Master's Degree in Building Engineering

Economic analysis of Italian building-integrated Energy Communities: Investment options and profit allocation

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Abstract

Renewable Energy Communities (RECs), supported by the EU Renewable Energy Directive (RED II/III) and national incentives such as those in Italy, are emerging as key enablers of the energy transition by building-integrating photovoltaic (BIPV) systems and battery energy storage systems (BESS) at the local level. However, beyond technical and economic optimization, RECs face challenges in investment options, energy trading, and equitable benefit distribution. Existing studies often overlook the diversity of household attributes, leading to potential inequities that undermine participation and long-term viability.

This study focuses on two main PV-BESS system investment strategies, community self-invests and a third party invests, developing an Mixed Integer Linear Programming (MILP)-based Energy Management System (EMS) optimization framework that maximizes community profits while ensuring fairness in individual households returns based on various household attributes. The model jointly optimizes PV–BESS capacity sizing, energy flow scheduling, demand response, energy peak shifting, and investment distribution across heterogeneous households. Several investment strategies and fairness-oriented allocation mechanisms and energy-saving incentives — considering household types, consumption patterns, and energy-saving behavior — are evaluated under the Italian regulatory context. Results demonstrate improved self-consumption, bill saving ratio, and Quality of Experience (QoE) without sacrificing economic efficiency. Meanwhile, by comparing the scenario with Italian sharing electricity incentives, studying the influence of political incentives in BIPV investment. The findings provide actionable insights for designing sustainable, inclusive, and policy-compliant community energy system investments.

Keywords:
Renewable Energy Communities (RECs), Energy Management System (EMS), Building integrating Photovoltaics (BIPV), Energy Fairness, Investment, Profit distributions

Content

Introductions

Research Context

Climate change and energy transition have become central to global sustainable development. Climate research and action should not be confined to the 2100 time frame, but must focus on long-term socio-environmental feedback mechanisms and deep decarbonization pathways. As key enablers of the EU's energy transition, Energy Communities (ECs) can drive distributed renewable energy deployment, enhance energy independence, boost local economic returns, and play a positive role in social equity. The EU has established ECs' legal status, participant eligibility, grid connection requirements, and financial support mechanisms through regulations like the Renewable Energy Directive (RED II/III). At the national level, countries like Italy have implemented supporting legislation and economic incentives to facilitate renewable energy projects including photovoltaic (PV), battery storage systems (BESS), and building-integrated photovoltaics (BIPV). However, constructing Energy Communities involves not only technical and economic aspects but also multidimensional challenges such as institutional design, investment models, energy trading and pricing mechanisms, and equitable benefit distribution—all equally crucial for both academic research and policy formulation.

Research Motivation

As global attention on sustainable development grows, community solar systems have gained prominence as an efficient and eco-friendly energy solution. However, their widespread adoption still faces multiple challenges. To maximize economic benefits while ensuring optimal operation, the key lies in optimizing energy system scheduling and household investments. Optimizing scheduling enhances energy efficiency and reduces waste, while investment optimization boosts user engagement and makes the system more cost-effective. Moreover, integrating community energy pricing mechanisms and equitable profit-sharing models into Energy Management Systems (EMS) requires not only technical improvements but also consideration of socioeconomic factors to ensure fair energy access for vulnerable groups. Addressing these challenges is crucial for building a sustainable and inclusive community energy ecosystem.

Research gaps

On the economic side, despite many papers focusing on the energy community and P2P market, few researchers further consider a residential building as an energy community and sharing a collective renewable system, different resident attributes (such as household type, energy consumption level, income level, environmental awareness, etc.), and designs based on reasonable investment strategies for the different resident attributes.

On the social side, despite many researches discussing optimizing energy usage efficiency and maximizing the total welfare of a community by optimizing algorithms, whereas few studies go deeply into incentives for classified households. The energy-saving, eco-friendly, and low-income households can be treated in an unfair and unreasonable way. The equity of the community to each resident cannot be guaranteed.

Research Objectives

The main aim of this study is to check the financial feasibility of energy communities under two different investment situations, while also thinking about the fair sharing of benefits among community members. The research will test two investment ways: (1) community self-investment and (2) investment from an third party. Plus, the study will look into different ways for sharing benefits and apply energy saving incentive methods . This study plans to make a MILP-based Energy Management System (EMS) model that optimizes Photovoltaic (PV) and Battery Energy Storage System (BESS) sizes, energy sharings, and encourages more people involved in energy saving.

The study will look at several investment plans and fair ways to share benefits, made to fit the features of individual households. It will see how these plans affect the return on investment for households, their own consumption of energy, and their Quality of Experience (QoE) in different households types.

The goal is to give ideas on how to reach a good balance between economic efficiency and social fairness, making sure Renewable Energy Communities (RECs) can last and grow in the long run. By putting together technical, economic, and fairness ideas into one optimization setup, this research wants to help make sustainable community energy management solutions that include everyone and follow set rules.

Structure of dissertation

This dissertation is organized into five chapters. *Chapter 1* provides a review of the research background and policies of the renewable energy community in the EU. *Chapter 2* reviews the relevant literature on technical and economic methods, including BIPV&BESS cutting-edge techniques and technologies, community energy optimization methods, and investment and profit allocation strategies. *Chapter 3* based on two main investment scenario, introduces the architecture of building-integrating Energy Management Systems (EMS) and their energy sharing schemes with given pricing rules, and further explores investment and profit distribution strategies, including incentive strategies. *Chapter 4* provides a detailed case-study simulation and analysis and verification of the proposed optimization strategies. *Chapter 5* concludes the dissertation and outlines future research directions.

Chapter 1 Energy communities in the European

1.1. Background and context

1.1.1. Climate change

Over the past 25 years, CO2 emissions have increased by more than 50%, pushing climate change to alarming levels. If current emission level persist, the temperature increase could exceed the +2°C threshold by 2100, causing severe damage to ecosystems and impacting human living standards. [1]

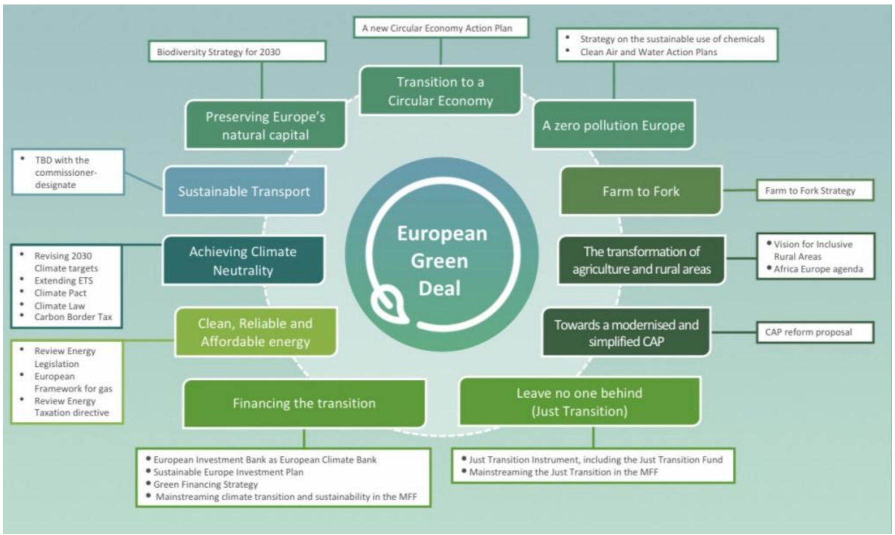


Fig. 1.1 Details of European Green Deal [1]

Producing and consuming energy is a major cause of climate change. When fossil fuels – coal, oil and gas – are burnt, they release carbon dioxide into the air, contributing to global warming. Energy use and production account for 75% of total EU greenhouse gas emissions. Reducing these emissions is a necessary action to fight climate change and reach the EU's 2050 goal of climate neutrality. Investing in renewables and cleaner forms of energy is also key to increasing energy independence. Renewable energy – whether solar, wind or hydro – can be produced in the EU, which reduces dependence from imports, and creates new jobs and business opportunities locally.

1.1.2. Energy crisis and increasing energy price

In 2022, the war between Russia and Ukraine had a catastrophic impact on the energy market, driving energy prices to record - high levels. EU countries responded in a united and prompt manner. Just weeks after Russia invaded Ukraine, the leaders of the 27 EU member states made a decision that the EU would end its reliance on Russian fossil fuels as quickly as possible. They planned to achieve this by diversifying energy supplies and suppliers, cutting down on the use of fossil fuels, and accelerating the move towards cleaner energy. The European Commission soon rolled out the REPower EU plan, which is a framework for enhancing the EU's energy independence and promoting clean energy.

1.2. Policy Framework and Goals

1.2.1 The policies and directives in EU

In accordance with the eco-friendly initiatives introduced in recent years, the European Commission put forth in 2016 a bold collection of strategies known as "Clean Energy for all Europeans" or the *Clean Energy Package*, abbreviated as CEP. This package encompasses four Regulations and four Directives, which were deliberated upon during the inter-institutional "trilogue" talks involving the European Council, representing the interests of the Member States, the European Parliament, speaking for the European Citizens, and the European Commission. The talks concluded with the enactment of the eight legislative acts in May 2019. The Regulations and Directives that constitute the package are: [2]

- Energy Performance of Buildings Directive (EU) 2018/844
- Renewable Energy Directive (EU) 2018/2001
- Energy Efficiency Directive (EU) 2018/2002
- Governance of the Energy Union and Climate Action Regulation (EU) 2018/1999
- Electricity Regulation (EU) 2019/943
- Electricity Directive (EU) 2019/944
- Regulation on Risk-Preparedness in the Electricity Sector (EU) 2019/941
- Regulation on the European Union Agency for the Cooperation of Energy Regulators (EU) 2019/942

The ambitious targets that the EU wants to achieve are part of the so-called clean energy transition towards a carbon-free economy. In particular, the CEP aims to fulfil by 2030 these targets:

- 55% Reduction in greenhouse gasses emissions
- 42.5% of Renewable Energy Sources (RES) consumption
- 11.7% Energy efficiency improvement (compared to the baseline scenario set in 2020)

Buildings as the key sectors where consumption should decrease, 42% of energy should come from renewables. the directive sets the target of decreasing the average energy use of residential buildings by:at least 16% by 2030, at least 20-22% by 2035. The end goal is that by 2050 100% buildings in the EU should be zero-emission buildings.In addition, more infrastructure should be developed in buildings for bikes and electric cars.[2]

The European Commission identified, during the development of the CEP, that the central aspects are the importance of being pioneers in the world's clean - energy transition and the positive impacts for member states in terms of new jobs, GDP growth, and investments.

Investments in clean energy across the globe have witnessed a significant surge, increasing by over 40% in recent years. This remarkable growth has been particularly pronounced in the sectors of renewable energy and energy efficiency. Between the years 2015 and 2022, renewable energy investments soared by an impressive 152%, while energy efficiency investments followed closely with a substantial increase of 139%. This trend underscores a global shift towards more sustainable and environmentally friendly energy solutions, driven by heightened awareness of climate change and the urgent need to reduce carbon emissions. The substantial investment in these areas not only reflects a growing commitment from both public and private sectors but also signals a transformative change in the way energy is produced and consumed worldwide. This period of rapid growth has laid a solid foundation for future advancements in clean energy technologies, promising a brighter and more sustainable future for generations to come.[8]

1.2.2 Italian policies and regulations

Incentives

Only a few member states have implemented a true incentive model for RECs for economic sustainability. Italy is notable as, for nearly three years since the Legislative Decree of September 16, 2020, it has set a clear incentive scheme for Energy

Communities.

REC has three types of revenue channels plus one subsidy:

1)Shared electricity incentive (Tariffa Premio per l'Energia Condivisa, TCEC)

The distribution of electricity shared between REC members (i.e. energia condivisa). The level is equivalent to approximately 110 €/MWh (0.11 €/kWh) for a period of 20 years. Based on the amount of electricity shared in real time, not total generation.

The incentive mechanism pays RECs with a 110 €/MWh premium tariff for the shared energy, which is the energy fed into the grid by a prosumer and consumed by another community member. This clear scheme has enabled studies on the possible distribution of incentives among REC members in some Italian case - studies. [3]

2)Investment subsidy (Contributo a fondo perduto, PNRR support)

From the PNRR (National Recovery Plan), for towns with a population of ≤ 50,000, up to 40% of the investment will be covered. It can be superimposed on TCEC, but "double subsidy" should be avoided ——. The same energy cannot be counted twice.

3)Grid fee relief

Because the shared power is absorbed locally in the medium and low voltage grid, part of the transmission and system costs are exempted. Approximately 0.02-0.03 €/kWh savings.

The policy was further expanded between 2021 and 2022, raising the capacity ceiling from 200 kW to 1 MW and introducing more legal entities eligible for participation, such as cooperatives, non-profit associations, and local government consortia.[4]

Renewable power feed-in grid pricing mechanism

Electricity produced by plants of any power rating, powered by renewable sources such as wind, solar, geothermal, wave, tidal, and hydraulic energy, limited, for the latter source, to run-of-river plants; Article 13, paragraphs 3 and 4, of Legislative Decree No. 387/03 and paragraph 41 of Law No. 239/04 provided, for certain types of electricity production plants, the possibility of requesting the withdrawal at an administered price of the electricity produced and fed into the grid (dedicated withdrawal). The dedicated withdrawal regime is an alternative to the normal electricity sales regime and is reserved.[5]

Fig. 1.2 Italian electricity zonal price [6]

According to the regulations of ARERA and GSE , northern Italy adopted Ritiro dedicato as a PV feed-in pricing mechanism in conjunction with I prezzi minimi garantiti (46.4 €/MWh in 2025) as a means of protecting minimum returns for producers.When the regional hourly price (Prezzo zonale orario) in North Italy is nearly 106 €/MWh in 2024 which lower than the minimum guaranteed price (I prezzi minimi garantiti), the benefit of producers will be guaranteed.[6]

$$PR_{RD} = \max(PR_{zon}, PR_{min})$$

PR_{RD}: Ritiro dedicato price(feed-in)

PR_{zon}: Prezzo zonale orario

PR_{min}: I prezzi minimi garantiti (€46.4 /MWh)

1.3. Renewable Energy Communities(REC) in EU

The EU and the UK currently have nearly 4,000 Energy Communities (ECs), with a total membership of approximately 900,000 members, averaging 844 members per EC. Germany, the Netherlands, Denmark, and the UK are leading nations, with distinct differences in dominant renewable energy types: The Alps region focuses on hydro power and biomass, Germany/Spain/France prioritizes solar power, while the Netherlands/Denmark emphasizes wind energy. ECs based on hydro power, biomass, and wind energy have higher average membership numbers than solar-based ones.

Retail-oriented ECs in Spain and Belgium far exceed average membership levels, with members often also serving as their customers. National or regional EC associations and intermediary organizations acting as "industry nurturers" have facilitated business model innovation and cross-sector collaboration. Local legislation under EU directives from 2020-2022 accelerated EC growth in countries like Italy and Spain, particularly by allowing new entities such as municipalities, social enterprises, and NGOs to enter the market.[7]

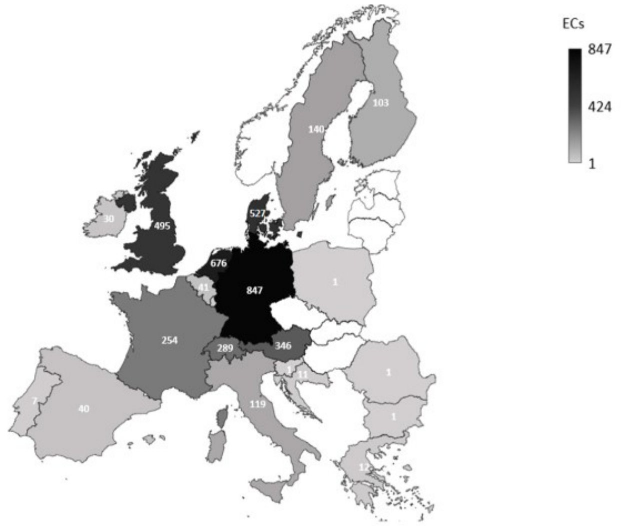


Fig. 1.3 Numbers of Energy community in EU [7]

1.3.1 The status quo of EC in European countries

The European Directive 2018/2001 defined in the European regulatory framework innovative configurations for energy sharing, collective production and self-consumption, known as RECs. [3]

Germany:

Established legal frameworks for energy cooperatives and citizen energy projects early on, featuring stable regulations and comprehensive policies targeting community renewable energy. All residents, businesses, and public institutions can participate, with strict equity dispersion requirements to prevent control by single major investors. Implementing long-term feed-in tariff (FIT) policy, low-interest loans from KfW Bank, and tax incentives; sustained and predictable incentives. Simplified network access procedures with transparent fees, encouraging virtual sharing and local power markets. Germany leads the nation in energy communities (thousands of cooperatives, diverse technologies including PV, wind, biomass, and energy storage, large installed capacity, short investment payback period (6-10 years), high social participation, and strong trust).

Denmark:

There are pretty straightforward rules for citizen energy projects, which say that there's gotta be a minimum amount of local folks as shareholders. It really pushes for local residents to invest first, and companies can only get involved if they stick to the local shareholding limits. There are financial and tax perks, and fixed prices for selling electricity back to the grid that help out wind power projects, and some even get tax cuts. Grid companies have to make sure community projects get the same shot, and the approval process is quick. Wind power groups are the big players; you see a lot of big wind farms run by the community in coastal and rural spots; and when locals own a big chunk, more people are on board with it.

Netherlands:

It clearly spells out what energy cooperatives are, and they've had solid policy support right from 2014. It really pushes for folks living close by each other to get involved, and while companies can join in too, the community always stays in the driver's seat. The "Postcode Rooises" setup: People living in certain spots team up to make their own electricity so they don't have to pay those pesky energy taxes, and they get some extra cash for investing too. Even though the government helps out with the costs of hooking up to the grid, sometimes there just aren't enough distribution lines, and that can cause a bit of a jam. Community solar projects are the big thing, and some even mix in wind power; these projects, which are medium-sized (ranging from tens to hundreds of kW), are really popular with folks and save them a ton on their electricity bills.

Spain

In the same substation or within a 500 - meter radius, shared generation is totally okay, and both businesses and public institutions can get in on it. There are capital subsidies available, which come from EU funds and local governments, along with tax reductions and some regional incentives to sweeten the deal. When it comes to grid access, though, there are capacity constraints, and how long it takes to get approval really depends on how efficient the local government is. There are photovoltaic - led projects going on, and some new energy storage pilots are popping up too. Community projects are mainly happening in sunny regions, like the southern and eastern areas. The payback periods for these projects are pretty short, usually between 6 - 9 years, and more and more people are getting involved over time.

Portugal

Policy incentives include CIEG exemptions: 50% exemption for individual self-consumers (CIEG, part of electricity tariffs, 29% of price), full exemption for energy communities. A one-time subsidy of 2500 € per household is provided. Electricity pricing structure: Simple tariff (fixed daily rates) and time-of-use pricing (different rates for peak and off-peak hours).

Italy

In 2020, Italy introduced relevant legislation allowing individuals, businesses, and public institutions to form Renewable Energy Communities (RECs) and engage in energy sharing. [4] Energy self-consumers and RECs in Italy are in the rapid start-up phase but still face multiple challenges in policy, technology, and market. As of the end of 2022, registered energy communities and shared self-consumption projects in Italy were mainly pilot projects with relatively limited total installed capacity, concentrated mainly in northern regions (Piedmont, Lombardy, Trentino-Alto Adige). Due to insufficient funding, technology, and administrative capacity, southern regions have developed slowly and lack experience and infrastructure, leading to issues of energy equity. DL 162/2019 introduced the legal concept of energy sharing and RECs for the first time. Resolution No. 318/2020 of the Authority for Electricity and Gas (ARERA) established metering and economic incentive mechanisms for shared electricity. Initially, the allowed size limit was 200 kW, restricted to participants within the same low-voltage substation coverage area. The new law passed in 2021 (Legislative Decree 199/2021) raised the size limit to 1 MW and broadened the scope of participating entities.

Photovoltaics are the absolute main technology, accounting for more than 90% of the share, while energy storage systems are still in the pilot phase but are considered key to improving self-consumption rates and peak shaving and valley filling capabilities. The introduction of digital energy management platforms helps optimize energy allocation, record transaction data, and enhance transparency. Italy offers Superbonus 110 and Ecobonus schemes. Profitable PV systems with storage are feasible in Italy.[8]

Case studies demonstrate that Renewable Energy Communities (RECs) can deliver 10%-25% electricity cost savings for participants while generating additional revenue through surplus power sales. In the Mount Alpi project, public buildings and residents jointly invest in photovoltaic systems, achieving annual CO_2 emission reductions of approximately 150 tons via energy sharing, with investment costs recouped within 5-7 years. The energy community model also enhances local energy independence, fosters neighborhood collaboration, and drives local employment growth.[10]

Self-consumption and RECs project in Italy.

Single self-consumption	Costantino, Agritourism, Calabria
	Village Paradise, Agritourism, Valle d'Aosta
	Megabox, Company, Puglia
	C&F, Agricultural Society, Campania
	Le Cimate, Winery, Umbria
	MoliseGoloso, Cannery, Molise
	ecOstello, Hotel, Lazio
	Solis GreenLog, Logistics center, Abruzzo
	Green Station, Station, Basilicata
	WE(Y) Welfare Efficiency, Physiotherapy center, Piemonte
	Val Paradiso, Farm, Sicilia
Collective self-consumption	Condominium Torino, Condominium, Piemonte
	Donatello, Condominium, Piemonte
	H-Farm, Campus, Veneto
	La Casa dell'Energia, Buildings, Sardegna
	NZEB Building Social Housing, Buildings, Toscana
	Self-User Project, Condominium, Emilia Romagna
	RE(Y) Retail Efficiency, Shopping Mall, Veneto
	Qui Abito, Social Housing, Veneto
	University of Genova, Campus, Liguria
Renewable Energy Communities	Pinerolese, Piemonte
	Primero-Vanoi, Trentino-Alto Adige
	Roseto Valfortore, Puglia
	Alpina di Tirano, Lombardia
	Valle Susa, Piemonte
	Energia agricola a km 0, Veneto
	Green Energy Community, Emilia-Romagna
	Puglia Active Network, Puglia
	Smartgrid di Berchidda, Sardegna
	BloRin, Sicilia
	Prato allo Stelvio, Bolzano
	Società Elettrica Cooperativa dell'Alto But, Friuli-Venezia Giulia

Fig. 1.4 Self-consumption and REC in Italy[10]

According to the estimations of the RSE (Ricerca di Sistema Elettrico, a state - owned firm researching power systems) group, these values roughly correspond to 10 €/MWh for jointly operating self - consumption and 8 €/MWh for RECs.

Shared energy valorization overview.

Shared Energy Valorization	Jointly acting self-consumption	Renewable Energy Communities
ARERA contribute	10 €/MWh	8 €/MWh
MISE Incentive	100 €/MWh	110 €/MWh
Other Incentives	Superbonus 110% (alternative to the MISE incentive)	
	Installation tax discount 50% (up to December 31, 2020)	

Fig. 1.5 Shared energy valorization in Italy[10]

The so - called 10% indicator is the most widely spread social index. It represents the ratio of the global energy cost for each end - user to the total family income, with a time step of 1 year. An end - user is in an energy poverty state when he spends over 10% of his total income on energy. The 10% index is improved by taking into account a more precise income indicator, the equivalent economic situation indicator, ISEE, which is used in Italy to qualify for subsidized social benefits. In the REC layout, the outcomes of the 10% index assessment show that no end - user is in an energy poverty condition. Even with the 10%ISEE index, which is related to households' real economic situations, the energy poverty limit is not exceeded by any of the three households, demonstrating the effectiveness of the energy-sharing approach in tackling this critical problem.[8]

1.3.2 REC forms and barriers

Community energy projects can adopt various forms, contingent upon the level of stakeholder engagement in the initiative, the initial capital investment, and the unique attributes of the targeted area. Currently existing community energy endeavors have recognized the importance of being recognized through diverse legal structures that delineate ownership patterns, individual responsibilities, and the rights of each shareholder. The subsequent classifications will initially examine the legal framework of community energy projects before categorizing them based on their sizes.

REC forms

As reported in Ref [9], the most prevalent organizational methods for community energy are presented here:

Partnerships: Profit-driven energy generation enterprises, with governance and voting power based on partners' stakes. Profits are shared among members, and management is handled by an executive board.

Co-operatives: Membership is open and voluntary, with members in control and operating on the "one member, one vote" principle. They aim to benefit the local community or members, offering education and training. Profits are reinvested to enhance activities.

Municipal Ownership: Public utility companies in some European countries can provide energy services. Municipalities can play a key role in community energy, but transparency and accountability are crucial.

Community Trusts and Foundations: Charitable non-profit organizations focused on social benefits, allowing disadvantaged citizens to benefit without participation costs.

Non-Profit Customer-Owned Enterprises: Ideal for community projects in remote areas with small distribution grids. Members are households on the micro-grid, using revenues to maintain a reliable and affordable system.

Public-Private Partnerships (PPPs): Optimal for balancing local resource use and community benefits. Public entities partner with community groups, private firms, or NGOs to achieve common goals.

Understanding these forms helps stakeholders tailor community energy projects to local needs and ensure long-term success.

REC barriers

Ref [3] summarizes drivers and enabling factors for establishment of RECs according the literature analysis. The article focused on barriers and facilitators at individual, community, and institutional/legal levels when advancing Renewable Energy Projects (RES). Individual-level barriers include difficulties in securing capital for RES investments, reluctance to form groups, and lack of energy literacy. Facilitating factors encompass lower energy bills, economic incentives, group identity, and environmental concerns.

	Barriers	Enabling Factor
Individual	- difficulty to access the capital needed to invest in RES plants Low inclination in forming groups poor energy literacy	- Cheaper energy bill Economic drivers Identification to a group environmental concerns
Community	- low inclination of people in forming groups	- Presence of a "Key influencer" Interpersonal and mutual trust
Institutional/ legal	- Permission procedures and paperwork ever-changing regulatory framework	- Incentives/feed-in-tariffs institution leading Clear legislation and procedure Few institutional point of contacts

Fig. 1.6 Barriers types for energy community development [3]

Community-level barriers involve hesitancy in forming groups, while facilitators include the presence of "key influencers" and interpersonal trust. Institutional/legal barriers involve permitting procedures, paperwork, and evolving regulatory frameworks. Facilitating factors include incentives/subsidies, institutional leadership, clear legislation/procedures, and minimal institutional contact points.

In the Ref [11], the authors address a critical question in renewable energy policy: should self-consumption policies encourage the development of larger or smaller solar photovoltaic (PV) systems, and what are the resulting consequences for distribution networks and regulations. As determined by self - consumption policies, the selection of PV system size poses a complex dilemma. Bigger PV setups can generate more clean energy, thus cutting down greenhouse gas emissions and lessening grid dependence, usually at a more economical rate.

Nevertheless, large scale PV installations may place an excessive burden on local networks, leading to reliability problems and necessitating expensive upgrades. On the contrary, policies that support smaller installations can distribute energy more uniformly, yet they might produce less energy and hinder the progress toward renewable objectives. Achieving a balance among self - consumption policies, PV system size, and smart grid integration is a complicated challenge. This research uncovers the intricate relationship between energy policy, distribution networks, and regulation in self - consumption, where PV system size is of great importance.

Chapter 2 Review of Energy communities

2.1 Building integrating Photovoltaics Application

Ref [12] through a systematic review, analyzed building energy efficiency and sustainability, show that building energy efficiency is the key to achieving sustainable buildings, focusing on reducing environmental impact, reducing economic costs and improving social well-being. The study found that technologies such as high proportion of renewable energy applications, passive building design, energy simulation and optimization have a significant effect on improving building energy efficiency and reducing carbon emissions.

Building-integrated photovoltaics(BIPVs) are believed to be one of the segments of the worldwide solar business that is expanding the quickest, given their 50 % capacity rise from 2011 to 2017.[1]

The IEA Photovoltaic Power Systems Programme (IEA PVPS) Task 15 is to create an enabling framework to accelerate the penetration of BIPV products in the global market of renewables, resulting in an equal playing field for BIPV products, BAPV products and regular building envelope components, respecting mandatory issues, aesthetic issues, reliability and financial issues.[13]

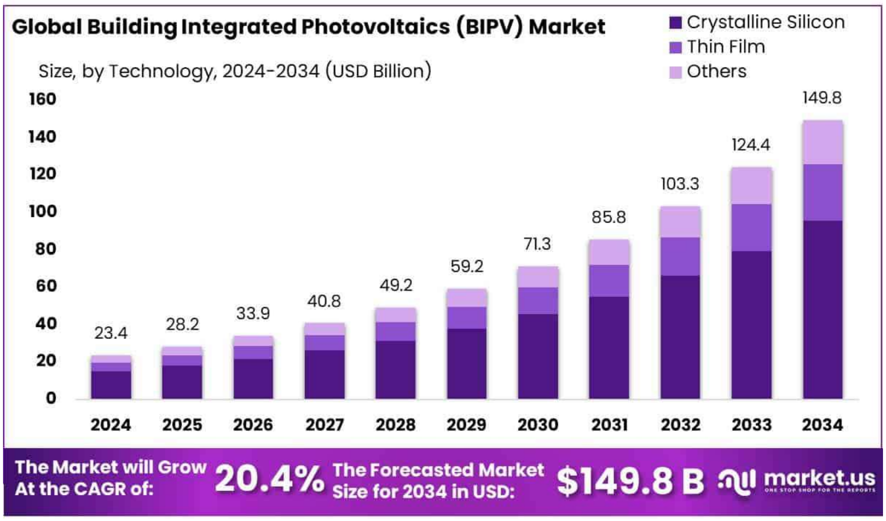


Fig. 2.1 Global building integrated PV market[13]

Buildings are crucial for urban energy efficiency as they account for a large part of urban energy demand. The radiation potential on building skins in different climates has been explored. In Europe, building energy use makes up 41% of total urban energy consumption. So, transitioning to self - energy consumption buildings in cities is a key step towards nearly zero energy cities. When solar panels are incorporated into architectural designs, it leads to net zero energy buildings where the energy generated on-site matches the energy used. The integration of photovoltaic technology with architecture fosters simultaneous progress in both areas, creating innovative design solutions that are aesthetically pleasing and functional. BIPV systems enhance a building's overall energy efficiency, reduce energy usage, and improve indoor comfort by lowering cooling and heating demands[14]. And Ref [15] mentioned that BIPV can generate renewable energy on-site and reduce traditional energy requirements, it's a valuable tool in power and energy resource management. BIPV systems use integrated solar panels to convert sunlight into electricity, making up for building energy use. Local power generation enables more energy independence and significant electricity bill savings, especially in high - price areas.

