated to describe the relationship between the PV system and the electricity demand. These were the self-consumption and self-sufficiency metrics. Self-consumption is the ratio of energy produced by the PV system that is used locally relative to the total energy produced by the PV system. Self-sufficiency is defined as the electricity that is produced by the PV system and used locally relative to the total electricity demand. Both metrics, shown here as Equations (2) and (3), are considered yearly and are unitless ratios between two energy quantities (kWh/kWh). A review of these factors is covered in [55].

$$\varphi_{sc} = \frac{\int_{t=t1}^{t2} \min(\mathrm{Load}(t), \mathrm{Generation}(t))}{\int_{t=t1}^{t2} \mathrm{Generation}(t)}, \quad (2)$$

$$\varphi_{ss} = \frac{\int_{t=t1}^{t2} \min(\mathrm{Load}(t), \mathrm{Generation}(t))}{\int_{t=t1}^{t2} \mathrm{Load}(t)} \quad (3)$$

where t is a given hour in the analysis and $t1$ and $t2$ are the start and the end of the year. Load is the electrical demand, and Generation is the electrical power available from the PV system. Finally, subscript sc is the self-consumption and subscript ss is the self-sufficiency. The self-consumption and self-sufficiency metrics are useful in understanding, with an awareness of the hourly functions, how the power from the PV system is used.

Since the model can calculate these key performance indicators based on either individual buildings or their sum, it is possible to calculate the impact of sharing the energy produced by the PV system. The BBR31 regulations were written with a single building as the focus. It is, however, possible to calculate the EP for the whole neighborhood and compare it to the individual buildings and their averages. The same is true for self-consumption and self-sufficiency. The ability to reward surplus energy produced within the technical system is one of the advantages of the emerging energy community's framework. Self-consumption is shown to be improved in a case with varying orientations of PV modules [12]. Here, the inclusion of cooling was analyzed and compared with apartment buildings.

4.4. Solar Power Model

PVsyst [56] was applied to simulate the electricity produced by the PV system. No information regarding the roof layout was available. Simple 3-dimensional models with Level of Detail 1 (LoD1, as described in [57]) of the area were used to place the solar panels using PVsyst modeling features. Whilst placing them, the solar panels were not placed in shaded areas. So, the modules were placed as if on a flat roof. The PV configuration layouts for the south-facing orientations were implemented with 10°, 15°, or 20° tilt angles. Moreover, an east–west and south–north PV configuration layout with a tilt of 10° was introduced to assess the best PV configuration layout for both building areas 1 and 2. Each different heightened building had to be considered individually for UBEM, but congruent buildings were grouped in building blocks that shared inverters for the PV system. The PV configuration layout difference resulted in a different number/capacity of the inverters, which would cause higher losses in the disaggregated building blocks. Nevertheless, this decrease is acceptable in practice. It would not be feasible to have one or a few central inverters. Instead, the system was modeled with an inverter per building block (a group of connected buildings).

Finally, due to the layout of the panels, different numbers of modules can be fitted to different PV systems depending on the orientation. The size of the PV system was the same for the three south orientations with 10-, 15-, and 20-degree tilts. However, since the modules could be placed side by side in the east–west and the south–north orientations, more modules could fit into those PV systems. On the one hand, this is a feature of choosing different orientations and should be taken into consideration when estimating the potential PV production from different orientations. On the other hand, comparing the results with different installed capacities is difficult, and variations in the results could either be due to changes in orientation or increased installed capacity. To counteract this, a simple linearized case was also applied to the results. There, the hourly solar production was divided by the ratio between the system's installed capacity and the installed capacity of the east–west orientation (an arbitrary choice). This paper focused on understanding the interaction between PV production and thermal and electrical demands. Hence, no economic optimization was carried out. Rather, the modules were placed to maximize the electricity produced. After the system was modeled, the results were also discussed with partial implementation of the full possible capacity as a percentage of the installed capacity.

5. Results

The results of the energy system model are divided into three sections. First, the two components and their results are presented for the PV systems; then, the thermal and electrical demands are presented. Thereafter, the SCOP results are presented. Finally, the choices of heating and cooling technologies and their impact on the KPIs are presented.

5.1. PV System Results

The PV system production varies with the orientation and tilt of the modules. Different orientations also have different quantities of solar modules that can be installed and different production. Therefore, the installed peak power for the different tilts and orientations is also compared to the east–west (EW) orientation using a capacity factor. Table 2 shows the results of the simulations for both building areas. Furthermore, for comparison, the specific production is stated relative to the installed capacity.

Table 2. Results from the photovoltaic system.

	Tilt and Orientation	10° South	15° South	20° South	10° East–West	10° South–North
Building area 1	PV area [m^2]	23,250	23,250	23,250	31,964	31,510
	Installed capacity [MWp]	4.871	4.871	4.871	6.697	6.602
	Capacity relative to EW [-]	0.727	0.727	0.727	1	0.985
	Production [MWh/y]	3737	3842	3920	4933	4856
	Specific production [kWh/kW peak]	767	789	805	737	735
Building area 2	PV area [m^2]	21,828	21,828	21,828	27,386	27,756
	Installed capacity [MWp]	4.574	4.574	4.574	5.738	5.816
	Capacity relative to EW [-]	0.797	0.797	0.797	1	1.014
	Production [MWh/y]	3443	3553	3612	4207	4220
	Specific production [kWh/kW peak]	753	777	790	733	726

5.2. Thermal Electrical Demand

The following section presents the combination of the different scenarios presented previously, which comprises a combination of the DH (the sum of SH and DHW) and cooling demand, as well as the EP and its difference regarding the BBR31 standards. Table 3 presents the DH and cooling demand results for both building areas 1 and 2.

Table 3. SH, DHW, cooling, operational electricity, and household electricity demands for building areas 1 and 2.

	Building Area 1					Building Area 2				
	SH	DHW	Cooling	Operational Electricity	Household Electricity	SH	DHW	Cooling	Operational Electricity	Household Electricity
Area [m^2]	195,150	195,150	195,150	195,150	195,150	151,621	151,621	151,621	151,621	151,621
Peak [kW]	4881	1540	6807	485	1828	3584	1209	5104	489	1306
Peak [W/m^2]	25	8	35	2	9	24	8	34	3	9
Total [MWh]	7631	4711	1403	2860	6523	5372	3696	954	2654	5098
Total [kWh/m^2]	39	24	7	15	33	35	24	6	17	33

Table 3 shows that both building areas have similar heating and cooling demands, where the SH stands as the element of difference between the presented parameters. The table is particularly effective because it shows how the energy demands are sized relative to one another and the peak. The cooling demand has a higher peak demand than the heating demand, but a significantly lower energy demand (about a tenth). The EP energy efficiency measure considers electricity produced by PV, which can offset electrical demand. Furthermore, it gives weight to different energy carriers, such as electricity and district heating water. As such, it is not possible to say directly that the components in Table 3 compose the EP energy efficiency metric EP, but it does give an idea of the breakdown of the demands.

The thermal demands for heating and cooling can be met with different systems. The efficiency of heat pumps, often measured with the COP factor, depends on source and sink temperatures [41,58]. An analysis regarding the dynamic COP of the Air Source Heat Pump (ASHP) and Ground Source Heat Pump (GSHP), for each hour throughout the year, was performed, as presented in Figure 4.

