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Shared energy in renewable energy communities: the benefits of east- and west-facing rooftop photovoltaic installations.

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Abstract

Renewable energy communities (RECs) offer a promising perspective for decarbonizing the building sector. This is accomplished by enhancing the uptake, among others, of citizen-owned rooftop photovoltaic systems. A key challenge lies in ensuring that photovoltaic generation matches the needs of community members, i.e. maximizing shared energy index. Indeed, the shared energy depends on the consumption habits of individual members and the rooftop characteristics, such as orientation and inclination of available pitches, which influence the production curve. Therefore, clear guidelines on which roof pitches are most suitable for PV generation within RECs might be helpful during the design of such communities. In this paper, we investigate the optimal orientations and tilt angles for PV systems in REC design. We conducted a robust Monte Carlo simulation of an energy community comprising 60 users, 30 of which are equipped with rooftop PV systems for a total of 150 kWp installed. Our analysis revealed that pitches with West and East offer comparable, if not better, shared energy values than those South-facing, consequently mitigating peak power dispatched to the grid. Besides, shared energy remains quite constant across various tilt angles. These findings suggest that buildings with non-South-facing roofs should not be overlooked, but embraced in the design of renewable energy communities as they can contribute significantly to shared energy.

Highlights:

- Evaluation of PV orientation and inclination in RECs' shared energy
- South-facing PV isn't the optimal for shared energy
- East/West orientations enhance shared energy slightly

- Shared energy remains quite constant across various tilt angles

Keywords: energy community, photovoltaics, shared energy, self-consumption, renewable energy

Word count: 5213 words.

Abbreviations

CEC	Citizen Energy Community
DSC	Demand-Synchronicity Correlation diagram
EC	Energy Community
EU	European Union
IEMD	Internal Market for Electricity Directive
IP	Injection Peak
KPI	Key performance indicators
P2P	Peer-to-peer
PV	Photovoltaic
REC	Renewable Energy Community
RED II	Renewable Energy Directive (recast)
SE	Shared Energy

1. Introduction

The European Union is at the forefront of the energy transition, striving for a sustainable model prioritising reduced greenhouse gas emissions and environmental conservation (Caramizaru and Uihlein, 2019). Recent global events have further complicated this shift. COVID-19 pandemic, coupled with geopolitical tensions, triggered an unprecedented increase of energy demands, materials and goods prices, reshaping the landscape of energy generation, distribution, management, and consumption. Against these challenges, the push for decarbonization and a cleaner, decentralized energy model remains unwavering, supported by the rapid advancements in renewable energy source (RES) technologies over the last two decades. The rapid integration of RES into the power grid is a multifaceted challenge. For example, the inherent variability of these sources requires smart and advanced control systems to maintain grid stability and reliability and to accomodate even more renewables, as well the increasing demands on most power systems (Banerjee et al., 2016).

The building sector in the European Union is one the major contributors to primary energy consumption (40% of primary energy) and CO_2 emissions (36%), according to the Energy Performance of Buildings Directive (European Union, 2021). To address this, the Clean Energy Package for all Europeans introduces the concept of Renewable Energy Community (REC) that pivots on the importance of a decentralized and democratically governed energy system led by citizen, small-medium enterprise and non-profit organization. RECs promote the widespread adoption of citizen-owned renewable energy assets, like rooftop photovoltaic (PV) systems, and optimizing energy sharing within the community, representing a forward-thinking approach to decarbonize the building sector and reducing the impact of rising renewable energy sources on the grid.

1.1 Literature Review on RECs

Energy communities (EC) have gained significant attention in the scientific literature in recent years. This topic is complex and requires a multidisciplinary approach, spanning various research domains (Lode et al., 2022): from energy and engineering to computer science, business, and management, economics and social science. Besides, there is ambiguity in energy systems literature concerning using the word “community”. A recent study (Bauwens et al., 2022) identified and classified 183 different definitions of EC. One of the first conceptual classifications of the meaning of community has been proposed by (Walker et al., 2007). The most recent extension of the original classification identify community as: outcome, process, actor, network, identity, place, scale, and technology. For instance, the technology dimension accounts for the perception of community in terms of technological devices that materially connect members. Another classification approach is to identify community as the activities they engage with, distinguishing between supply-side aspects (i.e., electricity and heat generation), demand-side activities (i.e., energy efficiency and conservation) and the integration of supply and demand-side activities. At last, it was suggested to classify the community according to their objectives distinguishing between economic, environmental, social, political, and infrastructural objectives (Bauwens et al., 2022).

At the European level, the definition of EC gaining road acceptance is provided by the RED2 (European Union, 2018) and IEMD (European Union, 2019) directives. Under these umbrella definitions, an EC is defined as a legally encoded market where participants have the rights to share, consume, produce, and engage in other energy-related services while offering their members economic, environmental and social benefits. The specificity of REC, with respect to the Citizen Energy Community (CEC), is in the renewable nature of the energy supply. The governance structures of RECs, often rooted in participatory and democratic principles, are crucial in ensuring community cohesion, trust, and shared vision. (Lowitzsch et al., 2020) explored the governance model of RECs emphasizing the importance of establishing regulatory sandboxes as a means to facilitate a more effective transposition of the EU directive into national law, allowing for experimentation of the EC enabling framework optimal conditions. (Haji Bashi et al., 2023) reviewed recently the transposition of the EU directive in the member states, identifying benefits, barriers, and regulatory misalignments compared to the European legislation.

Energy community projects are inherently shaped by their business models. (Ceglia et al., 2020) provided insights into the potential benefits of RECs, stressing the importance of renewable energy complementarity and spatial organization. While, (Sousa et al., 2019) and (F.G. Reis et al., 2021) offered a comprehensive overview of emerging energy community markets, delving into their motivations, challenges, and market designs.