Recently, Urban Energy Transition (UET) has emerged to promote distributed generation (DG) and realign building energy production and consumption. The energy prosumer notion is a leading solution to this goal. Prosumers can export surplus energy to the grid due to their production capacity and market and power system regulations. BIPV is a convenient way to change buildings from energy consumers to prosumers. The investigation revealed that the implementation of BIPV systems as a building envelope material has already passed the grid parity in 29 out of 30 EU countries if the corresponding cost to its role as a power generator is considered in the economic analysis.[16]

In Italy, nearly 300 MW of innovative BIPV technology has been installed across more than 15,000 facilities. Most of these innovative BIPV installations (around 80% of capacity and 90% of total units) use special components, thanks to lower costs and easier maintenance. Under previous feed-in tariff policies, there's approximately 18 GW of installed capacity, with about 2.5 GW classified as BIPV systems under different definitions (fully integrated and innovative integration). Italy's National Energy and Climate Plan targets adding 80 GW of solar PV capacity by 2030, including both ground-mounted and building-integrated installations.[17]

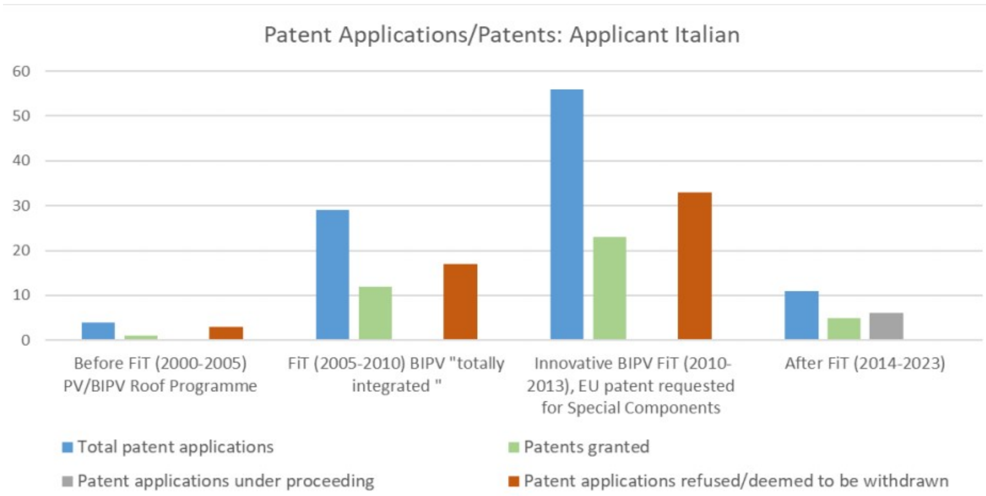


Fig. 2.2 Numbers of Italian PV/BIPV patents [17]

In the residential sector, batteries are usually not economically viable due to high maintenance cost. However, without this device, self - consumption is restricted and continuous grid purchasing can impact grid stability. In Ref [18] explored the possibility of implementing a fast-response super capacitor due to its relatively lower maintenance and showed that the implementation of this device results in 83% to 114% increase in the self-consumption. Ref [17] simulates 60households-5floors PV design. Hourly electricity consumption profile， evaluate the proportion of PV that can cover the total electricity consumption of the building.

2.2 Energy management system(EMS)

2.2.1 EMS key component

The Energy Management System (EMS) encompasses multiple critical components. Each component utilizes advanced technologies and methodologies to enhance system operational efficiency and sustainability.[19]

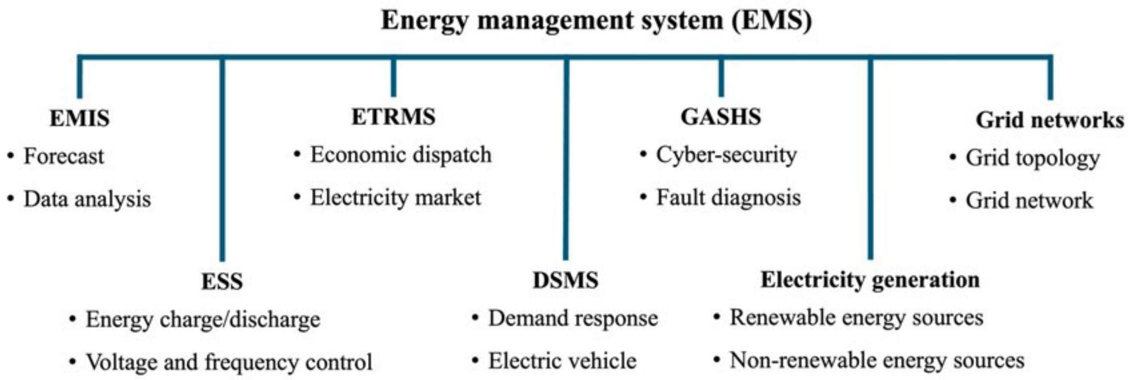


Fig. 2.3 Energy management system frame [19]

Energy demand and supply forecasting

Energy demand and supply forecasting is key to EMS. Demand forecasting uses machine learning and time series analysis to predict energy needs. Supply forecasting relies on meteorological models, simulations, and deep learning to forecast renewable energy from solar and wind.

Energy dispatch and optimization

Energy dispatch and optimization aim to enhance system efficiency through scheduling based on demand and supply forecasts. Techniques like linear programming and mixed-integer linear programming are used for energy management and capacity planning. Dynamic programming and heuristic algorithms solve complex optimization problems. Energy storage system management uses optimization and model predictive control to regulate battery operations.

Demand response

Demand response technology regulates user electricity consumption through real-time data monitoring and smart communication protocols. The Energy Management System (EMS) dynamically adjusts user loads via these technologies, reducing grid load fluctuations and enhancing stability. In terms of grid interaction, the EMS system works with bidirectional metering technology and grid stability analysis to achieve efficient coordination between micro-grids and the main grid, ensuring seamless connectivity.

Energy cost optimization

Energy cost optimization focuses on minimizing overall energy usage costs. Through cost modeling, economic dispatch models, and real-time market price optimization, Energy Management Systems (EMS) can schedule energy sources to achieve cost minimization. Additionally, energy efficiency and environmental benefit assessment evaluates the environmental impact of energy systems using Life Cycle Assessment (LCA) and carbon emission models, while developing emission reduction strategies to ensure sustainable system operation.

User and Device Management

User and Device Management plays an important role in EMS. Smart home systems and Internet of Things (IoT) technologies optimize energy use in homes and commercial buildings by monitoring and adjusting user-side loads in real time.

Data Analysis and Visualization

Data Analysis and Visualization supports energy optimization systems. Big data analytics platforms and visualization tools enable Energy Management Systems to analyze historical data and present results to decision-makers for real-time optimization and informed decisions.

2.2.2 Technical optimization methods

Mixed-integer Linear Programming (MILP) is extensively utilized in system scheduling, load management, and cost optimization. The model predictive control (MPC), dynamic programming (DP), linear programming (LP), hybrid algorithms (such as Genetic Algorithm + MILP), and machine learning algorithms (including Support Vector Machines (SVM), Artificial Neural Networks (ANN), and Deep Learning (DL)) are applied in predicting energy demand, optimizing power dispatch, and forecasting photovoltaic generation. Furthermore, Reinforcement Learning (RL) enhances energy management decisions by interacting with environmental factors in demand response, energy trading, and system optimization scenarios.

Ref [20] focus on P2P market mechanisms, competitive bidding strategies, and auction models, exploring solutions to energy management challenges in P2P-based energy trading. The studies examine widely adopted approaches such as game theory models, mathematical optimization methods, and machine learning techniques, while providing critical evaluations of these methodologies.

Optimisation Algorithm	Distinct Features
Linear programming	Linear objective function with linear constraints
Mixed integer linear programming	Variables can be a combination of integer and floating point numbers
Convex programming	Objective function and constraints should be convex
Second-order cone programming	Linear objective minimised over a second-order quadratic cone
Quadratically constrained quadratic programming	Quadratic objective function with quadratic constraints
Non-convex programming	Non-convex objective and/or non-convex constraints

Fig. 2.4 Comparison table for state-of-the-art optimization algorithms. [20]

Ref [21] presents a comparison study on two design optimization methods for renewable energy systems in these buildings, including a single objective optimization using Genetic Algorithm and a multi-objectives optimization using Non-dominated Sorting Genetic Algorithm (NSGAII). Building energy system models and renewable energy system models are developed and adopted, allowing the consideration of the interaction between building energy systems and renewable energy systems in optimization.

Ref [22] proposes an efficient scheduling strategy that integrates demand response with a tiered carbon trading mechanism. The approach employs combined heat and power (CHP) and power-to-gas (P2G) technologies to enhance the flexibility of smart energy systems (IES). The study also introduces an improved demand response model based on price elasticity matrices and energy supply substitution capabilities, covering three load types: thermal energy, electricity, and gas. This model was reconstructed using mixed integer linear programming (MILP) and solved through CPLEX.

Ref [23] proposes a self-scheduling model for home energy management systems based on the Random Mixed-integer Linear Programming (MILP) framework. The model considers both transferable and non-transferable loads from household appliances, while integrating operational characteristics of photovoltaic (PV) systems and battery energy storage systems (BEES). Additionally, the study examines the impact of three demand response programs (DRPs): time-of-use (TOU), real-time pricing (RTP), and tiered pricing (IBR) on the self-scheduling strategy. Through these demand response initiatives, the model optimizes household energy consumption to enhance system economic efficiency and operational performance.

Ref [24] presents a regional intelligent energy sharing framework (IESP) based on multi-agent systems. By establishing mathematical models for internal equipment and load, the framework optimizes regional energy economic dispatch through phased carbon emission cost and operational cost considerations. The study also develops a demand response model that incorporates user satisfaction with energy consumption, while designing a multi-IESP collaborative operation model using Nash game theory. Through the ADMM algorithm, the research validates the effectiveness of this approach in economic dispatch optimization, energy conservation, and carbon reduction across various operational scenarios.

Ref[25] introduces the Hierarchical Deep Reinforcement Learning(HDRL) framework to address community energy trading challenges. The framework breaks down real-time energy sharing and management into two sub-problems: household appliance scheduling and internal energy trading pricing. This approach enhances the efficiency of community energy transactions and optimizes power distribution.

By comparing MILP and model predictive control (MPC), Ref[26] proves the feasibility and effectiveness of community battery system in reducing residential power costs.

In recent years, artificial intelligence (AI) algorithms have been extensively applied in energy management systems (EMS). Ref [27] systematically reviews the application of AI in photovoltaic systems and identifies the main challenges and limitations currently faced. AI and machine learning algorithms such as Support Vector Machines (SVM), K-nearest Neighbors (KNN), Artificial Neural Networks (ANN), and deep learning are widely utilized in photovoltaic power generation prediction and optimization.

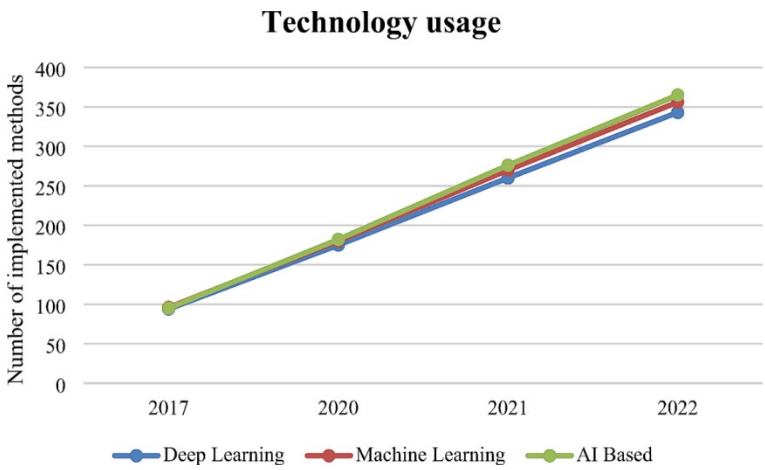


Fig. 2.5 Numbers of implemented AI methods in PV [27]

2.3 Energy trading and pricing mechanisms

To achieve energy sharing and trading among community members, energy trading models based on block-chain technology require establishing fair pricing strategies. These models must integrate market demand, supply dynamics, and grid interactions to ensure equitable trading conditions for all participants. Researching how dynamic electricity pricing mechanisms such as real-time rates or market-based pricing systems impact community energy management strategies is particularly crucial, especially in the context of large-scale renewable energy integration.

Ref [28] conducts a comprehensive review of relevant literature across economic and Engineering domains, with a specific focus on energy communities (ECs) and Peer-to-Peer (P2P) markets, are examined. This examination discusses significant obstacles and enablers of local energy trading, relating them to the framework of ECs. Among the assessed models, the community-based P2P model stands out for its high adaptability to ECs, primarily because of its potential to foster cooperation among prosumers. Additionally, this article explores crucial insights into sharing mechanisms and their integration within trading models. Ref [29] summarize three types: full P2P market; community-based market, hybrid P2P market and proposes recommendations on business models and grid operation.

Methodologies	Reference	Methods
Constrained optimisation	Morstyn and Mc-Culloch (2019)	Distributed price-directed optimisation mechanism for multi-objective problem, using Alternating Direction Method of Multipliers (ADMM).
	Moret and Pinson (2019)	Distributed optimisation approach, using iterative local optimisation and dual price adjustments with ADMM and the Karush-Kuhn-Tucker (KKT) conditions.
	Cortade and Poudou (2022)	Welfare maximisation within a dealing platform
	Perger and Auer (2022)	Bi-level optimisation with an upper-level problem and a lower-level problem (using KKT conditions). The resulting conditions are then transformed into a Mixed-Integer Linear Programming (MILP) condition using the Big M approach.
Game theory	Paudel et al. (2019)	The interaction between the sellers and buyers is modelled as a non-cooperative Stackelberg game, where sellers are leaders and buyers are followers. The seller selection competition among buyers is modelled as an evolutionary game and a distributed iterative algorithm is proposed to reach the stable state in a game. Also, the price competition among sellers is modelled as a non-cooperative game.
	Malik et al. (2022)	Cooperative game theory with a coalition formation model
Auction theory	Zhou et al. (2020)	Double-sided auctions

Fig. 2.6 Table of methods of energy optimization [28]

Ref [4] proposed a self-consumption scheme. In collective self-consumption within a user-owned network, a single meter upstream of the private network is used to identify the building's y points of connection （PoC). This PoC allows precise evaluation of the building's self-consumption.

In the virtual model, where the distributor owns the network, a single PoC for the self-consumption scheme is not feasible due to energy exchanges being measured at various points. Self-consumption occurs on the utility grid, with multiple PoCs—one for each community member. The hourly energy balance is calculated based on energy exchanges at each PoC.

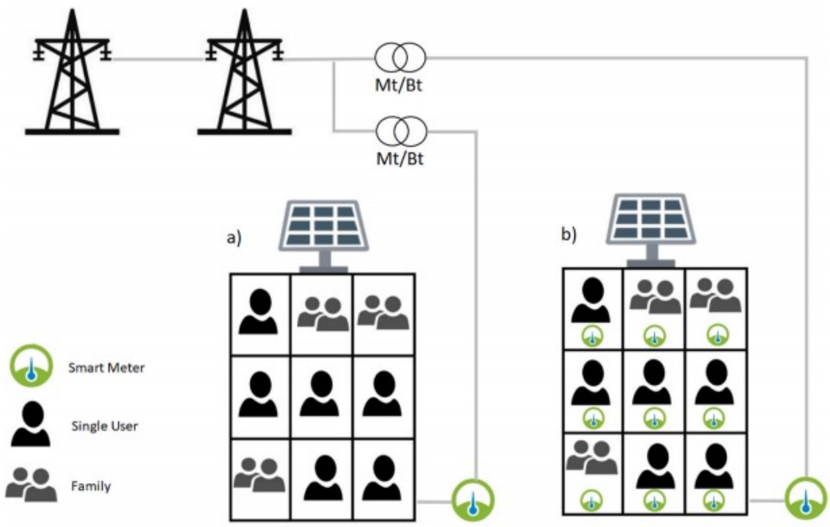


Fig. 2.7 Proposed self-consumption schemes: a) physical model, b) virtual model.[4]

Ref [30][31] analyzes four pricing mechanisms: proportional energy sharing, cost-sharing models (including bill sharing, medium market price, supply and demand ratio, and Shapley value based on alliance game theory). Each pricing mechanism is evaluated by the performance economy index. In Ref [32][33] four pricing forms are compared, including the grid retail price, FiT feed-in tariff, medium market price, and dynamic pricing based on supply-demand ratio， and fairness index is added for evaluation.

Ref [34] employs block-chain technology with cross-chain interoperability and proposes a dynamic bidding strategy for electricity trading that adjusts prices based on real-time market information. Using the Electricity bidding strategy, sellers consider the three-level relationship between demand/supply/supply/demand, and buyers bid according to their own needs and real-time electricity prices.

Ref [35] summarizes the types of electricity billing and energy communities, and proposes a pricing mechanism based on power grid topology and line loss to optimize system and social acceptance with alternating direction multiplier method (ADMM).

Ref [36] based on the Cournot model, two two-dimensional (2-D) Energy Transfer Process (ETPF) designs were developed for different scenarios, considering both the power supply conditions and preference parameters of LMO. By comparing the profit improvement differences between the 2-D ETPF and traditional one-dimensional (1-D) ETPF designs, the effectiveness of the proposed design was verified.

Ref [37] by taking the profit maximization of electricity sellers as the objective function, this paper introduces constraints such as price ceiling, risk assessment and user utility to construct the optimization model, and solves it through KKT condition.

Ref[38] sets up the prosumer and consumer sets, build a cost matrix according to the transaction price between producers and consumers, and use the form of electricity purchase reward from consumers for shangring offer to maximize the interests of consumers and producers. The optimal solution is obtained by Nash equilibrium.

In Ref [39], the Stackelberg game theory model is used to analyze the energy management and pricing mechanism in the P2P energy trading market. ESP motivates producers and consumers to participate in P2P transactions by setting internal transaction prices.

In Ref [40] , a standard nomenclature is defined to review some of the main pricing mechanisms for local energy transactions, an innovative pricing mechanism based on the economic principles of a post-delivery pool market is proposed, and other relevant approaches for local electricity market simulation such as Nash equilibrium or agent-based simulation are also revisited.

Ref [41] discuss different pricing mechanisms in the online peer-to-peer lending market, including the borrower pricing mechanism (BPM), auction pricing mechanism (APM) and platform pricing mechanism(PPM), and analyse the pricing differences among them.

Ref [42] studies the payment calculation of energy exchange between micro-grid and public grid based on Shapley value. Ref [43] calculate the individual's value of Sharley and convert it into the unified trading electricity price within the alliance to minimize the cost of individual producers and consumers.

2.4 Investment modes and profit distribution

Financing models

A project life-cycle framework comprises seven phases: 1) Initial Concept Development and Community Mobilization; 2) Feasibility Assessment and Resource Estimation; 3) Business Model and Financing Design; 4)Planning Approval and Legal Compliance; 5) Construction and Installation; 6) Operation and Maintenance; 7) Revenue Management and Reinvestment. Each phase includes task checklists and risk advisories to ensure smooth progress. Financing models include equity financing, debt financing, community equity fundraising, cooperative models, local government participation, crowdfunding, and Power Purchase Agreements (PPA).

Hybrid financing is advised to reduce risks and improve community engagement and profit-sharing. Projects with greater community ownership gain better social acceptance and stability. Transparent governance, including assemblies and committees, ensures stakeholder participation and oversight. Community involvement enhances project legitimacy and support during challenges. Key requirements are FIT, SEG, CFDs, grid regulations, land permits, and environmental assessments. Engage legal and technical advisors early to avoid financial losses from policy or procedural issues.[44]

In the Ref [46], an economic feasibility analysis for energy communities with two investment options is conducted: third party investment and self-investment, while also taking into account various cost allocation methods. An optimization model is developed to solve the optimal operation of the energy community with both investment options.

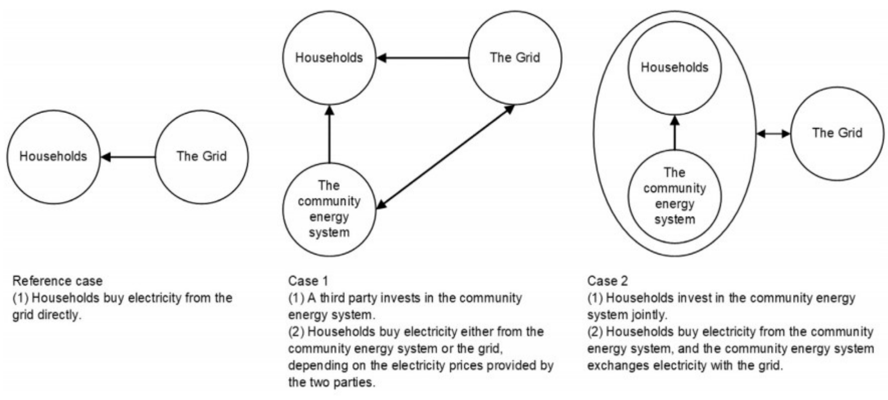


Fig. 2.8 Energy communities' investment modes [46]

Ref [47] proposes an optimal configuration model for a photovoltaic (PV) system, solar heating system, and BESS in order to obtain maximum profit for investors. A bi - level programming is adopted to optimize the battery operation strategy (inner layer), and the sizes of PV, solar heating systems, and batteries (outer layer, including max discharge/charge power and capacity). Sequential quadratic programming (SQP) and particle swarm optimization (PSO) are used as optimization methods.

Ref [45] presents a method of economic estimation for a PV charging station based on the utilization of retired electric vehicle batteries. The optimal capacity configuration of the PV combined energy storage charging station is given by the teaching-learning-based optimization (TLBO) and particle swarm optimization (PSO) algorithms respectively.

Profit distribution

The economic sustainability of Energy Communities (ECs) depends not only on power generation revenue but also on how these revenues are distributed among members. A fair and transparent revenue-sharing mechanism can: boost member engagement and trust; prevent concentration of benefits in a few hands; and maintain social legitimacy for long-term community operations. Unreasonable distribution models may lead to member attrition or conflicts, particularly when investment ratios and electricity consumption levels vary significantly. The distributable revenues of Energy Communities primarily come from three sources:

Revenue from electricity sales:

Income generated by selling surplus renewable energy to the grid (e.g., through feed-in tariffs or market prices).

Community Energy Sharing Incentives: Financial subsidies provided by governments or regulatory bodies for shared electricity generation within communities (e.g., Italy's €110/MWh incentive).

Energy Conservation Benefits: Reduced electricity purchase costs (i.e., savings on utility bills) achieved by members through self-consumption of renewable energy.

Research on investment and benefit redistribution in new energy communities has extensively examined community energy equity and stakeholder interest coordination.

At the business model level: "shared electricity incentive" has spurred studies on benefit redistribution using Shapley values or contribution-based game theory models. While Germany and the Netherlands also implement FiT premiums, their significantly different regulations make cross-border replication of these experiences challenging.[3]

In a real-world Renewable Energy Community (REC) project in an Italian village, the Shapley value method was employed to allocate the "shared electricity reward" of 110 €/MWh based on each member's marginal contribution to the community's surplus power. The results demonstrated that this mechanism not only gained participants 'recognition as "fair," but also effectively motivated residents and businesses to proactively adjust their electricity usage schedules. Consequently, the community's overall self-consumption rate increased by approximately 15%, validating the feasibility and motivational effectiveness of cooperative game theory models in micro-scale REC systems.[48]

In a simulated Renewable Energy Community (REC) for an Italian urban district, Ref [49] propose a "contribution allocation" framework that outlines five implementable distribution schemes and quantitatively compares them using a "fairness index". The study reveals two key conclusions: 1) Higher member load-to-generating capacity complementarity leads to greater collective benefits; 2) When member heterogeneity increases, adopting a "contribution-based" approach instead of simple equalization can boost individual returns by 8-12% while reducing dispute rates.

Ref [51] used a sample of 10 large residential/commercial households (REC) as the research unit, this study compares the payoff differences between "Cooperative Game Theory (Shapley value)" and "Non-Cooperative Game Theory (self-interested behavior)". Under the cooperative model, individual average earnings increase by approximately 7%. The inclusion of an "exit clause" prevents high-contributing members from withdrawing due to insufficient returns, significantly enhancing alliance stability.

Local context	Benefit distribution model
Small Village – Italy	Cooperative games through Shapley value
City – Italy	"Contribution distribution" method
City – Italy	Cooperative games through Shapley value
10 large residential/ commercial users – Italy	Comparison between cooperative and non-cooperative models

Fig. 2.9 Benefit distribution model of REC in Italy [51]

Ref [52] conducted a systematic comparison of four revenue redistribution mechanisms using real load and wind speed data from 200 households in the UK's Orkney Islands. The study optimized community wind turbine capacity to either 405 kW (fixed tariff) or 456 kW (dynamic Time-of-Use, ToU), with investment costs shared by all households. Results showed that both Method-1 (based on marginal contribution) and Method-2 (proportional instantaneous load allocation) achieved maximum total savings (69,663 £ under fixed tariff vs. 75,476 £ under ToU), significantly outperforming traditional approaches like "average allocation" and "annual electricity consumption allocation." Further equity analysis demonstrated that Method-1 enabled 67% of small and medium-sized households to reduce bills, while its inflection point remained insensitive to electricity prices between 8–24 p/kWh, proving its scalability in incentivizing majority participation while maintaining computational flexibility.

Ref [49] proposes three distinct economic approaches to assess the fair, equitable, and efficient distribution of community assets. RePro Justice (Recognition and Procedural Justice) dynamically adjusts the participation share based on the user's power exchange capacity, giving priority to taking care of disadvantaged members (such as households without their own power generation or storage equipment). In distributive justice, all members are entitled to fixed and equal shares. Each member has the same quota in both CPV and CESS, and can only use it within this allocated amount. Proportional-Sharing Economic Approach is an allocation method based on the investment shares of members to determine their usage rights, emphasizing "the one who invests more uses more."

Total-sharing economy	
RePro justice	Distributive justice
Manage exchanges with community assets according to the agents' exchange power and shares the operating costs equitably.	Manage operations in an economically fair way, partitions on community assets are shared equally among all members and exchanges are made according to these partitions.
Proportional-sharing economy	
The community manager is responsible for ensuring that energy exchanges carried out by each agent with community assets comply with their pre-established participation quotas.	

Fig. 2.10 Justice sharing schemes in REC [49]

The results showed that total sharing economy approach can enhance Social Welfare, especially being more friendly to consumers who do not own their own photovoltaic or battery systems. Strengthen energy equality and inclusiveness. Proportional-Sharing Economic Approach is detrimental to economically disadvantaged or non-invested members, and may undermine community cohesion. Ref[49] also compared total-Sharing economic and proportional-Sharing modes to understand how the participation of community members in collective asset , helping increase the fairness and equity of RECs.

Ref [53] proposes a comprehensive framework encompassing energy sharing optimization. A Mixed-Integer Linear Programming (MILP) model is formulated to minimize energy bills, considering the energy bought from the grid, the energy sold back to the grid, and the retailer and FiT prices. Four pricing schemes for energy transactions, and fairness metrics to validate the profit distribution of members in an energy community. Mid Market Rate and Supply-Demand Ratio Pricing reflect the best fairness.

The study[54] investigates the technical viability of rooftop photovoltaic (PV) systems in standard five-story, plate-type multi-family residential buildings under the "Citizen Energy Community" (CEC) framework. By leveraging actual hourly household electricity consumption data, it evaluates the extent to which PV can meet the building's total electricity needs, thereby providing design guidelines and optimization insights for the widespread adoption of rooftop PV and CEC. Additionally, it highlights that the average household size and electricity prices influence the scale and revenue on the "demand side," while grid connection capacity and energy storage alternatives impact the "supply side's" electricity generation capability. These four elements collectively constitute the critical sensitive area for the project's economic and technical feasibility.

Ref [55] presents a multi-story residential building with 40 households and 40 kWp rooftop photovoltaic as an example, a MILP model with a 5-minute time step was established. Five scenarios were compared, and the compromise solution that balances economy and comfort was found through the Pareto frontier. By utilizing the flexibility of residential loads (flexible demand) instead of investing in expensive energy storage, the goal was to maximize local photovoltaic power consumption, reduce electricity costs and carbon emissions.

To address how the European Energy Community (EC) can balance "fairness" and "individual freedom" demands beyond the current unified pricing system of Distribution System Operators (DSOs), Ref [56] proposes and compares three internal grid fee redistribution mechanisms within the EC: income-based (subsidizing low-income households), contribution-based (rewarding photovoltaic investors), and proximity-based (encouraging local consumption). The study examines whether these mechanisms can ensure all members' final electricity costs remain lower than in a "no EC" scenario without compromising economic viability, thereby achieving subjective recognition of fairness among participants.

