



# Investigation of the Peer-to-Peer energy trading performances in a local community under the future climate change scenario in Sweden



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## ABSTRACT

Peer-to-peer (P2P) energy sharing among neighboring households is a promising solution to mitigating the difficulties of renewable power (such as solar Photovoltaics (PV)) penetration on the power grid. Until now, there is still a lack of study on the impacts of future climate change on the P2P energy trading performances. The future climate change will cause variances in the renewable energy production and further lead to changes in the economic performances of households with various energy uses and affect the decision making in PV ownership and pricing strategies. Being unaware of these impacts could potentially hinder the P2P energy sharing application in practice. To bridge such knowledge gap, this paper conducts a systematic investigation of the climate change impacts on the energy sharing performance in solar PV power shared communities. The future weather data is generated using the Morphine method, and an agent-based modeling method is used for simulating the energy trading behaviors of households. Four comparative scenarios of different PV ownerships and pricing strategies are designed. The detailed energy trading performances (including the PV power self-sufficiency, cost saving, revenues, and compound annual growth rate) for the four comparative scenarios are analyzed under both the present and future climates and compared. The study results of a building community located in Sweden show that the future climate change is more beneficial to large energy use households while less beneficial to small households. High price of energy trading can improve the fairness of the economic performances in the community, especially when some of the households do not have any PV ownership. This study can help understand the future climate impacts on the energy sharing performances of building communities, which can in turn guide decision making in PV ownership and price setting for different households under the future climate change to facilitate real applications.

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## 1. Introduction

The latest report from International Energy Agency (IEA) (2021) on Roadmap to Net Zero by 2050 calls for scaling up solar and wind rapidly this decade, reaching annual additions of 630 gigawatts of solar photovoltaics (PV) and 390 GW of wind by 2030, four times the record levels set in 2020. In such context, increased number of renewable energy systems are now installed worldwide. A commonly used way for mitigating the negative impacts of large intermittent renewable energy penetration on the power grid is to install energy storage system, which can store the renewable energy in large production periods and discharge back power in low production periods. The integration of energy storage systems has been proven effective. However, such integration requires high investments on the energy storage system.

Moreover, the energy storage system capacity will inevitably decrease with time due to calendar degradation and frequent charging/discharging. Another cost-efficient and effective solution is to implement peer-to-peer (P2P) energy sharing among peer buildings (Soto et al., 2021). By P2P energy sharing, the large surplus renewable energy production can compensate with the large electricity demand in a same microgrid, thus leading to flattened power profiles at the aggregated level. A study conducted by Luthander et al. (2016) reported that a simple energy sharing among 21 residential buildings in Sweden, i.e., aggregate the electricity demand and supply of all the buildings, can easily improve the PV power self-consumption by over 15%.

Regarding P2P energy sharing, a lot of studies have been conducted in aspects of *design of community-level energy systems, advanced energy sharing controls, energy sharing community designs, and energy sharing microgrid technology*. Regarding the *design of community-level energy systems*, Huang et al. (2021) proposed a hierarchical design optimization method for the distributed

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energy storage system in PV-power-sharing neighborhoods considering energy sharing. The developed design method first optimizes the aggregated capacity of the distributed energy storage using genetic algorithm, and then coordinates the single storage capacity using non-linear programming. Case studies showed that the design optimization can not only reduce the required energy storage capacity at the aggregated level but also reduce the energy loss due to energy sharing and power transmission. Regarding *advance energy sharing controls*, Fan et al. (2018) developed a bottom-up control optimization of the distributed energy storage systems for an energy sharing community, which conducts the sequential optimization of the charging/discharging of distributed energy storage system considering the energy sharing between neighboring buildings. Compared to the individual control, such coordinated control can achieve better performances at the community-level as energy sharing enabled. Regarding the *energy sharing community design*, Jafari-Marandi et al. (2016) designed a homogeneity index for assessing the diversity of power demand and renewable power supply in an energy sharing community. The developed homogeneity index can be used for assessing whether a building community design is good or bad. In Huang and Sun (2019) a clustering based planning method was developed for optimizing grouping of buildings in a neighborhood to form energy sharing community. The developed design optimization methods can identify and combine the buildings with the largest diversity of power profiles (similar to increasing the homogeneity index in Jafari-Marandi et al. (2016)), and thus maximizing the energy sharing potentials. Regarding the *energy sharing microgrid technology*, a Swedish company Ferroamp, developed EnergyHub direct current (DC) microgrid system for energy sharing within a building community based on the Transmission Control Protocol/Internet Protocol (TCP/IP) protocol. The EnergyHub microgrid system was implemented in a real building community in Sweden (Ferroamp, 2018). Similarly, in Ayai et al. (2012) designed a DC microgrid system for integrating distributed solar PV system. The abovementioned studies pave way for the implementation of P2P energy trading within building communities in practice.

Another important aspect for P2P energy sharing is the P2P energy trading, which is related to business models and pricing strategies. Existing studies have also developed many business models for the P2P energy trading in building communities. For instance, Lovati et al. (2020a) proposed a P2P business model for a group of building prosumers considering the user behavior, electricity/financial flows, ownerships of renewable energy systems and trading rules inside the local electricity market. They also defined a behavior map of the district-scale renewable energy systems from three dimensions: local energy providers (emergent or controlled), local energy communities (individual or collective) and control algorithms (centralized or decentralized). In another study (Lovati et al., 2021), an agent-based modeling method was developed to analyze the P2P energy trading performances under different scenarios of PV system ownerships (i.e., all households have ownerships or only part of households have ownerships) and pricing strategies (i.e., high selling price, low selling price, and dynamic selling price). Their study results showed that smaller households have higher revenues and lower savings compared to larger households. An et al. (2021) proposed a business feasibility evaluation model to optimize the price of P2P electricity trading using genetic algorithm and Pareto optimum. The developed business model can maximize the profits of both the market participants (i.e., buyer and seller) in the P2P trading. Their developed model was validated in seven cities in Korea. Inspired by the flocking behavior of birds, Bandara et al. (2021) proposed a flocking-based decentralized double auction method for P2P energy trading within a neighborhood. Besides the buildings with

renewable energy systems installed, their study also considers the microgrid, electric vehicles, and charging stations as prosumers, which can participate in the P2P energy trading. The case study based on a residential PV data set from California, USA showed that the developed method can achieve the highest energy trading as compared to the conventional distributed double auction and centralized double auction.

The P2P energy trading performances are greatly affected by the climate change, as the climate change has large impacts on the building energy demand and renewable energy productions. Under climate change, the raised outdoor temperature would result in increased cooling energy use but decreased heating energy use. This will have large impacts on the energy demand in the buildings. For instance, Olonscheck et al. (2011) pointed out the cooling energy demand of the residential buildings in Germany increased by up to 59% and heating energy demand decreased by up to 75% in the period of 2031–2060 in comparison with the period of 1961–1990. Santamouris et al. (2015) reviewed the recent studies of climate change impacts on building energy use and summarized that the building energy use increased at a rate of 0.5%–8.5%/°C in response to outdoor temperature rise under climate change. On the other hand, climate change also gives rise to renewable resource variations and thus affect the renewable energy generation. For instance, de Lucena et al. (2009) pointed out both biodiesel and hydropower would decrease by 5%–10% in the northeast of Brazil under climate change, and thus result in insufficient renewable energy generation. Robert and Kummert (2012) found that in 2050s the average wind speed increased by 7.4% in winter and decreased by 9.2% in summer in comparison with 1961–1990, thereby leading to surplus wind energy in winter but insufficient wind energy in summer. As climate change affects both building energy demand and supply, it should be carefully considered in P2P energy trading performances. However, in the existing studies, the impacts of climate change on the P2P energy trading performances are rarely studied quantitatively.