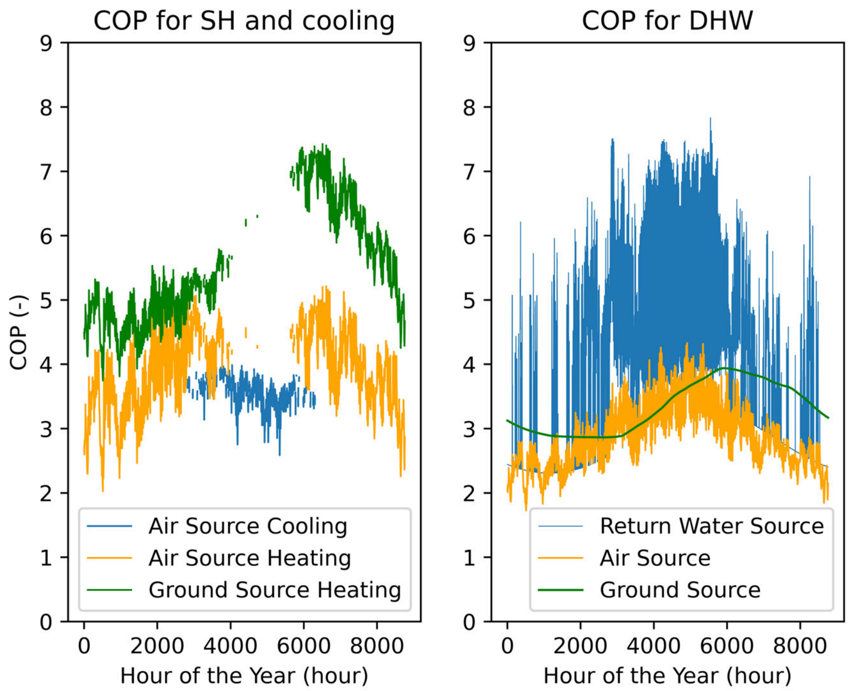


Figure 4. Hourly dynamic COP for cooling (ASHP only), as well as SH and DHW for the ASHP, WSHP, and GSHP, for heating, over the year.

Regarding Figure 4, a vertical GSHP system is consistently more efficient than an ASHP system. This is in part due to using ground temperatures as a source, as well as the coefficients set out by the When2Heat method [41], and has a few exceptions during the spring when the outdoor air is warmer than the ground. The SH performs better than the DHW system. The COP is expected to be better during the season in which the SH is not needed (if no load is present, no line is shown). This is in part due to the lower temperature at the sink side of the heat pump. Ground temperatures (as per [41]) do not vary as much as outdoor temperatures. The sink temperature also depends on the outdoor temperatures, except for DHW, which is set to 60 degrees Celsius. Therefore, the COP for a GSHP for DHW is more stable than the others, which either depend on outdoor temperatures for the source (ASHP) or sink temperatures (ASHP and GSHP for SH). Table 4 shows the impact of the dynamic application of heat pumps on the overall COP throughout the year. The SCOP of the different dynamic models of heat pumps shows how they perform when considering their COP when the demand takes place.

Table 4. Results of the overall yearly SCOP for the heat pumps modeled.

Technology	Thermal Demand	Dynamic SCOP
Air Source Heat Pump	SH + DHW	3.07
Return District Heating	DHW	3.84
Ground Source Heat Pump	SH + DHW	4.13
Air Source Heat Pump	Cooling	3.22
Air Source Heat Pump	SH + DHW and Cooling	3.09

Moreover, Table 4 presents the applied dynamic COP of both the ASHP and GSHP in Figure 4, which was used to calculate the yearly consolidated EP values, considering the EP value of each building block. The SCOP depends on outdoor and ground temperatures and on demand (and the temperatures when the demand occurs).

The SCOP depends on how much energy is demanded when the heat pump is operating at a given temperature sink and source. For the ASHP, for both cooling and heating, the load shifts the SCOP by shifting the weight between the cooling and heating loads. Heating is in higher demand, and as such, the SCOP tends towards heating.

5.3. Energy Performance

The choices for installed solar and heating technologies are independent of one another. However, they both shape the outcome of the energy system metrics. Table 5 presents the EP and its grade regarding the BBR31 standards for both building areas 1 and 2. The entire neighborhood was calculated in the same way as BBR describes for a single building. As discussed later, the EP methodology is specifically for single buildings and not for whole neighborhoods. But this allows for a condensed presentation of the results.

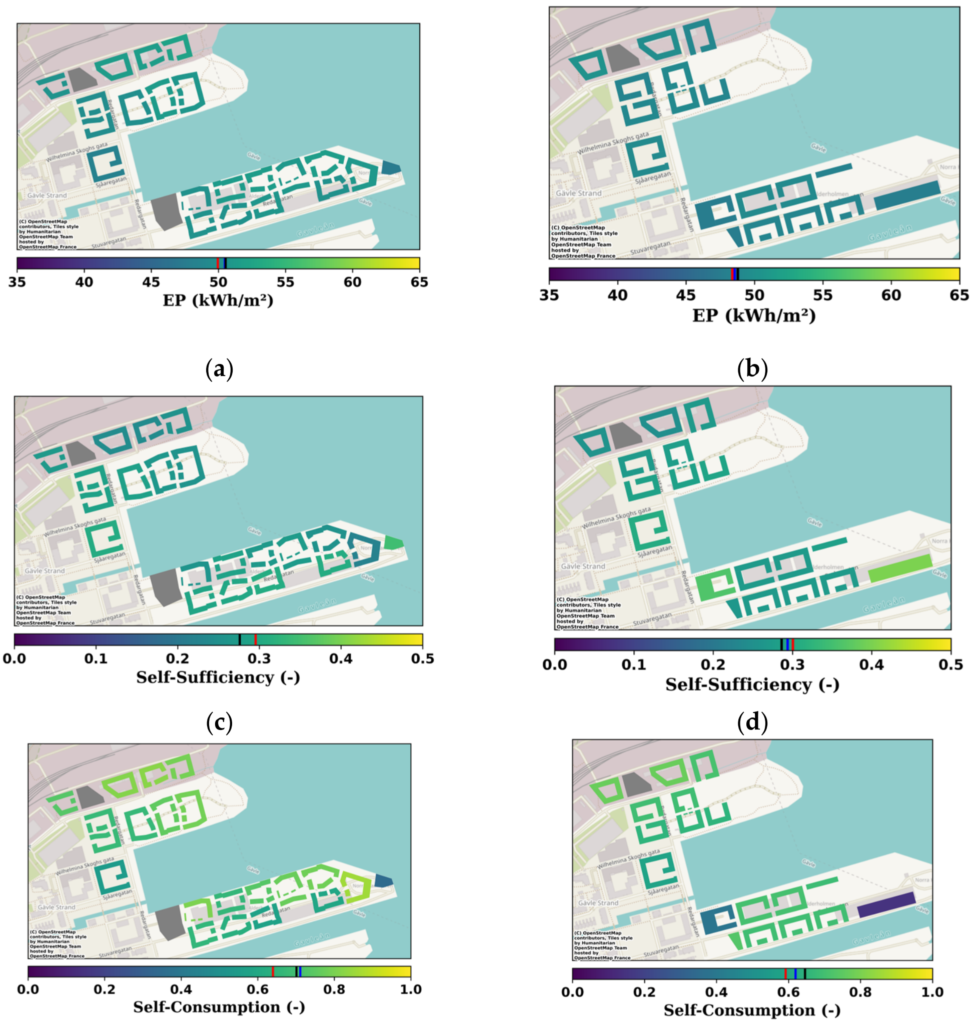
Table 5. Average EP results (kWh/m^2) and, in parentheses, the corresponding energy efficiency grade.