Energy communities have been introduced in the EU legislation with the explicit intention of maximizing the consumption within the EC of locally-produced renewable energy. In this perspective, a critical aspect of RECs is the sizing of technologies, which requires balancing load demands, renewable generation capacities, and storage solutions. Energy storage systems have been proven to increase the energy shared within the RECs (Pena-Bello et al., 2021). Nevertheless, their high capital cost is hindering their widespread in absence of explicit incentive (Fina et al., 2019). In this regard, (Gjorgievski et al., 2023) investigated a peer-to-peer (P2P) mechanisms to ensure the profitability of EC across 39 EU member states in the absence of explicit incentives, where the shared energy is exented from part of the network charges. On the other side, the virtual net-metering energy community approach is the main regulatory framework implemented across European member states (Minuto and Lanzini, 2022). From an EC member perspective, demand-side management strategies and an optimized sizing of PV capacity remain the most cost-effective measures to ensure a high level of bill reduction and shared energy within the community (Tostado-Véliz et al., 2022).

Concerning the modeling and design of energy communities, the literature proposes different tools (Minuto et al., 2022) and methodological approaches: techno-economic (Viti et al., 2020), optimization (Perger et al., 2021), metaheuristic and Monte Carlo simulation (Tomin et al., 2022a), multi-criteria (Cielo et al., 2021; Tomin et al., 2022b), agent based model (Fouladvand et al., 2022; Mussawar et al., 2023), game theory (Malik et al., 2022). (Gjorgievski et al., 2021) reviewed the social arrangements, indicators, methods and modeling objectives used to investigate energy communities, offering a technology perspective on ECs, ranging from solar-centric to wind-focused or even hybrid communities that integrate multiple renewable sources. Machine learning algorithms might offer a wide range of applications in the management of the energy community (Giannuzzo et al., 2024). (Hernandez-Matheus et al., 2022) systematically categorized the main ML algorithms based on their applications in forecasting, storage optimization, energy management systems, power stability and quality, security, and energy transactions. Advancements in smart grids technology have been instrumental in the evolution of RECs. For instance, distributed ledger technologies, reviewed recently by (Zia et al., 2020), might enable P2P energy sharing and trading among members, without the mediation of any third-party.

1.2. Scope, gap and contribution of the current study

In this paper, we adopt the EU definition of energy community where the technology dimension is "renewable", and the energy exchange among the members is "virtual". The renewable energy community modeled herein is powered by solar photovoltaic systems without energy storage. Electricity is shared virtually among members using the existing public distribution grid.

In the literature, several authors have explored energy communities with the aim of optimizing demand and production sizes to maximize economic indicators, energy exchanged within the community, or with the grid. For instance, the optimization of PV peak power in the case of energy communities based on photovoltaics. However, our study is rooted in the observation that the majority of energy community papers do not specify the orientation and tilt angle of the PV systems or evaluate their optimal angles. To quantify this observation, we conducted the following query on Scopus:

- Article title, Abstract, keyword: "energy community" OR "energy communities"
- Year range: 2020 – 2023
- Document type: Article

We analyzed in detail the top 10% of the 907 query results based on citations. Table 1 summarize our findings.

Table 1. PV orientation and tilt angle used in the most 10% cited paper on energy communities.

PV orientation	Number of papers	Tilt angle	Number of papers
Not declared	49	Not declared	50
East to West	7	10° - 40 °	8
South (for North hemisphere locations) / North (for South hemisphere locations)	6	Optimized by location	2
Optimized by minimizing energy bill / annual yield	2	Optimized by minimizing energy bill / annual yield	2
Horizontal	1	0°	1
Non photovoltaic system	35	Non photovoltaic system	37

Most of the literature that investigated solar photovoltaic energy communities do not specify the PV orientation and tilt angle used, even in optimization problems. This omission most likely implies that the best orientation is South-facing when the EC is located in the Northern hemisphere (or North-facing for Southern hemisphere sites). Six authors (Casalicchio et al., 2022; Ceglia et al., 2022; Fina, 2023; Karunathilake et al., 2020;

Mazzeo et al., 2021; Petrucci et al., 2022) explicitly stated their choice of rooftops with a South orientation without providing a rationale for their choice. Other authors (Fina et al., 2020; Minuto and Lanzini, 2022; Moncecchi et al., 2020; Neves et al., 2023; Perger et al., 2021; Roberts et al., 2022) modeled case studies of ECs where buildings have site-specific orientation and tilt angle features. Consequently, they did not investigate the impact of PV orientations or tilt angles other than those constrained by the site on EC performance. Similarly, PV tilt angle is often overlooked in energy community literature. We found only two authors optimizing the PV orientation and the tilt angle of the energy community. (Al Garni et al., 2019) examined the optimal orientation and tilt angle of 18 cities to maximize the annual electricity yield. In their research on minimizing electricity bills, (Viti et al., 2020) found that PV of buildings oriented slightly toward the west better match their energy demand and increase self-consumption.

While it was already known that PVs oriented to the west and east improved self-consumption for individual buildings (Rhodes et al., 2014), to the best of our knowledge, no other author has investigated orientation and tilt angle in an energy community context.

The novelty of our work lies in expanding the understanding of how to design energy communities (ECs), specifically identifying which rooftop tilt and orientation are most suitable for promoting the widespread adoption of new PV capacity without impacting the grid.

The current study aims to investigate the impact of the orientation and tilt angle of the PV systems on the EC's energy shared and injected into the main grid. In Section 3.1 we present the effects of these rooftop geometrical parameters on the synchronism between generation and demand profile for different orientation and tilt angle. In Section 3.2, we develop a Monte Carlo simulation to systematically investigate different configurations of an energy community comprising 60 households with PV systems (150 kWp).

2. Materials and Methods

In this work, the renewable energy community is modeled as a group of households behind the same point of common coupling. Some members are the prosumers of the energy community, having installed a rooftop photovoltaic system. Each household is modeled to exhibit a unique energy demand behavior. The PV-generated surplus power by households with PV systems is injected into the local distribution grid. Part of the electricity export is virtually shared within the energy community (i.e. self-consumed virtually by the community using the public grid) whenever there is a matching energy demand from the EC members. The exceeding quota (i.e., injected electricity that is not matching the community load) is simply available to the grid. Electricity is withdrawn from the grid when the self-generated electricity is insufficient to fully satisfy the overall energy demand.