However, the impacts of future climate change on the P2P energy trading are rarely studied. The future climate change will cause variances in the renewable energy production and further lead to changes in the economic performances of households with various energy uses and affect the decision making in PV ownership and pricing strategies. Being unknown about these impacts could potentially hinder the P2P energy sharing application in communities. Thus, this study conducts a systematic investigation of the future climate impacts on the P2P energy trading performances. The future weather data in Ludvika of Sweden is first derived from the present weather data using the Morphine method. Then, an agent-based modeling approach is presented for simulating the P2P PV power trading and interactions of households under different PV ownership scenarios and pricing scenarios. The performances of the P2P trading are then analyzed under both the present climate and future climate and compared. A case study is conducted using the data from a building community in Sweden. The major contributions of the present study are summarized as below.

- The impacts of future climate change on the P2P energy sharing performances of solar power shared building community, including the self-sufficiency, cost savings, revenues and compound annual growth rate (CAGR), are investigated and analyzed.
- The households in the community are divided into different groups based on the power demands, and the changes of performances for each group of households due to the future climate change are revealed.

- Four comparative scenarios of different PV ownership and power sharing prices are defined, and the future climate change impacts under different scenarios are studied.
- This study reveals the impacts of future climate change on solar powered building community energy sharing performances, which can help guide decision making in PV ownership and price setting for different households under the future climate change to facilitate real applications.

The structure of the paper is as followings. Section 2 describes the method for deriving the future weather data and modeling the energy trading behaviors. Section 3 presents the detailed building demand modeling and energy system models. In Section 4, the case studies are conducted based on a real building community in Sweden. Section 5 further summarizes the impacts of future climate change on the P2P energy sharing performances and extends the discussions. The brief conclusions are given in Section 6.

## 2. Methodology for investigating the future climate impacts

This section first introduces the method for predicting future climate data using the present climate data. Then, the agent-based modeling for the P2P power trading is presented, and the performance indicators considered in this study are described.

### 2.1. Prediction of the future climate using the Morphine method

#### 2.1.1. Climate models

Concerning future climate conditions, the Intergovernmental Panel on Climate Change (IPCC) is devoted to assessing the current and expected state of climate system and its impacts on societies and ecosystems using *global-scale* and *regional-scale* climate models. These two are the established tools for investigating the climate system response to expected future Greenhouses Gas (GHG) concentrations. Global Climate Models (GCMs) are characterized by coarse spatial resolution and for regional-scale climate studies finer-resolution Regional Climate Models (RCMs) are generally used. These latter models are driven by initial and boundary conditions provided by the GCMs. RCMs produce a more detailed climate information considering more realistic representation of orography features of a certain region.

#### 2.1.2. Future climate scenarios

In addition, future climate projections are produced considering different emission scenarios to which correspond different radiative forcing. The different emission scenarios will correspond different future climate conditions. Emission scenarios rely on assumptions about future GHG emissions, based on estimates of the development of the world economy, population growth, globalization, increasing use of green technology, etc. The amount of GHGs that are emitted depends on global evolution. Two main types of emission scenarios are considered in the current scientific literature. Special Report on Emission Scenarios (SRES) scenarios (Nebojsa and Rob, 2000) which was superseded by Representative Concentration Pathways (RCPs) (RHea, 2010) in 2014. These scenarios provide numerical information in terms of future radiative forcing (measured in  $\text{W/m}^2$ ). If there is an increased emission of GHGs, then there will be more radiative forcing. RCPs that are named with the level of radiation drift achieved in 2100 with 2.6, 4.5, 6.0 or  $8.5 \text{ W/m}^2$  (RHea, 2010). Considering results from the most recent IPCC assessment reports (Collins et al., 2013), extremes climate events magnitude and frequency are expected to globally increase. However, these changes are expected to largely varying according to spatial and temporal scales considered (Kovats et al., 2014).

Even taking into account substantial measures to limit future GHG emission, climatic changes projections for the next 30–60 years are already ‘locked in’, as consequence of GHG emission (Anon, 2019). This information is therefore essential in perspectives to plan and design future buildings and energy system. Future climate conditions will drive designers, engineers, and planners with significant opportunities to create or remodel more adaptive outdoor spaces, where will enhance the livability of, and quality of life for the future communities. In addition, given people usually spend around 90% time indoor nowadays (Anon, 2018), a correct design strategy plays a vital role in the creation of adaptive, resilient, livable built environment that can manage health and wellness risk caused by climate change impacts in the coming decades. Fig. 1 shows a subset of GCMs and RCMs in the climate scenario studies in Sweden. Considering combination of driving GCM and RCM, a multi-model ensemble is obtained. An ensemble approach is generally preferred to a one-model response (Knutti et al., 2010).

#### 2.1.3. Morphed method

In order to execute energy simulation under the future scenarios, an hourly dependent climate dataset is necessary for a dynamic simulation. Unfortunately, GCM/RCMs for limitation of data storing facilities generally provide outputs at daily time steps (only in few cases at 3–6 hourly time step). For this reason, a morphing method was applied to produce hourly climate datasets for use in building energy simulation tools, such as the prediction of the impacts of climate change on energy consumption for a medium-size office building (Amin Moazami et al., 2019), the investigation of climate change on an office building energy consumption with two climate models (Liping Wang and Brown, 2017), the energy consumption variation due to climate change for an office building in Japan (T. Shibuya, 2016) and in Shanghai, China (Deyin Zhao et al., 2017), and the estimation of climate change impact on energy consumption in a residential building in Kaunas, Lithuania (Audrius Sabunas, 2017) to ensure a globally consistent, statistically stable and available database from 60 years back through the current time and into the future.

However, there are limitations in this approach. Firstly, it uses the previous emission scenario, the HadCM3 A2 experiment ensemble, instead of the newest generation of emission scenarios (RCPs). However, as previously shown SRES scenario is largely consistent and comparable with results RCP climate projections. However, different from the yearly or monthly dependent variables under future scenarios, this method enables to project a free hourly climate datasets ready for use in energy simulation and are more practical for climate adaptive building/energy system design until RCM data becomes widely available for the public.

With the intention of the hourly future climate data projection, the authors therefore collect the latest 2020 climate data from SVEBY (data originally coming from SMHI) with the format of excel as baseline climate dataset. Each weather file in certain location around Sweden contains 8 different climate parameters for all hours of the year adapted for energy calculation programs. In accordance with the announcement from SVEBY, it is recommended to use, especially when verifying energy use. The next step, the excel based climate file is further processed by the author and further transferred into the format of ‘epw’. After then, the ‘CCWorldWeatherGen’ tool, developed by Energy and Climate Change Division, University of Southampton, UK, was processed for the ‘present-day’ weather files as the baseline data preparation for the future climate morphing in the next stage. The morphed weather data is compatible with the climate adaptive design assessment and the building performance simulation in the future study. To be mentioned here, the morphed future climate data using the RCM RCA4 that driven by the GCM MOHC-HadGEM2-ES for the period 2020, 2050 and 2080 respectively.