	Tilt and Orientation	10° South	15° South	20° South	10° East–West	10° South–North
Building area 1	DHC (Baseline)	64.5 (C)	64.6 (C)	64.6 (C)	64.0 (C)	64.0 (C)
	Normalized Thermal Demand	66.3 (C)	66.4 (C)	66.4 (C)	65.8 (C)	65.8 (C)
	Linearized Solar Production	64.1 (C)	64.2 (C)	64.2 (C)	64.0 (C)	64.0 (C)
	Static Heat Pump for Heating and Cooling	51.2 (B)	51.3 (B)	51.3 (B)	49.6 (B)	49.6 (B)
	Dynamic ASHP for Heating and Cooling	50.2 (B)	50.2 (B)	50.3 (B)	48.7 (B)	48.7 (B)
Building area 2	DHC (Baseline)	65.6 (C)	65.7 (C)	65.7 (C)	65.1 (C)	65.1 (C)
	Normalized Thermal Demand	67.2 (C)	67.3 (C)	67.3 (C)	66.7 (C)	66.7 (C)
	Linearized Solar Production	65.3 (C)	65.3 (C)	65.4 (C)	65.1 (C)	65.1 (C)
	Return District Heating and ASHP Cooling	59.1 (C)	59.2 (C)	59.2 (C)	58.7 (C)	58.8 (C)
	GSHP Heating and ASHP Cooling	52.5 (B)	52.5 (B)	52.6 (B)	51.2 (B)	51.2 (B)
	ASHP for Heating and Cooling	51.9 (B)	51.8 (B)	51.9 (B)	50.6 (B)	50.7 (B)

Table 5 presents the results for different PV systems, different accounting methods, and heating technologies. Besides establishing a minimum EP that must be met (75 kWh/m^2), a grade is assigned to the buildings depending on how far they fall below the current energy efficiency measure (75% and 50% for B and A, respectively). None of the configurations led to an A-grade building, despite being well insulated and the inclusion of PV systems. Fewer than 5% of the buildings attained the A grade [59]. The difference in weather between different cities in Sweden should be accounted for in the F-factor. The inclusion of cooling, which is often simply overlooked, added to the energy demand. The different solar configurations had a small impact on the EP value. These differences are likely within the error margin of the calculations and assumptions carried out. More interestingly, the choice of heating technology determined whether the buildings would be assigned a B or C grade. This, in turn, affects property prices, although this effect is lower in tenant-owned apartments than in high-value single-family houses [59,60]. Better loans are available for A- or B-grade buildings [61] (p. 116). These economic processes incentivize energy efficiency.

However, using the EP as a sole measure of efficiency for a building or an energy system can be questioned [13].

Figure 5 shows that there is an impact of the dynamic ability to share electricity on the EP of the buildings. It is very small (<1 kWh/m^2) compared to the arithmetic average of all the buildings. Some buildings are below average, and others are above average, so if energy sharing were allowed, some buildings would benefit while others would have a worse efficiency rating. Self-consumption and self-sufficiency do not have a square meter to account for the different heated areas of buildings. It is instead related to the energy demand, which is, in turn, somewhat dependent on the footprint. Self-sufficiency increases relative to the individual buildings and their average if energy is shared. More of the shared load is met by solar power. Isolating the impact of sharing alone, without the additional parking lot solar system, the effect is smaller. Self-consumption decreases relative to the average, likely because more solar power from the garage areas is exported. This matches the results in [12], indicating that the inclusion of cooling does not change these results. On a qualitative note, the maps do not hint at any clear patterns regarding the shading of one building onto another. There is no pattern in the south-to-north orientation, and the surrounding buildings have distinctly different results. It is also worth noting that the UBEM model by Johari [31] was not calibrated or validated to be applied to individual buildings.



(**a**) (**b**) (**c**) (**d**) (**e**) (**f**)

Figure 5. KPIs mapped for the individual buildings. On the left side, the maps show building scenario 1 and, on the right side, the maps show building scenario 2. The KPIs are the EP (**a**,**b**), self-sufficiency

(**c**,**d**), and self-consumption (**e**,**f**). The color scales are kept constant for each KPI. Buildings in grey are mobility hubs that shade nearby buildings and have solar electricity production, but they do not have electric or thermal energy demand, and hence, no meaningful KPIs. In the legend, a red marker is added if the whole system is allowed to share electricity among the buildings, a blue marker for sharing excluding the mobility hubs, and a black marker shows the arithmetic average for the KPIs of the buildings without energy sharing.

The impact of orientation on peak power exports and imports is shown in Figure 6. Self-consumption varied more across the different solar configurations and even across the scenarios as shown in Figure 7. The self-sufficiency varied only slightly across the different solar configurations. So, although most of the electricity (65 to 73%) is consumed internally, it only covers a quarter of the electrical loads (23 to 24%). Increasing PV production would likely increase self-sufficiency at the cost of lower self-consumption and a larger peak electrical export. Surprisingly, the south–north configuration had a lower peak export, the highest self-consumption, and the second lowest self-sufficiency (0.2% behind the highest). It is worth noting that the fact that the east–west and south–north configurations allow for more installed capacity is a feature of the photovoltaic system. If a district heating system is applied instead of electrifying heating and cooling demands (not pictured), the self-consumption is reduced to range from 50 to 57%, with the same pattern for orientation and tilt. Self-sufficiency increases to around 29% regardless of orientation. Since the two metrics only consider electrical demand, electrifying SH leads to a reduction in self-sufficiency, as more electricity demand is not met by solar production. The results match other similar studies on self-sufficiency [55,62].

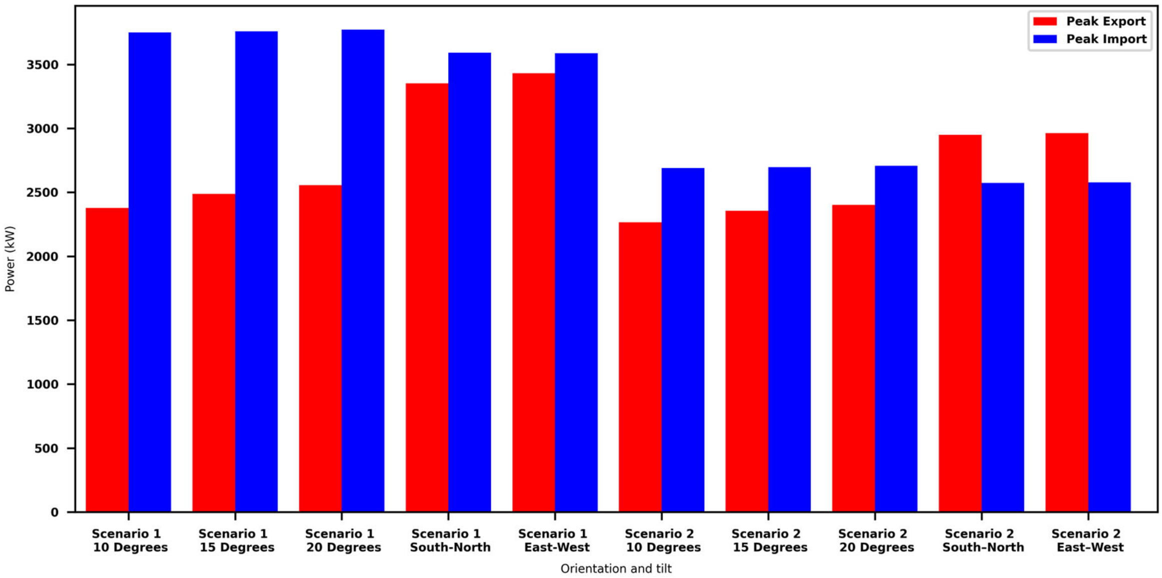


Figure 6. Peak export (red) and peak import (blue) for different building areas and PV systems.

Electricity exports can contribute to the surrounding energy system by meeting demand elsewhere, but this can also lead to voltage issues. Thus, the peak export and the total export of the system can be problematic. Applying heat pumps generally meets the thermal demand with electricity and thus leads to a reduction in the exported peak and total exported energy. Notably, electrifying DHW in conjunction with return heat utilization has a significant impact on the peak exported power; however, it does not impact the peak import as much as electrifying SH (which occurs in winter). It can therefore be a good compromise in the electrification process while having positive impacts on the district heating grid efficiency and capacity. This effect is more prevalent in the southern orientations due to the coincidence of PV system production and electrified DHW during the day.