The energy community power flow and energy balance are simulated in this work using a Python-based simulation tool developed by (Pena-Bello et al., 2021), available open-source on GitHub (Bello, 2023). The tool simulates a residential energy community where some members have installed PV systems or batteries. Since, in this work, we aim to investigate the direct influence of the photovoltaic inclination and orientation on the shared energy, the number of members owing storage systems is set to zero to avoid any influence due to storage charge/discharge dynamics. The simulation tool allows the selection of different energy sharing strategies within the community. In our study, we opted for the "self-consumption maximization" strategy.

2.1 Data sources

The annual PV profile with a 1-hour resolution is obtained using the Python *pvlib* module (Holmgren et al., 2023). A typical meteorological year's data, sourced from PVGIS, and a "Hanwha HSL60P6-PA-4-250T" PV module from the Sandia modules library are used. The resulting power profile represents the direct current output prior to the inverter as required by the simulation tool. Where, the alterneting current output is obtained considering an inverter efficiency of 94%. For the geographical setup, we used coordinates corresponding to the city of Turin, in Italy (latitude: 45.056°, longitude: 7.651°). The PV size, orientation and inclination are input parameters, with azimuth angles defined conventionally: -90° for East, 0° for South, and -90° for West.

The member's electricity demand profiles are sourced from a dataset of 1,000 synthetic Italian residential demand profiles used previously by (Minuto and Lanzini, 2022).

The input dataset is represented by the Demand-Synchronicity Correlation (DSC) diagram, proposed by (Minuto and Lanzini, 2022), and shown in Figure 1. The DSC diagram provides a holistic view of the members' distribution within the energy community, depicting the balance and synchronicity between production and demand. Each dot in the DSC diagram represents a household. The x-axis represents the Normalyzed Demand, where the households' energy demand is normalized dividing for the average PV generated energy per household in one year (2.5 kWp installed on average per household). Where, the PV profile has a 25° inclination and South orientation, generating 1483 kWh/year per kWp in DC. The y-axis represents the Synchronicity between demand profiles and PV generation, calculated using the Pearson Correlation Coefficient over the year, which evaluates the linear correlation between the two time series of the demand profile and the production profile. This can range from -1 to +1, with +1 indicating perfect generation-demand synchronism and -1 indicating perfect asynchronism. The DSC diagram is divided into four quadrants by the value of 0 Synchronicity and 0.42 that is the average Normalized Demand. The Q1 quadrant refers to households with asynchronous low energy demand, the Q2 quadrant refers to households with asynchronous high energy demand, the Q3 quadrant refers to households with synchronous low energy demand, and the Q4 quadrant refers to households with synchronous high energy demand.

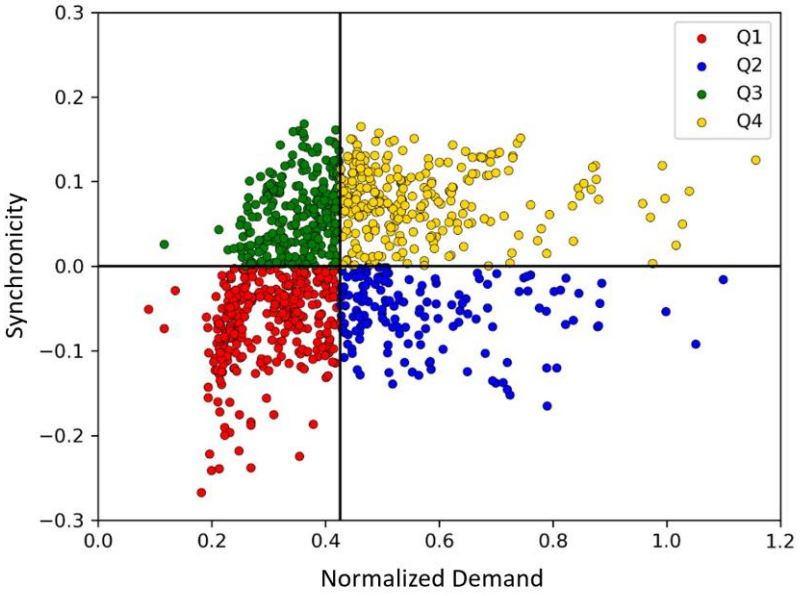


Figure 1: Representation of the household's demand profile dataset in the Demand-Synchronicity Correlation diagram. Each dot represents a household. On the y-axis the Synchronicity between energy demand a PV generation, on the x-axis the household yearly energy demand normalized by the yearly PV generation per household.

2.2 Simulation setup

In this study, we model an energy community comprising 60 households, 30 of which are equipped with PV systems with a total peak power of 150 kWp. The EC's production-to-demand ratio is set at 0.42. For instance, in the south-facing (25° tilt) PV configuration, it generates 222 MWh of electricity annually for a total energy demand of 94 MWh. The analysis goal is to assess the impact of PV system orientation and inclination on the energy shared within the community and the eventual reduction in peak energy fed into the main grid. To conduct this analysis comprehensively, we adopt a Monte Carlo simulation approach, executing 100 simulations for each EC configuration defined by specific PV inclination and orientation settings. These simulations are designed to assess the effects of various factors on the EC, such as synchronicity between member energy demand and renewable energy production, PV system ownership distribution, and PV sizing.