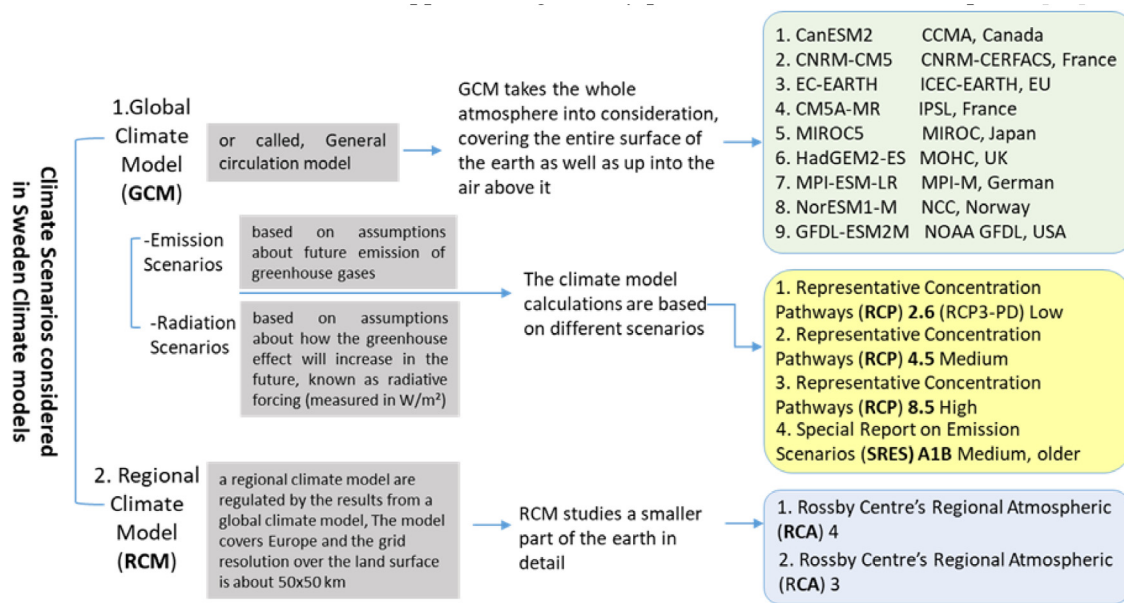


Fig. 1. The climate scenarios results produced by Swedish Meteorological and Hydrological Institute (SMHI)'s Climate Research.

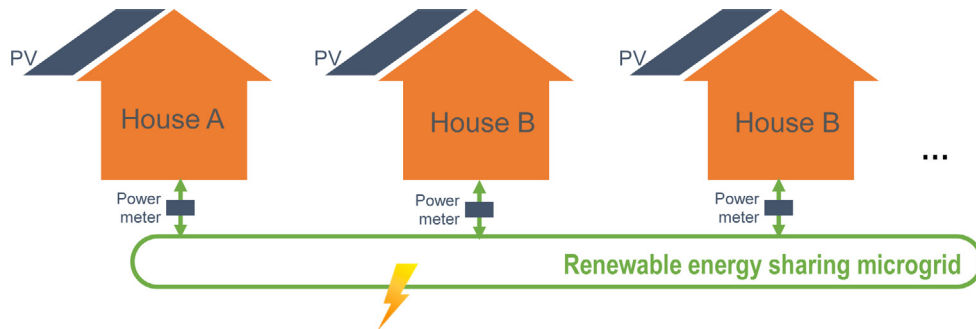


Fig. 2. Schematic of the P2P energy sharing in a community.

## 2.2. Agent-based modeling of the P2P energy sharing under different scenarios

Fig. 2 presents the schematics of the P2P energy sharing in a community. The energy sharing is implemented by connecting all the houses with one energy sharing microgrid. The surplus power from one house can be delivered to another house via the energy sharing network.

This study used the same agent-based modeling method as described in Anon (0000a). An agent based model is a model of a complex system in which the behavior of individual player/system is not controlled by a single algorithm, but it comes/emerges from the interaction of a number of sub-systems (i.e., the agents). Following the classification of dimensions of different control and algorithm in Anon (0000b), the simulations presented in this study are for individual and de-centralized systems causing an emergent behavior in the micro-grid. In other words, there are multiple PV owners in the micro-grid and each owner can set the price according to its own independent will. In general, the behaviors of each agent in a time-step can be summarized as shown in Fig. 3. The behaviors of each agent are considered the same in different PV ownership and pricing scenarios.

The agent based modeling is described by the following set of rules.

- Every household is considered as one independent agent.

- Every agent has an energy balance in each Hour of the Year (HOY). The energy balance is calculated as the deviation between its hourly PV power production (if it owns a PV system) and its hourly power demand. If the balance is negative, the agent will be a net buyer in that HOY, otherwise it will be a seller. This rule assumes that each household can sell only the excess PV production (after meeting its own demand).
- Each seller can set the price for the surplus power to be sold.
- If the electricity is offered by multiple sellers, the buying agent will select from the cheapest source.
- If the aggregated demand of the district exceeds the offer of the cheapest source, the demand of each household is met proportionally by the cheapest source. For example, if the cheapest source covers 30% of the aggregated demand in that HOY, each household is provided 30% of its power demand by the cheapest source.
- If the on-site renewable power exceeds the power demand in a certain HOY, the cheapest sources are consumed preferentially. Thus, the more expensive sellers risk to be in excess of the demand and sell part or all their power to the grid. Those who sell to the grid cannot set the price but are simply valued the price paid by the grid (which is always way lower than that of the local sellers).

In this study, four different P2P energy trading scenarios are considered and the economic performances of all these scenarios under both the present and future climate are studied and

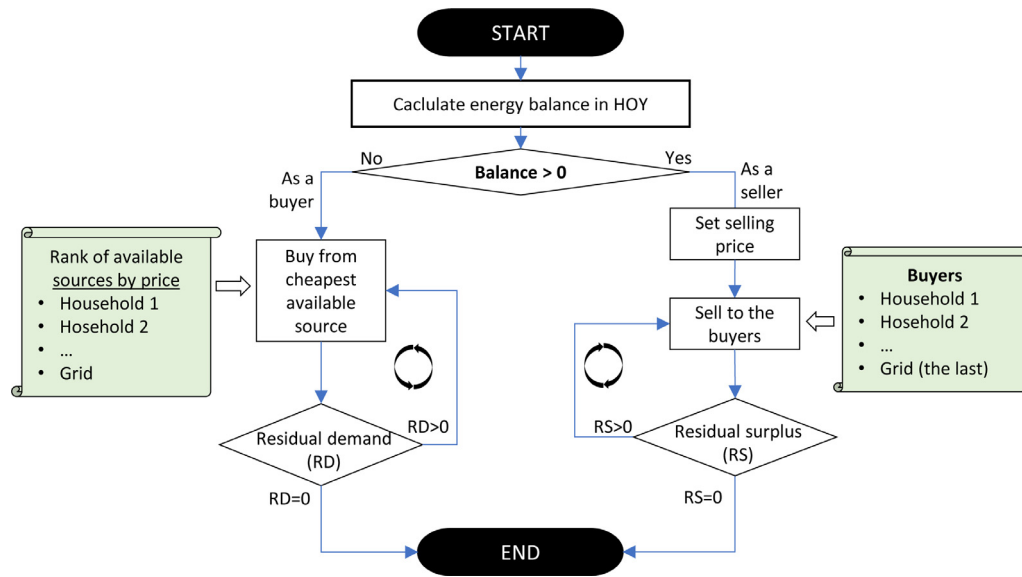


Fig. 3. Schematic of the agent-based modeling and behavior of each agent in every time-step of the simulation.

**Table 1**  
PV capacities per household and prices in the four different scenarios.

Scenario	Ownership of PV panels	Household PV capacity	Electricity price (SEK/(kW h))
1	100% of households have PV ownership	$\text{Capacity}_{PV, tot} / N_{\text{household}}$	1
2	100% of households have PV ownership	$\text{Capacity}_{PV, tot} / N_{\text{household}}$	1.19 (summer), 1.78 (winter)
3	Only 50% of households have PV ownership	$2 \times \text{Capacity}_{PV, tot} / N_{\text{household}}$ or 0	1
4	Only 50% of households have PV ownership	$2 \times \text{Capacity}_{PV, tot} / N_{\text{household}}$ or 0	1.19 (summer), 1.78 (winter)

compared. The details for each scenario are explained below. The percentage of ownership and price settings are also summarized in Table 1. The summer grid price is 1.2 SEK/(kW h) and the winter grid price is 1.8 SEK/(kW h). Note the abovementioned rules apply to all the considered scenarios.