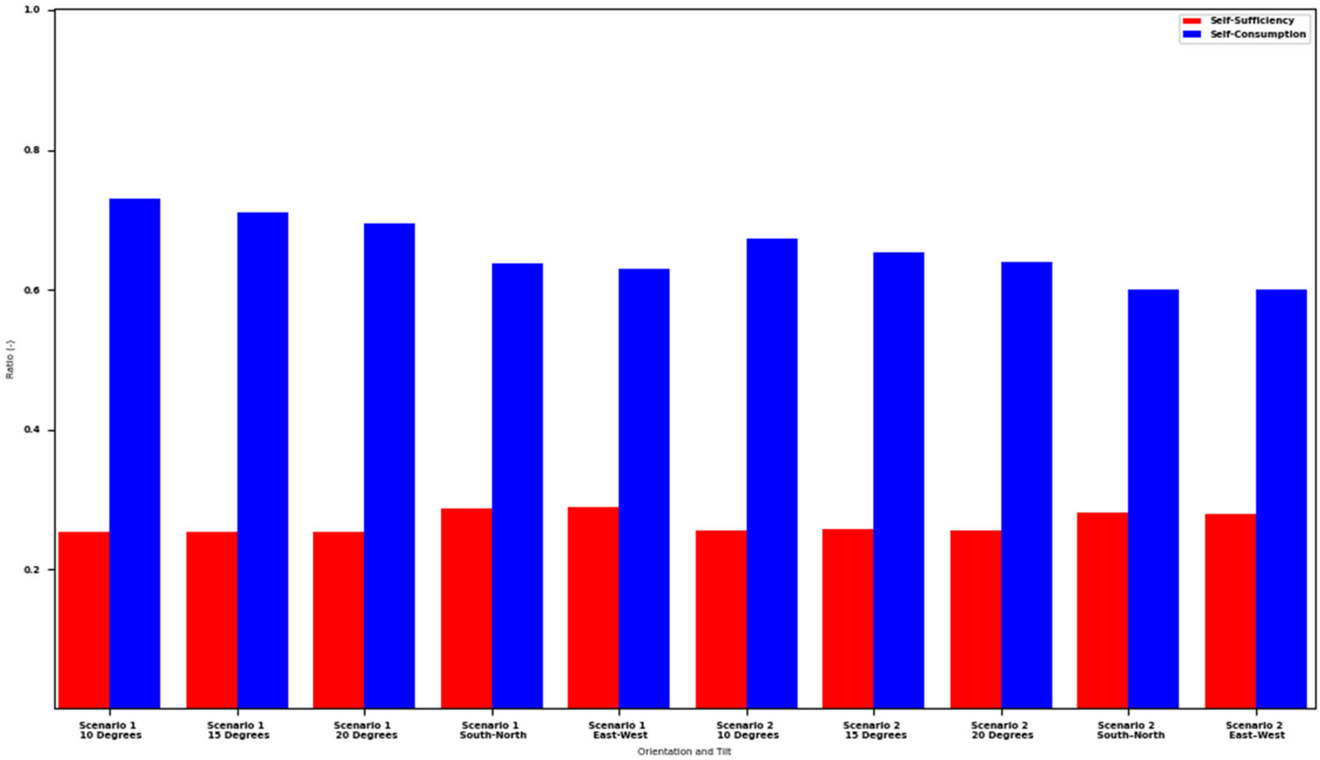


Figure 7. The results of linearized (i.e., all peak installed power is sized like the east–west configuration) with a GSHP for heating and an ASHP for cooling for self-sufficiency (red) and self-consumption (blue).

By varying the installed capacity of the PV system and the two variants for heating and cooling demands, it is possible to gain some insights. As expected, by increasing the size of the PV system, self-consumption, which is the ratio of electricity consumed internally to electricity produced, is reduced. More electricity is exported with a bigger system. This is reflected in how the rise in self-sufficiency slows with increasing capacity installed. The electrification of cooling has a larger effect on self-consumption. Since cooling and PV production occur in the summer, there is an overlap. The electrification of DHW, as seen in the difference between district primary and district return, also increases self-consumption. To a smaller extent, the electrification of heating causes an increase in self-consumption as some power is consumed internally, probably during the start and end of the heating season. Self-sufficiency, however, penalizes the system with an unmet demand. Therefore, electrifying heating causes this ratio to decrease. Electrifying cooling, on the other hand, has almost no impact on self-sufficiency since more demand is added and more demand is met. Although the difference is difficult to see in the figure, the east–west orientation has an overall higher self-consumption and self-sufficiency. The peak import and peak export of power can be seen as the maximum demand for electricity and the maximum demand for electricity uptake outside the neighborhood.

Although exported electricity can be seen positively, as it provides power for the nearby areas, it can be problematized. If the peak export is larger than the peak import and curtailment is to be avoided, then the peak PV production will shape the size of the physical electrical system. As shown in Figure 8, when the thin and thicker lines cross, this issue can happen depending on the technological choices and the orientation and size of the PV system.

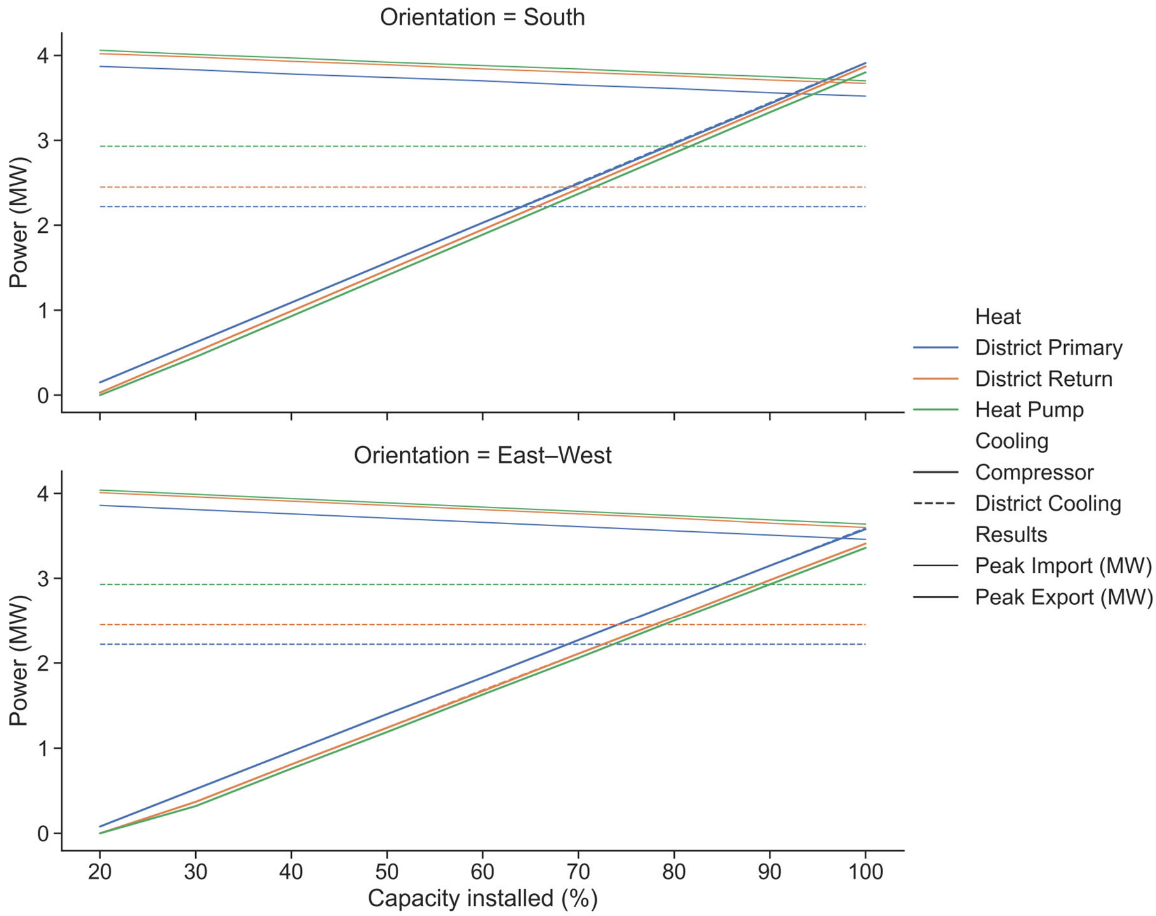


Figure 8. Peak import and peak export power for different installed capacities relative to the maximum capacity at east–west. Colors represent how heating demand is met. The style (full or dashed) of the lines shows how cooling demand is met. The thickness of the line indicates peak import (less thick) and peak export (thicker).