Ref [57] proposed an innovative centralized post-sharing method is proposed by introducing a two-stage mechanism. If it is found in the first stage that some members are facing rising costs, the second stage will be used to allocate the saved funds to ensure that all members can benefit from it. The initial stage evaluates internal price calculation using three distinct methods: Bill Sharing Method Net (BSMN), Mid - Market Rate Net (MMRN), and Supply - Demand Ratio Net (SDRN). The second stage determines the compensation methodology for the distribution of savings, guaranteeing that all community members reap benefits.

In Ref [58], regarding the issue of how the European Energy Community (EC) can balance the demands for "fairness" and "individual freedom" while maintaining the current unified pricing system for distribution companies (DSOs), this paper proposes and compares three internal network fee redistribution mechanisms within the EC: income-based (subsidizing low-income households), contribution-based (rewarding photovoltaic investors), and proximity-based (rewarding local consumption). This is done to test whether these mechanisms can ensure that the final electricity costs for all members remain lower than in the "no EC" scenario without undermining the economic feasibility of all members, thereby achieving the subjective recognition of fairness among the members. The results showed all three mechanisms can achieve "negotiable fairness" within the EC without undermining the overall economy.

Chapter 3 Methodology

The research framework for building-based renewable energy community (REC) first inputs basic parameters, including geographical and meteorological data, photovoltaic and energy storage data, household composition, load curves, and electricity price information. Based on this, two investment scenarios are identified: community self-investment and a third-party investment. In the community self-investment scenario, the community level optimizes PV and energy storage capacity through MILP optimization, considering various investment schemes such as equal investment and demand-based investment. Community internal transaction profits are distributed based on investment proportions and market electricity prices, and the energy-saving profit allocation mechanisms are set into various schemes such as Shapley value and dynamic demand ratio, while incorporating energy-saving incentives and protection for vulnerable groups. Subsequently, the economic viability and fairness of different households are compared in the short term and long term. In the third-party investment scenario, the process is similar, but there is no internal investment allocation mechanism. The focus is on capacity optimization, transaction price setting, energy-saving incentives, and comparisons of economic viability and fairness. The analysis encompasses multiple dimensions, including technical optimization, investment models, profit distribution, and social fairness. Meanwhile, both two investment strategies introduce the Italian Shared electricity incentive (Tariffa Premio per l'Energia Condivisa, TCEC) for a comparison with the scenarios without Italian Shared electricity incentive .

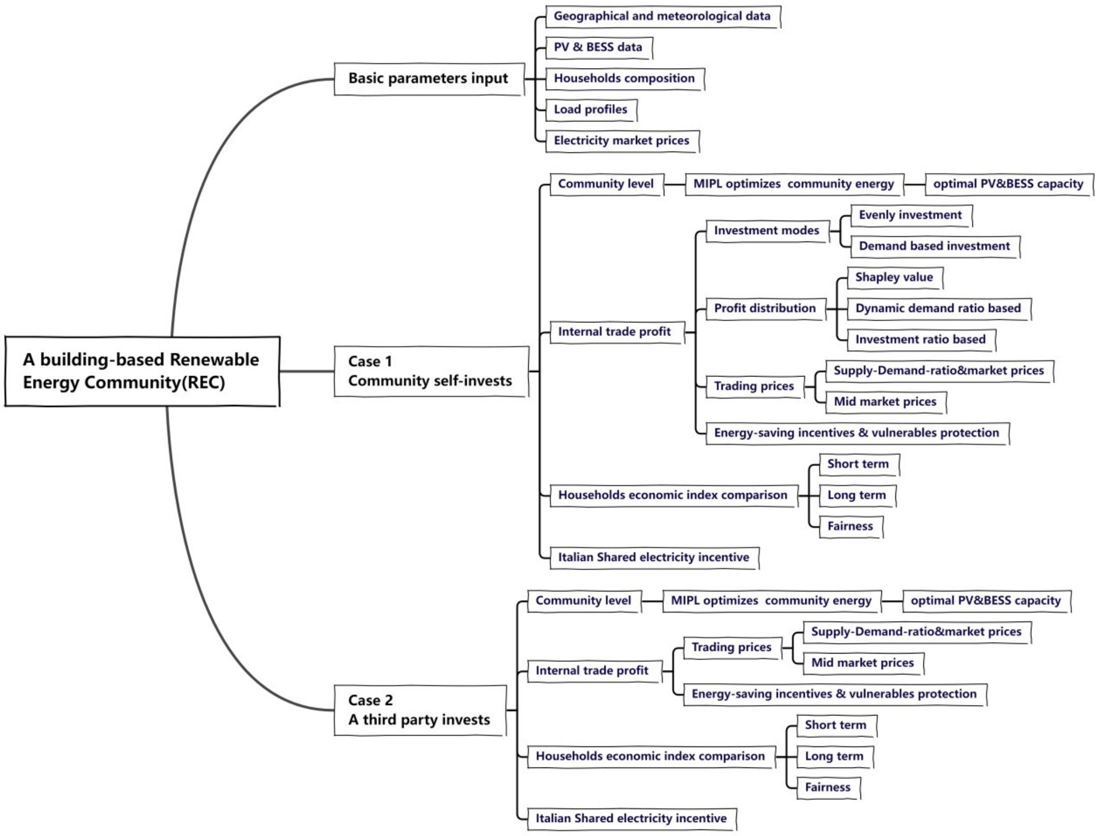


Fig. 3.1 Framework of methodology

3.1 Energy management system architecture

3.1.1 REC architecture

The following is the building-type energy community architecture simulated in this study. Photovoltaic devices are installed on building roofs, with electricity meters measuring power generation, and electricity can be directly supplied to individual households within the building or stored in battery energy storage systems (BESS). Each user is equipped with a private electricity meter (non-billing purpose), while the distribution system operator (DSO) installs billing meters for settlement. Electricity exchange is facilitated through a centralized exchange meter, enabling surplus electricity to be fed into the national grid or purchased from the grid during peak demand periods. This model effectively achieves local clean energy production, shared PV and energy storage regulation among users, laying the foundation for community energy self-sufficiency and flexible power management.

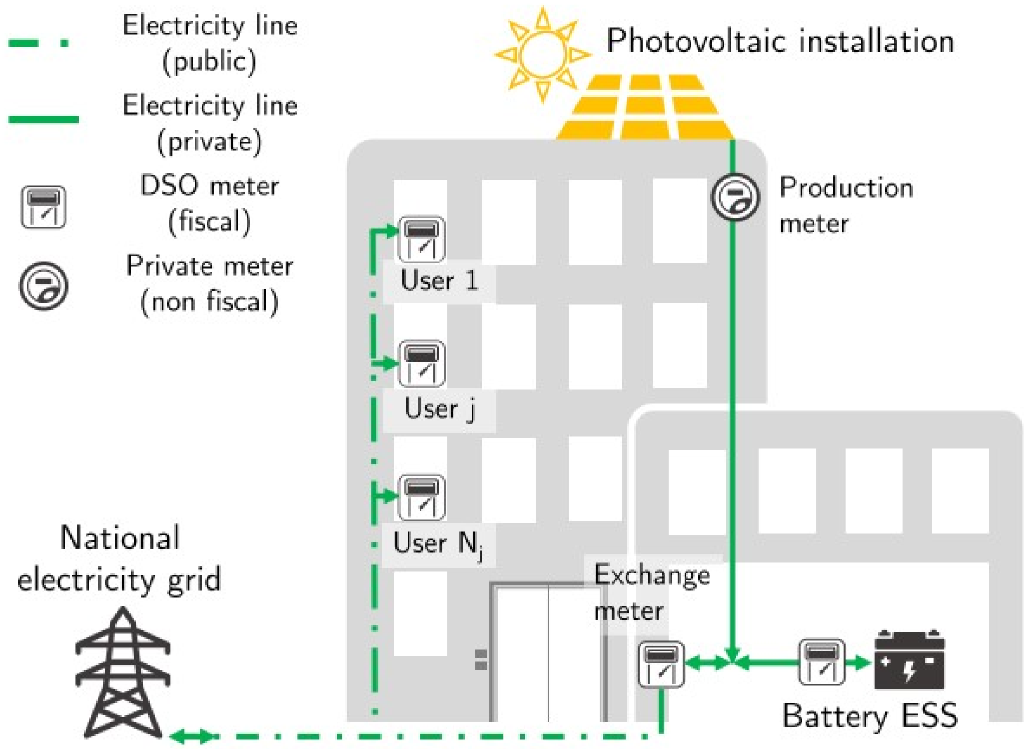


Fig. 3.2 REC architecture

There is no independent electricity seller within the community (that is, no entity privately owned and directly selling electricity to the community, with the community functioning as a whole externally). The community has internal PV power generation and a battery system for storing the PV power. The trade profits, both internal trade and feed in to grid, belong to the community as a whole, and then are redistributed to each household according to certain rules.

Energy Sources

In the system architecture, the energy sources of this system mainly include electricity. The grid serves as a power source to ensure power supply in case of a shortage of renewable energy sources. On-grid solar photovoltaic systems (PV) provide the community's internal power source. Excess power can be stored in the BESS or fed back into the grid. The Battery Energy Storage System (BESS) uses lithium batteries to store excess power withdrawn from PV and the grid.

Energy loads

Household appliances, including electrical ones such as lighting, cooking equipment, refrigerators, televisions, computers, washing machines, and other appliances, are used in this context. Cooling during the summer is considered only for a few households, which use air conditioners. Electricity is not utilized for heating or hot water supply, as the apartment building is connected to a central district heating system. Instead, hot water for kitchens and bathrooms is provided by gas-powered heaters.

3.1.2 Energy load profiles of households

1) Household types composition

Collecting household types of composition data from Istat website to rationalize the proportions of various households of the residential building model.

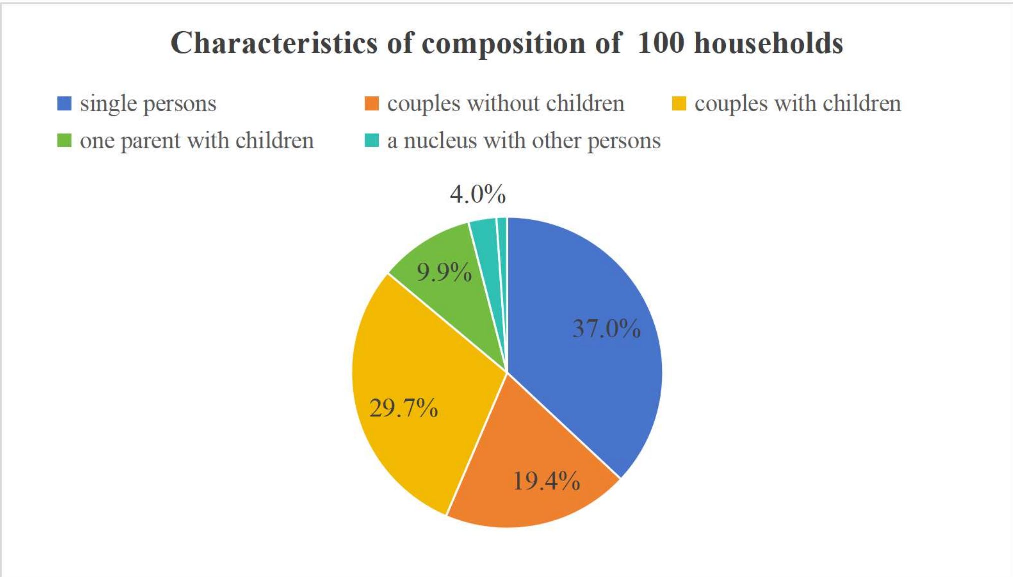


Fig. 3.3 Characteristics of composition of 100 households from Istat

A nucleus with other persons describes a core family unit (such as a couple with or without children) living with additional relatives or non-relatives, such as grandparents, aunts, uncles, or friends. It is sometimes called an "extended family."

2) Modeling hourly load consumption of various household types by LPG.

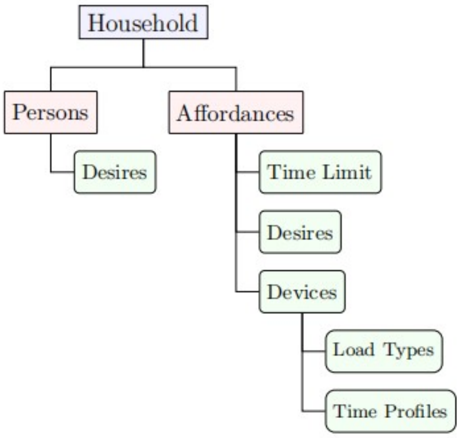


Fig. 3.4 Method of simulating households' load profile

Loadprofilegeneration(LPG) is a software to generate the load consumption of a family. Based on its persons and affordances. A household consists of individuals and their interactions with devices. People have needs and time constraints. Equipment is classified by load types and time profiles, which determine energy use. The model analyzes household energy demands and consumption by simulating behavior and device use. Expand a 50-households community based on household types and family characteristics. Electricity consumption is from appliances like stoves, washing machines, and lighting, defined in the Load Generation Profile (LGP) for energy data.

Based on the data of world bank in 2023, the electricity consumption per person in Italy is 5050 kWh/year. The annual electricity consumption for lighting, appliances, cooking, and refrigeration is approximately 21.6%, i.e. 1090 kWh per person per year. In Italy , based on data reported by ARERA in 2022, the following are the average annual electricity consumption figures (for lighting, appliances, cooking, and refrigeration) for households in Northern Italy:

1-person household consumes between 1,000 and 1,180 kWh annually.
2-person household consumes between 2,000 and 2,700 kWh annually.
3-person household consumes between 2,160 and 2,900 kWh annually.
4-person household consumes between 2,880 and 3,600 kWh annually.

3.2 Case 1 Community self-invests

This methodology is based on Ref[32][46] proposed a comprehensive layer framework encompassing energy sharing optimization by MIPL, and pricing schemes for energy transactions, and fairness metrics to validate the profit distribution of members in a residential building energy community. In this study, the layer framework is applied to the optimization of residential building energy and delve deeper into the characteristics of households.

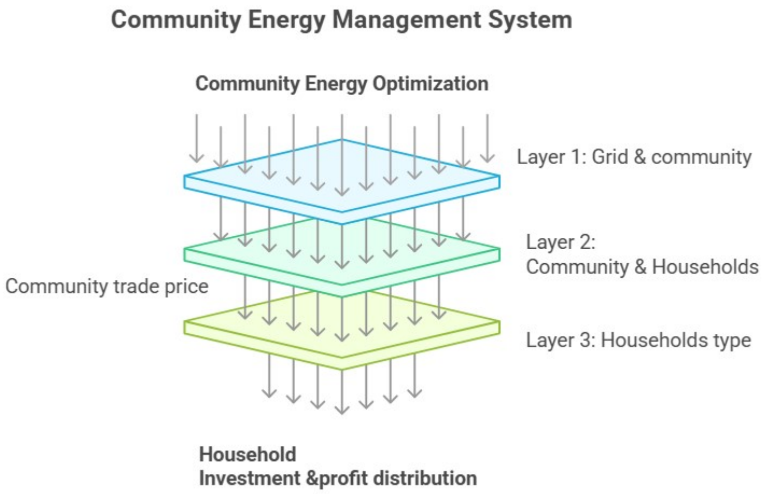


Fig. 3.5 Layers of EMS optimization

To optimize the configuration of photovoltaic (PV) and battery energy storage systems (BESS) jointly invested in by residents in a community and achieve fair and efficient distribution of benefits, this paper constructs a generalized two-layer optimization structure model. Within this community framework, all households are energy producers and consumers (Prosumers) who jointly invest in the construction of PV-BESS systems. Under the established benefit distribution rules, they enjoy the aggregated energy-saving benefits and power trading profits.

The upper-layer optimization model aims to maximize the net present value (NPV) of the entire community by optimizing the capacity of PV and BESS systems. Embedded within a mixed-integer linear programming (MILP) framework, it optimizes the community's energy flow (PV energy, battery charging/discharging, and grid interaction) with the objective of minimizing the community's grid electricity purchase bill. In addition, the power load is adjusted to optimize the distribution of power resources by peak shifting and shifting.

The lower-level model describes individual households' energy consumption behavior and energy flow responses. Based on different investment schemes and distribution rules, it evaluates metrics such as electricity cost savings, self-consumption rates, NPV, and return on investment (ROI) and QoE(quality of experience).

To break away from the traditional “producers-consumers separation” model, the model adopts a unified aggregated revenue redistribution mechanism, ensuring fairness, incentives, and transparency in interest distribution among individual households while obtaining the system's overall optimal solution. It also incorporates investment fairness and energy usage efficiency fairness. This method supports flexible embedding of various allocation strategies (such as investment ratios, energy consumption weights, and energy-saving performance), providing mathematical support for the design of energy-sharing communities.

Layer 1: Grid & community

Method: By employing MIPL to optimize the interaction Grid & community, including the energy withdraw and PV energy feed-in. By iterating the MIPL optimized daily results to optimize the BESS and PV capacity based on the NPV of community.

Objective:

-Optimizing energy withdrawal from the grid based on real-time pricing and demand.
-Maximizing the utilization of locally generated renewable energy.
-Optimizing the sizing of BESS and PV capacity to maximize the NPV of the community.

Index:

-Community energy bill reduction
-The electricity amount withdrawal from grid
-CO2 emission reduction

Layer 2:Community & Households

Method:

Set the internal dynamic PV energy trade price
Study various investment approaches & benefit distribution rule for energy fairness
Introduce incentive adjust scheme

Objective: Rationalize the community energy trade and the community return

*Index:*the return of internal (ROI), saving ratio and Quantitative indicators of unit energy(QoE）

Layer 3: Households type

Method： Five different family types, and normal and excessive consumption for comparison.

Index:

Long term index by evaluating households' NPV within PV life time.

Short-term index by comparing the bills and bill coverage ratio of households

3.2.1 Energy sharing strategies

(1) Community daily energy flows optimization

MIPL is used to optimize the daily energy flow of the community with the goal of minimizing the community's grid power purchase.

Objective function

1) Without Italian sharing electricity incentives

$$\min \mathrm{CommunityBill} = \sum (E_{\mathrm{grid,tocomm}}(\mathrm{t}) + E_{\mathrm{grid,tobess}}(\mathrm{t})) \times \mathrm{WithdrawPR}(\mathrm{t}) - \sum E_{\mathrm{PV,togrid}} \times \mathrm{FeedinPR}(\mathrm{t})$$

2) With Italian sharing electricity incentives

$$\min \mathrm{Community\ Bill} = \sum (E_{\mathrm{grid,tocomm}}(\mathrm{t}) + E_{\mathrm{grid,tobess}}(\mathrm{t})) \times \mathrm{WithdrawPR}(\mathrm{t}) - \sum E_{\mathrm{PV,togrid}} \times \mathrm{FeedinPR}(\mathrm{t})$$

$$- \sum (E_{\mathrm{PV,tocomm}}(\mathrm{t}) + E_{\mathrm{PV,tobess}}(\mathrm{t})) \times unitSubsidy$$

Community

The source of community energy is PV generation, BESS discharge and electricity purchased from the grid

$$\sum \mathrm{Demand(t)} = \sum \mathrm{E}_{\mathrm{PV,\ tocomm}}(\mathrm{t}) + \sum \mathrm{E}_{\mathrm{bess,\ tocomm}}(\mathrm{t}) + \mathrm{E}_{\mathrm{grid,\ tocomm}}(\mathrm{t})$$

Load Shifting

Regarding the load-shifting and peak-shaving simplified as 80% rigid load and 20%

shiftable load .

$$0 \le \sum E_{decrease}(t) \le 20\% \sum Demand_{comm}(t)$$

During 0:00-6:00 and 11:00-16:00,the shiftable load ratio limit 50% total community demand.

During 7:00-11:00 and 19:00-24:00, the shiftable load ratio limit 20% total community demand.

Constraints

The amount of electricity reduced is equal to the amount of electricity increased at other times.

$$\sum E_{increase}(t) = \sum E_{decrease}(t)$$

The reduced power shall not exceed the movable peak proportion of the total power.

$$E_{decrease}(t) \le Demand_{community}(t) \times Shiftable\ ratio(t)$$

The reduced power shall not exceed the shiftable peak proportion of the total power.

$$Actual\ Load_{comm}(t) = Demand_{comm}(t) + E_{increase}(t) - E_{decrease}(t)$$

(2) **Optimizing PV and BESS capacity:**

The daily energy flow to the optimal solution is transmitted to the lower layer to calculate the maximum annual community NPV, and the optimal PV and BESS capacity are obtained.

Objective function

$$\max\ NPV_{comm} = -Initial\ investment + \sum \frac{Annual\ Savings - Annual\ OPEX}{(1+r)^t}$$

Where,

$$Initial\ investment = Capacity_{PV} \times Unitcost_{PV} + Capacity_{BESS} \times Unitcost_{BESS}$$

$$\text{AnnualSaving} = \text{Load}_{\text{comm}} \times \text{WithdrawPR} - \text{Bill}$$

$$\text{Bill} = (E_{grid,tocomm} + E_{grid,toBESS}) \times WithdrawPR - E_{\text{PV,togrid}} \times FeedinPR$$

PV

PV generation goes to community load, battery energy storage system (BESS) and feeds into the grid.

$$\text{E}_{\text{PV,total}}(\text{t}) = \sum \text{E}_{\text{PV,tocomm}}(\text{t}) + \sum \text{E}_{\text{PV,toBESS}}(\text{t}) + \sum \text{E}_{\text{PV,togrid}}(\text{t})$$

BESS

Batteries can only be recharged from photovoltaic or the grid.

$$\text{E}_{\text{ch}}(\text{t}) = \text{E}_{\text{PV, tobess}}(\text{t}) + \text{E}_{\text{grid , toBESS}}(\text{t})$$

All battery discharge goes to community (not feed in to the grid)

$$\text{E}_{\text{dis}}(\text{t}) = \text{E}_{\text{BESS ,tocomm}}(\text{t})$$

SOC state

$$\text{SOC}(t) = SOC(t-1) + E_{ch}(t) \times \eta_{ch} - \frac{Edis(t)}{\eta dis}$$

The amount of power the battery limitation

$$(1 - DOD)\ AH \leq \text{SOC}_{\text{t}} \leq AH$$

Maximum charge/discharge power of battery

$$\text{Pmax} = \text{C}_{\text{rate}}^{\text{max}} \times \text{AH}$$

Mutual exclusion of charge and discharge：

$$\text{P}_{dis,max} \leq AH \times SOCmax \times M$$

$$P_{ch,max} \leq AH \times SOCmax \times (1 - M)$$

3.2.2 Trade Pricing Methodology

1. Italian electricity bill composition

Revisione della regolazione della bolletta 2.0: Approvazione de "la bolletta dei clienti finali di energia" published by l'autorità di regolazione per energia reti e ambiente in June 2024 presented that Italian electricity bill composition:

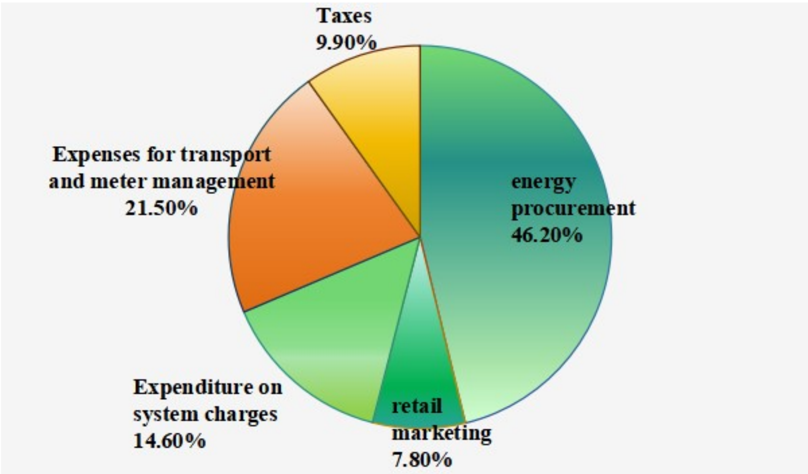


Fig. 3.6 Italian electricity bill composition

1) **Quota per consumi**, Variable charge per consumption. Including：

    Expenditure on energy:

        energy procurement (46.2%)=Ritiro dedicato

        retail marketing((7.8%)

    Expenditure on system charges (14.6%)

2) **Quota fissa and Quota potenza**(a set fixed fee that does NOT vary with the amount of electricity consumption)

    Expenses for transport and meter management (21.5%)

    Taxes((9.9%)

Based on the current fixed costs of the electricity bill established by ARERA, the total cost, for a hypothetical bill without consumption, is equal to €12.81 per month.

Simulazione bolletta bimestrale luce senza consumi fatturati

Voce di Spesa in Bolletta	€/bimestre	€/mese
Spesa per la Materia Energia	6,88€	3,44€
Spesa per il Trasporto e la Gestione del Contatore	16,43€	8,21€
Spesa per Oneri di Sistema	0€	0€
Iva e Imposte	2,33€	1,16€
Totale Bolletta	**25,64€**	**12,81€**

Table. 3.1 Fixed costs of the electricity bill from ARERA [6]

In case of an active user, the self-consumed energy is exempted from the variable costs in the electricity bill of the items of wholesale cost of electricity, network costs and operating costs. As a consequence, the more energy is self-consumed, the more the user can save money in the bill.[62]

2. The trade prices within community

Generally, there are usually three economic Paths of Community Photovoltaic Systems：

(1) Self-consumption

Under the premise that PV energy is allocated in proportion to the absolute initial investment, each investor has their own PV electricity quota, and the generated income is the saved cost of purchasing electricity from the power grid.

(2) Community sharing

Prosumers shares the surplus photovoltaic power with consumers, and the price can dynamically changes between Ritiro dedicato (PR_{RD})and the price withdraw from grid (WithdrawPR).

(3) Feed in to grid

Selling to Grid or GSE at the price of Ritiro dedicato (PR_{RD})

It is the view of the Italian energy Authority that support plans for Energy Communities will, in an initial phase, mimic the implicit incentives already provided to self-consumption systems, indicating that the shared energy within the community will be exempted from at least the variable portion of the wholesale cost of electricity and network costs on the electricity bill.[62]

The pricing scheme of community solar energy trading is based on the feed-in price of photovoltaic power as the lower limit, the retail price at which community residents purchase from the power grid as the upper limit, and the pricing strategy with the available photovoltaic power and the demand of households as two-way variables.

Based on Quota per consumi, the Ritiro dedicato price equals to energy procurement price that is 46.2% in variable part.

$$\mathrm{WithdrawPR(t)} = \frac{46.2\% + 7.8\% + 14.6\%}{46.2\%} \mathrm{PR_{RD}(t)} = 1.485\mathrm{PR_{RD}(t)}$$

$$\mathrm{PR_{RD}(t)} < \mathrm{TradePR(t)} < \mathrm{WithdrawPR(t)}$$

WithdrawPR: Purchasing price from grid

TradePR: PV energy trading price within community

According to Ref[46], segmented energy pricing strategy is always applied in energy transaction,The electricity price is low when electricity consumption is below the threshold, and high when electricity consumption exceeds that threshold. According to Ref[31][33][34], the Supply-Demand Ratio trading pricing model is more flexible and effectively responsive to market demand. The PV energy trade prices within community base on the ratio of PV and BESS energy supply and the community demand and the interaction of grid prices which changes every hour.

$$\mathrm{SDR} = \frac{\mathrm{E}_{PV} + \mathrm{E}_{\mathrm{BESS}}}{Demand_{comm}}$$

In this work, a combination of segmented Supply-Demand Ratio pricing integrated with TOU grid electricity pricing is proposed to use in community energy transition.

$$\mathrm{TradePR(t)} = \frac{1}{1+\mathrm{SDR(t)}} \times \mathrm{WithdrawPR(t)} + \left(1 - \frac{1}{1+\mathrm{SDR(t)}}\right) \times \mathrm{FeedinPR(t)}$$

3.3.3 Revenue and distribution

3.3.3.1 Community profit and Households' profit

The community revenue is the part of the PV power consumption offsetting the purchase from the grid and the part of the PV power feed in to the grid.

$$\text{Revenue}_{comm} = \sum \text{E}_{\text{PV},tocomm} \times \text{WithdrawPR} + \sum \text{E}_{PV,togrid} \times \text{FeedinPR}$$

The profit of households are the benefits of community PV power transactions and the part of the PV power feed in to the grid, as well as the savings of their own consumption.

$$\sum \text{Revenue}_{\text{i}} = \underbrace{\sum \text{E}_{\text{PV},tocomm} \times \text{TradePR} + \sum \text{E}_{PV,togrid} \times \text{FeedinPR}}_{\text{Trade profit}} + \underbrace{\sum \text{E}_{\text{PV},tocomm} \times (\text{WithdrawPR} - \text{TradePR})}_{\text{Saving}}$$

3.3.3.2 Revenue and distribution mechanism

In community photovoltaic projects, the reasonable design of investment and income distribution not only affects residents' willingness to participate, but also relates to the fairness and economic sustainability of the project. Based on the research of Ref [52], it is assumed that the investment cost is shared evenly by all households, and four income redistribution mechanisms are compared systematically: Method 1 marginal contribution, Method 2 instantaneous power sharing, Method 3 average sharing, and Method 4 annual electricity consumption sharing. Ref[49] compare the Total-Sharing Economic and proportional-Sharing economic models. Ref[31] proposes a compensation methodology which divides the total savings in the community into two parts: one continues to reward those who save money, and the other precisely recovers those who lose money to ensure that each member's final electricity bill is lower than what they would have paid if they had signed a separate contract with the retailer.

Based on above mentioned literature review, the following two typical investment and various profit distribution mechanisms are proposed, including a designed fair distribution mechanism which considers the energy-deficient or energy-saving households residents.