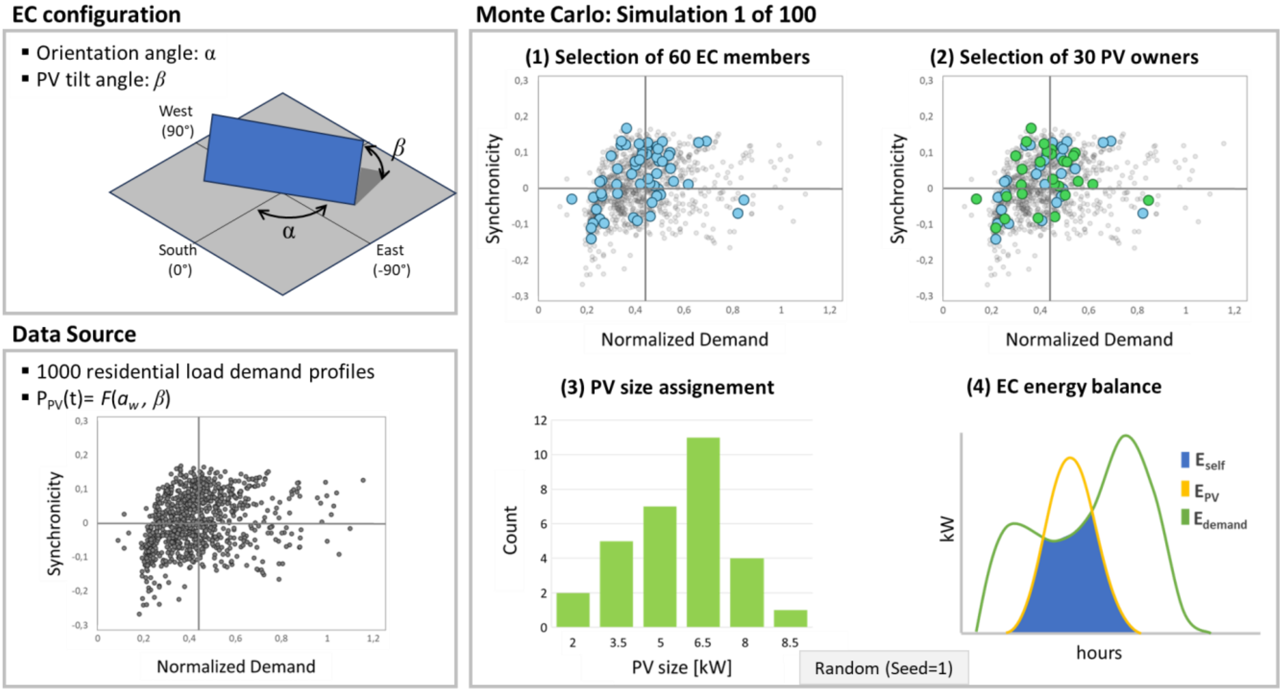


Figure 2: Schematic of the simulation methodology. A EC configuration is defined by selecting PV orientation and tilt angles. Each configuration undergo 100 Monte Carlo simulations: (1) 60 load demand profiles are chosen, (2) half of which are equipped with PV systems of (3) different sizes. The annual energy balance is determined by calculating the hourly virtual self-consumption within the energy community (4).

The methodology for our simulation is illustrated in Figure 2. The process begins with the selection of an EC configuration by setting the inclination and orientation parameters for the PV systems. For each configuration, 100 simulations are carried out. These simulations introduce controlled randomness in selecting demand profiles, determining PV system owners, and deciding the sizing of PV systems, facilitated by the use of seeds. Specifically, 60 demand profiles are randomly chosen from a database of household load demands (ad described in Section 2.1), and 30 EC members are randomly selected to receive PV systems. The size of each PV system is determined by a symmetrically truncated normal distribution, defined by the equation:

$$\text{PVsize}_{max} = 2 \cdot \text{PVsize}_{ave} - \text{PVsize}_{min} \tag{1}$$

with $PVsize_{ave}$ equal to 5 kWp and $PVsize_{min}$ set at 1 kWp.

To ensure that the outcomes of each EC configuration, despite incorporating elements of randomness, maintain consistency across variations in PV system orientations and inclinations, a consistent set of seeds is employed across the simulations. For instance, the 60 demand profiles selected during a simulation with seed n.1 remain identical whether the PV orientation is South or West, easing the comparison of results. Therefore, the sizes of the 30 PV systems within the community stay consistent. This methodology ensures that stable input factors, like demand profiles and PV system sizes, don't introduce unintended variations in the results. All results from the simulations are presented with a 95% confidence interval, emphasizing the statistical reliability of our findings. Moreover, under the assumption that the PV systems align with the orientation of the rooftop on which it is installed, all PV have same orientation and tilt angle.

The simulation outputs are the Shared Energy (SE) index and the Injection Peak. The Shared Energy index expresses how much of the energy generated by the community's PV systems (E_{PV}) is self-consumed (E_{selfc}) locally within the community without exporting it:

$$SE = \frac{E_{selfc}}{E_{PV}} \cdot 100 \tag{2}$$

where E_{selfc} is defined as minimum between PV energy generation and EC demand for any timestep.

The second KPI is the Injection Peak (IP). The latter represents the maximum value of the power injection at the point of common coupling during any given timestep over the simulated year:

$$IP = max(P_{PV}(t) - P_{EC}(t)\ )\ \forall\ t\ \in [0, 8760] \tag{3}$$

where P_{PV} is the total power generated by all PV systems and P_{EC} is the total energy demand within the energy community in each timestep (t) of the simulation. The IP indicator holds significant relevance for the electrical distribution system as it offers an estimate of power grid flow inversion. Inversions can pose challenges, especially when the grid is not designed to handle backflow, therefore it is crucial to reduce as much as possible this peak to ensure the stability and efficiency of the distribution system, reducing potential risks and infrastructural strain.

3. Results

3.1. Energy Community characterization

3.1.1. Effect of rooftop orientation

In this section, we aim to explore how the rooftop orientation affects the performance of the REC members on the demand-synchronicity correlation diagram. Table 2 details the annual energy yields of a 1 kWp PV system across various orientations in DC. The southward orientation produces the peak energy of 1483.6 kWh, serving as a reference. West and East orientations show power output reductions by 19.48% and 16.80%, respectively.

Table 2. Annual energy production from a 1 kWp PV System with different orientations

PV Orientation	90° (W)	45° (SW)	0° (S)	-45° (SE)	-90° (E)
DC Energy output (kWh)	1194.6	1390.5	1483.6	1420.6	1234.4
Reductions in output energy with reference to the South-facing orientation [%]	19.48	6.28	-	4.25	16.80

In Figure 3, we show how the community's members distribution within the DSC diagram is affected by modifying the orientation of the installed PV panels. Arrows on the graph signify the movement of a household's position when the PV orientation shifts from a South orientation, denoted by the arrow's tail, to an East orientation, denoted by the arrow's tip. The arrows are colored based on the quadrant they belonged to in the South orientation. It is observed that the direction and magnitude of the arrows vary among households. Still, collectively, each quadrant demonstrates a distinct group behavior. This trend is evident when examining the noticeable shifts in both the Normalized Demand distribution (Figure 3 - top panel) and the Synchronicity distribution (Figure 3 - right panel).