Regarding the peak export of electricity, the following can be determined from Figure 9. The choice of cooling system has no impact on the maximum export. That is, during the hour with the highest PV production, there is no cooling demand. Conversely, there is some DHW and even SH during that hour, reflected in the distance between the differently colored thicker lines. Unsurprisingly, the peak export is almost linearly dependent on the size of the PV system. The peak import is defined primarily by the choice of cooling and heating technologies. If electrified cooling is applied, the system has a larger peak import, and there is PV production in those hours (as shown by the slightly negative gradient). The peak import is also dependent on whether DHW is electrified or not. However, the difference is smaller if a system has electrified cooling. The combination of the ideal cooling system (which is set up to meet any demand) and the weather-dependent COP of an ASHP causes the import to be highest in the summer. Cooling systems would not be sized to meet the ideal peak demand. There would be some hours of discomfort. Furthermore, a GSHP could potentially provide cooling with a lower electricity demand, thereby making the peak import dependent on the heating demand.

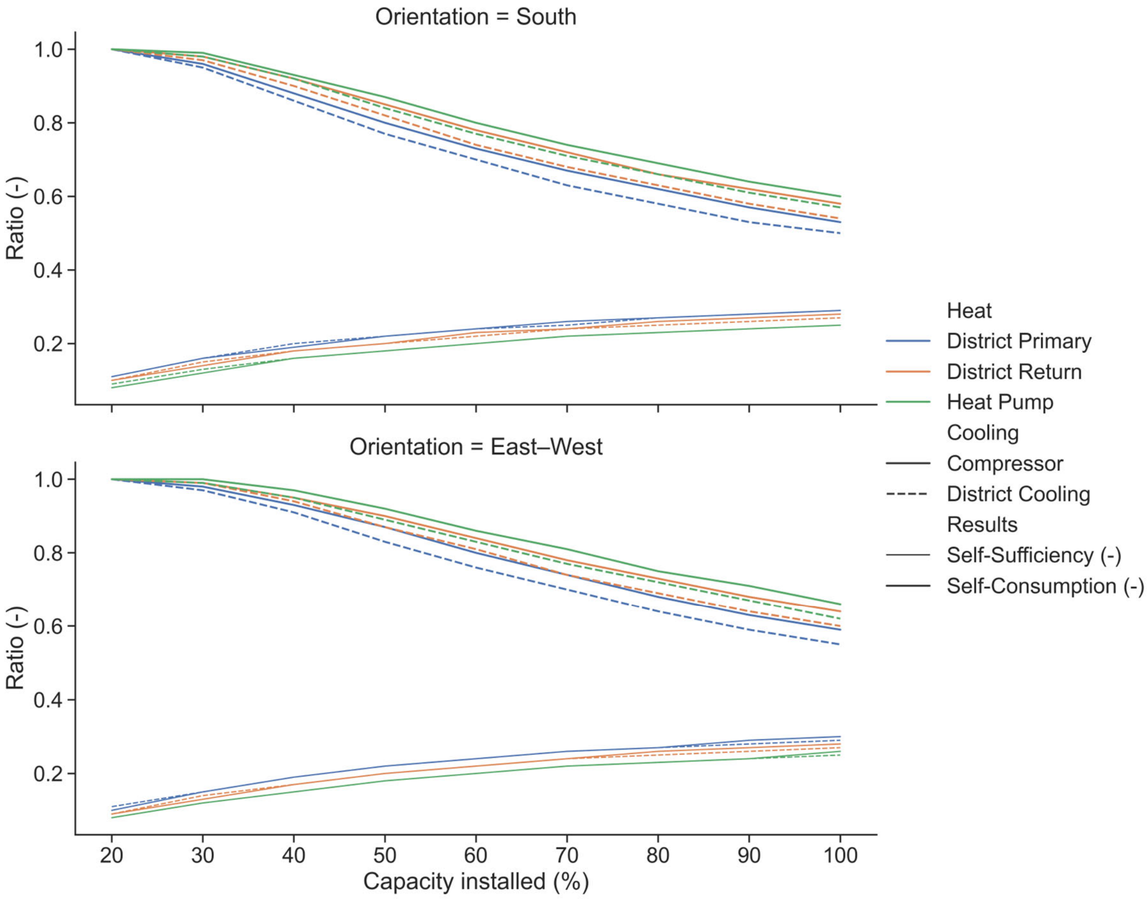


Figure 9. Self-sufficiency and self-consumption for different installed capacities relative to the maximum capacity at East–West. Colors represent how heating demand is met. Style (full or dashed) lines show how cooling demand is met. The thickness of the line indicates self-sufficiency (less thick) and self-consumption (thicker).

5.4. Dynamic System Balance Analysis

As both building areas' graphical representations are similar, this section only presents the system's graphical balance analysis for building area 1 to keep this manuscript as compact as possible.

Moreover, the overall yearly system balance for scenario DHC is presented in Figure 10. This scenario is useful for visualizing the system as it breaks down the two thermal demands (heating and cooling) and shows the electricity production from the PV system (on the positive axis) and demand (on the negative axis), which is the sum of individual and operative.

The higher electrical efficiency of the HPs provides a higher surplus during the summer, leading to more electricity being exported into the grid, which can be seen from the differences presented in Figure 11. Despite the high peaks shown on the graph, considering all the electrical demands of a heat pump-driven system, only about a tenth of the hours have an export of electricity.

Figure 12 isolates the net electricity demand for CC cooling and the electricity production by the PV system. There are a few periods where the PV system is not able to cope with the cooling demand. PV production can supply cooling demand, resulting in a small percentage of imported electricity from the grid on specific days of the summer period. Table 3 shows that while the peak for cooling demand is high, the demand is relatively low. The demand for cooling requires little energy throughout the summer. The peak demand does not quite match the electricity production.

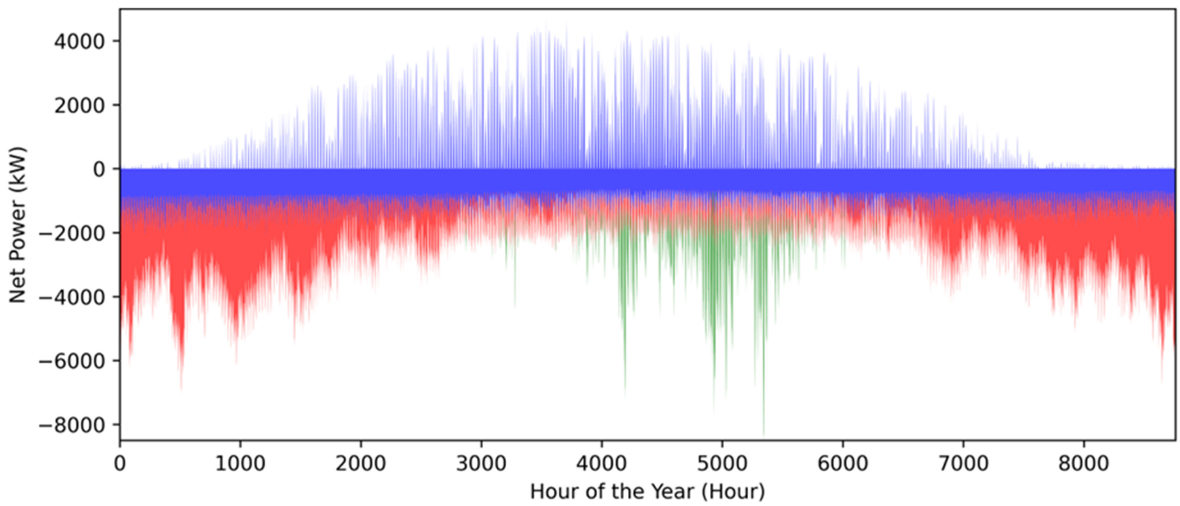


Figure 10. Overall yearly system balance for scenario DHC, which comprises all the metrics, such as PV production (here, the east–west orientation is in blue on the positive axis), heating demand (SH and DHW together in red), cooling demand (in green), and electricity demand (in blue on the negative axis).