- **Scenario 1:** All households have an ownership of the PV system. Every household invests an equal share of the whole PV system. The price for the sale within the micro-grid is agreed for the long term as the 83% of summer grid price (thus 1 SEK/(kW h) in both winter and summer at the year 0).
- **Scenario 2:** Similar to Scenario 1, all residents have an ownership of the PV system. The price for the sale within the micro-grid is agreed for the long term as 99% of the grid price, therefore whoever buys electricity from another household has almost no savings compared to the grid.
- **Scenario 3:** Only half of the households agree to purchase the PV system. Each PV equipped household has an equal share of the total system. The price for the sale within the microgrid is agreed for the long term as the 83% of the summer grid price, like Scenario 1.
- **Scenario 4:** Like Scenario 3, only half of the residents agree to purchase the PV system. Each PV equipped household has an equal share of the total system. The price for the selling surplus power within the microgrid is agreed for the long term as 99% of the grid price, like in Scenario 2.

### 2.3. Performance indicators for analysis

This study will investigate three economic performance indicators: namely the cost savings, the revenues, and Compound

Annual Growth Rate (CAGR). The savings (SEK) represent the reduction in the electricity costs due to the avoided purchase of the electricity from the external grid. The revenues (SEK) indicate the incomes obtained by each shareholder of the PV panels for selling the surplus PV power from their shares. The CAGR (%) is the average rate of return that would be required for an investment to grow from its beginning balance to its ending balance. The calculation of the three indicators is introduced below.

The cost savings includes two parts: (i) the savings from using the self-produced PV power and (ii) the savings from purchasing power at a cheaper price within the community. The calculation of cost savings  $Cost_{save}$  (SEK) is shown by Eq. (1).

$$Cost_{save} = \sum_{Ts=1}^{8760} ((P_{self, Ts} \cdot d_{grid, Ts}) + P_{peer, Ts} \cdot (d_{grid, Ts} - d_{peer, Ts})) \quad (1)$$

$Ts$  (h) is the internal simulation time-step of the model.  $P_{self, Ts}$  (kW h) is the power self-consumed by a household in the specific time-step, which is calculated as the smaller one of the hourly electricity demand and hourly PV power production.  $d_{grid, Ts}$  (SEK/(kW h)) is the cost of electricity offered by the external grid in the specific time-step, i.e., the grid electricity price.  $P_{peer, Ts}$  (kW h) is the amount of electricity purchased from a peer household within the local community in the specific time-step.  $d_{peer, Ts}$  (SEK/(kW h)) is the cost of electric power offered by a peer in a specific time-step.

The revenues are obtained either from selling power to the public grid or from selling power to the peers in the community. Note the price of selling power to the public grid is much lower than selling to the peers as feed-in-tariff can increase the grid stress. The calculation of revenues  $Cost_{revenue}$  (SEK) is expressed

by Eq. (2).

$$Cost_{revenue} = \sum_{Ts=1}^{8760} ((P'_{peer.Ts} \cdot d'_{peer.Ts}) + (P'_{grid.Ts} \cdot d'_{grid})) \quad (2)$$

$P'_{peer.Ts}$  (kW h) is the amount of electricity sold by the selling household to all peer households in the specific time-step.  $d'_{peer.Ts}$  (SEK/(kW h)) is the electricity price set by the selling household to the peers in the specific time-step.  $P'_{grid.Ts}$  (kW h) is the amount of electricity sold by the selling household to the grid in the specific time-step.  $d'_{grid}$  (SEK/(kW h)) is the feed-in-tariff. This price is static, thus is independent by the time-step.

The calculation of CAGR is expressed by Eq. (3).

$$CAGR = \left[ \left( \frac{Income - (CAPEX + OPEX)}{CAPEX} \right)^{\frac{1}{lifetime}} - 1 \right] \cdot 100 \quad (3)$$

*Income* (SEK) is the cumulative income of the household derived by the ownership of the share of the PV system during its lifetime. It is calculated according to Eq. (4). *CAPEX* (SEK) is the capital costs. It includes the turn-key cost of the system including design and installation costs. It can be calculated by multiplying the unitary cost by the installed capacity (see Table 3). *OPEX* (SEK) is the operational costs. The operational costs include a standard annual cost of 80 SEK/kWp each year for the substitution and cleaning of the modules, as well as the substitution of the inverter in case of rupture. The cost of inverters is set as 3.5 KSEK/kWp and is assumed to be changed at least once in the planned lifetime of the system. The *Lifetime* is assumed to be 30 years in the analysis.

$$Income = \sum_{T=0}^{lifetime} (Cost_{save} + Cost_{revenue}) \cdot (1 - \Delta\eta \cdot T) \cdot (1 + \Delta d \cdot T) \quad (4)$$

$Cost_{save}$  is the cost saving and calculated by Eq. (1), and  $Cost_{revenue}$  is the revenue and calculated by Eq. (2).  $T$  is the number of years since the installation of the PV system.  $\Delta\eta$  is the change of the PV production efficiency due to component degradation, which is assumed to be 1% per year.  $\Delta d$  is the change in the price of the electricity for the consumer, it is assumed to be +2% per year in the design stage.

Besides these economic indicators, the PV power self-sufficiency (SS) is also calculated for the households within the energy sharing community. The self-sufficiency represents the percentage of power demand which is met by the on-site PV production as compared to the total demand. It is calculated by Eq. (5).

$$SS = \frac{E_{d,pv}}{E_{d,pv} + E_{d,grid}} \quad (5)$$

$E_{d,pv}$  (kW h) is the aggregated electricity demand that is supplied by the PV system during the whole year.  $E_{d,grid}$  (kW h) is the aggregated electricity demand that is supplied by the power grid. A larger SS indicates a better performance since a building becomes less dependent on the power grid. Note for the households in the community, even though some of them do not have an PV ownership, they still have self-sufficiency as they can use the surplus PV power from the peers inside the community.

### 3. Buildings and system modeling

This section introduces the building information for electricity demand modeling, as well as the modeling of PV systems.



Fig. 4. Case building cluster located in Ludvika, Sweden.

Table 2

Configuration of the simulation households.

Groups	Household ID	Number of households	Occupant number
1	1–2	2	Five
2	3–7	5	Four
3	8–12	5	Three
4	13–27	15	Two
5	28–48	21	One

#### 3.1. Building modeling

This study considered a real building cluster located in Ludvika, Dalarna region, Sweden. This building cluster consists of three separate buildings, as shown in Fig. 4. The building cluster (all the three buildings) includes 48 dwelling units over three floors, and most of the apartments have one or two bedrooms. The total façade surface gross area of the complex is 2146 m<sup>2</sup>, the total roof surface gross area is 1750 m<sup>2</sup>. These buildings will be improved by a series of renovation plans including installation of PV and direct current (DC) micro grid. It is assumed the heating is provided by district heating system. So, the PV panels will only need to provide power supply to the domestic electricity demand (e.g., lighting, TVs, dish wash). In this study, the electric demand used for the study was generated using Load Profile Generator (LPG) (Lovati et al., 2021) assuming population characteristics as described in Table 2. In total, there are 48 households in the three multi-family apartment blocks.

#### 3.2. Renewable energy system modeling

The power generation from the PV panel  $P_{PV}$  (kW) is calculated by Eq. (6) (Lovati et al., 2020b) and simulated in TRNSYS (i.e., an energy simulation platform),

$$P_{PV} = \tau \times I_{AM} \times I_T \times \eta \times CAP_{PV} \quad (6)$$

where  $\tau$  is the transmittance-absorptance product of the PV cover for solar radiation at a normal incidence angle, ranging from 0 to 1;  $I_{AM}$  is the combined incidence angle modifier for the PV cover material, ranging from 0 to 1;  $I_T$  (W/m<sup>2</sup>) is the total amount of solar radiation incident on the PV collect surface;  $\eta$  is the overall efficiency of the PV array;  $CAP_{PV}$  (m<sup>2</sup>) is the PV surface area. Eq. (6) shows the calculation of the PV power production for each hour. In each hour, the values of parameters (including the hourly solar radiation) in this equation are updated and then used for the calculation of the hourly PV power production in TRNSYS. This equation is calculated 8760 times to simulate the PV power production during a full year period.