1. Shapley values approach

All profit, including both intra-community trading income and savings are distributed by Shapley value.

Shapley values originate from cooperative game theory and can calculate fair allocations for each member by considering all possible combinations of participants and their marginal contributions.

$$\phi_i(v) = \sum_{S \subseteq N \setminus \{i\}} \frac{|S|! \cdot (|N| - |S| - 1)!}{|N|!} \cdot [v(S \cup \{i\}) - v(S)]$$

v(S) represents the total net cost savings of members within alliance S in an energy-sharing scenario. In this study, v(S) is obtained through optimized calculations of MIPL, regulating photovoltaic power generation, energy storage scheduling, grid electricity purchases, and system maintenance costs for a given combination of participants. The total sum of revenue allocations is ensured to equal the overall revenue, while members with equal contributions receive equal allocations and non-contributors receive zero allocations.

This dissertation studies different types of households. Based on the consideration of computing power, there is no need to calculate the Shapley value for each individual user, but only calculate it according to household types, i.e, {i} represents 5 household types in sequence. The calculated Shapley value of household types is then allocated to individuals according to the proportion of population.

2. Equal Investment

Under this mechanism, the total community investment cost is evenly distributed among households, meaning each household bears the same initial investment amount and subsequent annual operation and maintenance expenses.

$$\text{Initial invest}_i = \frac{\text{Total Initial invest}}{\text{Households number}}$$

$$\text{OPEX}_i = \frac{\text{OPEX}_{comm}}{\text{Households number}}$$

Subsequently, all subsequent returns distributes by the following methods

(1) All profit, including both intra-community photovoltaic power trading income and savings from reduced electricity purchases due to self-consumption—are also distributed evenly to households.

$$\text{Revenue}_i = \frac{\text{Revenue}_{comm}}{\text{Community Size}}$$

(2) The intra-community trading income is distributed evenly to households, while the savings are also distributed by the dynaimic loads ratio of households.

$$\text{Invest Profit}_i = (\sum(E_{PV,tocomm} + E_{PV,tocomm}) \times TradePR + \sum E_{PV,togrid} \times FeedinPR) \times \frac{1}{\text{Community}Size}$$

$$\text{Saving Profit}_i = \frac{\text{Load}_i}{\sum \text{Load}_i} \times \sum(E_{PV,tocomm} + E_{BESS,tocomm}) \times (WithdrawPR - TradePR)$$

(3) The intra-community trading income is distributed evenly to households, while the savings are distributed by the Shapley value of households.

$$\text{Invest Profit}_i = (\sum(E_{PV,tocomm} + E_{PV,tocomm}) \times TradePR + \sum E_{PV,togrid} \times FeedinPR) \times \frac{1}{\text{community size}}$$

$$\text{Saving Profit}_i = \phi(\upsilon)_i \times \sum(E_{PV,tocomm} + E_{BESS,tocomm}) \times (WithdrawPR - TradePR)$$

3. Demand based proportional investment

Under this mechanism, each household contributes to the PV system's initial investment based on its annual electricity consumption as a percentage of the community's total usage.

$$\text{Initial invest}_i = \text{Total Initial invest} \times \frac{\text{Demand}_i}{\text{Demand}_{comm}}$$

$$\text{OPEX}_i = \text{OPEX}_{comm} \times \frac{\text{Demand}_i}{\text{Demand}_{comm}}$$

Subsequently, all subsequent returns distributes by the following methods

(1) All profit are distributed to households based on investment ratio.

$$\text{Revenue}_i = \text{Revenue}_{comm} \times \frac{\text{Demand}_i}{\text{Demand}_{comm}}$$

(2) The intra-community trading income is distributed by investment ratio, while the savings are also distributed by the dynaimic loads ratio of households.

$$\text{Invest Profit}_i = (\sum(E_{PV,tocomm} + E_{PV,tocomm}) \times TradePR + \sum E_{PV,togrid} \times FeedinPR) \times \frac{\text{Demand}_i}{\text{Demand}_{comm}}$$

$$\text{Saving Profit}_i = \frac{\text{Load}_i}{\sum \text{Load}_i}(t) \times \sum(\text{E}_{\text{PV},tocomm} + \text{E}_{\text{BESS},tocomm}) \times (WithdrawPR - TradePR)$$

(3) The intra-community trading income is distributed by investment ratio, while the savings are distributed by the Shapley value of households.

$$\text{Invest Profit}_i = (\sum(\text{E}_{\text{PV},tocomm} + \text{E}_{\text{PV},tocomm}) \times TradePR + \sum E_{PV,togrid} \times FeedinPR) \times \frac{\text{Demand}_i}{\text{Demand}_{\text{comm}}}$$

$$\text{Saving Profit}_i = \phi(\upsilon)_i \times \sum(\text{E}_{\text{PV},tocomm} + \text{E}_{\text{BESS},tocomm}) \times (WithdrawPR - TradePR)$$

4. Justice sharing approach

To balance equity and efficiency for diverse communities, this study proposes two hybrid solutions incorporating SIt regulation to redistribute benefits. These solutions target energy-deficient or energy-saving households (individuals with low electricity consumption) and economically disadvantaged families with high demand but lower per capita usage. Building upon existing investment frameworks, the proposed mechanisms aim to support vulnerable energy households while incentivizing community-wide electricity conservation efforts.

For the revenue from PV energy trade with the community and grid, this part continues to follow the previously mentioned returns based on the investment proportion (evenly divided or based on energy demand ratio). For the savings part from consuming PV energy, the returns follow the rule that introduces a RePro Justice factor(SIt).

$$\text{Saving Profit}_i = \sum \text{E}_{\text{PV},tocomm} \times (WithdrawPR - TradePR) \times \text{SIt}$$

$$SIt = \alpha \times \frac{Demand_i}{\sum Demand_i}(t) + (1 - \alpha) \times W_i$$

Dynamic demand ratio $\frac{Demand_i}{\sum Demand_i}(t)$ is the saving profit proportional allocation leads to a real-time demand ratio. The more consumed PV energy, The more saving .

Saving incentive factor W_i is by setting a threshold energy consumption value P0, to make energy-deficient or energy-saving households to get more profit.

Firstly, introducing a minimum energy guarantee threshold P0 [kWh/year] and a Saturation Reverse Sigmoid Function

$$w(P) = 1 - \frac{1}{1 + e^{-k(P-P_0)}}$$

When the ratio of the actual household energy consumption P to the threshold P0 $P/P_0=1$, $w(P) = 1$ this means that at this point, the household load is regarded as a "basic/critical demand"

When $P/P_0<1$, this household gain more weight (caring for the weaks)

When $P/P_0>1$, the weight is close to 1, the marginal weight hardly increases any more.

Saving weight factor is set between 1±50% range.

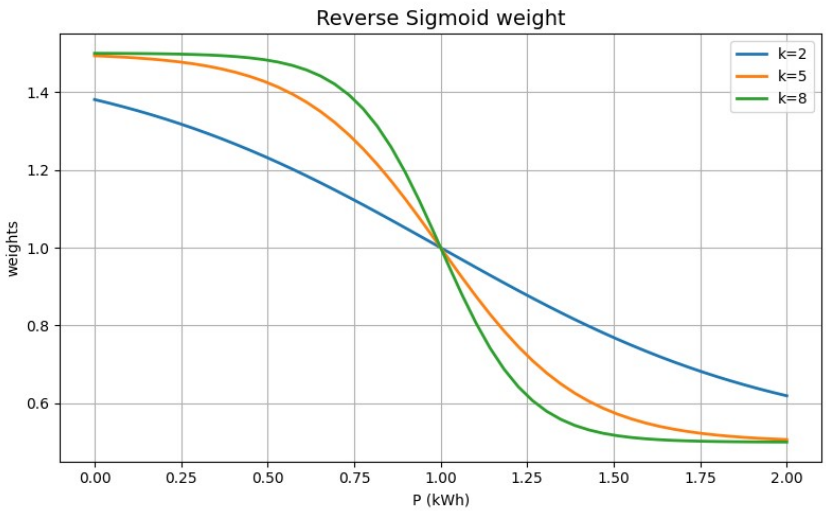


Fig. 3.7 Reverse Sigmoid weight with different k curve value

Curve sheer k controls the slope of reverse Sigmoid Function:

k=2, small slope, weight changes are "moderate" , highly inclusive but with weak discrimination

k=5, medium slope, normal S-shaped - Balances energy consumption fairness and investment efficiency

k=8, large slope, emphasizing strict boundaries, prevent high load from occupying resources.

Finally, the saving incentive factor of all households are normalized， $W_i = \frac{w_i(P)}{\sum w_i\,(\mathrm{P})}$

(1) Equal Investment per Household with SIt

This approach maintains the fundamental logic of equalizing initial investment distribution across households, ensuring uniform funding per unit. However, improvements have been made in profit allocation: Transaction profits (i.e., earnings from internal community electricity trading) continue to be distributed proportionally based on investment ratios (i.e., equal per household); while savings profits (i.e., cost reductions achieved through reduced grid consumption via photovoltaic systems) are allocated according to each household's Electricity Saving Index (SIt). The SIt is determined by the ratio of a household's electricity load to the community's total load. A lower ratio corresponds to a higher SIt value, resulting in greater savings profits.

$$\text{Invest Profit}_i = (\sum(\text{E}_{\text{PV},tocomm} + \text{E}_{\text{PV},tocomm}) \times TradePR + \sum E_{PV,togrid} \times FeedinPR) \times \frac{1}{\text{Community}Size}$$

$$\text{Saving Profit}_i = \text{SIt}_i \times \sum(\text{E}_{\text{PV},tocomm} + \text{E}_{\text{BESS},tocomm}) \times (WithdrawPR - TradePR)$$

As the 3.3.2 mentioning, a 3-person household consumes between 2,160 and 2,900 kWh annually. Here, setting the threshold P0 is the smaller value between total electricity consumption of the community divided by the number of households and 2800 kWh,

$$\text{P0} = \min\{\frac{\sum \text{demand}}{\text{household numbers}}, 2800\text{kWh}\}$$

(2) Investment Proportional to Annual Electricity Consumption with SIt

The initial investment is allocated according to the proportion of households annual power consumption; part of the transaction income is returned according to the proportion of investment; and the savings income is redistributed according to SIt to reflect the user's power efficiency and photovoltaic matching degree.

$$\text{Invest Profit}_i = (\sum(\text{E}_{\text{PV},tocomm} + \text{E}_{\text{PV},tocomm}) \times TradePR + \sum E_{PV,togrid} \times FeedinPR) \times \frac{\text{Demand}_i}{\sum \text{Demand}_i}$$

$$\text{Saving Profit}_i = \text{SIt}_i \times \sum(\text{E}_{\text{PV},tocomm} + \text{E}_{\text{BESS},tocomm}) \times (WithdrawPR - TradePR)$$

As the 3.3.2 mentioning, the average electricity consumption is 1090 kWh per person per year.

Here P0s are set for different household types.

Household characteristic	P0[kWh/year]
Single persons	1100
Couples without child	2200

Couples with children	3000
One parents with children	1800
A nucleus with others	5000

Table. 3.2 Energy guarantee threshold P0 for households

It comprehensively considers the dual fairness logic of "the more who uses, the more they invest" and "the better who utilizes PV, the greater the savings"; it can better balance economic efficiency and behavioral guidance (i.e., encouraging residents to use more electricity during the day); in most practical communities, this approach is often regarded as the design with the most "procedural justice".

Summary

Equal investment	All profit distributed evenly
	Investment profit distributed evenly+Saving profit distributed by dynamic demand ratio
	Investment profit distributed evenly+Saving profit distributed by Shapley Value
Demand proportional investment	All profit distributed by investment ratio(demand ratio)
	Investment profit distributed by investment ratio+Saving profit distributed by dynamic demand ratio
	Investment profit distributed by investment ratio+Saving profit distributed by Shapley Value
Equal investment+SIt	Investment profit distributed evenly+Saving profit distributed by SIt
Demand proportional investment +SIt	Investment profit distributed by investment ratio+Saving profit by SIt

Table. 3.3 Summary of investment methods and the profit distribution mechanism

3.3 Case 2 A third party invests

In this investment scenario, MIPL is also used to optimize the community energy, but the objective function is changed to prioritize the interests of third parties, that is, to maximize the maximum profit of investors.

Objective funcion

$$\max \text{Profit} =$$

$$\sum (E_{pv,tocomm}(t) + E_{bess,tocomm}(t)) \times TP(t) + \sum E_{PV,togrid} \times FeedinPR(t) - E_{grid,tobess}(t)) \times WithdrawPR(t)$$

It is worth noting that the community energy trading price is not introduced in Case 1's community self-investment scenario, where the community's overall revenue depends on electricity consumption (savings) and photovoltaic power generation (revenue). However, in Case 2, the community energy trading price directly determines the returns for third parties. Therefore, in scheme 2, two price mechanisms are set up, in addition to the supply-demand ratio pricing in Case 1, there is also the mid-market price(mid TP) mechanism as a comparison.

The interest of residents is the difference between the purchase of photovoltaic electricity and the grid, and the interest of the third investor is the income from the purchase of electricity by residents and the income from photovoltaic feed-in.

3.4 Evaluation Indicators

The evaluation criteria are divided into horizontal and vertical parts, economic indicators and environmental indicators, community level and households type level，including NPV (Net Present Value) over the project's lifetime, ROI (Return on Investment), Annual net saving, saving ratio, QoE (Quality of Experience for per unit power saving), as well as environmental impact assessment and carbon footprint reduction metrics.

3.5 Uncertainty analysis

Ref [60][61] mentions the uncertainties associated with the various solar energy investments mentioned in the article include solar radiation data, which is one of the main factors affecting energy output assessments, technical parameter uncertainties such as photovoltaic module degradation rates and reflection losses, fluctuations in module prices, LCOE, and variations in electricity rates across different regions. And Monte Carlo-based uncertainty analysis is useful to analysis the uncertainty in PV investment.

Chapter 4   Simulation and results

4.1 Case study simulation

To validate the models and the procedures developed in Chapter 3, a reference case study is established, simulating a building REC composed of a reference commercial - residential building case in Torino, Northern Italy. The models will be employed to assess the economic viability of creating a REC with investment from the community itself or a third - party. 50 households are taken into account, having available space on their roof as shown in Figure 4.1.

Fig. 4.1 The studied building live-action shooting

The east-west and north-south roofs each account for 1/4 of the total roof. According to the photovoltaic power generation direction correction coefficient, the total power generation correction coefficient is

PV Reduction coefficient	1.0(S)	0.85(W/E)	0.6(N)

$$1 \times \frac{1}{4} + 0.85 \times \frac{1}{4} + 0.85 \times \frac{1}{4} + 0.6 \times \frac{1}{4} = 0.825$$

PV Parameters：

Solar Irradiation	From database PVGIS
Roof area(m2)	796.3
Roof utilized rate	85%
Available roof installed area(m2)	640
Tilt angle	30
Module dimension(mm):	2376 x 1128 x 5
Numbers of installed PV module	238
Module peak power(W)	450
Total installed gross capacity(kW)	238×0.45=107.1 (Adopted 100)
Actual gross generation(kW)	0.825×100=82.5
Technology	Crystalline silicon
Conversion efficiency	15%
System loss	14%
Degradation rate	0.5%
Initial unit investment cost(€/kW)[63]	1,180
Initial investment cost(€)	118,000
Opex (€/kWh/yr)[63]	1% Initial investment
Lifecycle	20 year

Table. 4.1 PV input data

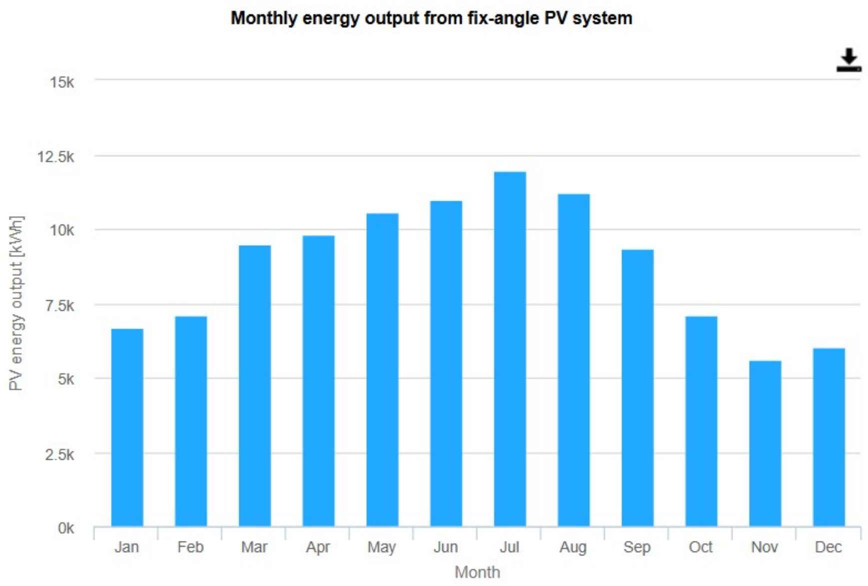


Fig. 4.2 Monthly PV energy generation

BESS Simulation

Currently, for a 4hour battery, the capital expenditure factor is estimated to be approximately 370 - 410 k€/kWh. It's anticipated that prices will keep dropping over time, with projections that they may reach values near 250 k€/kWh in the long run. In this study, the highest price of 410 k€/kWh is selected.

Charge efficiency	95%
Discharge efficiency	95%
SOC initial	50%
SOC min	10%
SOC max	90%
C_{rate}	0.5
Power of charge/discharge (kW)	0.5capacity
Degradation	2%
Battery investment cost (€/kWh)[64]	410
Initial investment cost(€)	20,500.00
Battery Opex [€/kWh/yr][64]	2%Initial investment

Table. 4.2 Battery input parameters

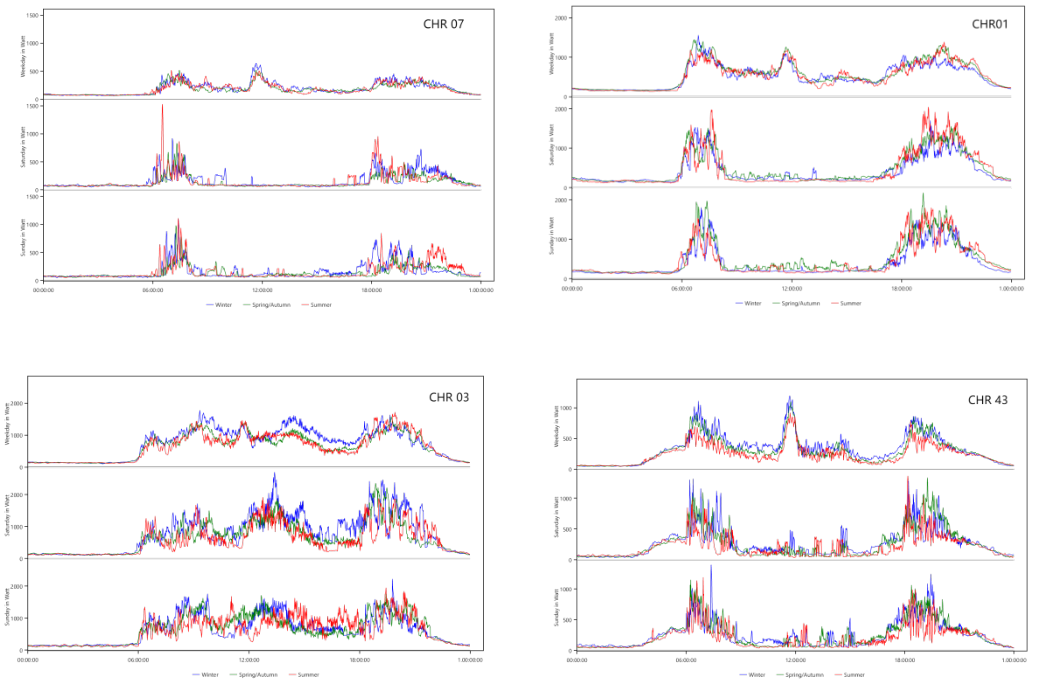
The annual interest is set at 3%.

Household load profile Simulation

By LGP software to simulating households' annual energy profiles. Based on the annual per capita electricity consumption of 1,080 kWh mentioned in Chapter 3.3.2, households who consume less than the benchmark (energy-saving households) and those who consume more than the benchmark (over-consumption households) each account for half of the community-to-household types. The annual electricity consumption of over-consumption households is set at 1.3-1.4 times that of energy-saving households. 50 Households,Total consumption 114251.23 kWh.

NO.	Family characteristics	Load[kWh/year]	Family characteristics	Load[kWh/year]
CHR07	Single persons	965.60	Single persons(excessive)	1501.39
CHR01	Couples without child	2064.22	Couples without child(excessive)	3096.32
CHR03	Couples with children	2764.49	Couples with children(excessive)	3641.43
CHR43	One parents with children	1504.95	One parents with children(excessive)	2407.92
CHR14	A nucleus with others	4378.56	A nucleus with others excessive)	6129.98

Table. 3.3 The electricity demand of households



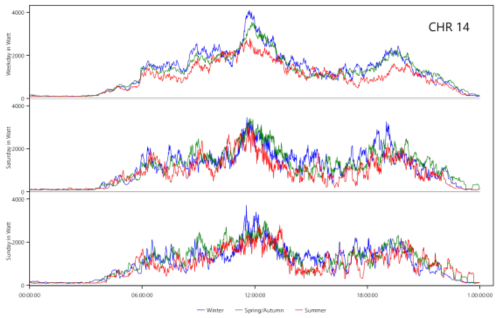


Fig. 3.3 Average daily electricity curves of households on weekday and weekend

Grid Price（Time-of-use energy pricing）

Electricity price data was downloaded from the Gestore Marcati Energetici (GME) website[59]. For northern Italy in 2023zonal price. As mentioned in chapter1.2.2 above, Ritiro dedicato， which is the higher price between zonal price and i prezzi minimi garantiti , as a PV feed-in pricing mechanism. And the residents' electricity withdrawed price depending on the contract signed, there are different differences. As Quota per consumi mentioned in chapter 3.5.1, the residential grid purchase price here is calculated in proportion to the zonal price.

Energy trading pricing applies two schemes,i.e., mid-market price(midTP) and dynamic supply-demand-ratio price(sdrTP).

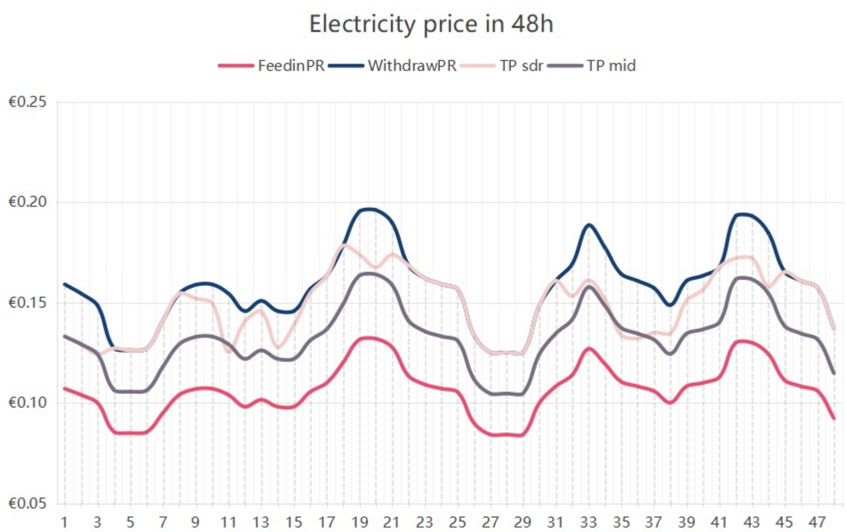


Fig. 3.4 Market and community trading electricity prices

Uncertainty analysis

In this study, 300 uncertainty scenarios were generated, each representing a unique realization of the system's cost and financial assumptions. The number of samples (n = 300) was selected to balance statistical significance and computational tractability, in line with recommendations from Monte Carlo-based uncertainty studies.

The following input parameters were considered uncertain:

PV Investment Cost :

Modeled using a log-normal distribution with a maximum of 1180 €/kWp and a shape parameter σ = 0.15, reflecting the right-skewed nature of technology costs and their dependence on market conditions and system scale. This distribution ensures non-negativity and captures the asymmetric uncertainty in capital expenditure (CAPEX) of PV systems.

BESS Investment Cost :

Similarly, the battery storage investment cost was modeled with a log-normal distribution centered around a maximum value of 410 €/kWh and a higher shape parameter (σ = 0.25) to reflect greater market volatility and technological uncertainty associated with battery systems.

Discount Rate:

The social discount rate, a key factor in evaluating long-term investment returns, was modeled with a triangular distribution bounded between 2% and 5%, with a mode at 3%.

PV and BESS Operation & Maintenance (O&M) Costs:

Annual O&M costs were expressed as a percentage of the initial investment. These were modeled using normal distributions with:

PV O&M: mean =1%, standard deviation = 0.3%

BESS O&M: mean = 2%, standard deviation = 0.2%

Grid power price (€/kWh):

According data from tradingeconomics[61], household prices of electricity in Italy from 2016 to 2025 increased from raound 50 €/MWh to 110 €MWh. From 2021 to 2023, due to the war between Russia and Ukraine, electricity prices soared, and in 2024, they fell, but overall they were higher than before 2021.

Fig. 3.5 Italy electricity spot prices [61]

To account for electricity market uncertainty, here introduced price multipliers to simulate possible fluctuations in grid electricity prices. The purchase price was randomly varied within -10% to +50%, while the feed-in tariff is the two third of purchase price.

These reflect industry norms and moderate variability due to maintenance contracts, labor costs, and system aging.

All random variables were independently sampled. For each scenario, a vector of sampled input values was generated and passed to the economic simulation model. This approach yields a representative ensemble of plausible system behaviors under input uncertainty, enabling a robust analysis of Net Present Value (NPV) distribution and risk.

4.2 Case 1(community self-invests) results and analysis

4.2.1 PV and BESS optimal capacity

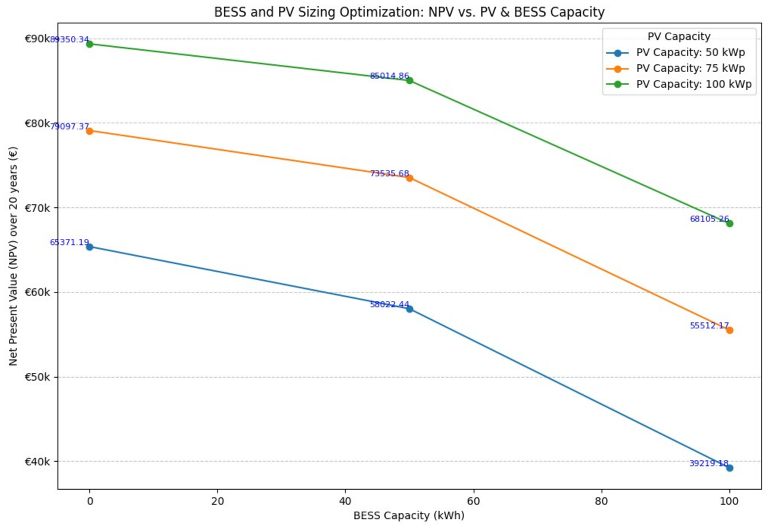


Fig. 4.6 NPVs based on PV & BESS capacity

The results from the Optimal NPV analysis indicate that investing in 100kWp photovoltaic systems without BESS yields a maximum NPV of €89,350.34. However, for the 100kWp PV system scenario, deploying a 50 kWh BESS achieves an NPV of €85,014.86, which is nearly equivalent to the non-invested BESS option at €4,336. Considering emergency backup power requirements, this study selects a 50kWh BESS system as the optimal configuration. This setup enables approximately 3.5 hours of energy storage capacity for the community grid.

Capital Metric	Value
BESS Capacity (kWh)	50
Installed PV Capacity (kWp)	100
Initial PV Cost (€)	118,000.00
Initial BESS Cost (€)	20,500.00
Initial Total Investment (€)	138,500.00
Total Annual OPEX (€)	1,590.00
NPV (€)	85,014.86
Baseline Cost (€)	19,065.96
Annual Grid Cost(€)	2,452.29

Annual Savings (€)	16,613.71
Net Annual Savings (after Opex) (€)	15,023.71

Table. 3.4 Economic Values with chosen PV & BESS capacity

Economic Analysis

Figure3.4 illustrates the cumulative *Net present value (NPV)* of the community photovoltaic (PV) and battery energy storage system (BESS) over a 20-year period, based on the optimal configuration of 50.0 kWh BESS capacity and 100.0 kW PV capacity. The system starts with a negative NPV due to the high initial investment cost, reaching approximately €138,500.00 in the first year. By 20th year , the cumulative NPV reaches approximately €85014.86, indicating strong long-term profitability and a payback period of roughly 11 years.