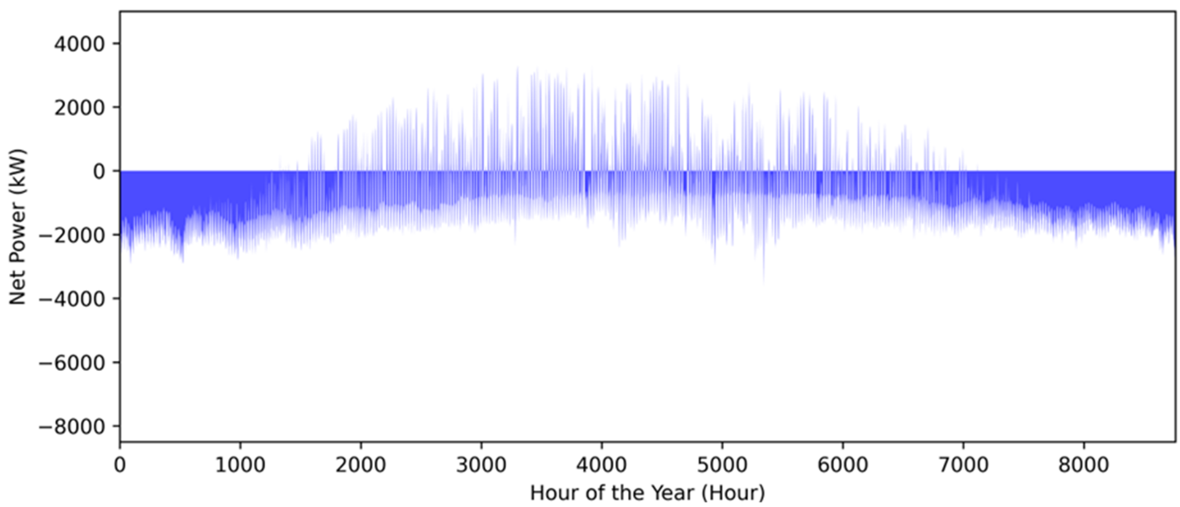


Figure 11. Overall yearly system balance for scenario HPCC (fully electrified), which comprises all the metrics, such as PV, HPs, CCs, and electricity use. This is for building area 1 with a GSHP for heating and an ASHP for cooling.

In Figure 13, the mismatch between PV and the cooling peak during one day in the summer period is likely due to thermal inertia and people arriving home and using more energy to cool down their households. So, while some of the cooling demand can be covered by electrification and solar power production, a simple system would require electricity from the grid during the hottest hours, which could lead to higher stress on the electrical distribution grid during peak hours. This problem could be circumvented by a smart system that leverages the thermal inertia of the building, if it has access to predictions of the cooling demand and the availability of solar production.

Figure 13 also shows how different configurations of PV systems produce power throughout the day. The south-facing systems produce power depending on their tilt. The higher the tilt, the higher the peak production and the lower the production during the morning and afternoon. Similarly, the east–west- and the south–north-oriented modules produce less power in general and at noon, but they produce more power than the south-facing modules in the morning and afternoon. The production in the afternoon is particularly relevant in this context as it catches more of the delayed cooling demand.

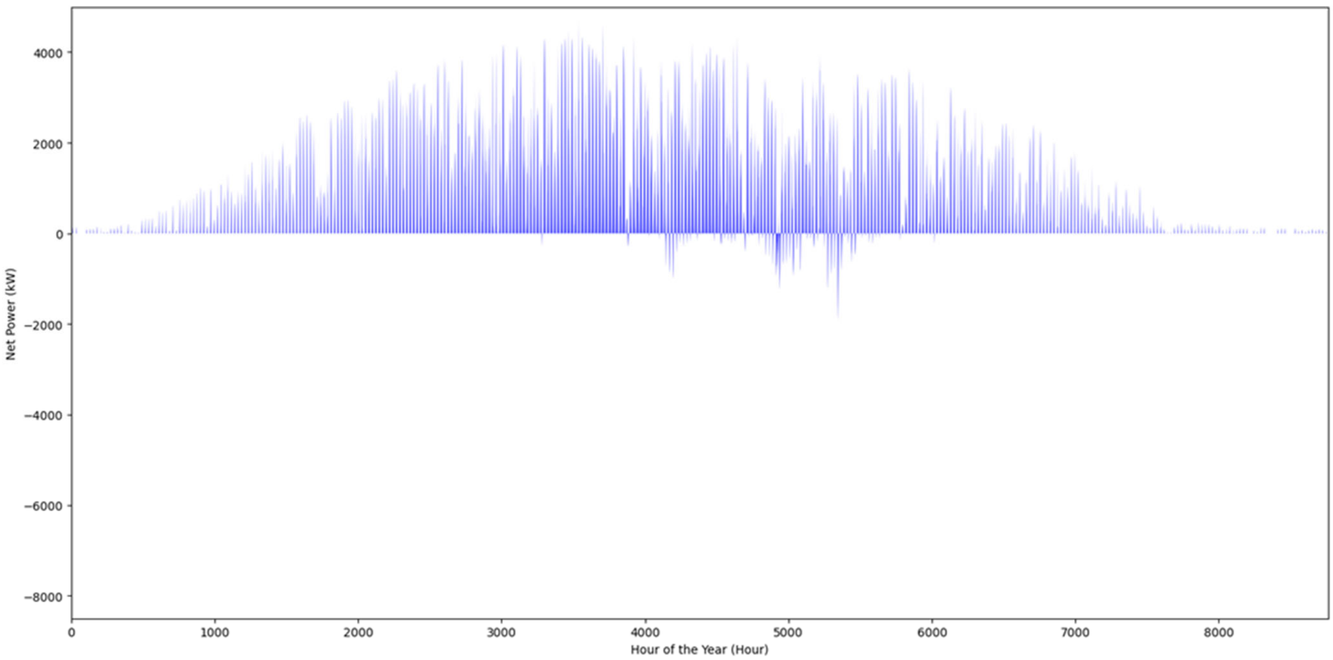


Figure 12. Yearly system balance representation of surplus and deficit, on an hourly basis, for only PV system production and a dynamic ASHP for cooling.

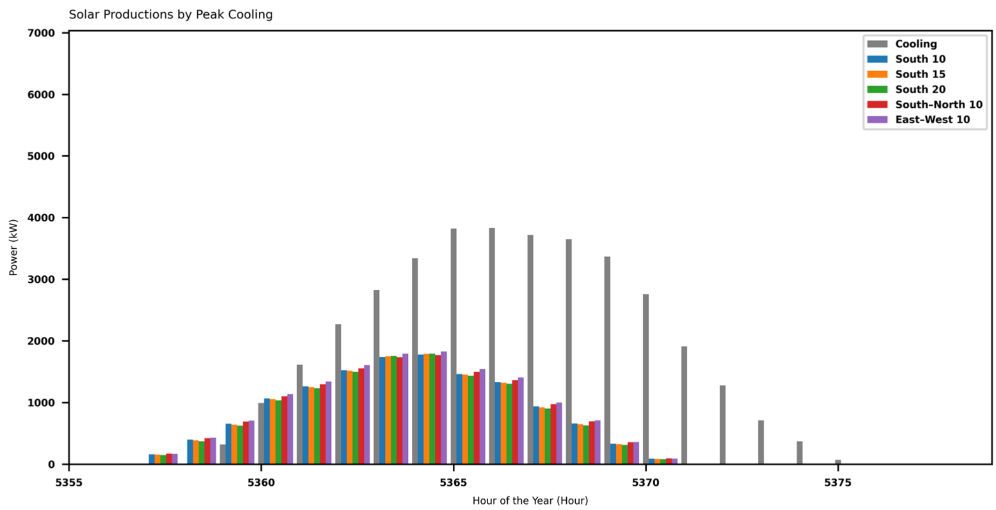


Figure 13. System balance representation of one mid-summer day of the cooling load and differences in the linearized PV system production. The cooling peak demand and power production are offset by a few hours.