In this study, the PV system capacity was sized under the present weather data using the design optimization tool developed in the Horizon 2020 EnergyMatching project. The capacity of the PV systems was optimized to maximize the self-sufficiency of the building community while meeting the constraint of keeping

**Table 3**  
Input parameters for PV system capacity optimization.

Parameters	Values
Unitary cost of the PV system	12000 SEK/kWp (ca. 1175 €/kWp)
Planned lifetime of the system	30 years
Degradation of the PV system	–1%/year (annual percentual efficiency losses)
Nominal efficiency of the system	16.5%
Performance ratio at standard test conditions	0.9
Price of the electricity from external grid	1.2 SEK/(kW h) (Summer), 1.8 SEK/(kW h) (Winter)
Price of the electricity sold to the external grid	0.3 SEK/(kW h)
Annual discount rate	3%
Growth of electric price for consumer	+1.5%/year (annual percentual price increases)
Optimized capacity of the installed PV system	65.5 kWp <a href="#">Huang et al. (2018)</a>

a positive net present value. For details about the design optimization of PV systems, please refer to [Pflugradt and Muntwyler \(2017\)](#). [Table 3](#) summarizes the parameters used for optimizing the PV system capacity. These cost parameters are also used in the economic analysis of P2P trading.

#### 4. Case studies and results analysis

The case studies are conducted based on a case building community located in Ludvika, Sweden. In this section, the weather data and PV power production under both the present and future scenarios are first analyzed and compared. Then, the P2P energy trading performances under the two climates are compared and discussed.

There are 48 households considered in the case studies. The PV system capacity is optimized under the present climates and the optimized capacity is 46.5 kWp, as calculated in [Huang et al. \(2019\)](#). In the four considered scenarios, the PV system allocated for each household is 1.36 kWp in Scenarios 1 and 2, while is either 2.73 kWp or 0 in Scenarios 3 and 4. In the following analysis, the PV system capacity is kept the same under both the present climate and the future climate. In other words, the climate change will be the sole factor affecting the P2P energy trading performances. In the economic performance analysis, it is assumed a 2% increase in the electricity prices in each year.

##### 4.1. Comparison of the present and future climates

Statistical analysis is conducted to compare the solar radiation in the current and future climates. [Fig. 5](#) shows the comparison of the hourly solar radiation and associated PV power production of the system (as specified in [Section 3.2](#)). As can be seen from [Fig. 5\(a\)](#), in the small solar radiation range 0~1000 kWh/m<sup>2</sup>, the future scenario has lower occurrence as compared to the present scenario. While in the large solar radiation range 1500~3000 kWh/m<sup>2</sup>, the future scenario has larger occurrence. The large solar radiation mostly occurs in summer while the small solar radiation mostly occurs in winter. This means that in the future there are more solar radiation in summer while less solar radiation in winter. The frequency analysis shows a similar trend for the PV power production: with an increased frequency in large summer period while decreased production in winter period. The maximum hourly PV power production is about 40 kW h under the present climate, while the maximum production under the future climate is about 42 kW h (about 5% increase).

[Fig. 6](#) compares the monthly PV power production under the present climate and future climate. As can be seen, during summer months in the future, i.e., from April to October, the PV system has more power production compared to the present scenario. The increase of power production reaches maximum in August at about 28.8%, followed by 24.8% in July. While in future winter months, i.e., January, February, March, November and

December, the PV system has less power production compared to the present scenario. In total, the annual PV power production increased by 10.7% under the future weather compared to the present scenario.

##### 4.2. Comparison P2P energy sharing performances

###### 4.2.1. Energy performances

[Fig. 7](#) presents the cumulative probability distribution of PV power self-sufficiency under both the present and future climates with different PV ownerships. The blue curves show the performances under the present climate and the red curves show the performances under the future climate. [Fig. 7\(a\)](#) shows the case in which 100% households have an equal PV ownership (for Scenarios 1 and 2), and [Fig. 7\(b\)](#) shows the case in which 50% households have an equal PV ownership (for Scenarios 3 and 4). Note in this study, the PV power self-sufficiency is calculated based on the community-produced PV power. In other words, even though a household does not have PV ownership, this household still can have a self-sufficiency, as its demand can be partly covered by PV power from its peers. [Table 4](#) summarizes the mean and ranges of the self-sufficiency under different climates and different PV ownerships.

When 100% of the households have an equal PV ownership, the values of PV power self-sufficiency are evenly distributed within a narrow range (i.e., 0.2~0.34) for all the households. Due to the climate change, the distribution of PV power self-sufficiency shifted slightly to the right side with larger values. As summarized in [Table 4](#), the mean value of household PV power self-sufficiency increased by 5.4% in the future compared to the present climate. Meanwhile, the ranges of self-sufficiency shifted rightward. This is because of the increased PV power production under the future climate, which can help improve the overall self-consumption of the community.

When only 50% of the households have an equal PV ownership, the values of PV power self-sufficiency have wider ranges (i.e., 0.12~0.4). This is because for the households with a PV ownership, the allocated PV capacity is twice the value in the case with 100% household PV ownership. Consequently, the self-sufficiency is much larger for these households. For the households with no PV ownership, they can only purchase PV power from their peers to meet the power demand, and thus their self-sufficiency is much lower. A gap can be observed under both climates in the self-sufficiency distribution between the households with and without ownership. Again, the climate change has a positive impact on the self-sufficiency. The average self-sufficiency increased by 6.2% under the future climate. Note that the maximum value of self-sufficiency decreases under the future climate. This is because the increase of PV power production occurs in summer period (see [Fig. 6](#)), where most of the households can also be very self-sufficient. While in the winter period under the future climate, the PV system has reduced power



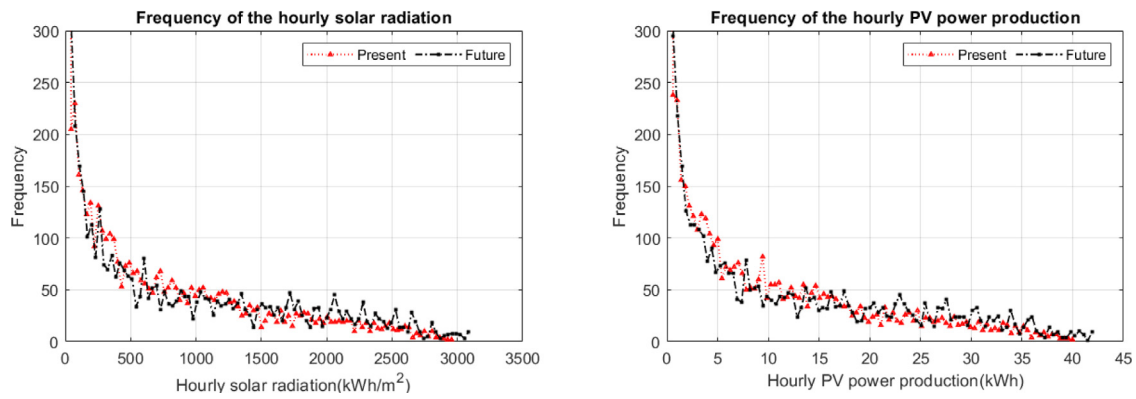


Fig. 5. Comparison of the frequency of (a) solar radiation and (b) PV power production under the present and future climates.

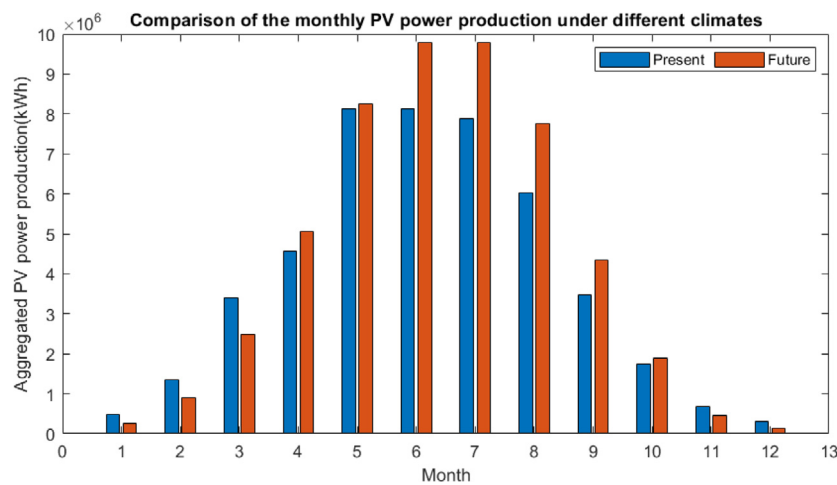


Fig. 6. Comparison of the monthly aggregated PV power production under the present and future climates.