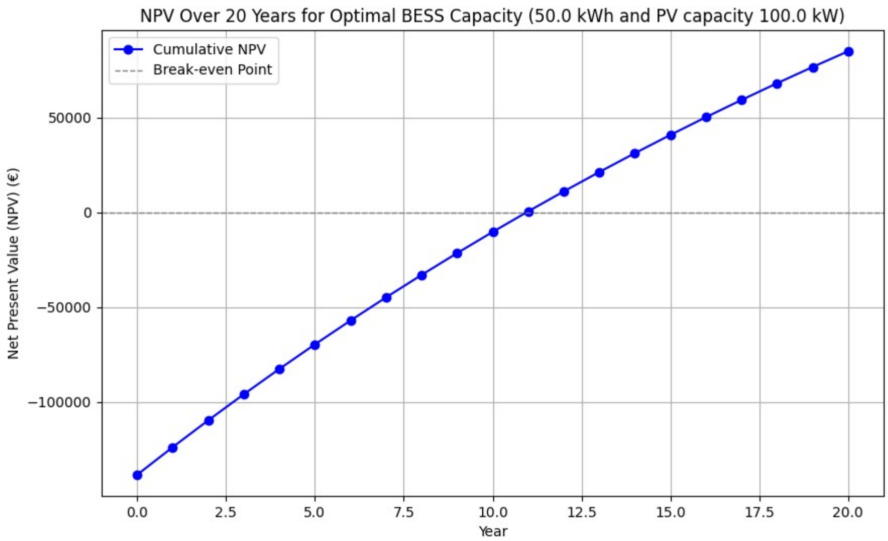


Fig. 3.7 NPV Over 20 Years for Optimal PV-BESS Capacity

Levelized Cost of Electricity(LCOE)

$$LCOE = \frac{\text{Initial Invest} \times \text{CRF} + \text{OPEX}}{E_{PV}} = \frac{138500 \times 0.0672 + 1590}{107889.11} = 0.102€/kWh$$

Where, $\text{CRF}=\frac{r\times(1+r)^T}{1+r^T-1} = \frac{0.03\times(1+0.03)^{20}}{(1+0.03^{20})-1} = 0.0672$

In Ref [60], the modeled Levelized Cost of Electricity (LCOE) for residential use in Italy in 2020 ranges from 0.068 to 0.099 €/kWh . According to the report titled "Levelized Cost of Electricity for Renewable Energy Technologies," the LCOE for rooftop photovoltaic (PV) systems in 2024 is estimated to be between 0.07 and 0.14€/kWh. Therefore, the LCOE of 0.102 €/kWh presented in this study is reasonable.

4.2.2 Community energy flow optimal MIPL solution

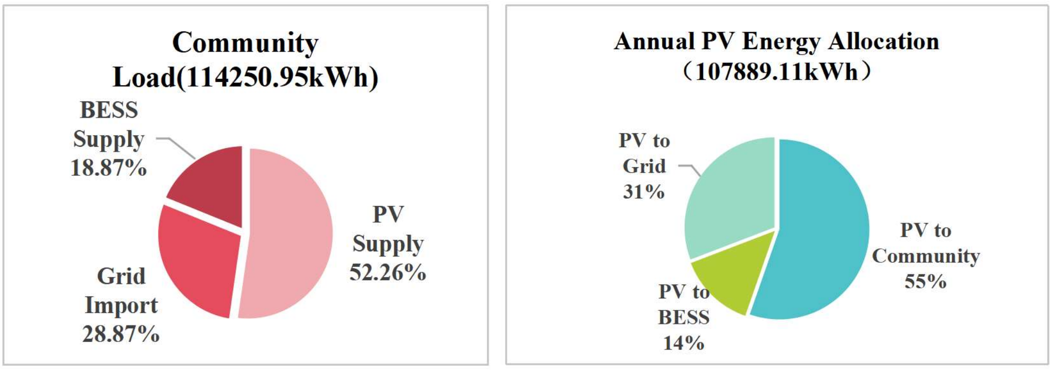


Fig. 3.8 Community energy composition and Annual PV energy allocation

PV Self-consumption rate:

$$SC = \frac{E_{PV,comm} + E_{BESS,comm}}{Total\ PV\ generation} \times 100\% = 55\% + 14\% = 69\%$$

PV Self-sufficiency rate:

$$SS = \frac{E_{PV,comm} + E_{BESS,comm}}{Total\ Load} \times 100\% = 52.26 + \% + 18.87\% = 71.13\%$$

The photovoltaic (PV) system achieves a self-consumption rate of 69%, indicating that the majority of the PV-generated electricity is directly utilized within the community, either for immediate load supply or through storage in the BESS for regulating peak electricity consumption. This relatively high self-consumption level reflects effective integration between PV generation and local demand, reducing reliance on grid imports and mitigating potential curtailment of surplus PV energy. The PV self-sufficiency rate reaches 71.13%, meaning that over 70% of the community's total annual electricity demand is met by locally generated PV electricity. This high degree of self-sufficiency highlights the system's capacity to enhance energy autonomy and resilience, while simultaneously reducing exposure to volatile grid electricity prices.

As can be seen in the Figure 3.9 below, the electricity demand during the day is almost met by PV. During the peak hour of night, the battery discharges to meet the peak demand. In the early morning when the grid price is low, the battery charges and households buy electricity from the grid.

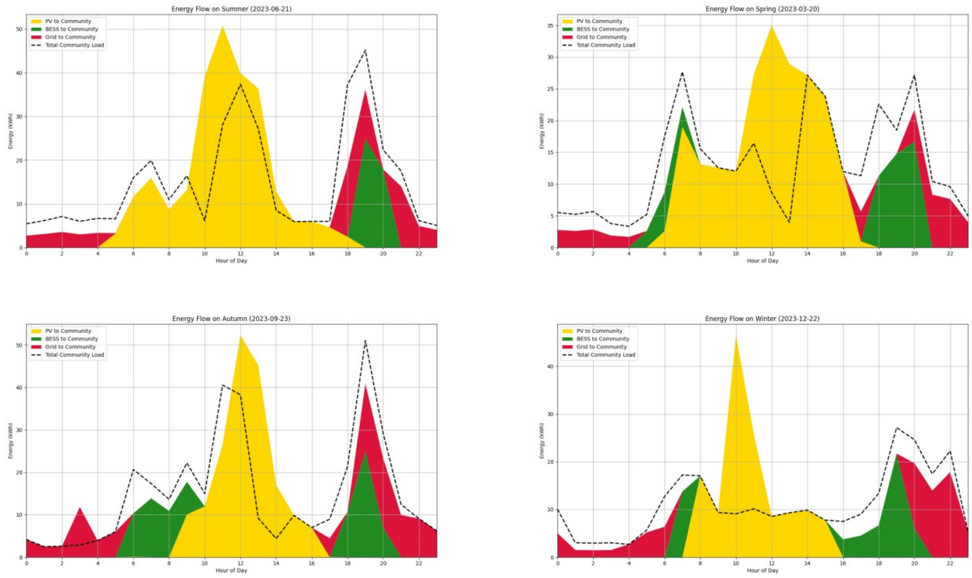
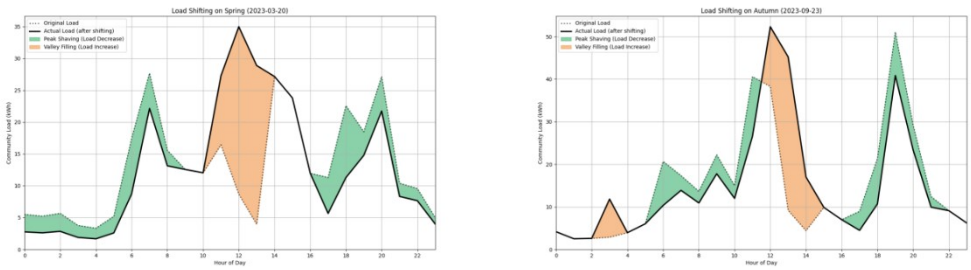


Fig. 3.9 Community energy flow in equinox and solstice

By peak shifting, the adjustable electricity consumption was moved to the period of PV generation and the period of relatively low grid price, and the Annual saving of the community increased from € 15,159.64 to € 16,613.71, an increase of 9.2%, and the NPV increased from € 63,381.91 to € 85,014.86, an increase of 34%.



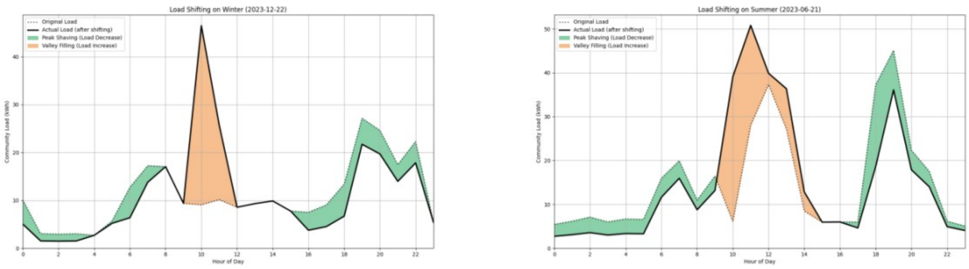


Fig. 3.10 Shifting load in equinox and solstice

The majority of generation during midday is allocated directly to community loads and to the battery energy storage system, with only a small fraction exported to the grid. This pattern reflects a high level of local utilization in periods of limited PV supply, maximizing self-consumption and minimizing reliance on external electricity sources.

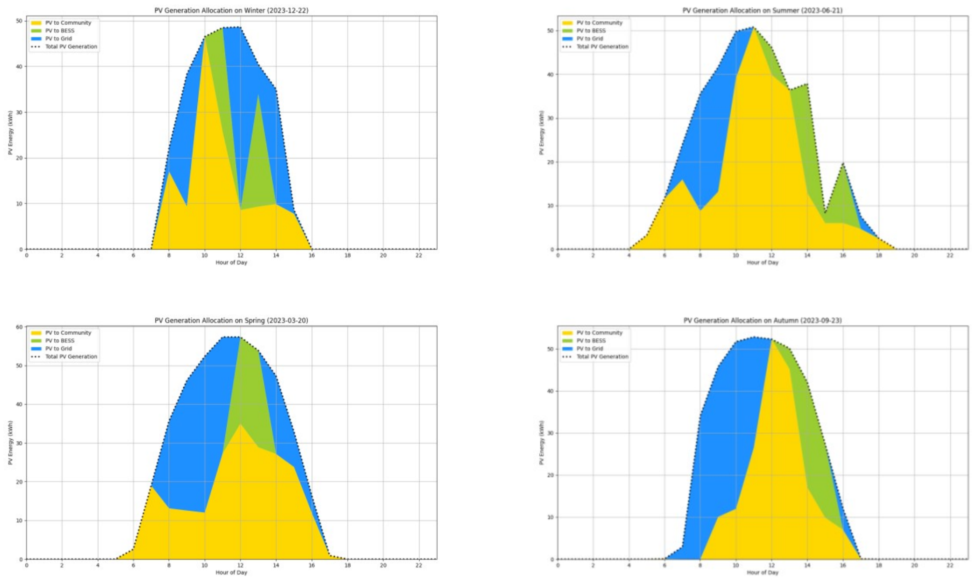
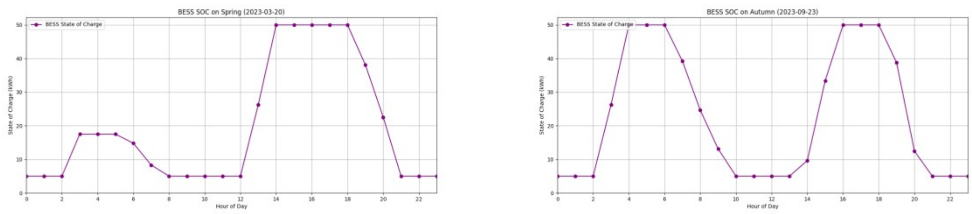


Fig. 3.11 PV energy generation allocation in equinox and solstice

BESS is charged during midnight when the grid price is lower and during midday when PV generation is high. BESS is discharged when the community load is high.



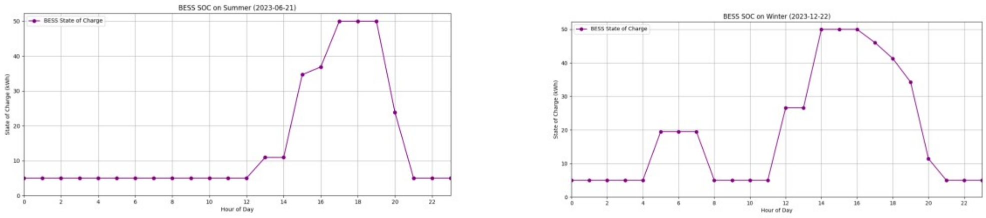


Fig. 3.12 BESS charge/discharge in equinox and solstice

The National CO2emission factor equal to 255 kgCO2/MWh[65] for the electricity withdraws from the National grid

$$CO_2\text{reduction} = \sum E_{pv} \times 255\text{kgCO2/MWh} = 107.89\text{MWh} \times 255\text{kgCO}_2\text{/MWh} = 27511.95\text{kg}$$

4.2.3 Uncertainty Analysis

A Monte Carlo-based uncertainty analysis was conducted on the community PV and battery energy storage investment. The simulation over 300 stochastic scenarios yielded the following financial outcomes:

Mean NPV (€): 101,942.04
Std Dev (€): 40,502.28
P10 (€): 46,376.54
P50 / Median (€): 102,149.07
P90 (€): 155,454.01
Positive NPV Probability (%): 100.00

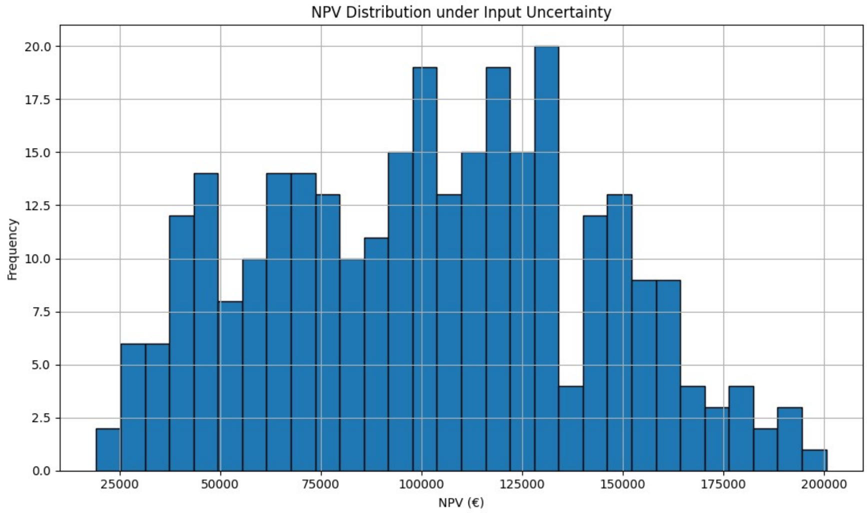


Fig. 3.13 NPV distribution uncertainty

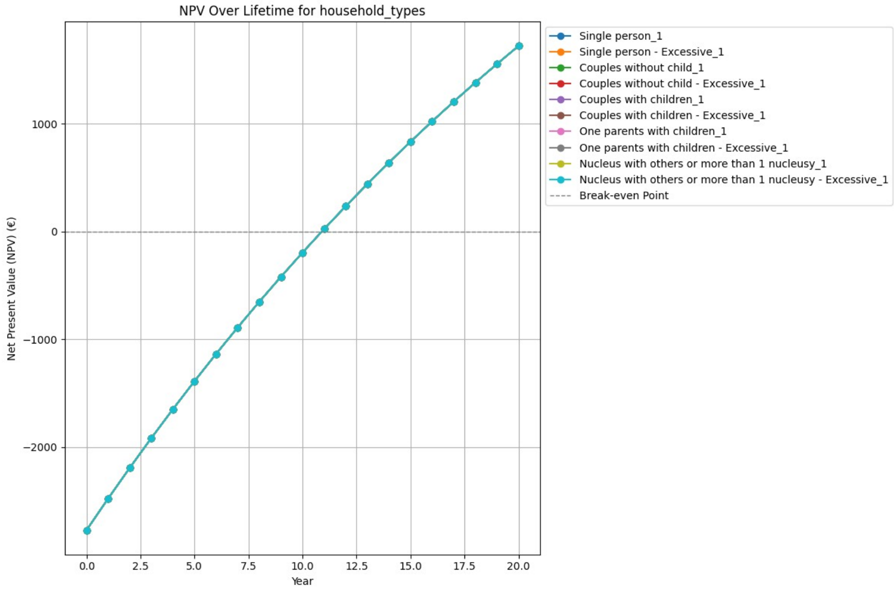
The uncertainty analysis incorporating PV/BESS costs, O&M, discount rate, and particularly electricity price volatility (−10% to +50% for purchase price) reveals a robust financial performance. The average NPV exceeds €100,000 with a 100% probability of positive returns, suggesting that the project remains financially viable under a wide range of economic conditions. The P50 value of €102,149.07 is higher than the current NPV, and the high P90 value of €155,454 highlights the potential upside in favorable market scenarios.

4.2.4 Households' economic results and analysis

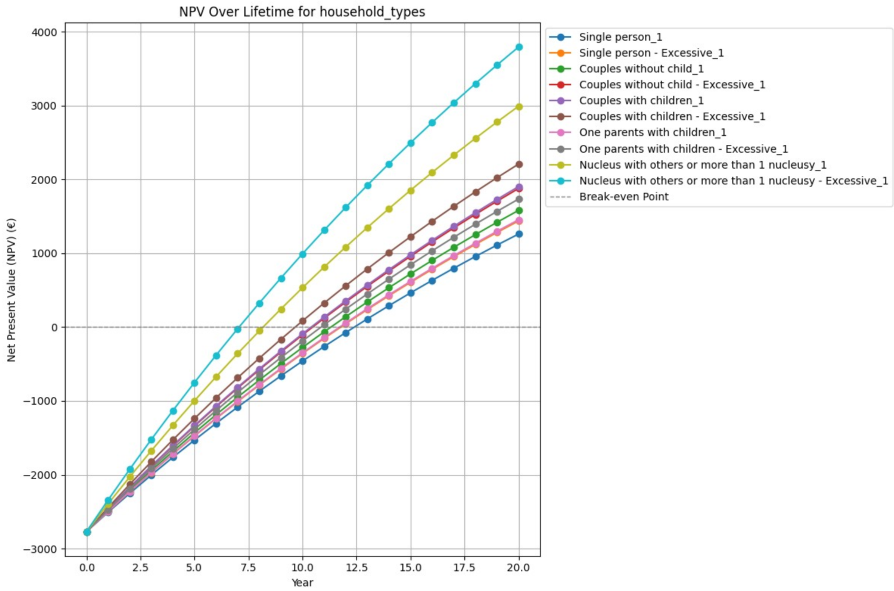
Household types	Shapley values	Household types	Shapley values
Single person	0.016	Single person - Excessive	0.018
One parents with children	0.018	One parents with children - Excessive	0.020
Couples without child	0.019	Couples without child - Excessive	0.021
Couples with children	0.022	Couples with children - Excessive	0.025
Nucleus	0.026	Nucleus - Excessive	0.031

Table. 4.5 Household types' Shapley values

1. Equal Investment



(a) All profit distributed evenly



(b)Investment profit distributed evenly+Saving profit distributed by dynamic demand ratio

Fig. 4.14 NPVs of households over 20years

In the Figure 4.14(a), the scheme of all profit distributed evenly, shows the NPV lines of all households are coincident. As it is an equal investment, the initial investment (€2770) and NPV(€1720.39) of each household are the same, and the investment return cycle is consistent with the community return cycle, which is about 10.5 years. The Figure 4.14(b) shows under the scheme of investment profit distributed evenly+Saving profit distributed by dynamic demand ratio, the benefit will tilt to the nucleus households massively.

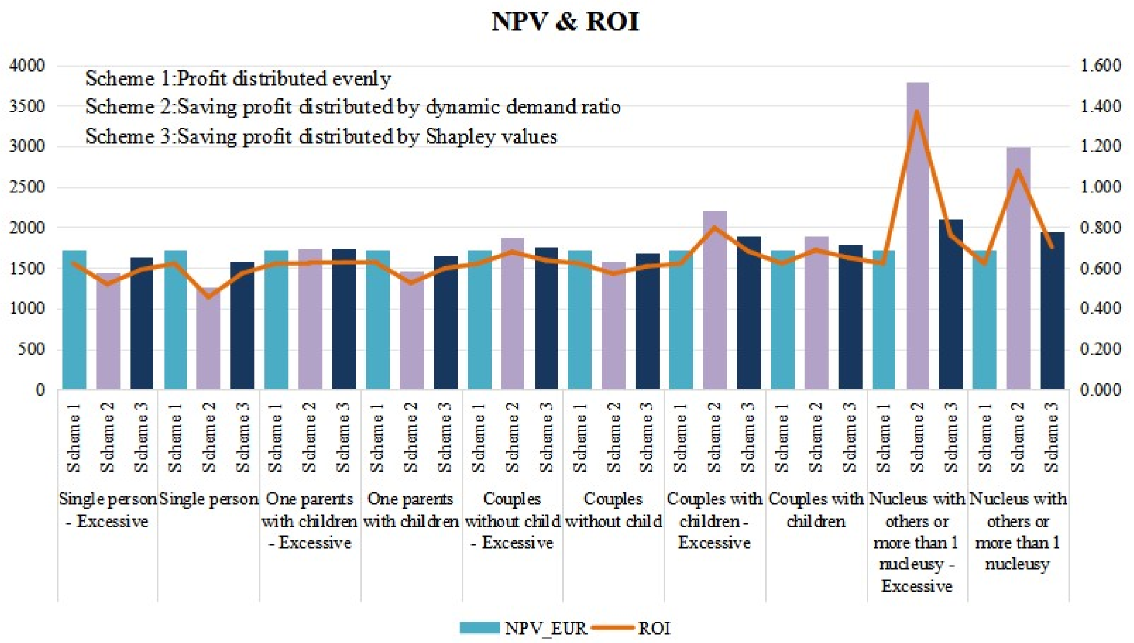


Fig. 4.15 Comparison of NPVs and ROIs of households

Figure 4.15 compares NPV and ROI outcomes of three profit distribution schemes under equal investment. Scheme 1 (even profit distribution) gives uniform NPV (€1720.39) across household types. Scheme 2 (saving profit distributed by dynamic demand ratio) differentiates based on demand patterns or energy usage behaviours, causing moderate NPV variation among low and medium demand families, but has the significantly higher NPV spread among high demand families (like nucleus). Single person families drop to €1437.70, Couple without child families drop to €1580.43, while nucleus families rise to €2990.97. With Scheme 3 (saving profit distributed by Shapley values) households contributing more to cost savings gain a slightly larger NPV than Scheme 1.

The ROI in Scheme 1 is 0.621, and in Scheme 3, for most families fluctuates around 0.621, But in Scheme 2, for high-demand families (nucleus families and couples with children - excessive ones), the ROI gets a significant rise, up beyond 1.00.

For short term economic evaluation, the comparison of the net saving and the baseline cost among households under the three given schemes.

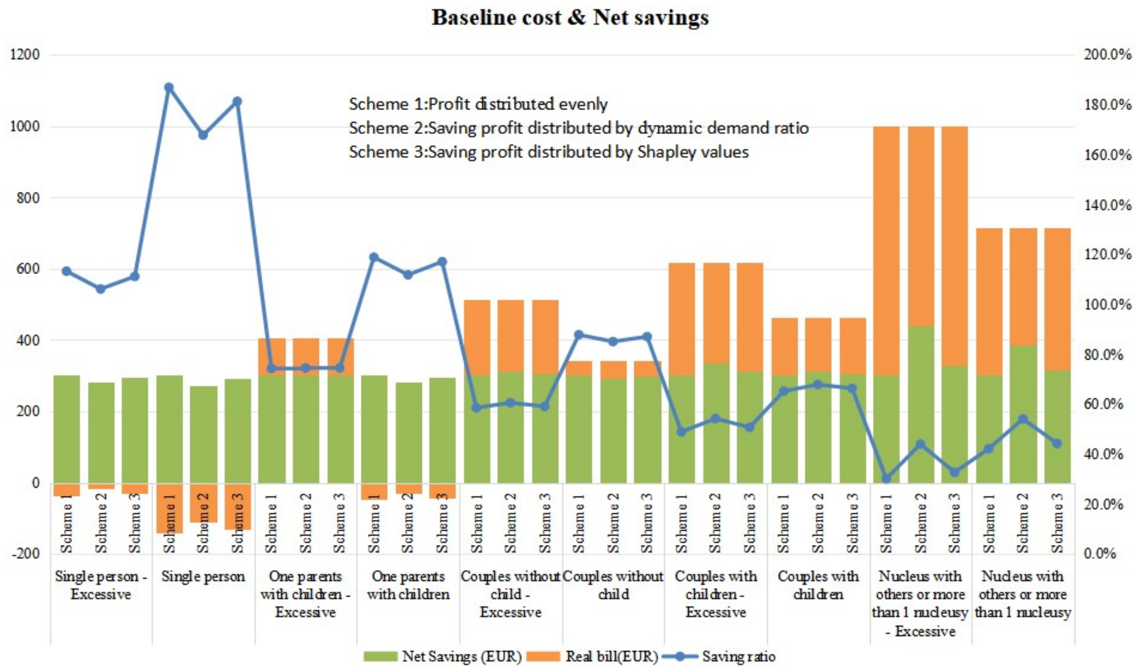


Fig. 4.16 Comparison of Baseline costs and net savings of households

The Figure 4.16 shows the baseline costs and net savings of each family type under the equalized investment with three benefit distribution mechanisms. Negative values mean surplus income.

For households with low electricity consumption, such as those consisting of a single person or single-parent families, their net savings can entirely cover their annual electricity bill and still yield surplus income under all three distribution schemes. Their saving ratio experiences only slight fluctuations. In contrast, nucleus families are noticeably affected by the different schemes. Furthermore, within the same household type, those with excessive consumption tend to profit significantly more than those with normal consumption levels.That means under the equal investment, the profit tilts to those families who consume more energy.

Under the scheme 1 profit distributed evenly scheme, all households achieve the same annual return of €301.82. Single-person households even have a surplus incomer of €140.37, achieving a remarkable 186.9% savings rate. However, for high-consumption households with multiple occupants (Nucleus family), the savings rate has only around 42%. These households cannot offset their substantial electricity expenses through such modest savings, indicating insufficient conservation. The couples families have have only a slight fluctuate with 3 different schemes. Detailed data can be found in the appendix.

Quantitative indicators of fairness

$$QoE = 1 - \frac{\sigma(T)}{95\%\sigma(T)}$$

$$\sigma(T) = std\sum\left(\frac{Net\ \text{Savings}}{Demand}\right)_i$$

$\sigma(T)$: The standard deviation of saving

$95\%\sigma(T)$:The 95th percentile unit savings value $\sigma(T)$， represents the "upper limit" reference for the level of savings.

Approaching 1 ⇒ The electricity usage benefit for all individuals is nearly the same

Approaching 0 ⇒The electricity usage benefit for all individuals is severe imbalance

	$\sigma(T)$	$95\%\sigma(T)$	QoE
Scheme 1:Profit distributed evenly	0.087	0.313	0.723
Scheme 2:Saving profit distributed by dynamic demand ratio	0.071	0.281	0.747
Scheme 3:Saving profit distributed by Shapley values	0.074	0.256	0.709

Table. 4.6 QoE comparison

Scheme 2 demonstrates the most balanced performance across fairness (low standard deviation 0.071), efficiency (high QoE 0.747), and acceptable variance range, making it the overall optimal solution. Scheme 3 outperforms in controlling extreme variances (minimum 95% σ(T)=0.256), but its overall QoE of 0.709 is slightly inferior. This may be due to excessive benefits being skewed towards high-contributing households, potentially causing perceived degradation among low-load households. While Scheme 1 is simpler to implement, it exhibits the largest variance (0.087) and falls short in both fairness and efficiency metrics.

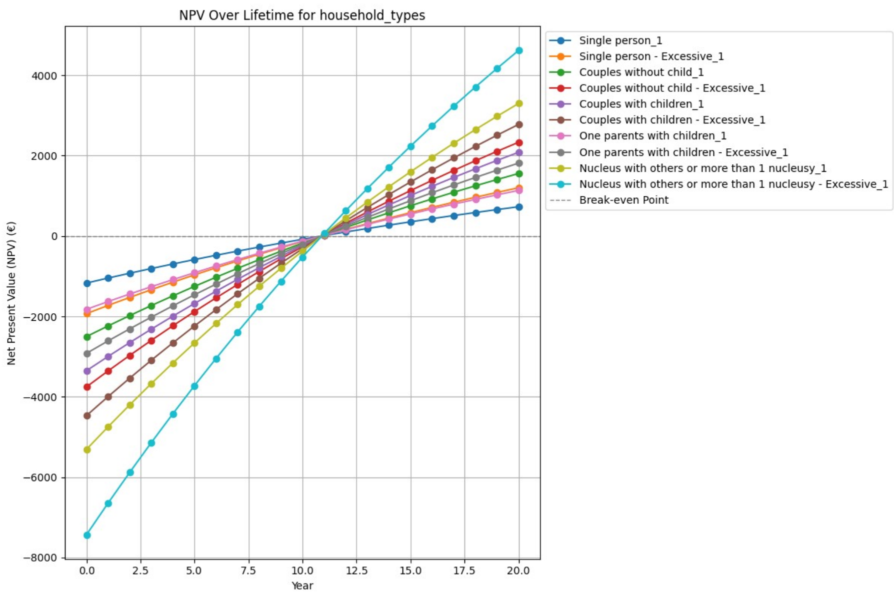
Overall, under Equal investment, for low-demand households have the highest annual savings rate , and for high-demand households have the highest NPV over their life cycle.

Scheme 1 (evenly profit distribution) gives uniform NPV across household types, an egalitarian approach ensuring equity in monetary returns but ignoring household energy consumption variations, which may lead to inefficiencies and reduced incentives for high - demand households.