For the South orientation, the Normalized Demand distribution shows a single peak centered around 0.42 and exhibits a right-skewed asymmetry. Meanwhile, the Synchronicity distribution features a more symmetric dual peak. As the panels shift to an East orientation, there's an expected reduction in production, leading to a shift towards higher values of Normalized Demand. In fact, all arrows in the DSC diagram point to the right. On examining synchronicity, the transition from South to East reveals a more pronounced polarization of the curve towards extreme values. Observing the DSC diagram, quadrants Q1 and Q2 primarily show arrows pointing downward (indicating reduced synchronicity), while quadrants Q3 and Q4 have arrows pointing upwards (indicating increased synchronicity).

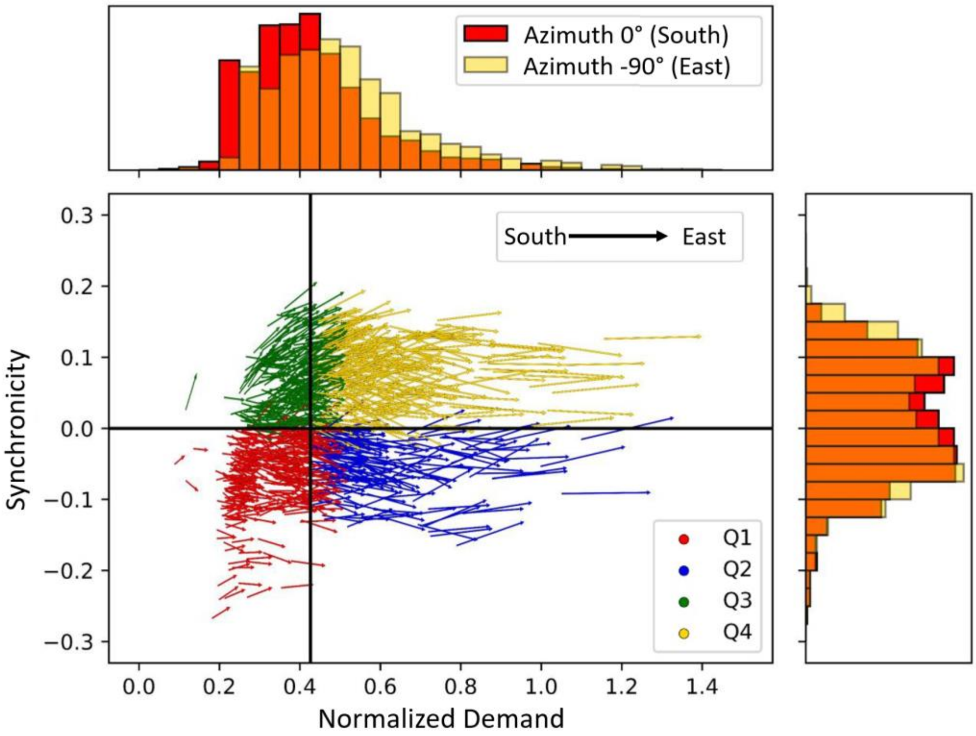


Figure 3: Shifts in the DSC diagram due to PV orientation changes. Arrows indicate household position change from South (0°) to East (-90°), colored by their position in the South case. Top panel: Normalized Demand distribution for South (Red) and East (Yellow), with Orange bars indicating the overlap between the two distributions. Right panel: Synchronicity distribution for both orientations.

The effect of varying the orientation from South toward West is depicted in Figure 4. It is noted that the Normalized Demand undergoes a shift and broadening of the symmetrical peak as the orientation similarly to the East case. In contrast, concerning synchronicity, the two distinct peaks merge into a singular symmetric peak centered around zero. Besides, distributions for other orientations (Southwest, Southeast) show intermediate behavior and are reported in the supplementary materials (S2).

Synchronicity captures the correlation between the members demand profile and the production profile. This means that those members whose daily demand profile has a more pronounced consumption towards the evening rather than at noon will have greater synchronicity with a west-facing PV than with a south-facing one. Conversely, a member whose demand profile has consumption typically located in the morning will have greater synchronicity with an east-facing PV than with a south-facing one. These phenomena underlie the increase or decrease in synchronicity of certain users compared to different PV orientations shown in Figures 2 and 3.