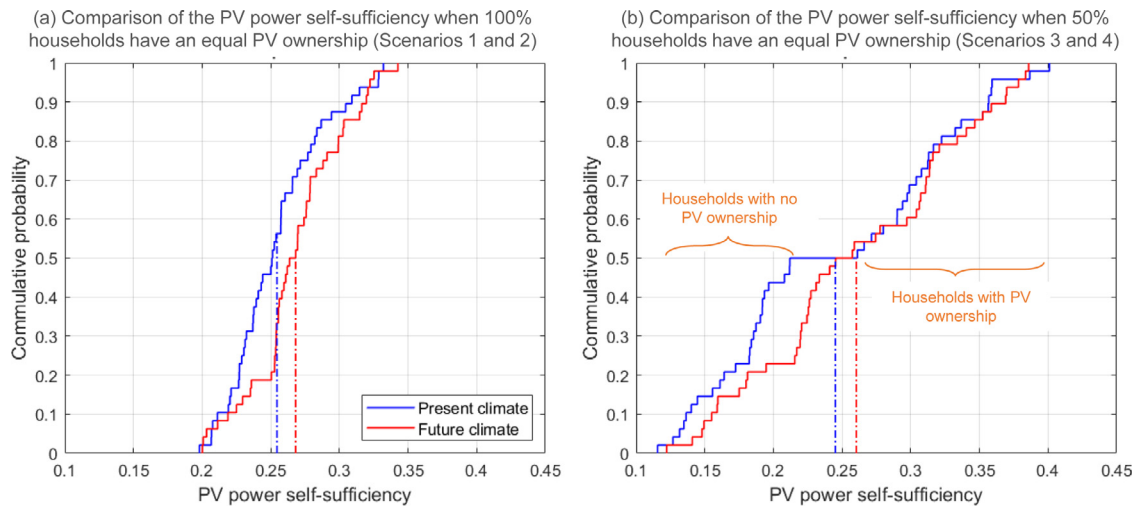


Fig. 7. Comparison of the PV power self-sufficiency distributions under both the present and future climates with different PV ownerships (a) 100% households have an equal PV ownership (for Scenarios 1 and 2) (b) 50% households have an equal PV ownership (for Scenarios 3 and 4).. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

production, leading to reduce self-sufficiency. Overall, the decrease of self-sufficiency in winter leads to decreased annual self-sufficiency.

Table 5 summaries the amount of energy trading during a full year between different groups of households (see Table 2 for the details of groups) under both the present and future

climates in Scenario 1. The values in the table indicate the amount of energy sold from the row-group households to the column-group households. For instance, the value in the first row and first column represents that households in Group 2 together sold 1776 kW h electricity to households in Group 1. As can be seen, due to the climate change, the amount of shared energy will



**Table 4**  
Comparison of the PV power self-sufficiency under.

PV ownership		Climate	Ranges	Mean	Change
100% households have PV ownership (Scenarios 1 and 2)	Fig. 7(a)	Present	(0.20~0.33)	0.25	5.4%
		Future	(0.20~0.34)	0.27	
50% households have PV ownership (Scenarios 3 and 4)	Fig. 7(b)	Present	(0.11~0.40)	0.24	6.2%
		Future	(0.12~0.39)	0.26	

**Table 5**  
Summary of energy trading (kW h) among any two households within the community in the full year for Scenario 1.

	Group 1	Group 2	Group 3	Group 4	Climate
Group 2	1776	–	–	–	Present
	2106	–	–	–	Future
	19%	–	–	–	Increase
Group 3	777	158	–	–	Present
	898	176	–	–	Future
	16%	11%	–	–	Increase
Group 4	1540	597	119	–	Present
	1791	694	139	–	Future
	16%	16%	17%	–	Increase
Group 5	1054	459	104	51	Present
	1233	540	123	61	Future
	17%	18%	17%	21%	Increase

increase a lot under the future climate. The amount of shared energy increased by 11%~21%. This is because of the larger PV power production in the future, which leads to more surplus PV power for sharing. Note that Group 1 households are large energy end-users with five occupants, while Group 5 households are small energy end-users. Thus, the aggregated energy sharing from small energy end-users to large energy end-users are positive, indicating more selling than purchasing.

#### 4.2.2. Economic performances

Fig. 8 compares the cost saving (as calculated by Eq. (1)) and revenues (as calculated by Eq. (2)) of each group of households under both the present and future climates. The different colors represent different groups of households characterized by the number of occupants (see Table 2). In total, there are five colors corresponding to the five groups. The hollow markers represent the performances under the present weather data, and the filled markers represent the performances under the future weather data.

In all the four scenarios, the large energy end-users (i.e., Group 1 with five occupants) have larger savings in the electricity costs but smaller revenues. This is because these large energy end-users can use the PV production to meet more demands, and thus leading to larger electricity cost savings. While on the other hand, the smaller energy end-users (i.e., Group 5 with one occupant) have larger revenues but smaller savings in the electricity costs. This is because their power demand is already small. As a result, the amount of power demand which can be changed to be supplied by the household's own PV system or the community shared PV power is limited, which eventually leads to lower cost savings. But these small energy end-users can sell their surplus PV power to the community, and thus the revenues are higher.

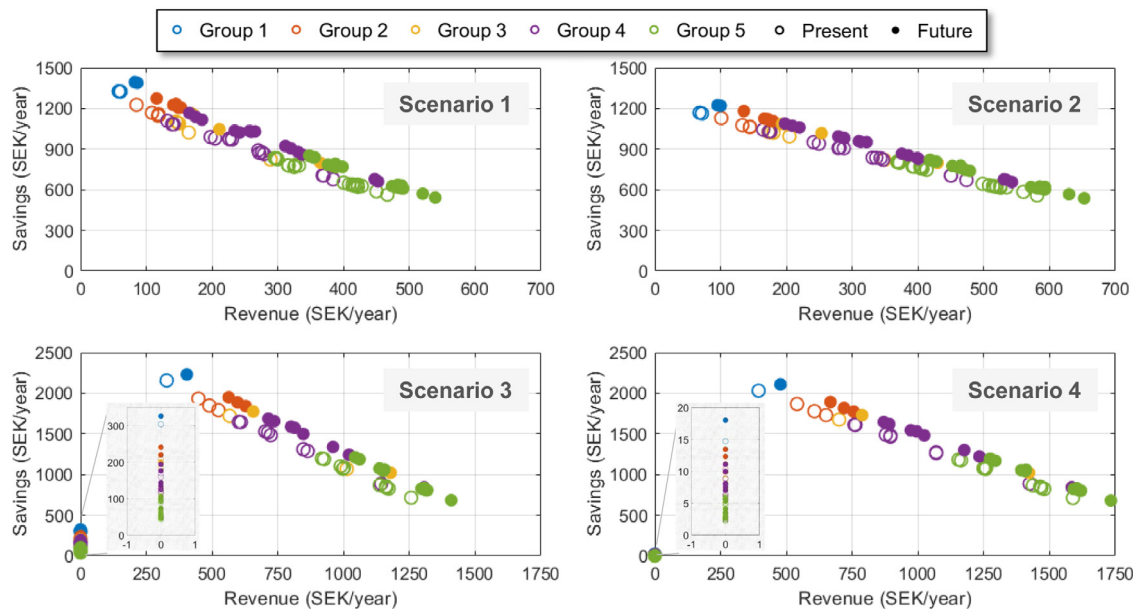
In Scenario 1, for large energy end-users, both the revenues and savings will increase slightly in the future, due to the increased PV power production in the future. For small energy end-users, the revenues will increase at a higher level compared to large energy end-users. For instance, for the end-user with the highest revenue (i.e., the rightmost hollow and filled circles), its annual revenue increased from 466 SEK to 540 SEK (ca. 15.9% increase). However, the savings in the electricity costs of small energy end-users are reduced slight. This is because the increase of PV power production due to climate change is distributed in summer months (i.e., from June to October, see Fig. 6). The

small energy end-users can already achieve good self-sufficiency in these months, and thus the PV power production increase in the future will not contribute to the cost saving. While in winter months under the future climate, the PV power production will reduce, which will lead to reduce cost savings. As a whole, the small energy end-users have less electricity cost savings in the future climate.