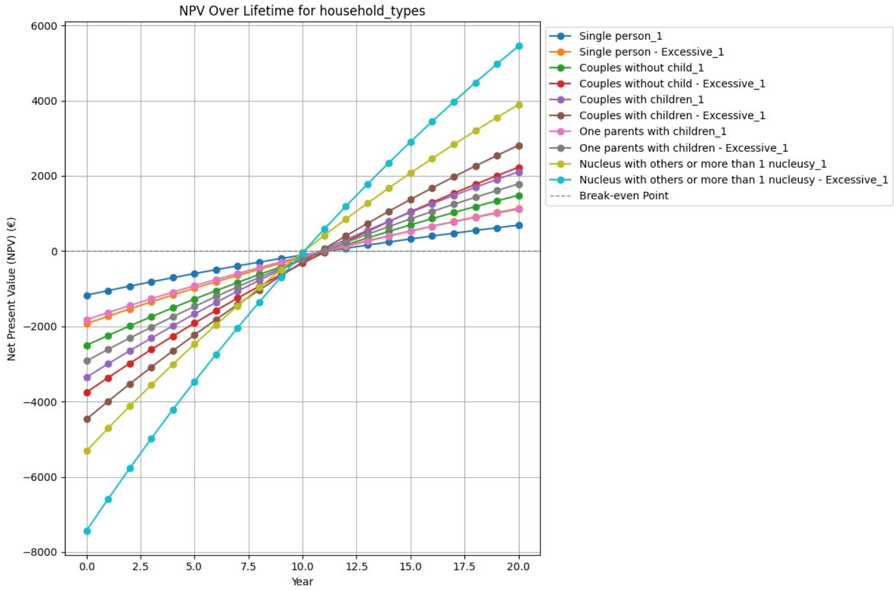
Scheme 2 (saving profit distributed by dynamic demand ratio) differentiates based on demand patterns or energy usage behaviors, which greatly benefits those families consuming more energy during the PV generating period and high-demand families， which is suitable for encouraging the optimization of PV electricity consumption behavior.

Scheme 3 (saving profit distributed by Shapley values) maximizes allocative efficiency by aligning rewards with marginal contributions but risks worsening inequality, possibly needing fairness mechanisms or policy adjustments.

2. Investment Proportional to Electricity Consumption



(a)All profit distributed by invest ratio



(b)Investment profit distributed evenly+Saving profit distributed by dynamic demand ratio

Fig. 4.17 NPVs of households over 20years

In the Figure 4.17(a), the chart indicates a positive trend, with all households achieving a positive NPV around the eleventh year. Nucleus households exhibit the highest growth rate and NPV, primarily due to their high electricity consumption and substantial investments, which yield greater returns and superior long-term gains. Initial investments are substantial, amounting to €5307.87, yet returns accelerate, resulting in a €3296.61 NPV and the shortest cost recovery period. Single-person households, with lower electricity usage, incur minimal losses and experience a slower NPV growth, NPV resulting in €727.00. Investments correspond with demand: households with higher consumption invest more and receive greater returns.

The Figure4.17(b) shows under the scheme of investment profit distributed by investment ratio and saving profit distributed by dynamic demand ratio, the benefit will tilt to the nucleus households , NPV of nucleus families rise up to €3895.24.

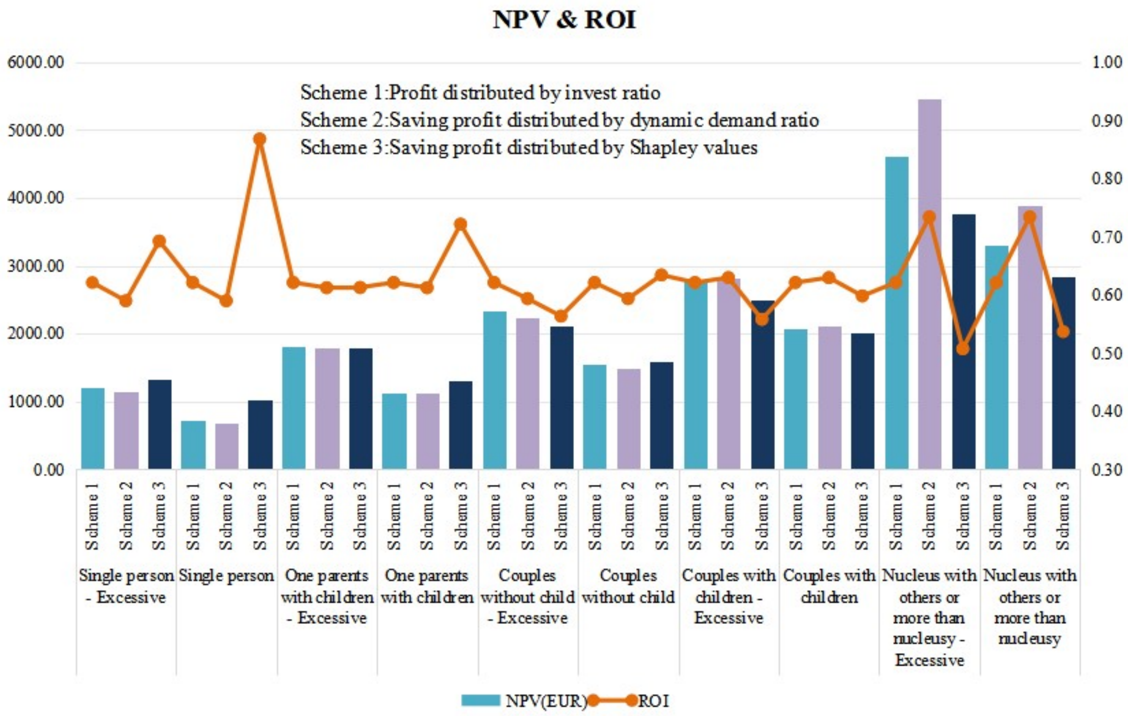


Fig. 4.18 Comparison of NPVs and ROIs of households

Figure4.17 compares NPV and ROI outcomes of three profit distribution schemes under demand proportional investment. Scheme 1 (profit distributed by investment ratio) NPV is proportional to the investment proportion, and the ROI is 0.621. Scheme 2 (saving profit distributed by dynamic demand ratio) differentiates based on demand patterns or energy usage behaviours, causing moderate NPV variation among low and medium demand families, but has the significantly higher NPV spread among high demand families (like nucleus)， since the nucleus families consume more electricity during daytime PV generation, get a larger savings which rises from €3296.61 to €3895.24. Scheme 3 (saving profit distributed by Shapley values) low demand families gain a slightly larger NPV than Scheme 1, while medium and high demand family gain a lower NPV than Scheme 1, especially those excessive consumption families. This is the opposite of equal Investment Scheme 3.

The ROI in Scheme 1 is 0.621, and in Scheme 2, for most families fluctuates around 0.621, But in Scheme 3, for high-demand families (nucleus families and couples with children - excessive ones), the ROI gets a significantly decrease, dropping to 0.5.

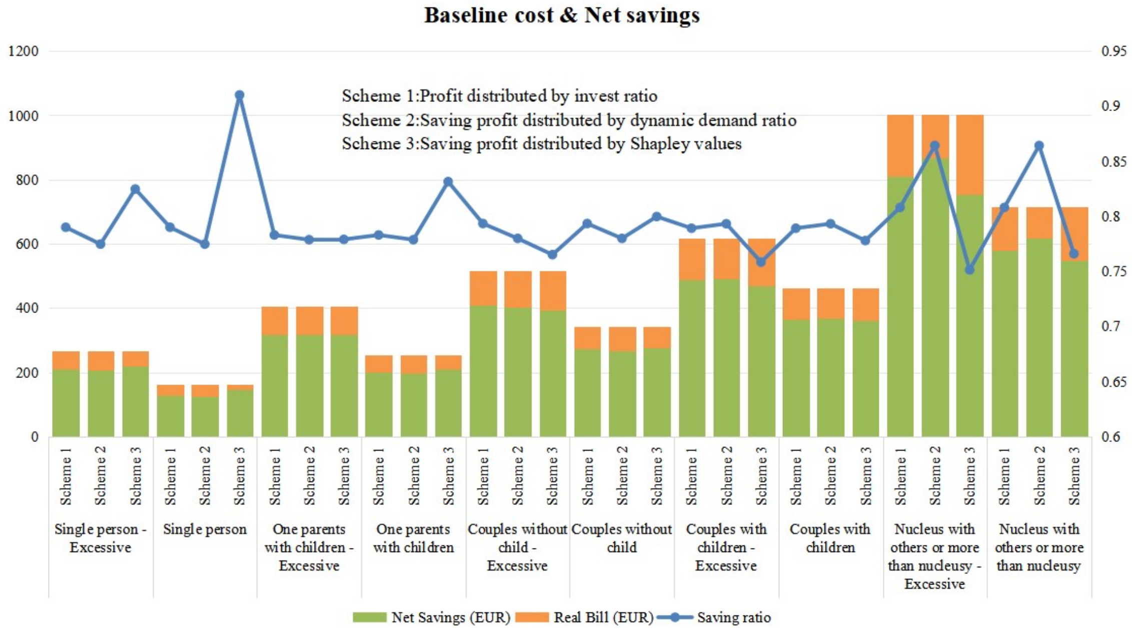


Fig. 4.19 Comparison of baseline costs and net savings of households

The Figure4.18 shows， under the 3 distribution schemes, all saving of households can almost cover the bills. The savings rate also fluctuated around 0.78 on average. Only under Scheme 3, the savings rate of single-person households increased significantly from 0.78 to 0.91, while that of nuclear households decreased from 0.80 to 0.75. However, both were within an acceptable and insensitive range of changes.

	$\sigma(T)$	$95\%\sigma(T)$	QoE
Scheme 1:Profit distributed by investment ratio	0.000	0.132	1.000
Scheme 2:Saving profit distributed by dynamic demand ratio	0.003	0.133	0.981
Scheme 3:Saving profit distributed by Shapley values	0.009	0.147	0.904

Table. 4.7 Comparison of QoE

Scheme 1 represents the optimal solution pursuing absolute fairness (i.e., perfect alignment with investment ratios, σ(T)=0). Scheme 2 achieves a moderate balance between reflecting actual electricity consumption patterns (with σ(T) ≈ 0.003) and maintaining efficiency without significantly compromising fairness. As a refined adjustment, Scheme 2 demonstrates a quality of experience (QoE) intermediate between those of Scheme 1 and 3. While Scheme 3 emphasizes contribution-based allocation, its fairness advantage becomes less pronounced when investments are proportionally allocated based on power consumption, with QoE values notably lower than those of the first two schemes.

Overall, under the demand-proportional investment, all three profit-sharing mechanisms can ensure that approximately 80% of households' bills are covered, while naturally guaranteeing high equity (QoE). For medium-demand households, the effectiveness of these mechanisms is nearly identical. However, the impacts of Scheme 2 on high-demand families and of Scheme 3 on lower-demand families are noticeable.

3. Equal Investment per Household with SIt

To establish a fairness-efficiency balanced framework applicable to heterogeneous communities, protecting both energy-deficient individuals (single-person households with low electricity consumption) and economically disadvantaged families with high demand but lower per capita usage; and incentivize community households to adopt PV energy, two hybrid schemes incorporating SIt regulation with distinct threshold P0 settings is proposed, based on the aforementioned investment models, to implement an equitable benefit redistribution mechanism.

Under equal investment, different P0 setting rules are added, the same value or according to the difference of family type, in order to study its fairness.

Type	P01[kW/y]	P02[kW/y]	Demandratio
Single person	1100	2800	0.85%
Single person - Excessive			1.39%
One parents with children	1800		1.32%
One parents with children - Excessive			2.11%
Couples without child	2200		1.81%
Couples without child - Excessive			2.71%
Couples with children	3000		2.42%
Couples with children - Excessive			3.23%
Nucleus with others	5000		3.83%
Nucleus with others - Excessive			5.37%

Table. 4.8 P0 assigned for households' types

(1) SIt with same P0=2800kWh/year

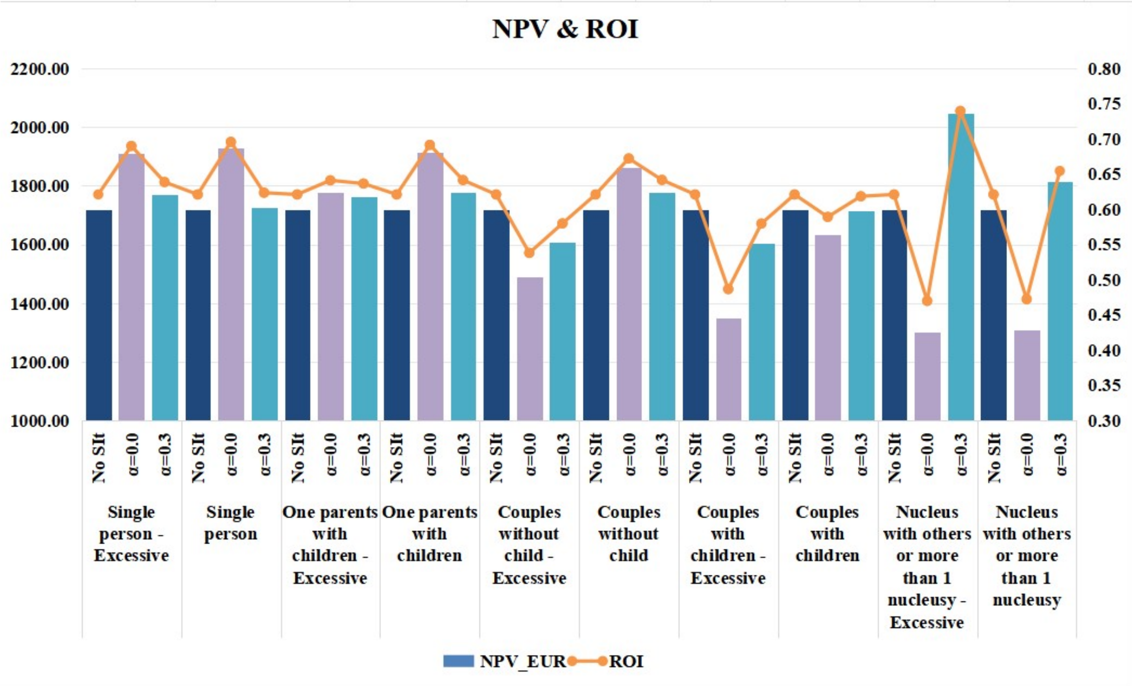


Fig. 4.20 Comparison of NPVs and ROIs of households

When all households are set to the same P0 value, and α = 0 (i.e., the saving benefit is fully optimized for energy savings), low-energy-consuming users achieve a higher NPV than before the SIt setting, regardless of whether their energy consumption is normal or excessive. However, moderate-energy-consuming users experience varying NPV increases or decreases depending on whether their energy consumption is excessive. For high-energy-consuming users, the situation is entirely disadvantageous, as their electricity consumption far exceeds P0, resulting in a significant decrease in NPV, approximately 24%. However, when α = 0.3, with 70% focused on energy savings and 30% on PV usage/self-consumption contributions, low-energy users and moderate-energy users with normal consumption still achieve slightly higher NPVs than without the SIt mechanism. However, moderate-energy users with excessive consumption remain at lower NPV levels, while high-energy users achieve significant NPV growth (5.4%), particularly for excessively energy-consuming nucleus households, with an increase of 19.1%.

Thus, under the assumption that all households have the same P0, when the focus is on energy savings, it benefits low-energy-consuming households, while when the focus is on PV usage/self-consumption contributions, it favors high-energy-consuming households.

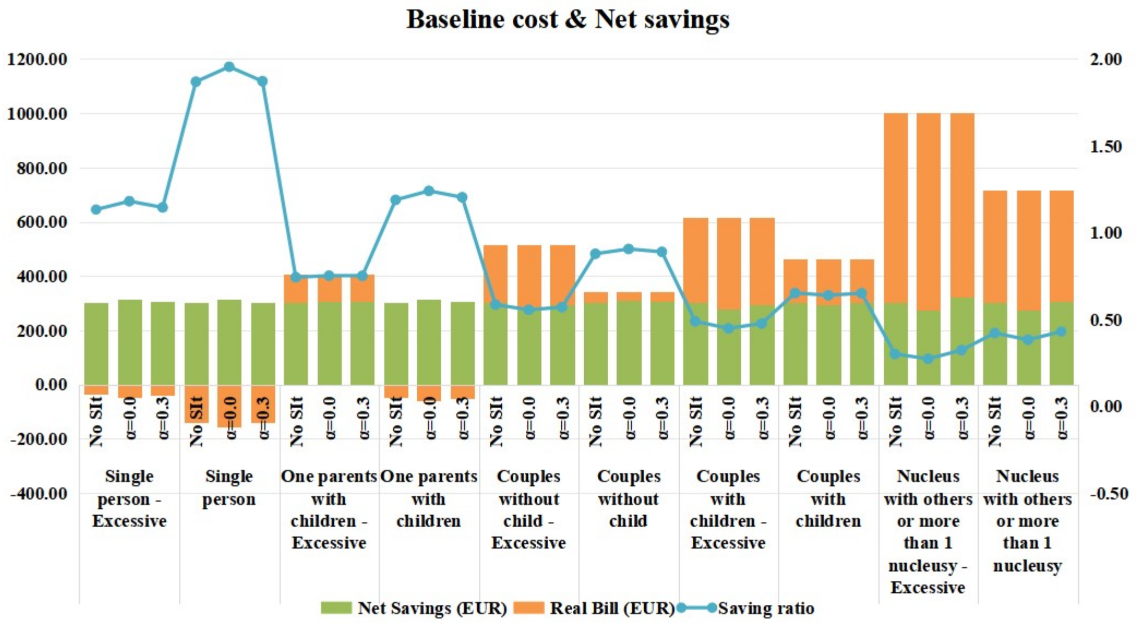


Fig. 4.21 Comparison of baseline costs and net savings of households

In terms of annual savings, the impact on households comparing before the introduction of SIt was as follows: when α=0, most users experienced a fluctuation of approximately 4.3%, while high-energy users saw a decrease of 10%. When α = 0.3, the fluctuation for all users was relatively moderate, at around 2.1%. Users were not very sensitive to this.

Uniform P0	**$\sigma(T)$**	**95%$\sigma(T)$**	***QoE***
Equal Investment	0.087	0.313	0.723
Equal investment+SIt(α=0)	0.094	0.327	0.712
Equal investment+SIt(α=0.3)	0.087	0.313	0.722

Table. 4.9 Comparison of QoE

When α=0， Standard deviation rises to 0.094, QoE drops to 0.712, suggesting a slight increase in income disparity. When α=0.3， Standard deviation is 0.087as same as without SIt, QoE 0.722, This indicates a more balanced of fairness with and without SIt under savings incentives.

(2) SIt with individual-specific P0

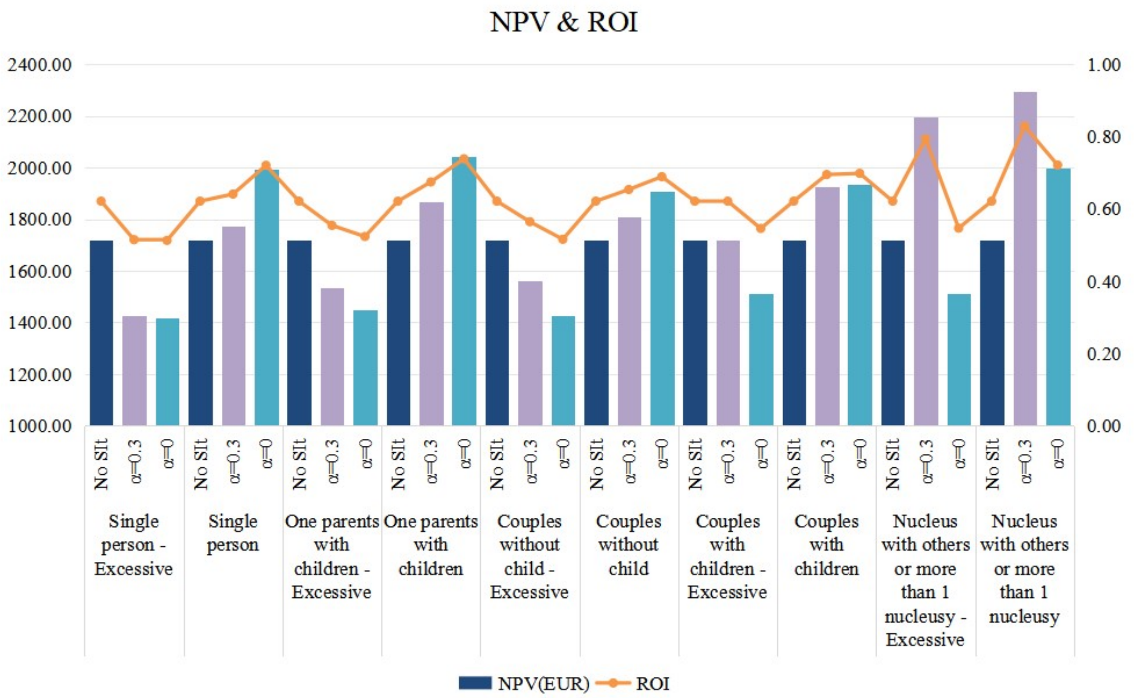


Fig. 4.22 Comparison of NPVs and ROIs of households

Compared to the same P0 setting mentioned above, the individual-specific P0 more accurately identifies energy-efficient households. When α was 0, only considering the saving index, both NPV and ROI for regular consumption households increased compared to the inclusion of SIt and previous configurations, an increase of 10%~18%, while all over-consumption households experienced significant declines of 12%~17% in both metrics. When α was raised to 0.3, the NPV improvement for low-energy households decreased or remained slightly decrease to baseline levels. Medium-consumption households showed minimal gains, whereas high-consumption functional households demonstrated notable growth, nucleus families increase from €1720.39 to €2295.63, an increase of 20%, and regular consumption couples families also get a larger NPV. This indicates that even with a slight tilt toward PV energy usage efficiency, high-consumption households consistently benefit.

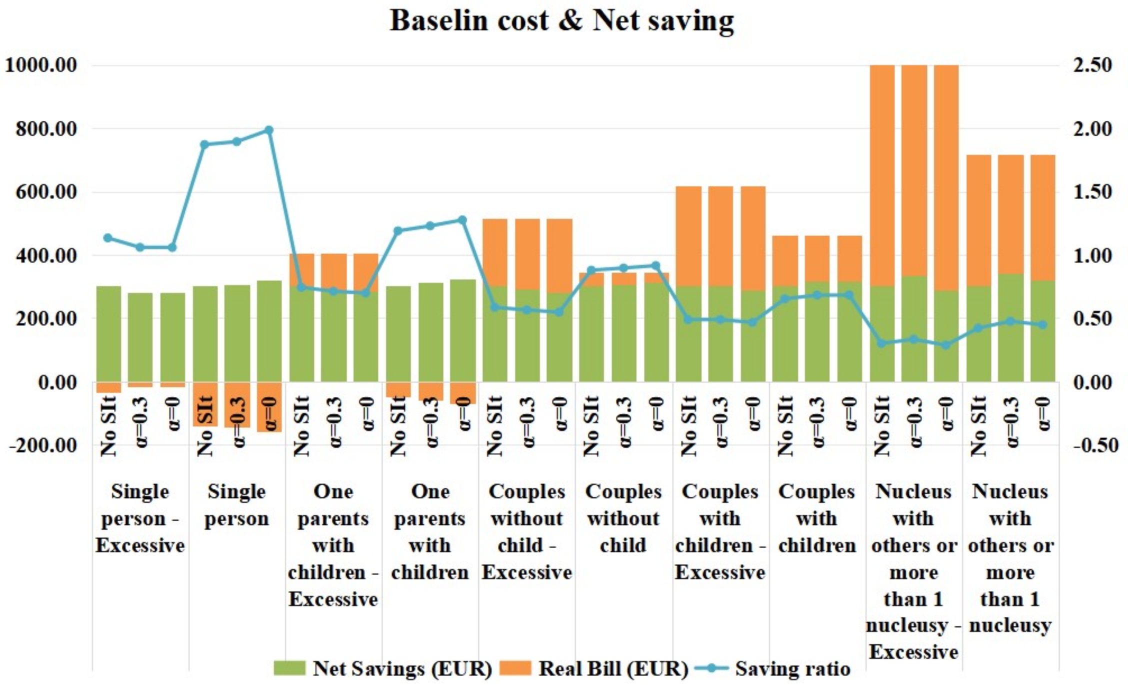


Fig. 4.23 Comparison of baseline costs and net savings of households

After the implementation of the SIt mechanism, the annual bill fluctuation for each household is not significantly different from that before the implementation of SIt. When α=0, the fluctuation range for low energy-consumption households is around ±6.7% and for medium and high energy-consumption households is around ±4.7%, while α=0.3, that for high energy-consuming households is an increase of 10%~12.6%. All households' annual bill fluctuation with and without the SIt mechanism is around ±€40. The sensitivity for households is not high. Compared with the savings rate, the variation range of bills under the influence of SIt is acceptable.

Individual-specific P0	$\sigma(T)$	95%$\sigma(T)$	QoE
Equal Investment	0.087	0.313	0.723
Equal investment+SIt(α=0）	0.094	0.332	0.716
Equal investment+SIt(α=0.3)	0.087	0.316	0.724

Table. 4.10 Comparisonof QoE

The SIt (α=0.3) mechanism assigns 30% of the weight to PV usage and 70% to energy-saving behaviors. σ is 0.087 as same as no SIt, while QoE increases to 0.724—the highest among the three parameters. This demonstrates that the solution maintains a reasonable reward structure while ensuring optimal fairness, effectively incentivizing energy conservation without discouraging high electricity consumers.

Overall, to evaluate profit redistribution fairness and behavioral guidance under equal investment, three SIt-based approaches were compared: (1) Equal Investment without SIt, (2) Equal Investment with P0 based on uniform baseline, and (3) Equal Investment with P0 based on individualized baselines. Meanwhile,by studying the relationship between saving factor and PV usage factor to realize the households types' sensitivity to the SIt distribution schemes.

Results show the basically equal investment strategy offers the smoothest NPV distribution and highest QoE, but fails to reward energy-saving behavior and may lead to inefficiencies. The uniform-P0 SIt mechanism slightly favors low-consumption households while maintaining positive returns for high-load households, but it cannot reflect the efficiency saving between regular and excessive consumption users in the same household type, and there is damage to the interests of high energy consuming users. In contrast, the individualized-P0 SIt strategy significantly increases NPV and ROI for energy-saving households and reduces returns for excessive households considering the household types, enhancing equity and QoE over the uniform-P0 model. Overall, the individualized SIt mechanism when α=0.3 demonstrates superior fairness and targeted incentive effectiveness, especially in communities with diverse consumption behaviors.

4. Investment Proportional to Electricity Consumption with SIt

Based on the investment method based on the proportion of annual electricity consumption, the electricity threshold P0 is only set individualized-P0 based on the household types.

Type	P0[kW/y]	Demand ratio
Single person	1100	0.85%
Single person - Excessive		1.39%
One parents with children	1800	1.32%
One parents with children - Excessive		2.11%

Couples without child	2200	1.81%
Couples without child - Excessive		2.71%
Couples with children	3000	2.42%
Couples with children - Excessive		3.23%
Nucleus with others	5000	3.83%
Nucleus with others - Excessive		5.37%

Table. 4.11 P0 assigned for households' types

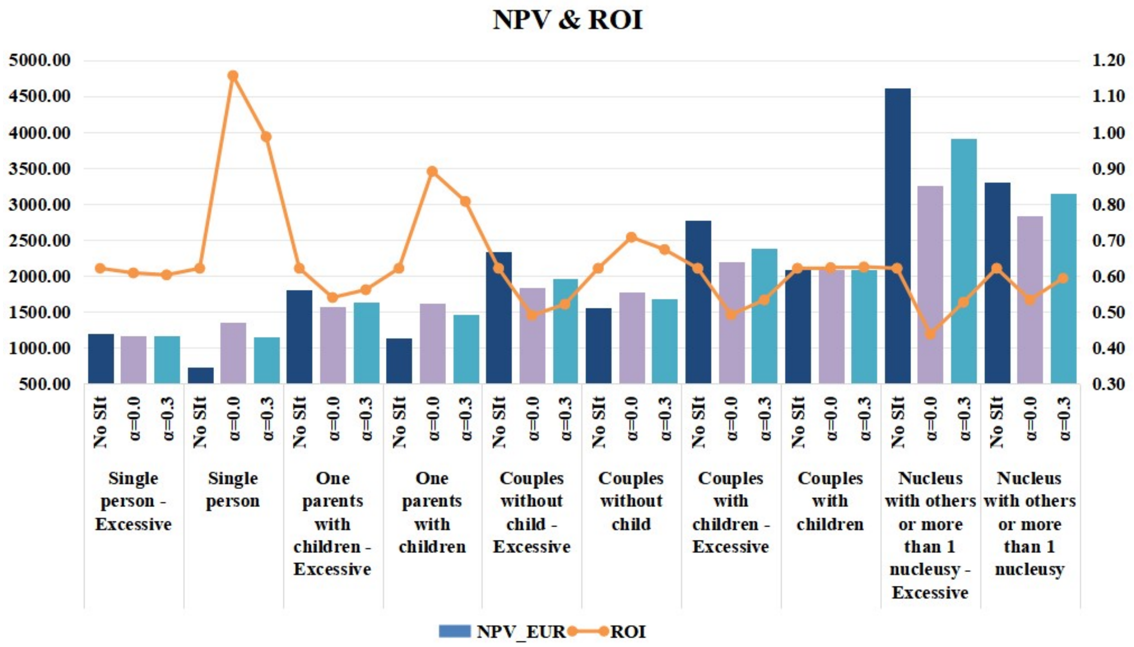


Fig. 4.24 Comparison of NPVs and ROIs of households

The Figure4.24 above shows that when alpha = 0, i.e., and the savings are entirely driven by the savings rate, the NPV of all households with normal electricity consumption increases. The most significant increase is seen in single-person households, which rise from €727 to €1,354.40, an increase of 86.3%, with the ROI rising from the baseline of 0.621 to 1.17. Households without children see an increase of 13.9%. However, the NPV of normal-usage Nucleus households decreased by 14.1%, indicating that even if they did not exceed the P0 baseline usage, the savings benefits were still captured by users with higher savings rates. For over-usage households, the NPV decrease ranged from 2.1% to 29.5%, depending on the extent of over-usage.