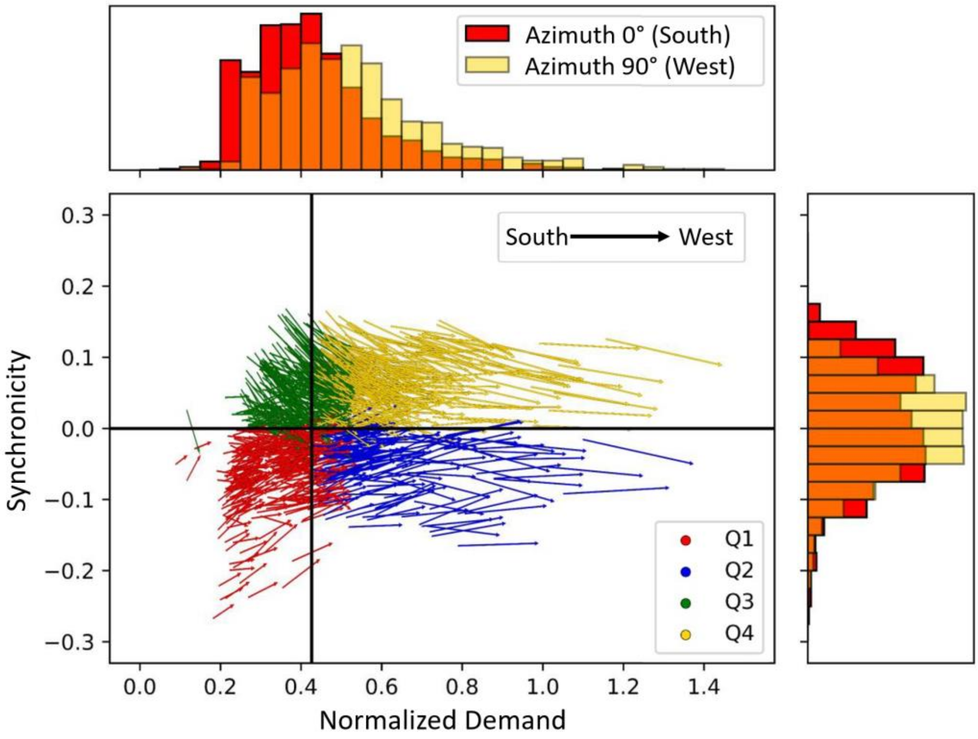


Figure 4: Shifts in the DSC diagram due to PV orientation changes. Arrows indicate household position change from South (0°) to West (90°), colored by their position in the South case. Top panel: Normalized Demand distribution for South (Red) and West (Yellow), with Orange bars indicating the overlap between the two distributions. Right panel: Synchronicity distribution for both orientations.

3.1.2. Effect of rooftop tilt angles

In this section, we aim to explore how the rooftop tilt angle affect the position of energy community members on the demand-synchronicity correlation diagram. Table 3 illustrates the annual energy outputs of a 1 kWp PV system at various rooftop tilt angles. The optimal tilt angle for the given location is 40°, which achieves the maximum energy production of 1513.0 kWh in DC. As the tilt angle deviates from this optimal angle, energy production decreases. Notably, the 20° tilt angle the most significant reduction, albeit it is a modest 3.63%.

Table 3. Annual energy production from a 1 kWp PV System with different rooftop tilt angles

Inclination	**20°**	**25°**	**30°**	**35°**	**40°**
DC Energy output (kWh)	1458.1	1483.6	1501.4	1511.4	1513.0
Decrease compared to 40° (%)	3.63	1.94	0.77	0.11	-

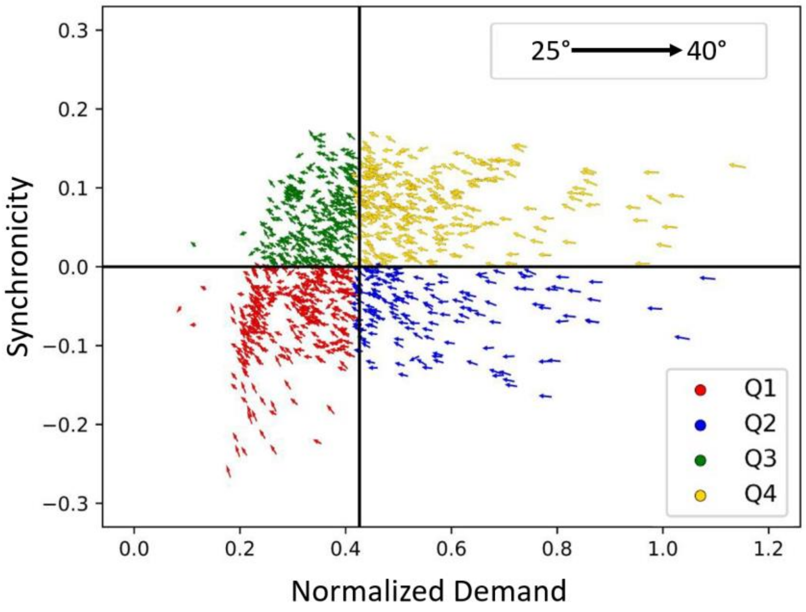


Figure 5. Shifts in the DSC diagram due to rooftop tilt angles changes. Arrows indicate household position change from a pitch angle of 25° to 40°, colored by their position in the 25° angle.

In Figure 5, the Demand-Synchronicity Correlation diagram illustrates the comparison between the energy community distribution for a PV system with a tilt angle of 25° angle respect to 40° (optimal tilt angle for the selected location). The former was selected as it served as the reference value in the simulation setup described in section 2.2. Analyzing the variations in the normalized demand distribution between these angles is minimal. Nevertheless, there is a discernible trend: as the tilt angle increases from 25° to the optimal 40°, the distribution shifts to the left on the diagram, signifying decreased normalized demand values. This shift aligns with expectations, as tilts further from the optimal angle inherently yield less annual energy, affecting the denominator of the normalized demand and thereby reducing its value. In addition, across the range of inclinations, changes in Synchronicity were marginal, with the deviations from the 25° being almost imperceptible.

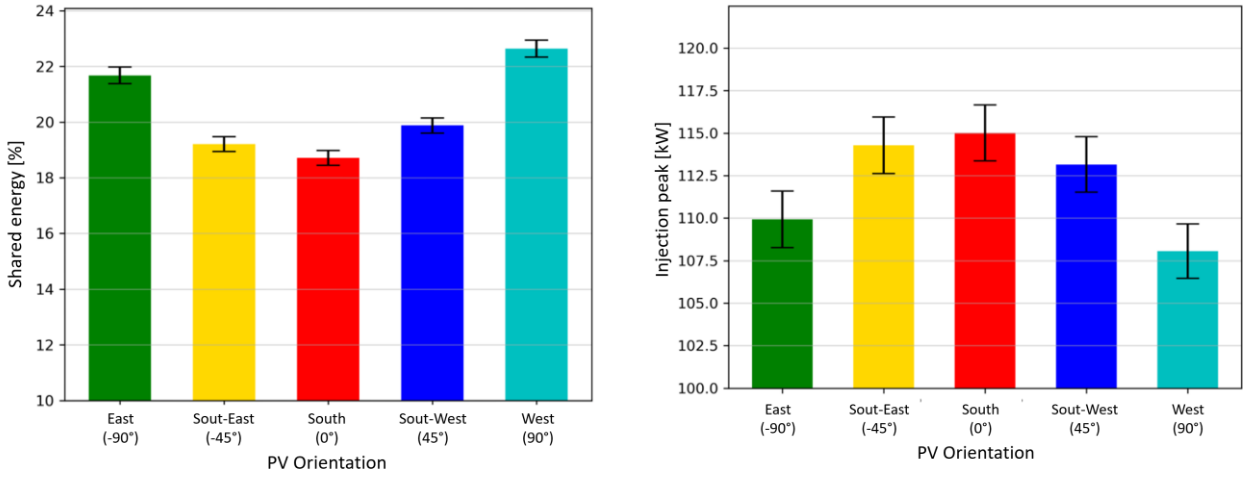
Delving deeper into other inclinations (reported in the supplementeary materials S3): a 20° tilt angle results in reduced PV production compared to 25°, leading to a rise in normalized demand, manifesting as a rightward shift in the DSC diagram. Conversely, inclinations of 30°, 35°, and 40° produce greater energy than the 25° tilt, decreasing the normalized demand and causing a leftward shift. However, the Synchronicity differences between various tilts were minimal, and no pronounced directional trends were observed.