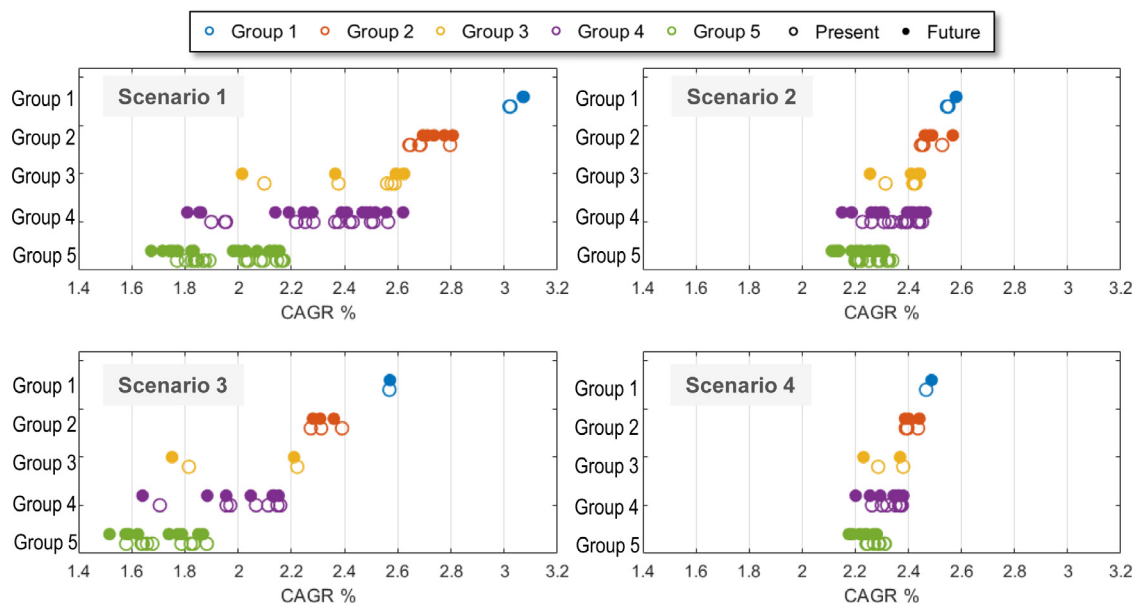
In Scenario 2, due to a higher energy trading prices within the community (i.e., 99% of the grid price), the saving of electricity costs becomes smaller, but the revenue becomes larger as compared to Scenario 1. Again, for large energy use households (i.e., Group 1 with five occupants), both the savings and revenues will increase under the future climate. For instance, for the end-user with the lowest revenue (i.e., the leftmost hollow and filled circles), its annual revenue increased from 68 SEK to 95 SEK (ca. 40% increase), and its annual cost saving decreased from 1169 SEK to 1224 SEK (ca. 4.7% increase). But for small energy use households (i.e., Group 5 with one occupant), the savings will be reduced slightly, but the revenues will be increased a lot under the future climate. For the end-user with the highest revenue (i.e., the rightmost hollow and filled circles), its annual revenue increased from 580 SEK to 652 SEK (ca. 12.4% increase), and its annual cost saving decreased from 557 SEK to 537 SEK (ca. 3.6% decrease).

In Scenarios 3 and 4, since only 50% of the households have PV ownership, the revenues and savings for these households with PVs are much larger compared to Scenarios 1 and 2. Since in Scenario 4, the selling price of power within the community is higher than Scenario 3 (very close to the grid price), the average cost savings are relatively lower, but the revenues are higher. As can be seen, for the households with PV ownership, the impacts of climate change are very similar to Scenarios 1 and 2: the climate change leads to increased savings and revenues for large energy end-users. While for small energy end-users, it leads to reduced cost savings but larger revenues. Note for the households without PV ownership, the climate change also has positive impacts by increasing their savings in the electricity costs. This is because there is more power shared by the peer households in the community, which is contributed by the enhanced PV power production. In Scenario 4, the cost savings of these households are much smaller than Scenario 3.

Fig. 9 compares the CAGR (Compound Annual Growth Rate) of each household in the four scenarios under both the present



**Fig. 8.** Comparison of savings and revenues of each household under both the present and future climates for the four scenarios. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)



**Fig. 9.** Comparison of the CAGR in the four scenarios under both the present and future climates.

and future climates. Note in Scenarios 3 and 4, the CAGRs are calculated only for the households with an PV ownership. If a household has no investment in the PV system, the CAGR is 0. Table 6 compares the mean of CAGR for each group of households in all the scenarios. A larger CAGR indicates a better economic performance.

It can be observed in Fig. 9 that Scenario 2 is fairer than Scenario 1 in terms of CAGR, as well as Scenario 4 compared to Scenario 2. This is consequence of the difference in price: Scenarios where local electricity is sold at a very low price favors larger households (i.e. group 5 and 4) over smaller ones due to their larger annual cumulative consumption of local electricity. In general, savings produce a larger benefit compared to revenues because they amount to the whole price of the electricity, but their advantage becomes minor when local electricity is expensive. In other words, expensive local energy generates more

revenues from the sale of electricity within the community, this consequentially reduces the savings potential for the receiver of this local energy. Contrary to what stated in a previous study, it can be seen in Fig. 9 that owners of larger shares of PV, in scenarios with uneven ownership (i.e., 3 and 4), cannot reach the same CAGR they obtain when having smaller shares. This is due as well to the fact that they have a larger PV system relative to their size, and therefore the share of electricity self-consumed is minor. Unsurprisingly, the scenarios with higher prices of local electricity (2 and 4) are characterized by a smaller difference in CAGR between different ownership structures. In other words, there is less difference in Scenario 2 from 4 than Scenario 3 from 1. Despite having a lower CAGR the cumulative earning of these households is almost double to what they had in Scenario 1 or 2. In a case in which the local electricity has the same price of the

**Table 6**  
Comparison of CAGR (%) under both the present and future climates for different groups.

Scenario	Climate	Group 1	Group 2	Group 3	Group 4	Group 5
1	Present	3.02	2.69	2.44	2.29	1.97
	Future	3.07	2.74	2.44	2.29	1.90
	Relative changes	2%	2%	0%	0%	−3%
2	Present	2.55	2.47	2.40	2.35	2.26
	Future	2.58	2.49	2.40	2.34	2.20
	Relative changes	1%	1%	0%	−1%	−3%
3	Present	2.57	2.33	2.02	2.03	1.74
	Future	2.57	2.32	1.98	2.01	1.69
	Relative changes	0%	0%	−2%	−1%	−3%
4	Present	2.47	2.41	2.33	2.34	2.28
	Future	2.49	2.41	2.30	2.32	2.23
	Relative changes	1%	0%	−1%	−1%	−2%

electricity from the grid the CAGR would be the same regardless of the ownership structure.