When alpha = 0.3, the NPV decline for over-consuming users decreases, but it remains lower than that of normal-consuming households of the same type, and the savings incentive continues to play a significant role.

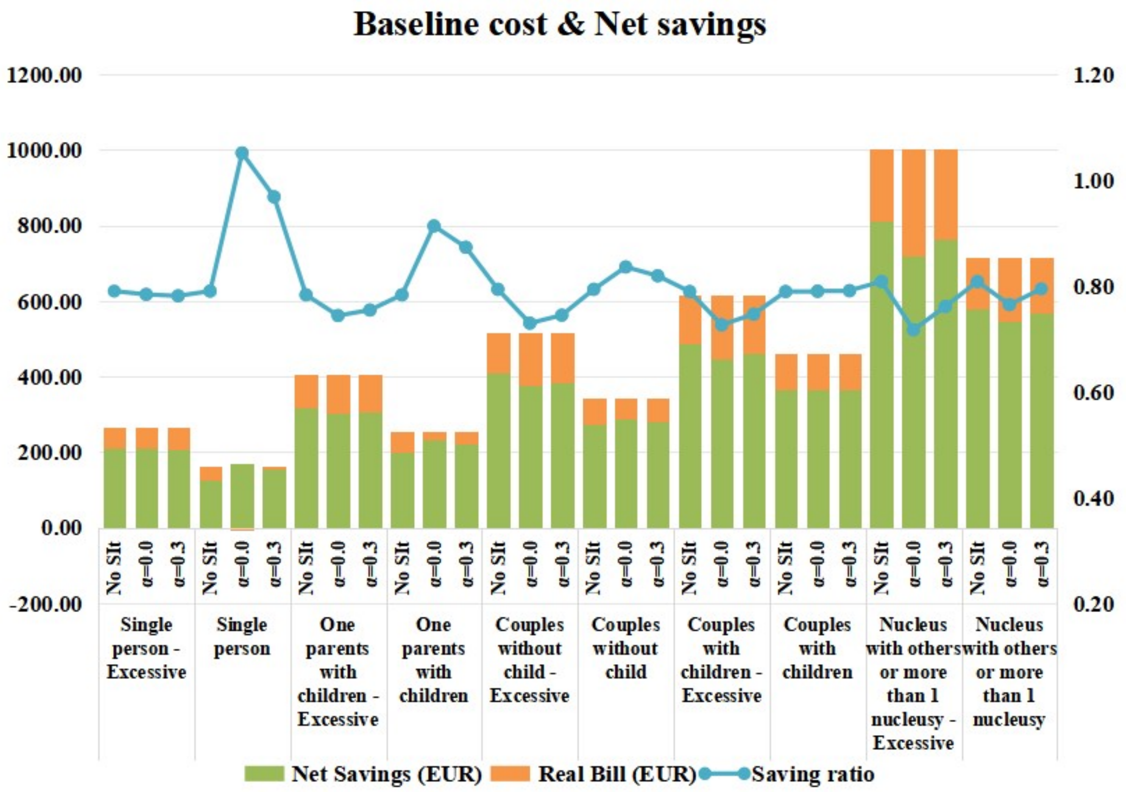


Fig. 4.25 Comparison of baseline costs and net savings of households

When α=0, the annual net savings for Single person increased from €127.55 to €169.71, representing a 33.1% growth， and for One Parent with Children households showed 16.6% increase. The medium consumption households like Couple Without Children and Couple With Children households,the variation fluctuates in the range -8.1% to 4.5%. For Nucleus households-Excessive, the annual net savings varied in the range of -11.3% to -5.4%, which indicates they suffer a negative impact on SIt if they cannot achieve a greater energy consumption reduction than others.

When α=0.3, the magnitude of net savings becomes more moderate, especially for high-energy-consuming users, such as couples with children - excessive and nucleus families. However, the savings incentive mechanism still plays a role.

	$\sigma(T)$	$95\%\sigma(T)$	QoE
Proportional investment	0.000	0.132	1.000
Proportional investment+SIt(α=0）	0.021	0.176	0.883
Proportional investment+SIt(α=0.3）	0.014	0.162	0.913

Table. 4.12 Comparison of QoE

The Proportional Investment (Original Scheme) achieves the most ideal fairness standard with QoE=1.000. However, as it completely disregards energy-saving behaviors or electricity efficiency, it appears "neutral" or even "weakly incentivizing" from an incentive perspective. The inclusion of SIt (α = 0.3) introduces energy-saving rewards and an efficiency mechanism for PV energy usage, resulting in slight fluctuations in ROI among different households (σ = 0.014) and a minor decline in fairness(0.913). The SIt (α = 0) rewards a small number of households that “save electricity/transfer a lot of load,” especially the single person families, widening the gap and lowering the overall experience.

Overall, in equal investment , SIt is merely a“fine-tuning mechanism with little impact on fairness and efficiency, but under the investment method based on annual electricity consumption, the sensitivity to SIt is significantly higher, and extreme differences are markedly amplified. The 95% σ(T) increases from 0.132 to 0.176 (+33%) at α=0, and to 0.162 (+23%) at α=0.3. Moreover, when α=0.3, the energy-saving incentive mechanism remains effective. For most households, regular electricity users demonstrate higher NPV and ROI compared to their over-consumption counterparts. However, high-demand households such as nuclear families and couples with children face the risk of their energy-saving incentives being overshadowed by those from medium-and low-demand households，but for the regular consumption ones, ROI can still stay at 0.6 level, just a slight drop compared to 0.62.

4.2.5 Italian Sharing of electricity incentives

Italy's PV subsidy scheme for Renewable Energy Sources provides incentives for immediate energy sharing (energia condivisa) among community members. The program offers rates of up to €120/MWh for ≤ 200 kW projects, €110/MWh for 200 to 600 kW systems, and €100/MWh for 600 kW to 1 MW installations. These subsidies remain available for 20 years. In this case, €110/MWh is taken as the value of the subsidy.

Under the same goal of minimizing the electricity cost of the community, Figure 4.26 shows that under the consideration of the subsidy of €110/MWh, the return on investment cycle of the community is shortened to about 7 years, annual saving from Sharing of electricity incentives is €8814.86, total annual saving is €25,214.42, and the cumulative NPV of 20 years reaches €212,971.72, far exceeding the €85014.86 before the policy subsidy is considered. ROI of 20years reaches 1.54.

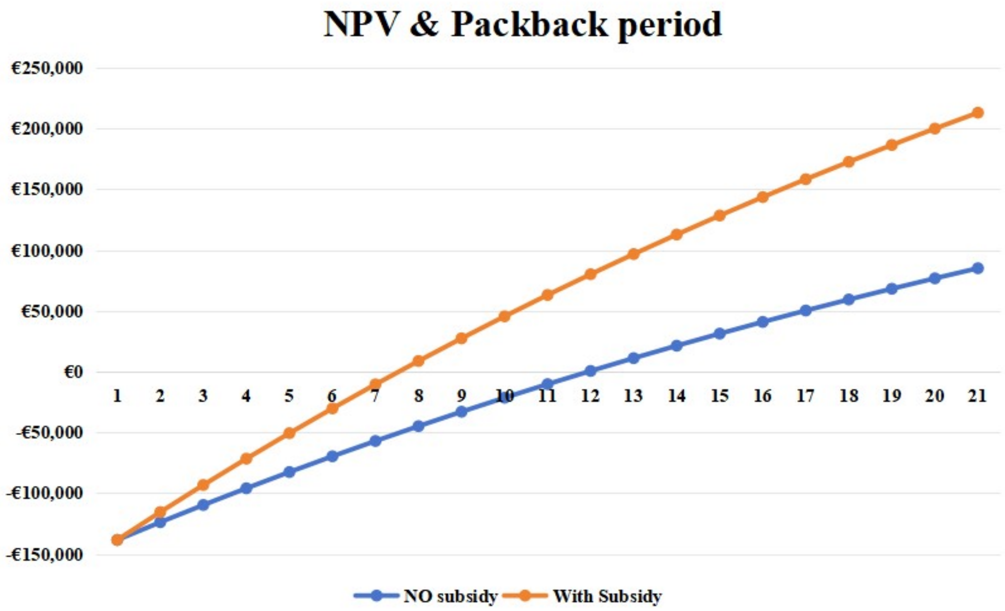


Fig. 4.26 NPV over 20 years with Italian Sharing of electricity incentives

This indicates that TCEC incentives not only shorten the payback period by approximately 4 years but also substantially boost long-term returns by about €120,000 . Overall, the TCEC subsidy mechanism effectively improves project cash flow and risk-reward ratios, enhances the attractiveness and feasibility of community investments, and serves as a key policy tool to drive the economic viability of the Renewable Community (REC) model.

4.3 Case 2(a third party invests) results and analysis

4.3.1 A third party invests

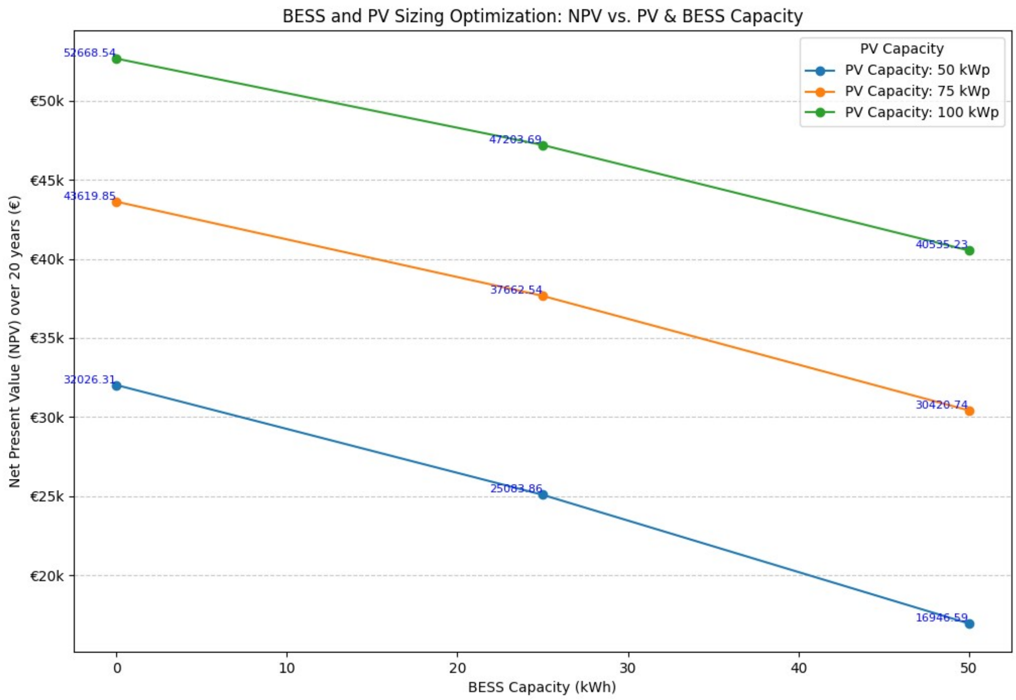


Fig. 4.27 NPVs with various PV & BESS capacity

The Figure4.27 illustrates the 20-year net present value (NPV) under SDR transaction pricing for different combinations of photovoltaic (PV) capacity and battery energy storage system (BESS) capacity. The results show that as BESS capacity increases, NPV exhibits a significant downward trend, indicating that under current electricity prices and cost conditions, battery investment does not yield additional economic benefits. In contrast, the larger the PV capacity, the higher the overall NPV, with the 100 kWp PV system achieving the highest NPV (approximately €52,668), which remains above €41,000 even when equipped with a 50 kWh battery. Overall, PV expansion takes precedence over BESS expansion, with energy storage primarily reflecting system flexibility value rather than direct economic returns.

Simulate the investment plan with the highest NPV (PV100kWp) and the community self-investment (100kWp&BESS50kWh) to be correct.

Scenarios	Pricing	Initial invest	Annual profit	NPV (20y)	ROI
PV 50kWp NO BESS	mid price	-€59,000.00	€6,118.40	€25,149.49	42.63%
PV 100kWp NO BESS	mid price	-€118,000.00	€11,043.90	€46,305.33	39.24%
	sdr price		€11,471.61	€52,668.54	44.63%
PV 100kWp BESS 50kWh	mid price	-€138,500.00	€11,644.60	€34,742.28	25.08%
	sdr price		€12,180.69	€42,717.96	30.84%

Table. 4.13 Economic values in different PV&BESS scenarios

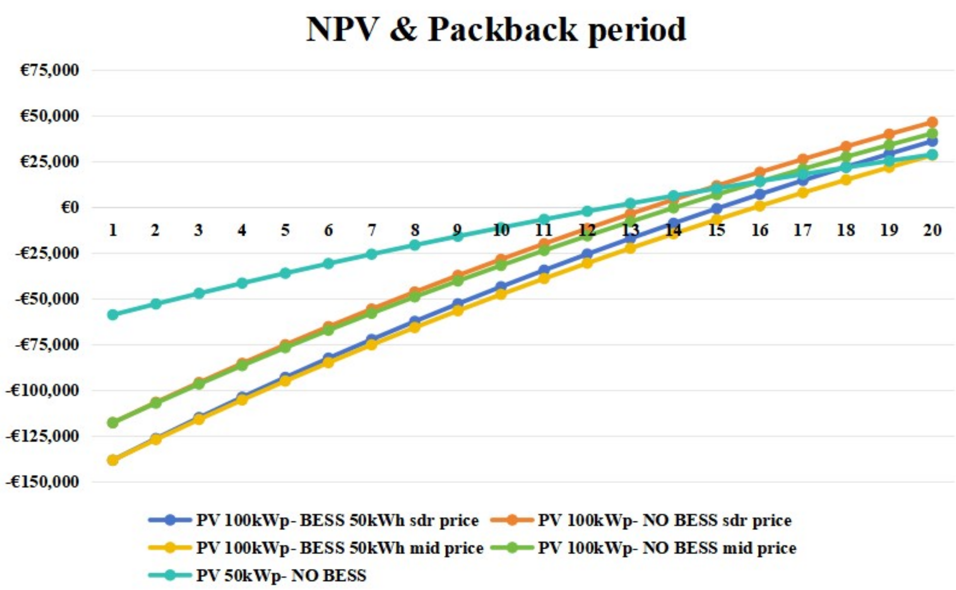


Fig. 4.28 Payback period in different PV&BESS scenarios

The investment return period depicted in the figure spans 12-16 years, longer than community self-investments (approximately 2 years). When only installing PV , ROI ranges between 39.24% and 54.28%, which is closed to the ROI 54.62% in Ref [46], the lower than the approximately 62% of community self-investments. Under both pricing strategies, dynamic demand pricing outperforms fixed pricing in profitability (showing better NPV and ROI performance), though the advantage is not significant (NPV only exceeds by about 6.3k€ to 8.0k€). Installing battery storage systems (BESS) proves uneconomical based on current price assumptions: while BESS can increase annual profits by approximately €600 to €700, the high initial capital expenditure (CAPEX) means the discounted "additional returns" cannot offset the "additional costs", resulting in reduced NPV and ROI. Installing PV alone remains the optimal investment strategy.

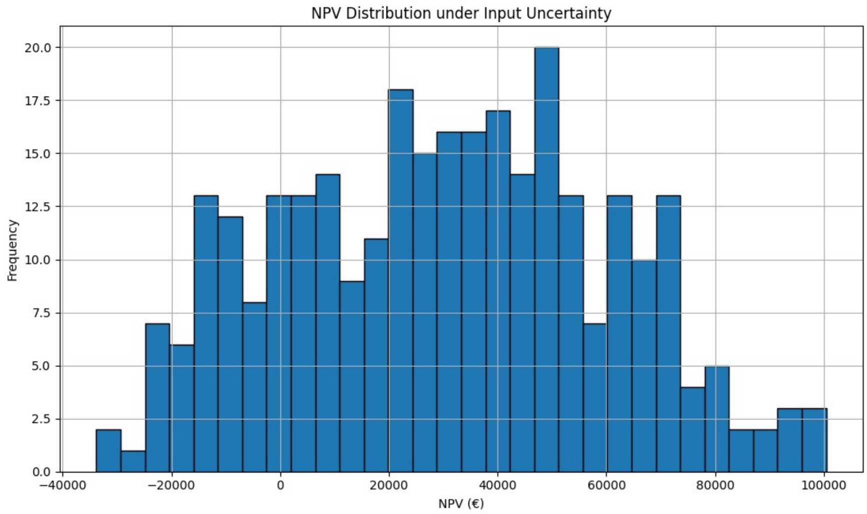


Fig. 4.29 NPV distribution under uncertainty

Mean NPV (€): 30,294.10
Std Dev (€): 29,704.08
P10 (€): -10,691.65
P50 / Median (€): 31,393.90
P90 (€): 70,256.59
Positive NPV Probability (%): 81.33

Under the a third-party investment model, community solar projects demonstrate an average Net Present Value (NPV) of approximately €30,294, though with significant volatility (standard deviation approaching €29,704). While the median value is positive at €31,393.90, notable risks persist as the 10% remains negative (-€10,691.65), indicating potential losses in adverse scenarios. However, most projects remain profitable, with the 90% reaching €70,257 and an 81.33% probability of achieving positive NPV. Overall, this model offers moderate returns with inherent risks, demonstrating less stability compared to community self-invested projects.

The following is a comparison of the energy composition of the community. It can be seen that after the battery is configured, the PV directly provides about 12% less energy than without the battery, and the battery provides an additional power source of 20% of the total energy consumption. The electricity purchased from the grid decreases from 42.4% to about 29%.

Scenarios	Pricing	From PV	From BESS	From grid
PV 100kWp+NO BESS	mid price	57.60%	-	42.40%
	sdr price	57.60%	-	42.40%
PV 100kWp +BESS 50kWh	mid price	51.50%	18.70%	29.90%
	sdr price	49.20%	21.70%	29.10%

Table. 4.14 Community energy composition in different scenarios

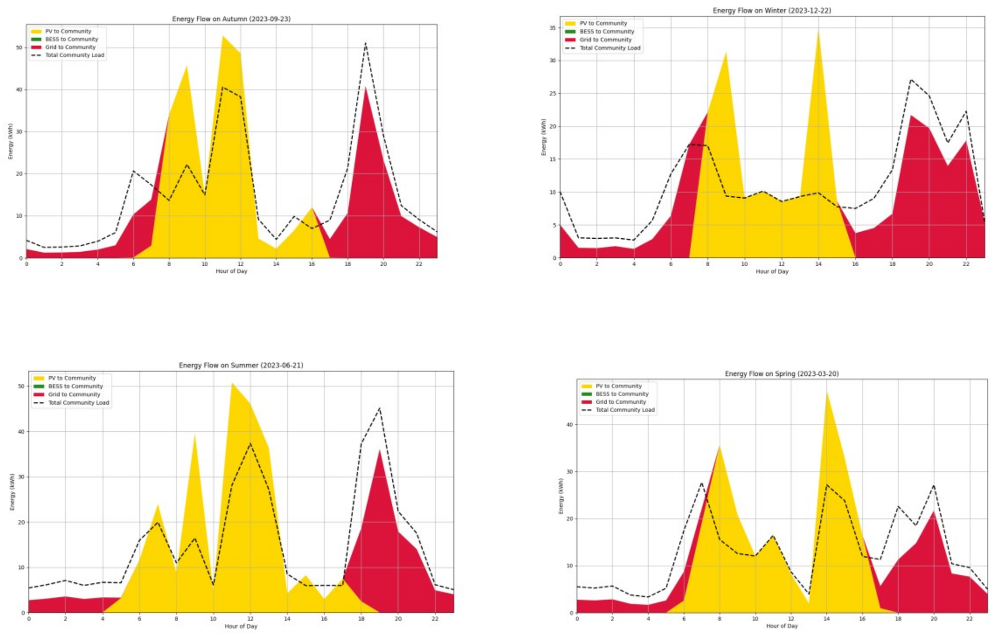


Fig. 4.30 Community energy flow in equinox and solstice with PV 100kWp

Figure 4.30 presents the community's hourly energy flows on four representative seasonal days. Clear seasonal differences emerge in the balance between PV generation, grid reliance, and load demand.

In summer (June 21), PV output is abundant, covering over 70% of community load from 7:00 – 14:00 and reducing grid dependence. However, the evening peak (19:00 – 21:00) still relies on external supply due to lack of stored energy. Spring (March 20) and autumn (September 23) have similar solar dominance but higher variability. In contrast, winter (December 22) is the most constrained: PV output is limited to short midday periods, meeting less than 40% of daily load, and grid dependence is significant all day, especially during peaks.

Through peak and valley optimization, the adjustable electricity consumption can be adjusted to the daytime pv production period to effectively utilize solar energy.

Overall, the seasonal analysis demonstrates that PV generation can substantially offset grid electricity during spring, summer, and autumn, but winter performance exposes structural vulnerabilities. Enhancing BESS capacity or integrating demand-side management strategies would be necessary to smooth seasonal imbalances and further reduce grid reliance.

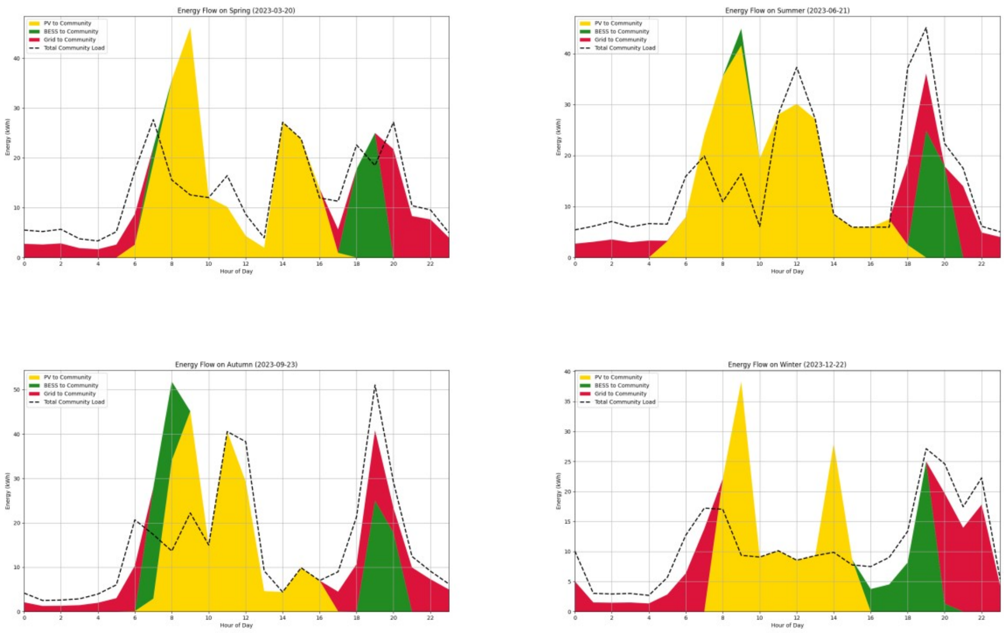


Fig. 4.31 Community energy flow in equinox and solstice with PV 100kWp & BESS 50kWh

Figure 4.31 shows the seasonal energy flow of the community after integrating a 50 kWh battery storage system (BESS). Compared with the no-storage scenario, the addition of BESS markedly smooths the mismatch between PV generation and community demand, particularly in spring, autumn, and winter.

In summer, abundant midday PV surplus is partially stored and later discharged during the evening peak (19:00-21:00), effectively reducing grid imports by nearly 25% compared with the no-battery case. Spring and autumn show similar benefits: BESS absorbs excess PV in the morning and provides significant evening peak-shaving, with daily PV coverage of community load increasing from ~60 – 70% to ~75 – 80%.In winter, when PV production is low and concentrated around midday, the BESS still plays a crucial balancing role by shifting limited solar generation to evening hours.

Overall, the integration of BESS enhances self-consumption and self-sufficiency across all seasons. The improvement is most pronounced during shoulder seasons (spring and autumn), where PV generation and demand are better aligned. This highlights the structural role of storage not only in reducing grid reliance but also in increasing the economic value of PV generation by shifting surplus into high-demand, high-price periods.

4.3.2 Households' economic results and analysis

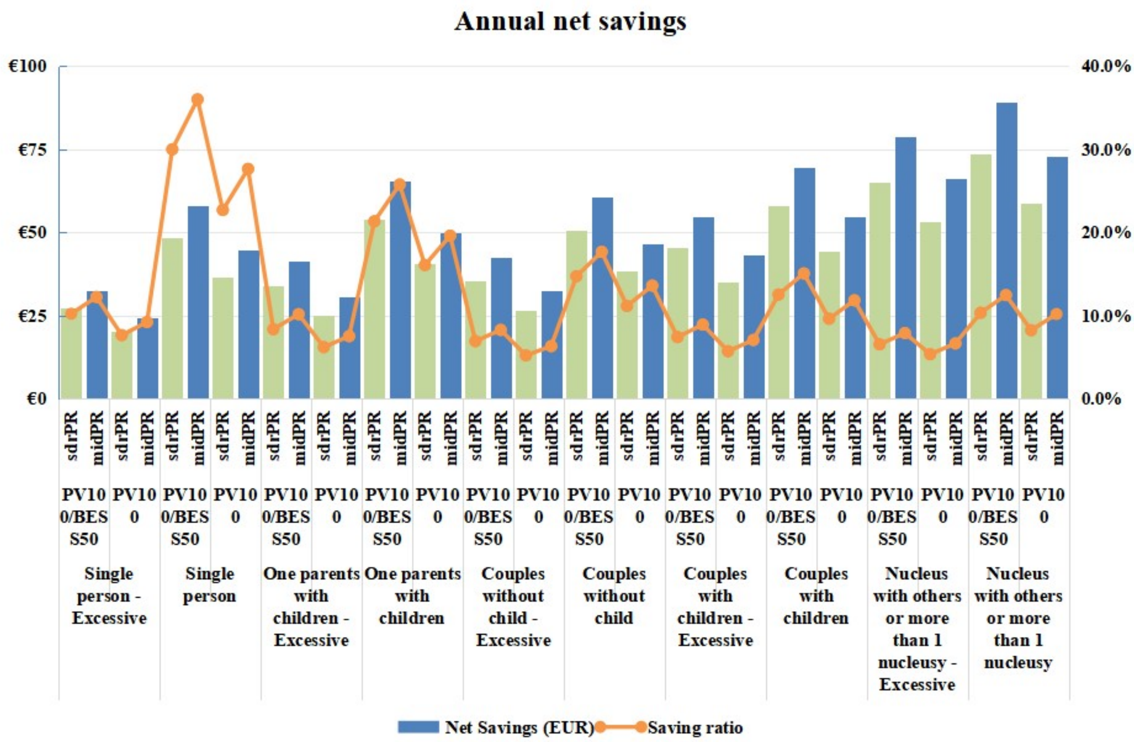


Fig. 4.32 Households' annual net savings & saving ratios

Overall trend: In the comparison between the mid-market price and the dynamic SDR price, the annual savings for residents under the mid-market price pricing (blue bars) are higher. In the comparison between third-party investment in community solar panels and no investment, investing in solar panels increases annual savings for residents, with low-energy households seeing an increase of 30% to 35% and high-energy households (nucleus households) seeing an increase of 18% to 22%.

Households with the highest savings: "Nucleus with others or more than 1 nucleus (multi-person/large families)" households achieve the highest annual savings, up to 60 – 80 €/year. These households have high electricity loads and high self-consumption ratios, so purchasing third-party PV electricity yields greater benefits. The lowest savings are for the "Single person" household type, especially the "Excessive" version (low load), with annual savings of only around 25 – 45 €/year. Due to low electricity consumption, the benefits that can be shared are limited. However, because of their low electricity consumption, their bill coverage rate is the highest, with normal low-consumption households (Single person, One parent with children) reaching 0.25 to 0.36. Note that while the absolute savings amount is not high, the savings ratio relative to electricity expenses is more significant.

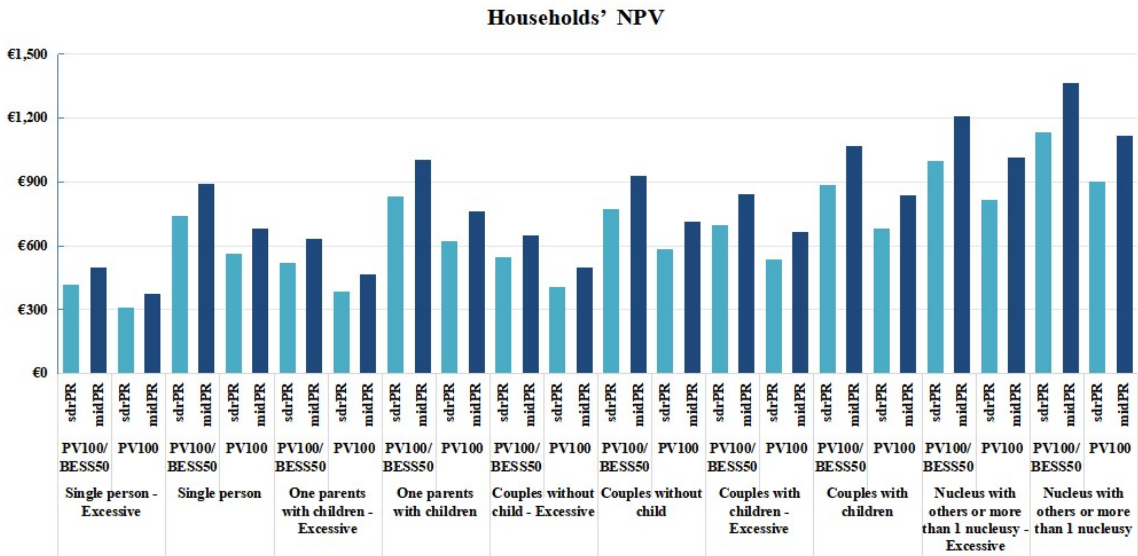


Fig. 4.33 NPVs of households with different pricing schemes and PV & BESS capacity

Over a 20-year usage cycle, the impact of the mid-market price and SDR dynamic price on NPV is not significant. For low-energy households, the difference is less than €100, while for high-energy households, the difference is approximately €230 under the mid-market pricing model. However, when equipped with batteries, NPV is significantly higher than without batteries, with a difference of approximately €100 for low-energy households and approximately €210 for high-energy households. The SIt incentive mechanism has the greatest impact, with normal-usage households having an NPV that is 1.3 times higher than that of excessive high-energy households and 1.7 times higher than that of excessive low-energy households.