5.5. Return Heat Reutilization

Utilizing district heating for DHW has benefits, but it does not address the problem of additional electricity production in the summer. In this paper, the system was modeled with a limited supply of returning district heating. The dynamic hourly results are shown in Figure 14. Since returning heat is in limited supply, it is used first to cover the SH demand. Additional heat is then used to preheat DHW. During the winter, however, there is insufficient returning hot water to cover the entire SH demand, and although it is used as a source for DHW heat pumps, no additional heat preheats the cold water. In the summer, without SH demand and with higher temperatures and flows available in the returning water, DHW heat pumps operate very efficiently. This leads to an increase in electricity demand in the winter and to a smaller degree in the summer. If the return flow available was increased, more energy would be sourced from the return in the winter (first covering the SH, then improving the efficiency of the DHW heat pump), but the impact in the summer would be small. Similarly, if the priority was changed (i.e., the DHW preheat took precedence), more primary district heating would be needed, and the DHW heat pump would be more efficient in the winter, but there would be no effect in the summer. As stated in Ahrens Kayayan et al. [13], a temperature drop in the returning district heating system would improve its efficiency. However, the previous paper did not include DHW preheating or a DHW heat pump. Thus, the temperature drops for the returning hot water are larger. This is true for the whole year, but it is stronger during the summer.

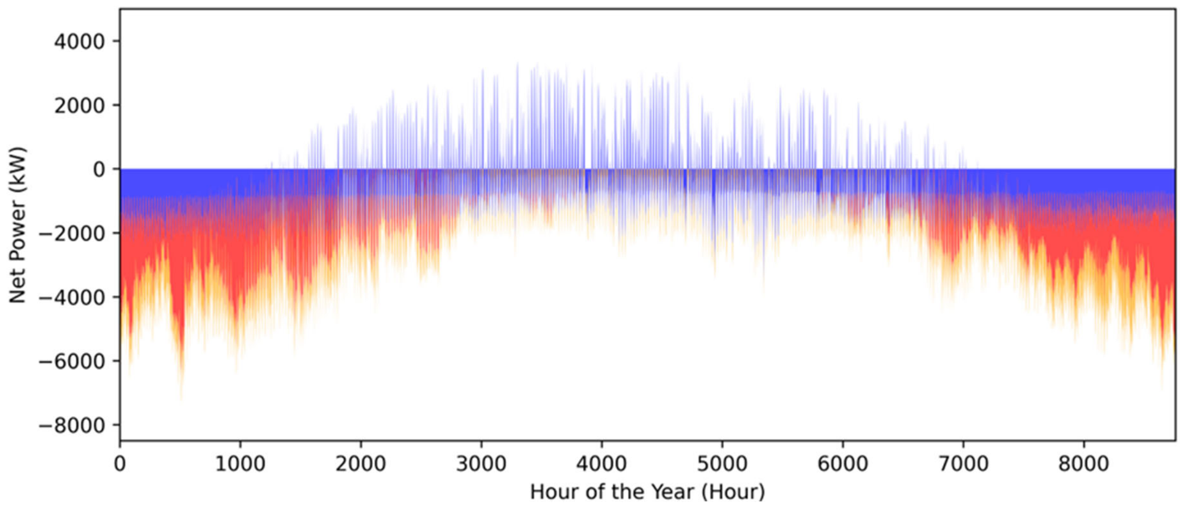


Figure 14. Return heat utilization for Scenario 1 with the east–west orientation PV system and a dynamic ASHP and a dynamic WSHP for DHW.

Additionally, since Sweden does not have a very warm climate, the energy for cooling demand is not very high, but the peak power demand for cooling is high. If the cooling demand is electrified and the heating demand is not, the peak electricity demand occurs in the summer rather than in the winter. This differentiates Sweden (and likely Scandinavia) from southern Europe, since it has a high demand for heating during the winter period. On the one hand, by electrifying the DC system into a CC system, PV production can cope with most of the cooling demand. On the other hand, the cooling demand is not large enough to significantly impact the export of electricity out of the district in terms of energy. The demand for cooling is also not directly aligned with PV production, and without a smart system, it causes import and export peaks in the summer in terms of momentary power.

6. Discussion

A system overview can be divided into different metrics. Therefore, it is important to clarify the purpose of our analysis by providing a comprehensive discussion of the calculated energy performance and the energy interactions between heating, cooling, and electricity demand and generation for the Nyhamn district in Gävle, Sweden, under various electrification scenarios. This discussion delves deeper into the results, evaluates their implications, and suggests potential pathways for future research and policy development.

The method used in this study combines UBEM with monitored hourly values of electricity use and simulates PV production using monitored local climate data from the same year as the monitored values of electricity use. This method is novel since weather-related behaviors of the tenants in the buildings and the electricity used to operate the buildings are included. Therefore, the calculated values of, i.e., the amount of individually consumed electricity, are more accurate compared to standard input values of tenant electricity use with the corresponding assumed profiles of electricity use and values for operating the building.

The energy performance (EP) results for both building areas in Nyhamn under different scenarios reveal significant variations in energy performance. Notably, scenarios involving HP and CC units (scenario HP + CC) consistently show lower EP values compared to the baseline (scenario DH + DC). The reason for the differences in the EP results is the chosen SCOP for the HP units, as it is higher than the ratio of the weighting factors used for electricity and district heat (1.8 and 0.7, respectively); this is why the calculated EP is lower for buildings using HPs. The same applies when DC systems are compared to CCs. When analyzing cooling systems, it is important to consider how their electricity consumption impacts the overall energy balance. Specifically, it is important to consider whether the electricity used by the cooling system leads to a reduction in peak electricity exports and an increase in on-site electricity consumption (i.e., in matches in time with the PV production). This paper shows that there is a small mismatch between solar production and cooling demand. The EP can be influenced by the type of cooling system used. If the SCOP of the cooling system is higher than the critical value determined by the $EP_{elect.}/EP_{cool.}$ ratio (in this case, $1.8/0.6, \approx 2.83$), the EP will be lower if cooling is electrified. This principle applies not only to compression chillers but also to HPs, where a higher COP generally leads to a lower EP, indicating better energy efficiency.

The energy demand for buildings in Sweden, as a Nordic country, differs from buildings in most European countries due to the relatively high heating demand during the winter, even for well-insulated buildings. The cooling demand has a high peak, but, in total, a low energy demand. Electrification of cooling, therefore, impacts the peak electrical demand during the summer when there is usually no bottleneck in the power grid. The dynamic COP and SCOP of the heat pump of the cooling load require further investigation. Unlike heating, cooling COP calculations have not been researched where weather-based validated sources can be used. Changing the COP would lead to a higher or lower electrical load in the summer and more pronounced peaks because the cooling demand is also dependent on outdoor conditions. A sensitive analysis with variations in the relationship between the wet bulb temperature and COP could be developed in future research to produce more robust results. The EP, however, is not as affected by the low energy compared to other energy demands, such as SH and DHW. This high peak is in part due to the idealized cooling method, i.e., whenever there was a cooling demand, it was met. In reality, cooling systems are not sized for the peak demand; rather, some hours of discomfort are deemed acceptable.

This study also tests the influence of building design and layout on energy performance, where buildings with larger roof areas for PV installations and lower heights tend to perform better in terms of energy efficiency. This is evident from the lower EP values in building area 2, which has a more straightforward roof height layout compared to building area 1. The findings suggest that, from a strict energy perspective, urban planners and architects should prioritize designs that maximize roof space for PV installations and minimize a building's exposure to external environmental factors. There is a trade-off with the choice of building height, which reduces the exposed envelope of a building relative to its livable footprint but also increases the electrical demand under a relatively smaller roof area available for PV systems. This trade-off, however, is reduced when optimizing for a district rather than singular buildings. Other nearby spaces, such as mobility centers in an area, could be used for power generation, and bottlenecks within neighborhoods are usually not a constraining factor. This approach can significantly improve the energy performance of buildings and contribute to the overall sustainability of urban districts.