As can be seen from the relative changes of CAGR in the four scenarios in Table 6, in the future the large energy end-users (i.e., Group 1) will have 0~2% higher CAGR values, as compared to the present scenario. This is because the large energy end-users will have increased savings (as more PV power can be used to meet their own power demand) and revenues (as more PV power can be sold), as can be seen from Fig. 8. While the CAGR values will decrease by 2~3% for small energy end-users (i.e., Group 5) in the future scenario as compared to the present scenario. This is because the CAGR is more correlated to the cost savings contributed by the PV system. Compared to being sold to the peer households, the PV power can make bring more benefits to the household economics if it is used by the household itself. Since in the future scenarios, the small energy end-users have reduced cost savings (see Fig. 8), their CAGR values are smaller.

## 5. Discussion of the study results

This section summarizes the performance changes under the future climate change and discuss findings from the analysis for the real application. Table 7 summarizes the performance variations under the future climate change for different energy use households considering different scenarios. From Table 7 and the case study results in Section 4.2, the following findings can be obtained.

- Overall, the future climate change will increase the difference between the CAGR of different households. The households with large CAGR under the present climate will have even larger CAGR in the future (i.e., the economic performances become better), while the households with small CAGR under the present climate will have even smaller CAGR in the future (i.e., the economic performances become worse).
- The future climate change is more beneficial to large energy use households, i.e., they can have increased cost savings, revenues, and CAGR. This is because the large energy use households can consume more of the increased PV power production under the future climate.
- The future climate change is less beneficial to small energy use households. This is because the increased PV power production in the future summer will not help increase the self-consuming of the small energy use households (as they are already self-sufficient). On the contrary, the decrease of PV power production in the future winter will reduce the self-consuming of the small energy use households, which will reduce the cost savings and eventually the CAGR.

Based on these findings, the following conclusions can be drawn to guide the decision making of the PV ownership and price setting under the future climate change to facilitate real applications.

- It is not economical for a household to have a PV ownership larger than its demands, especially under the future climate change. When a household have surplus power frequently, it has to either sell the power to the community or to the grid, which makes the return of investment worse (especially when selling to the grid at a much cheaper price).
- Specially, for small energy use households, if they want to improve the economic performances in the future, they can set their share of PV ownership equivalent to their demands in the community. In this study, despite their small demand, they have equal ownership as the large energy use households. As a result, they have surplus power production frequently and will have to sell it. If they can reduce the PV ownership to be equivalent to their demands, the unnecessary surplus PV power exports can be reduced and thus the CAGR values will be higher.
- High price of energy trading can improve the fairness of the economic performances in the community, especially when the some of the households in the community do not have any ownership of the PV system. It can help keep the CAGR values of various households with a PV ownership in a narrow range, and thus leading to similar return of investment in a PV system. Therefore, if a community wants to incentivize all the households to have some share of the PV system, it is preferable to set the energy sharing price high.
- Another way to improve the CAGR of PV ownership to mitigate the negative impacts of future climate change on the small energy use households is to install energy storage system. This can help keep more PV power to be used by the household itself. However, the investment of energy storage system could potentially increase the payback period of the total system (including PV and energy storage).

## 6. Conclusion

This study has conducted a systematic investigation of the impacts of climate change on the P2P energy trading performances under different pricing strategies and PV ownerships. Case studies have been conducted using the data from a building community located in Ludvika, Sweden. The future weather data of Ludvika was produced using the Morphine method. An agent-based modeling method was developed to simulate the household P2P trading behavior. Four different scenarios, i.e., two with different PV ownership (100% households have an ownership, or 50%

**Table 7**  
Summary of the performance variations under the future climate change.

Households	Scenarios	Performances			
		SS Cost	savings	Revenues	CAGR
Small energy users	1: Equal PV ownership, low trading price	↑	↓	↑	↓
	2: Equal PV ownership, high trading price	↑	↓	↑	↓
	3: Half PV ownership, low trading price	With PV Without PV	↓ ↓ ↑ ↑	↑ ↑ –	↓ –
	4: Half PV ownership, high trading price	With PV Without PV	↓ ↓ ↑ ↑	↑ ↑ –	↓ –
	1: Equal PV ownership, low trading price	↑	↑	↑	↑
	2: Equal PV ownership, high trading price	↑	↑	↑	↑
Large energy users	3: Half PV ownership, low trading price	With PV Without PV	↓ ↑ ↑ ↑	↑ ↑ –	↑ –
	4: Half PV ownership, high trading price	With PV Without PV	↓ ↑ ↑ ↑	↑ ↑ –	↑ –

Note: '↑' indicates performance improving, i.e., the performance becomes better in the future. '↓' indicates performance deteriorating, i.e., the performance becomes worse in the future. '–' represents not applicable. Double symbols represent relatively more changes in the performances.

households have an ownership) and two with different prices (a cheap price or prices close to the grid prices), were considered and the P2P performances under the four scenarios were studied and compared. The key findings from this study are summarized as below.

- Due to the climate change, the annual PV power production will increase by 10.7% in Ludvika in the future scenario compared to the present scenario. The PV power production will increase dramatically in summer months (e.g., 24.8% in July and 28.8% in August) but decrease in winter months.
- Overall, the future climate change has positive impacts on the self-sufficiency. The increased PV power production in the future scenario will lead to an increased in the household PV power self-sufficiency. For the case that 100% of the households have a PV ownership, the average PV power self-sufficiency will increase by 5.4% in the future scenario. For the case that 50% of the households have a PV ownership, the average PV power self-sufficiency will increase by 6.2% in the future scenario.
- Due to the increased PV power production in the future scenario, the sum of cost savings and revenues will increase for all the households under all the pricing strategies and PV ownerships. For large energy end-users, both the cost savings and revenues will increase. While for small energy end-users, the cost savings will be reduced slightly, as in the future winter scenario, the PV power production will be reduced, leading to reduced PV power self-usage.
- Overall, under the equal PV ownership scenarios, the future climate change will increase the difference between the CAGR of different households. The households with large CAGR under the present climate will have even larger CAGR in the future (i.e., the economic performances become better), while the households with small CAGR under the present climate will have even smaller CAGR in the future (i.e., the economic performances become worse). This is because the large energy use households (which already have large CAGR under the present climate) can consume more of the increased PV power production under the future climate. While the small energy use households (which already have small CAGR under the present climate) have to sell more surplus PV power under the future climate.
- It is not economical for a household to have a PV ownership larger than its demands, especially under the future climate change. When a household have surplus power frequently, it has to either sell the power to the community or to the grid, which makes the return of investment worse (especially

when selling to the grid at a much cheaper price). The return worsens in relation to the investment, but in terms of shear earnings it improves (i.e., in terms of the gross SEK that a household earns).

- High price of energy trading can improve the fairness of the economic performances in the community under both the present and future climates. It can help keep the CAGR values of various households with a PV ownership in a narrow range, and thus leading to similar return of investment in a PV system. If a community wants to incentivize all the households to have some share of the PV system, it is preferable to set the energy sharing price high.

It should be mentioned that the study has not considered the impacts of the uncertainties/errors of the weather prediction results from the morphing method. The associated uncertainty analysis will be considered as a part of our future studies. This study has discussed the ownership of PV systems, but for those households with an ownership, the PV capacity is the same. Future work will consider more diversified PV ownership considering the individual household power demand. Another potential factor affecting the P2P energy trading performances is the integration of energy storage. When households have their own energy storage, they may tend to store their surplus power in the storage, instead of sharing the surplus with the peer households in the community. Future work will also try to investigate the impacts of energy storage integration on the P2P energy trading performance.

#### CRedit authorship contribution statement

**Pei Huang:** Conceptualization, Methodology, Validation, Writing – original draft, Writing – review & editing. **Marco Lovati:** Conceptualization, Methodology, Validation, Writing – original draft, Funding acquisition. **Jingchun Shen:** Methodology, Resources, Writing – review & editing. **Jiale Chai:** Methodology, Writing – review & editing. **Xingxing Zhang:** Conceptualization, Writing – review & editing, Funding acquisition.

#### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.



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