3.2. Energy Community simulations

This section presents the outcomes of our simulations focusing on an energy community comprised of 60 households, where half own a PV system. The primary aim is to investigate the effects of varying orientations and inclinations of rooftop PV installations on the shared energy index and the peak injection into main grid, as elaborated in section 2.2. These KPIs are examined across five distinct rooftop orientations and inclinations. To ensure the accuracy and robustness of these findings, all results presented in the following include a 95% confidence interval, determined from 100 simulations evaluated through the Monte Carlo approach.

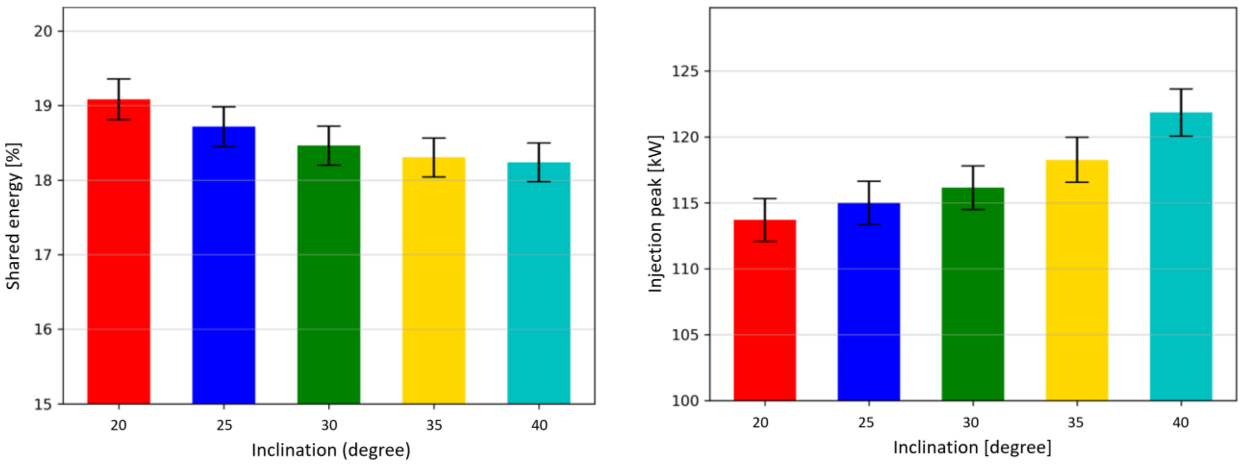
Figure 6a illustrates how shared energy index is affected by changes in rooftop orientation at 25° inclination. Interestingly, the results challenge conventional expectations. The south-facing orientation, commonly perceived as optimal (as it registers the highest annual renewable energy yield), exhibits the lowest shared energy index (18.7%). The east and west orientations, despite their sub-optimal energy generation capabilities, record higher shared energy values of 21.6% and 22.6%, respectively. This represents an increase in shared energy index by up to 20.8% (i.e. 3.9 percentage points) when compared to the south-facing orientation.

Figure 6b delves into the injection peaks across varying rooftop orientations. These findings align more closely with the trends in PV generation. The south orientation, with its higher energy output, shows the highest power injection into the main grid, measured at 115 kWp. Conversely, the less productive east and west orientations demonstrate reduced injection peaks.



(**a**) (**b**)

Figure 6. Comparison of the energy community SE (a) and IP (b) across five PV systems orientations. Error bars indicate 95% confidence interval.



(**a**) (**b**)

Figure 7**.** Comparison of the energy community SE (a) and IP (b) across five PV systems inclination. Error bars indicate 95% confidence interval.

Figure 7a illustrates how SE fluctuates with changes in rooftop inclination at constant south orientation. Despite the optimal roof inclination for electricity generation for the selected locality being at 40°, the highest shared energy index (19%) is achieved at rooftop inclination of 20°, even though the yield increase is just 3.8% (i.e. 0.7 percent points) increase respect to the 40° configuration.

Figure 7b delves into the injection peaks across varying rooftop inclinations. The IP is aligned with the trends in PV generation. The 40° inclination, with optimal energy generation, shows the highest power injection into the main grid, measured at 122 kWp. Conversely, the less productive 20-degree PV showed reduced injection peaks.

The counterintuitive results observed for the increase in SE for the west and east orientations, despite the reduction in PV generation, can be attributed to the enhanced synchronicity between demand and generation for certain households. Specifically, those with higher energy demands in the early mornings for the east orientation or those with elevated energy demands in the late afternoon for the west orientation.

Conversely, the rise in shared energy index for tilt angles lower than the optimal is attributed to the decrease in surplus energy generated that is fed into the grid. This surplus does not contribute to self-consumption (which forms the numerator of the KPI) but is factored into the denominator, thereby reducing the SE value.

Using the Monte Carlo approach, we've ensured the robustness of our findings. This method provides a confidence interval that clearly highlights discernible differences in outcomes across various orientations and tilt angles.

4. Discussion

This study offers crucial insight for the design and planning of energy communities supplied by rooftop photovoltaic (PV) installations. It presents a comprehensive analysis of how rooftop orientation and tilt angle affect the share energy and injection peak indicators of a solar energy community.