The performance of PV systems under different configurations was analyzed, revealing that east–west and south–north orientations with a 10° tilt angle provide the highest electricity production. This optimization is crucial for maximizing the benefits of PV installations in high-latitude regions like Gävle. Regarding solar power, east–west and south–north orientations produce power during different hours than south orientations at different tilts. When accounting for the difference in installed capacity, this leads to a reduction in the EP, peak power, and exported electricity. The reason for the higher electricity production is that no spacing between rows of PV models is necessary, and the installed peak capacity is higher compared to when the PV system is installed due south with adequate distance between the PV module rows. The study highlights the importance of addressing shading effects to optimize PV system performance. Buildings with higher shading profiles, particularly in the afternoon or morning, require careful planning to mitigate energy losses. The results indicate that optimizing the orientation and tilt angle of PV modules can significantly enhance PV system performance. Additionally, addressing shading issues through strategic placement and design can further improve the efficiency of PV systems, ensuring maximum energy generation throughout the year. Nevertheless, the PV production per square meter of installed roof area for the different orientation layouts is similar regarding smothering the "peak shaving"; therefore, the PV system layout selected for analysis was the one that yielded the most power: the 10° tilt with an east–west orientation.

Moreover, a viable technical solution to fulfill the cooling demand during the summer would be to employ short-term electrical storage units or demand-side management tools [48]. Nevertheless, this would require the electricity distribution grid to supply power to fulfill the cooling demand. Additionally, ref. [63] showed that PV self-consumption could decrease the stress on the electricity distribution grid, as it was possible to increase the relative self-consumption by 13–24% with a battery storage of 0.5–1 kWh/kWp and between 2 and 15% with demand-side management tools. This should be analyzed on a per-case basis. Economic viability should be addressed in more detail for both the solar systems and the application of batteries. Electricity pricing in Sweden has two components: a fixed network fee, applied per kilowatt hour, and an energy cost, which can be either fixed or dependent on the spot electricity market. Self-consumption allows the consumer to avoid both network costs and energy costs. Electricity is sold on a spot price basis with a bonus, which is being phased out. Increasing the size of the system implies a higher capital cost that is expected to be recouped. Although an economic analysis was not carried out here, the trend in Figure 9 points to an optimum economic size of the system. The inclusion of batteries improves self-consumption, which is economically interesting. However, the prices of short-term electrical storage in Sweden, at the time that this paper was developed, were typically not favorable [64]. This subject is further complicated by the rollout of EVs, which can work as battery storage (although only when parked, which, in residential settings, does not match solar production), and market flexibility, which may change the economic calculations of battery storage. However, these topics are outside the scope of this paper and are explored in more detail elsewhere [12,64].

Regarding energy sharing, power systems do not change based on how efficiency or the electricity produced by PV systems is measured. The voltages and power flow for the same PV orientations and thermal electrification settings will be equal regardless of whether the power is considered shared or not. Even more technical metrics, such as the EP, self-sufficiency, and self-consumption, are human artifacts. However, the metrics incentivize system choices. Thus, defining the boundaries at certain system levels, here, either at the building or neighborhood level, influences what is considered optimal, technically beneficial, and economically feasible. The energy efficiency measure is negligibly affected by sharing, except for the buildings that share a grade. Solar metrics, on the other hand, are affected by the sharing criteria. Again, the electricity would have flown the same way with or without conceptual sharing. But by sharing, the energy that is not exported out of the neighborhood is rewarded by the metrics. Furthermore, as shown in Figure 9, a smaller amount of solar integration could lead to higher levels of self-consumption at a small cost to self-sufficiency. With energy sharing, the PV system can cover a few buildings rather than having fewer modules per building. Future research could analyze and optimize PV systems in neighborhoods for better access to solar resources and a stronger connection to the local transformer. Conversely, optimization can show that a building-level distribution is preferable. Regardless, these analyses suggest that the energy community framework can be used to establish a legal definition in Sweden.

As discussed in Ahrens Kayayan et al. [13], using heat from the return reduces losses along the returning water to the ground and increases the efficiency of flue gas condensation. In this paper, a heat pump is applied to the substation to cover the DHW demand. This entails additional electricity use throughout the year. In the winter, return heat is used for space heating, which leaves less energy available to preheat and supply the heat pump.

In the summer, the flow is reduced, but there is the possibility of using it to preheat the DHW and improve the COP of the DHW WSHP. The dynamic COP presented unusually high values for the summer (as high as 8) when the temperature difference between the return and the DHW setpoint is small. This is a common problem in estimating COP [41,58]. To counteract this, a static analysis was carried out, and a year-round SCOP was set to 4.5. The results are not presented here since they do not differ significantly.

Despite the lower COP in the winter due to limited energy in the returning water, the DHW WSHP is still regarded as an improvement since it has a limited negative impact on the winter electricity demand and a moderately positive impact on both the peak power and overall energy exports, which occur in the summer. Furthermore, although the impact on the district heating network was not quantified, it is expected to have an overall positive impact.

7. Conclusions

The method used in this study allows for hourly granularity in thermal and electrical demand modeling and can be applied during the early stages to influence decisions that impact energy performance. The Urban Building Energy Model provides valuable insights into the energy interactions between heating, cooling, and electricity usage in a residential area.

Three scenarios for two potential topologies of a planned residential neighborhood were evaluated, varying the electrification of heating and cooling demands. The results show that electrification, particularly full electrification and electrification of the heating unit, can significantly lower the energy performance (EP). Electrification was carried out with dynamic heat pumps using the existing methodology for heating.

This paper concludes the following:

- Future research should be applied to modeling, normalizing, and simulating heat pumps for the cooling loads in Sweden.
- Heat pumps and district heating systems can collaborate to extract more heat from returning district heating and improve the SCOP of DHW heat pumps.
- The mismatch in PV production and cooling loads in the summer warrants further research into whether energy storage systems could be applied.

A simplified linear method was applied to model the cooling heat pump. The methodology for cooling is not as well established as heating and warrants further research. Future research could aim to estimate COPs simply based on weather conditions, as there are equivalents for heating [32,47]. Similarly, the normalization method for cooling loads for residential areas in Sweden needs to be defined, which will most likely require cooperation between research and the SMHI. Finally, this paper addresses the technical parameters influenced by energy sharing. Social changes are well documented in energy communities [21,26], but further research can be carried out to map the impact of these social phenomena on technical systems in order to quantify technocratic advantages.

This paper also shows the interplay in different scenarios of electrification, such as the use of HPs and CCs instead of DH and DC. The use of HPs and CCs slightly lowers the peak export of electricity but substantially increases the peak imports during the winter. Return heat utilization leads to small increases in winter imports and reductions in summer exports and allows for increased utilization of low-temperature water.

When designing neighborhoods, the systemic effects of the chosen heating technology should be considered. When calculating the EP, it is easier to obtain a low number if HPs and compressor chillers with a high COP are used. Since the district heating system in Sweden uses mainly waste heat or secondary biofuels, the environmental benefit of space heating electrification in housing areas is questionable. Domestic hot water can be electrified efficiently at a cost of a slightly higher peak power in the winter. Higher temperatures (higher than the available return, but not outside of a heat pump's capacity) and low but constant energy demand make it a good candidate for electrification. The use of return district heating can make the electrification of DHW more effective and provide system benefits. Trends in increased insulation in buildings and the changing climate are expected to increase the demand for cooling. The cooccurrence of cooling demand and PV power production also makes the electrification of cooling relevant. Most of the cooling load, except for the peak demand hours, could be covered by PV systems. There is, however, a time mismatch between production and the peak demand, which could be addressed by energy storage.

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Abbreviations

The following abbreviations are used in this manuscript:

UBEM	Urban Building Energy Model
EP	Energy Performance
EU	European Union
BBR	Swedish National Board of Housing, Building and Planning and its 31st iteration of building regulations
ECs	Energy Communities
PV	Photovoltaic
DHW	Domestic Hot Water
SH	Space Heating
DH	District Heating
DC	District Cooling
CC	Compressor Cooling
COP	Coefficient of Performance
SCOP	Seasonal Coefficient of Performance
HP	Heat Pump
ASHP	Air Source Heat Pump
WSHP	Water Source Heat Pump
GSHP	Ground Source Heat Pump
SMHI	Swedish Meteorological and Hydrological Institute
When2Heat	Refers to the method introduced in [41]

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