Traditionally, the southward-oriented rooftop has been favored for its optimal energy yield. However, our study introduces a nuanced perspective, especially when considering energy communities. Interestingly, even with their reduced annual energy yield, rooftops with eastward and westward orientations recorded the highest shared energy index. This indicates a minor impact of the renewables on the grid network, as shown by the injection peak indicator, which is reduced for the west and east orientations compared to the south. This can be attributed to a better synchronicity between energy demand and PV production during early mornings and late afternoons. Our findings suggest a shift in perspective: maximizing energy yield, as achieved by the southward orientation, does not necessarily equate to optimizing energy sharing within a community framework. This is especially important considering the need to increase renewable energy penetration in the system without compromising the stability and resilience of the grid network. Conversely, the energy self-consumed virtually by the energy community achieves the highest value for southward PV orientation at the expenses of higher injection peak into the grid. This is a significant aspect in contexts were the absolute shared energy within the energy community is explicitly incentivized, such as in Italy (Minuto and Lanzini, 2022), or where there are implicit incentives policies, like the discount on the network charges investigated by (Gjorgievski et al., 2023).

EC with smaller PV size tend to have a higher SE index, because of the reduction of the denominator E_{PV}. However, as the size of the PV installation reduces, The SE index saturates at 100% because the amount virtually self-consumed by the community (E_{self}), defined as minimum between E_{demand} and E_{PV}, will be equal to E_{PV}. This trend is consistent across all PV orientations. As the PV size diminishes, the differences in performance between various orientations disappear, with all orientations potentially achieving a 100% SE index. SE index capture the crucial aspect for the design a balanced energy community where all renewable generated energy can be utilized by the community without excessively impacting on the grid.

Another factor that might hinder the use of west and east PV orientations is economic disincentivization if grid injection remains a primary income source for the energy community. However, in scenarios with high PV penetration, like the CASIO electricity market (Zhao et al., 2022), where surplus generated energy is not remunerated, the techno-economic evaluation of these orientation will eventually change.

From a policy recommendation standpoint, this insight is invaluable for promoting the widespread adoption of citizen-owned rooftop photovoltaic (PV) to decarbonize the building sector and reduce the impact of new renewable energy sources on the grid. It suggests that there should be no undue emphasis or restriction on south-faced rooftop PV installations in the design and feasibility study of energy communities. In fact, other orientations, which many authors might have previously overlooked, can be equally, if not more, effective. This new perspective broadens the horizons for energy and city planners, as it significantly expands the potential of rooftops that can be deemed suitable for PV generation in renewable energy communities.

Moreover, the influence of rooftop pitch inclination on SE further accentuates the complexity of PV system installations. Our findings indicate that even at non-optimal angles, such as 20°, SE can be optimized, albeit with a slight reduction in annual energy yield. Consequently, this challenges the conventional emphasis on optimal tilt angles and suggests that a range of inclinations can be effective, depending on the specific goals of the energy community.

Certain limitations to our study warrant mention. The investigated energy community was not optimized to maximize the shared energy index.However, this doesn't undermine the general results. In fact, this condition allows us to discern differences that might not be noticeable in a community with saturated shared energy.

Our investigation was confined to a single location. While this specificity allows for a detailed analysis, the results might be influenced by variations in PV yield from other regions. Such variations could shift the community's position on the DSC diagram and potentially alter the average shared energy. Nevertheless, it's crucial to emphasize that these changes in yield would likely not affect the observed impact of tilt angle and orientation on synchronicity.

On the other side, the increase in shared energy at certain orientations might be overestimated due to PV model uncertanties in calculating yield for different azimuths and tilt angles, but this does not change the general message of the paper.

Furthermore, it remains an intriguing avenue for future research to systematically explore how a system's geolocation might influence shared energy. For instance, PV panel degradation effects might vary based on orientation due to different exposures to atmospheric agents. As a result, these findings might not remain consistent throughout the panel's lifespan. Local effects, such as dust accumulation or dirt on panels at specific orientations, can also influence the outocome. Another aspect to consider is using consumption and production profiles with sub-hourly resolution. Exploiting higher-resolution profiles could offer a more granular perspective and unveil clipping effects, potentially affecting synchronicity and shared energy values.

5. Conclusions

This study embarked on an in-depth exploration of the influence of rooftop PV orientation and tilt angle on the shared energy within renewable energy communities. The findings challenge conventional wisdom in several key areas:

- Rooftop Orientation: Contrary to the prevailing emphasis on southward-oriented rooftops for optimal energy yield, our results underscore the significant potential of eastward and westward orientations in enhancing shared energy index within a community and reducing the injection peak into the grid. These orientations, despite their reduced annual energy yield, exhibited superior synchronicity between energy demand and PV production during early mornings and late afternoons.
- Tilt angle: The study also highlighted that non-optimal tilt angles, such as 20°, can still achieve optimized shared energy. This finding suggests a broader range of effective inclinations, depending on the specific objectives of the energy community.
- Implications for Energy Communities: The results advocate for a more inclusive approach in the design and planning of energy communities. Rather than an undue emphasis on south-faced rooftop PV installations, a diverse range of orientations and inclinations should be considered.

- Recommendations: energy modelers should recognize the value of previously overlooked or undervalued rooftop orientations. Policymaker should enhance implicit and explicit incentives on the shared energy. Expanding the potential of suitable rooftops for PV generation can significantly enhance the efficacy of renewable energy communities of decarbonize the building sector without impacting on the grid.

However, it's essential to acknowledge the study's limitations, including its confinement to a single location and the use of hourly resolution profiles. Future research could delve into the influence of geolocation on shared energy and employ higher resolution profiles for a more granular perspective.

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CRediT authorship contribution statement

Minuto, F D: Conceptualization, Methodology, Data curation, Investigation, Visualization, Writing - original draft, Writing - review & editing. **Crosato, M**: Software, Investigation. **Schiera, D. S.**: Methodology, Software, Investigation, Writing - review & editing. **Borchiellini, R**.: Funding acquisition. **Lanzini, A**: Conceptualization, Supervision, Writing - review & editing.

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