	$\sigma(T)$	**95%$\sigma(T)$**	***QoE***
PV100 -BESS 50-midPR	0.015	0.050	0.709
PV100 -BESS 50-sdrPR	0.018	0.060	0.709
PV100 -NO BESS-midPR	0.011	0.038	0.710
PV100 -NO BESS-sdrPR	0.013	0.046	0.710

Table. 4.15Comparison of QoE with different pricing schemes

The results show that under the condition of setting SIt incentive mechanism, whether there is a battery or not and the two pricing modes do not affect the fair experience of users, and QoE 0.709-0.710 remains almost unchanged, but σ +0.002 to +0.003, Sigmoid Max +0.008 to +0.010), indicating that sdrPR and installing amplifies disparities among households, even though overall QoE remains stable.

4.3.3 Scenario with Italian sharing electricity incentives

Third-party companies (investors) may join Renewable Energy Communities (REC) as members/cooperators. If the contract stipulates that residents primarily benefit from electricity cost savings while investors mainly receive subsidies plus grid-connected electricity revenue, the Technology Contracting and Energy Credit (TCEC) issued by the Government-Sponsored Energy Operator (GSE) to the REC will be transferred to investors according to internal regulations. If not specified in the contract, investors can only receive the electricity sales revenue (PUN pricing) from their invested power stations, with subsidies retained within the community. In Italy, many Energy Service Companies (ESCOs) or cooperative developers typically fund photovoltaic installations on behalf of residents to establish REC: Residents enjoy affordable electricity prices (self-consumption rates <market rates); Investors recover capital expenditures and retain most TCEC plus grid-connected income; The community enforces legally compliant profit distribution ratios through established regulations.

Chapter 5 Conclusion and Future Prospective

5.1 Conclusion

The main objective of this thesis was to develop a tool for simulating energy flows and evaluating the economic feasibility of Renewable Energy Communities in Italy. The research involved multiple levels of analysis, culminating in the final modeling of Energy Communities under the Clean Energy Package. The author conducted an analysis of most European countries to demonstrate the maturity of community energy projects and self-consumption systems, which will affect the implementation of European Directives.

The thesis work subsequently introduces a method to evaluate the economic viability of Renewable Energy Communities. Despite the abundance of studies on energy communities, including peer-to-peer (P2P) markets and new energy institutions trading with residential markets, most of these studies focus on constructing communities that utilize individual photovoltaic (PV) systems or institutional PV systems as resources. Only a few studies delve into community residents jointly investing in new energy systems as collective resources, sharing investment and management expenses, and researching suitable benefit distribution according to the disparities in household composition within the community. This research aims to tackle the problem of new energy facilities as collective public assets and to investigate investment and benefit distribution based on differences in household types. Through setting up a mathematical model, the research further analyzes the cost recovery period, fairness of revenue distribution, and how community members' electricity consumption behavior impacts their own benefits under a collective investment model. Based on five different household types, the research compares households with normal electricity consumption and those with excessive consumption within the same type. It proposes a benefit distribution mechanism based on electricity demand and contribution, and explores its applicability and stability under various scenarios. Additionally, the study includes a comparison with third-party investment in solar equipment. Furthermore, it introduces an electricity-saving incentive mechanism to encourage members to actively participate in energy-saving behaviors, achieving dual optimization of economic and environmental

benefits. The tool is validated with a case study built as a collection of a residential building with 50 households in Italy.
For realization of the study, this study has developed an integrated Mixed-Integer Linear Programming (MILP)-based Energy Management System (EMS) optimization framework for community solar energy systems, focusing on minimizing community electricity cost while ensuring fairness in individual returns. The model jointly optimizes PV-BESS capacity sizing, energy flow scheduling, demand response in community lever, load Shifting and investment modes and profit redistribution in various schemes across heterogeneous households. The simulation results provide valuable insights into the economic, environmental, and social fairness of different investment strategies and benefit allocation mechanisms.

The simulation results demonstrate that the proposed optimization framework significantly improves the economic and energy efficiency of community solar energy systems. The optimal capacity of PV and BESS was determined through MILP. NPV over 20 years of €85,014.86 is achieved by simulating a 100kWp PV system and a 50kWh BESS, and community annual saving is €16,613.71. The community's self-consumption rate reached 69%, and the self-sufficiency rate was 71.13%,showing effective integration of PV generation with local demand. The Levelized Cost of Electricity (LCOE) was calculated to be 0.102€/kWh, which is within a reasonable range compared to existing studies. Reduction of CO_2 reaches 27511.95kg.

Different community investment strategies and profit distribution methods demonstrate a clear trade-off between fairness, efficiency, and incentive compatibility, which interact with each other. Under identical investments, households with lower demand achieve the highest annual savings rate, while those with higher demand gain the most in terms of life cycle net present value. The uniform profit distribution method (Scheme 1) ensures equal outcomes but overlooks differences in demand load, potentially reducing efficiency. The dynamic demand ratio approach (Scheme 2) enhances efficiency by incentivizing households to consume more during photovoltaic generation periods, thereby optimizing behavior. However, the Shapley-based method (Scheme 3) achieves the highest allocation efficiency, though without corrective measures, it may exacerbate inequities.

In contrast, demand-based investment naturally aligns contributions with consumption, ensuring fairness by covering approximately 80% of household expenses. Here, the choice of redistribution scheme makes little difference: while the Scheme 1 offers some benefits to high-income households, the Scheme 3 proves more equitable for low-income families.

When integrated with a fair SIt mechanism, equal investment yields more stable Net Present Values (NPVs) but reduces efficiency. The uniform P0 SIt slightly favors low-demand users but fails to distinguish between over consumption and efficient consumption within the same household type. The personalized P0 significantly enhances fairness and incentives by increasing returns for energy-efficient households while penalizing excessive consumption, thus outperforming the uniform model. However, using SIt with demand-based investments dramatically increases sensitivity, exacerbating disparities: high-demand households risk reduced benefits when outperformed by smaller yet more efficient users. Overall, equal investment with personalized SIt (α=0.3) achieves the optimal balance between fairness and incentives, whereas demand-proportional investment ensures stable fairness but weakens behavioral motivation.

The uncertainty analysis showed that the project stays financially sound under many economic situations, with a 100% likelihood of good returns. The research also found that the community energy flow optimization greatly cut down grid dependence, especially during peak times, through useful peak-shifting methods.

The outcomes point out big differences between community self-investment and third party investment models. Under self-investment, the community gets a quick payback time of about 11 years and a return on investment (ROI) over 60%, much better than the third party investment model, where returns last 12 – 16 years with ROI between 39 – 54%. This shows that in the case of community collective investment, the electricity cost saved by buying PV is part of the residents' earnings, and the earnings are more than those of outside investment.

For households, however, the outcomes differ in emphasis. In the third party model, residents gain savings through purchasing PV electricity, with annual benefits ranging from €25 to €80 depending on household type. Large households with high loads achieve the highest absolute savings (up to €80/year), while low-load households benefit more in relative terms, with bill coverage ratios of 0.25-0.36. By contrast, under self-investment, households directly capture long-term NPV gains, but the fairness and incentive outcomes depend heavily on the chosen redistribution mechanism (equal, demand-ratio, Shapley-based and saving incentive schemes).

Regarding system configuration, both models indicate that PV-only investment is superior, as battery storage reduces NPV due to high CAPEX and limited additional revenue. Nonetheless, in community self-investment, the system configuration is still set to equip a 50kWh battery to prevent power outages and store low-cost electricity. The introduction of SIt mechanisms—especially individualized-P0, in both investment modes, significantly improves fairness by rewarding energy-saving and PV energy usage efficient behaviors.

Overall, self-investment maximizes financial returns and enables fine-tuned fairness mechanisms, while third-party investment lowers entry barriers and provides moderate but stable bill savings, especially attractive for low-demand households unwilling or unable to invest.

5.2 Future Prospective

While this study has developed and validated a comprehensive optimization framework for Renewable Energy Communities (RECs), there remain multiple avenues for future exploration. First, the behavioral aspects of energy communities warrant deeper investigation. Although the current study incorporates energy-saving incentives (SIt) to encourage electricity conservation, future research could employ agent-based modeling or machine learning to more accurately capture household decision-making patterns, adaptation strategies, and peer influence dynamics. These methodologies will help us better understand how various social interactions and user participation impact the fairness, efficiency, and long-term sustainability of RECs.

And numerous points remain to be expanded upon. This research primarily focuses on photovoltaic and battery storage systems. However, the key to achieving cross-industry collaboration and deep carbon reduction lies in integrating multiple energy solutions like electric vehicles, heat pumps, and district heating. Such integration enables better coordination across sectors and enhances resilience against seasonal demand fluctuations. Additionally, future studies should thoroughly examine financing and management models for renewable energy certificates, comparing cooperative frameworks, municipal-led projects, and mixed-ownership schemes to assess their fairness and inclusivity. Incorporating variables like technological costs, electricity pricing, and policy incentives into modeling would make economic evaluations more reliable. Finally, implementing this framework through real-world projects in Italy and other regions with diverse socioeconomic contexts would significantly boost its practical value and policy relevance. By combining technological optimization with behavioral patterns, institutional frameworks, and policy incentives, future research can lay a comprehensive foundation for expanding renewable energy communities and establishing them as crucial pillars of energy transition.

Appendix

Economic Results

Equal investment

Scheme 1:Profit distributed evenly

Type	baseline_cost EUR	net_savings EUR	Real Bill EUR	initial_investment EUR	NPV EUR
Single person	161.45	301.82	-140.37	2770.00	1720.39
Single person - Excessive	266.40	301.82	-35.43	2770.00	1720.39
One parents with children	253.89	301.82	-47.93	2770.00	1720.39
One parents with children - Excessive	406.22	301.82	104.40	2770.00	1720.39
Couples without child	343.68	301.82	41.85	2770.00	1720.39
Couples without child - Excessive	515.52	301.82	213.69	2770.00	1720.39
Couples with children	462.76	301.82	160.93	2770.00	1720.39
Couples with children - Excessive	617.01	301.82	315.18	2770.00	1720.39
Nucleus with others or more than 1 nucleusy	715.77	301.82	413.94	2770.00	1720.39
Nucleus with others or more than 1 nucleusy - Excessive	1002.08	301.82	700.25	2770.00	1720.39

Scheme 2:Saving profit distributed by dynamic demand ratio

Household type	Baseline Cost (EUR)	Net Savings (EUR)	Real Bill (EUR)	Saving ratio	NPV_EUR
Single person - Excessive	266.40	282.82	-16.42	1.06	1437.71
Single person	161.45	270.89	-109.44	1.68	1260.15
One parents with children - Excessive	406.22	302.73	103.49	0.75	1733.92
One parents with children	253.89	283.91	-30.02	1.12	1453.82
Couples without child - Excessive	515.52	312.36	203.15	0.61	1877.16
Couples without child	343.68	292.42	51.26	0.85	1580.43
Couples with children - Excessive	617.01	334.58	282.43	0.54	2207.70
Couples with children	462.76	314.07	148.69	0.68	1902.52
Nucleus with others or more than 1 nucleusy - Excessive	1002.08	441.11	560.97	0.44	3792.57
Nucleus with others or more than 1 nucleusy	715.77	387.23	328.54	0.54	2990.98

Scheme 3:Saving profit distributed by Shapley values

type	baseline_cost_EUR	net_savings_EUR	Realbill EUR	initial_investment_EUR	NPV_EUR
Single person	161.45	264.09	-102.63	2770.00	1158.9238
Single person - Excessive	266.40	286.29	-19.89	2770.00	1489.2937
One parents with children	253.89	293.83	-39.94	2770.00	1601.4455
One parents with children - Excessive	406.22	330.20	76.03	2770.00	2142.4995
Couples without child	343.68	306.57	37.10	2770.00	1791.0386
Couples without child - Excessive	515.52	342.69	172.82	2770.00	2328.382
Couples with children	462.76	357.33	105.42	2770.00	2546.2272
Couples with children - Excessive	617.01	397.37	219.64	2770.00	3141.9129
Nucleus with others or more than 1 nucleusy	715.77	494.49	221.28	2770.00	4586.7912
Nucleus with others or more than 1 nucleusy - Excessive	1002.08	422.21	579.87	2770.00	3511.3986

Proportional Investment

Scheme 1:Profit distributed by investment ratio

Household type	Baseline Cost (EUR)	Net Savings (EUR)	Real Bill (EUR)	Saving ratio	NPV_EUR
Nucleus with others or more than nucleusy - Excessive	1002.075961	809.6986391	192.3773223	0.808021218	4615.254383
Nucleus with others or more than nucleusy	715.7685438	578.3561708	137.412373	0.808021218	3296.610274
Couples with children - Excessive	617.0090149	486.8757719	130.133243	0.789090208	2775.175148
Couples without child - Excessive	515.5157065	408.9878006	106.5279058	0.793356624	2331.216392
Couples with children	462.7567612	365.156829	97.59993223	0.789090208	2081.381361
One parents with children - Excessive	406.2237056	318.0573576	88.16634799	0.782961096	1812.915995
Couples without child	343.6771377	272.6585338	71.01860389	0.793356624	1554.144261
Single person - Excessive	266.3994171	210.4493265	55.95009053	0.789976678	1199.55392
One parents with children	253.889816	198.7858485	55.10396749	0.782961096	1133.072497
Single person	161.4541922	127.5450464	33.90914577	0.789976678	727.0023759

Scheme 2:Saving profit distributed by dynamic demand ratio

Household type	Baseline Cost (EUR)	Net Savings (EUR)	Real Bill (EUR)	Saving ratio	NPV_EUR
Nucleus with others or more than nucleusy - Excessive	1002.075961	866.0313691	136.0445923	0.864237246	5453.343158
Nucleus with others or more than nucleusy	715.7685438	618.5938351	97.17470876	0.864237246	3895.245113
Couples with children - Excessive	617.0090149	489.4064221	127.6025928	0.793191688	2812.824832
Couples without child - Excessive	515.5157065	402.0223216	113.4933849	0.779844952	2227.587652
Couples with children	462.7567612	367.0548166	95.7019446	0.793191688	2109.618624
One parents with children - Excessive	406.2237056	316.3158072	89.9078984	0.778673925	1787.006122
Couples without child	343.6771377	268.0148811	75.66225659	0.779844952	1485.058435
Single person - Excessive	266.3994171	206.3728269	60.02659019	0.774674469	1138.905899
One parents with children	253.889816	197.6973795	56.1924365	0.778673925	1116.878826
Single person	161.4541922	125.0744405	36.37975163	0.774674469	690.2459994

Scheme 3:Saving profit distributed by Shapley values

Household type	Baseline Cost (EUR)	Net Savings (EUR)	Real Bill (EUR)	Saving ratio	NPV_EUR
Nucleus with others or more than nucleusy - Excessive	1002.075961	752.8020938	249.2738675	0.751242543	3768.777462
Nucleus with others or more than nucleusy	715.7685438	548.2300183	167.5385255	0.76593198	2848.409197
Couples with children - Excessive	617.0090149	467.9066203	149.1023946	0.758346489	2492.962072
Couples without child - Excessive	515.5157065	394.4075578	121.1081487	0.765073795	2114.299195
Couples with children	462.7567612	359.966693	102.7900682	0.777874519	2004.165244
One parents with children - Excessive	406.2237056	316.4248162	89.79888937	0.778942272	1788.627901
Couples without child	343.6771377	274.841156	68.83598163	0.799707417	1586.616169
Single person - Excessive	266.3994171	219.7019416	46.69747542	0.824708793	1337.209469
One parents with children	253.889816	211.092142	42.79767403	0.831432096	1316.159068
Single person	161.4541922	146.9545712	14.49962093	0.910193593	1015.767094

Equal Investment with SIt P0=2800kWh

Household type	File Name	Baseline Cost (EUR)	Net Savings (EUR)	Real Bill (EUR)	Saving ratio	NPV_EUR	ROI	Savings increase rate	NPV increase rate
Single person - Excessive	No SIt	266.40	301.82	-35.43	113.3%	1720.39	0.62	0.0%	0.0%
	α=0.0	266.40	314.66	-48.26	118.1%	1911.32	0.69	4.3%	11.1%
	α=0.3	266.40	305.11	-38.71	114.5%	1769.24	0.64	1.1%	2.8%
Single person	No SIt	161.45	301.82	-140.37	186.9%	1720.39	0.62	0.0%	0.0%
	α=0.0	161.45	315.74	-154.29	195.6%	1927.41	0.70	4.6%	12.0%
	α=0.3	161.45	302.28	-140.83	187.2%	1727.23	0.62	0.2%	0.4%
One parents with children - Excessive	No SIt	406.22	301.82	104.40	74.3%	1720.39	0.62	0.0%	0.0%
	α=0.0	406.22	305.56	100.66	75.2%	1775.97	0.64	1.2%	3.2%
	α=0.3	406.22	304.71	101.51	75.0%	1763.36	0.64	1.0%	2.5%
One parents with children	No SIt	253.89	301.82	-47.93	118.9%	1720.39	0.62	0.0%	0.0%
	α=0.0	253.89	314.94	-61.05	124.0%	1915.54	0.69	4.3%	11.3%
	α=0.3	253.89	305.63	-51.74	120.4%	1777.03	0.64	1.3%	3.3%
Couples without child - Excessive	No SIt	515.52	301.82	213.69	58.5%	1720.39	0.62	0.0%	0.0%
	α=0.0	515.52	286.37	229.15	55.5%	1490.40	0.54	-5.1%	-13.4%
	α=0.3	515.52	294.16	221.35	57.1%	1606.43	0.58	-2.5%	-6.6%
Couples without child	No SIt	343.68	301.82	41.85	87.8%	1720.39	0.62	0.0%	0.0%
	α=0.0	343.68	311.36	32.32	90.6%	1862.22	0.67	3.2%	8.2%
	α=0.3	343.68	305.68	38.00	88.9%	1777.68	0.64	1.3%	3.3%
Couples with children - Excessive	No SIt	617.01	301.82	315.18	48.9%	1720.39	0.62	0.0%	0.0%
	α=0.0	617.01	276.79	340.22	44.9%	1347.92	0.49	-8.3%	-21.7%
	α=0.3	617.01	294.13	322.88	47.7%	1605.85	0.58	-2.6%	-6.7%
Couples with children	No SIt	462.76	301.82	160.93	65.2%	1720.39	0.62	0.0%	0.0%
	α=0.0	462.76	295.89	166.87	63.9%	1632.08	0.59	-2.0%	-5.1%
	α=0.3	462.76	301.34	161.41	65.1%	1713.22	0.62	-0.2%	-0.4%
Nucleus with others or more than 1 nucleusy - Excessive	No SIt	1002.08	301.82	700.25	30.1%	1720.39	0.62	0.0%	0.0%
	α=0.0	1002.08	273.68	728.40	27.3%	1301.61	0.47	-9.3%	-24.3%
	α=0.3	1002.08	323.91	678.17	32.3%	2048.90	0.74	7.3%	19.1%
Nucleus with others or more than 1 nucleusy	No SIt	715.77	301.82	413.94	42.2%	1720.39	0.62	0.0%	0.0%
	α=0.0	715.77	274.13	441.64	38.3%	1308.40	0.47	-9.2%	-23.9%
	α=0.3	715.77	308.06	407.71	43.0%	1813.18	0.65	2.1%	5.4%

Equal Investment with SIt individual P0

Household type	File Name	Baseline Cost (EUR)	Net Savings (EUR)	Real Bill (EUR)	Saving ratio	NPV_EUR	ROI	Savings increase rate	NPV increase rate
	No SIt	266.40	301.82	-35.43	113.3%	1720.39	0.62	0.0%	0.0%
Single person - Excessive	α=0.0	266.40	314.66	-48.26	118.1%	1911.32	0.69	4.3%	11.1%
	α=0.3	266.40	305.11	-38.71	114.5%	1769.24	0.64	1.1%	2.8%
	No SIt	161.45	301.82	-140.37	186.9%	1720.39	0.62	0.0%	0.0%
Single person	α=0.0	161.45	315.74	-154.29	195.6%	1927.41	0.70	4.6%	12.0%
	α=0.3	161.45	302.28	-140.83	187.2%	1727.23	0.62	0.2%	0.4%
	No SIt	406.22	301.82	104.40	74.3%	1720.39	0.62	0.0%	0.0%
One parents with children - Excessive	α=0.0	406.22	305.56	100.66	75.2%	1775.97	0.64	1.2%	3.2%
	α=0.3	406.22	304.71	101.51	75.0%	1763.36	0.64	1.0%	2.5%
	No SIt	253.89	301.82	-47.93	118.9%	1720.39	0.62	0.0%	0.0%
One parents with children	α=0.0	253.89	314.94	-61.05	124.0%	1915.54	0.69	4.3%	11.3%
	α=0.3	253.89	305.63	-51.74	120.4%	1777.03	0.64	1.3%	3.3%
	No SIt	515.52	301.82	213.69	58.5%	1720.39	0.62	0.0%	0.0%
Couples without child - Excessive	α=0.0	515.52	286.37	229.15	55.5%	1490.40	0.54	-5.1%	-13.4%
	α=0.3	515.52	294.16	221.35	57.1%	1606.43	0.58	-2.5%	-6.6%
	No SIt	343.68	301.82	41.85	87.8%	1720.39	0.62	0.0%	0.0%
Couples without child	α=0.0	343.68	311.36	32.32	90.6%	1862.22	0.67	3.2%	8.2%
	α=0.3	343.68	305.68	38.00	88.9%	1777.68	0.64	1.3%	3.3%
	No SIt	617.01	301.82	315.18	48.9%	1720.39	0.62	0.0%	0.0%
Couples with children - Excessive	α=0.0	617.01	276.79	340.22	44.9%	1347.92	0.49	-8.3%	-21.7%
	α=0.3	617.01	294.13	322.88	47.7%	1605.85	0.58	-2.6%	-6.7%
	No SIt	462.76	301.82	160.93	65.2%	1720.39	0.62	0.0%	0.0%
Couples with children	α=0.0	462.76	295.89	166.87	63.9%	1632.08	0.59	-2.0%	-5.1%
	α=0.3	462.76	301.34	161.41	65.1%	1713.22	0.62	-0.2%	-0.4%
	No SIt	1002.08	301.82	700.25	30.1%	1720.39	0.62	0.0%	0.0%
Nucleus with others or more than 1 nucleusy - Excessive	α=0.0	1002.08	273.68	728.40	27.3%	1301.61	0.47	-9.3%	-24.3%
	α=0.3	1002.08	323.91	678.17	32.3%	2048.90	0.74	7.3%	19.1%
	No SIt	715.77	301.82	413.94	42.2%	1720.39	0.62	0.0%	0.0%
Nucleus with others or more than 1 nucleusy	α=0.0	715.77	274.13	441.64	38.3%	1308.40	0.47	-9.2%	-23.9%
	α=0.3	715.77	308.06	407.71	43.0%	1813.18	0.65	2.1%	5.4%

Proportional Investment with SIt individual P0

Household type	File Name	Baseline Cost (EUR)	Net Savings (EUR)	Real Bill (EUR)	Saving ratio	NPV_EUR	ROI	Net Savings increase rate	NPV increase rate
	No SIt	266.40	210.45	55.95	0.79	1199.55	0.62	0.0%	0.0%
Single person - Excessive	α=0.0	266.40	208.78	57.62	0.78	1174.77	0.61	-0.8%	-2.1%
	α=0.3	266.40	208.06	58.34	0.78	1164.01	0.60	-1.1%	-3.0%
	No SIt	161.45	127.55	33.91	0.79	727.00	0.62	0.0%	0.0%
Single person	α=0.0	161.45	169.72	-8.26	1.05	1354.40	1.16	33.1%	86.3%
	α=0.3	161.45	156.32	5.13	0.97	1155.15	0.99	22.6%	58.9%
	No SIt	406.22	318.06	88.17	0.78	1812.92	0.62	0.0%	0.0%
One parents with children - Excessive	α=0.0	406.22	302.10	104.12	0.74	1575.57	0.54	-5.0%	-13.1%
	α=0.3	406.22	306.37	99.86	0.75	1639.00	0.56	-3.7%	-9.6%
	No SIt	253.89	198.79	55.10	0.78	1133.07	0.62	0.0%	0.0%
One parents with children	α=0.0	253.89	231.85	22.04	0.91	1624.92	0.89	16.6%	43.4%
	α=0.3	253.89	221.60	32.29	0.87	1472.50	0.81	11.5%	30.0%
	No SIt	515.52	408.99	106.53	0.79	2331.22	0.62	0.0%	0.0%
Couples without child - Excessive	α=0.0	515.52	375.96	139.56	0.73	1839.78	0.49	-8.1%	-21.1%
	α=0.3	515.52	383.78	131.74	0.74	1956.12	0.52	-6.2%	-16.1%
	No SIt	343.68	272.66	71.02	0.79	1554.14	0.62	0.0%	0.0%
Couples without child	α=0.0	343.68	287.20	56.48	0.84	1770.47	0.71	5.3%	13.9%
	α=0.3	343.68	281.44	62.23	0.82	1684.85	0.67	3.2%	8.4%
	No SIt	617.01	486.88	130.13	0.79	2775.18	0.62	0.0%	0.0%
Couples with children - Excessive	α=0.0	617.01	448.06	168.95	0.73	2197.62	0.49	-8.0%	-20.8%
	α=0.3	617.01	460.46	156.55	0.75	2382.18	0.53	-5.4%	-14.2%
	No SIt	462.76	365.16	97.60	0.79	2081.38	0.62	0.0%	0.0%
Couples with children	α=0.0	462.76	365.71	97.05	0.79	2089.55	0.62	0.2%	0.4%
	α=0.3	462.76	366.11	96.65	0.79	2095.57	0.63	0.3%	0.7%
	No SIt	1002.08	809.70	192.38	0.81	4615.25	0.62	0.0%	0.0%
Nucleus with others or more than 1 nucleusy - Excessive	α=0.0	1002.08	718.29	283.79	0.72	3255.27	0.44	-11.3%	-29.5%
	α=0.3	1002.08	762.61	239.47	0.76	3914.69	0.53	-5.8%	-15.2%
	No SIt	715.77	578.36	137.41	0.81	3296.61	0.62	0.0%	0.0%
Nucleus with others or more than 1 nucleusy	α=0.0	715.77	547.03	168.74	0.76	2830.53	0.53	-5.4%	-14.1%
	α=0.3	715.77	568.50	147.27	0.79	3149.94	0.59	1.7%	4.4%

A third party invests with SIt individual P0

Household type			Baseline Cost (EUR)	Net Savings (EUR)	Real Bill (EUR)	Saving ratio	NPV （EUR）
Single person - Excessive	PV100/BESS50	sdrPR	266.40	27.14	239.26	10.2%	415.85
		midPR	266.40	32.52	233.88	12.2%	498.29
	PV100	sdrPR	266.40	20.28	246.12	7.6%	310.75
		midPR	266.40	24.47	241.93	9.2%	374.98
Single person	PV100/BESS50	sdrPR	161.45	48.40	113.05	30.0%	741.72
		midPR	161.45	58.12	103.34	36.0%	890.56
	PV100	sdrPR	161.45	36.61	124.84	22.7%	561.00
		midPR	161.45	44.59	116.86	27.6%	683.35
One parents with children - Excessive	PV100/BESS50	sdrPR	406.22	33.85	372.38	8.3%	518.64
		midPR	406.22	41.17	365.05	10.1%	630.92
	PV100	sdrPR	406.22	25.05	381.17	6.2%	383.91
		midPR	406.22	30.44	375.79	7.5%	466.41
One parents with children	PV100/BESS50	sdrPR	253.89	54.12	199.77	21.3%	829.33
		midPR	253.89	65.36	188.53	25.7%	1001.51
	PV100	sdrPR	253.89	40.75	213.14	16.0%	624.40
		midPR	253.89	49.73	204.16	19.6%	762.02
Couples without child - Excessive	PV100/BESS50	sdrPR	515.52	35.53	479.98	6.9%	544.52
		midPR	515.52	42.48	473.03	8.2%	650.97
	PV100	sdrPR	515.52	26.64	488.87	5.2%	408.30
		midPR	515.52	32.45	483.07	6.3%	497.22
Couples without child	PV100/BESS50	sdrPR	343.68	50.57	293.11	14.7%	774.85
		midPR	343.68	60.62	283.05	17.6%	928.97
	PV100	sdrPR	343.68	38.22	305.46	11.1%	585.62
		midPR	343.68	46.66	297.01	13.6%	715.05
Couples with children - Excessive	PV100/BESS50	sdrPR	617.01	45.52	571.49	7.4%	697.57
		midPR	617.01	54.80	562.21	8.9%	839.79
	PV100	sdrPR	617.01	35.07	581.94	5.7%	537.39
		midPR	617.01	43.37	573.64	7.0%	664.65
Couples with children	PV100/BESS50	sdrPR	462.76	57.86	404.90	12.5%	886.60
		midPR	462.76	69.61	393.15	15.0%	1066.64
	PV100	sdrPR	462.76	44.35	418.41	9.6%	679.62
		midPR	462.76	54.62	408.14	11.8%	836.96
Nucleus with others or more than 1 nucleusy - Excessive	PV100/BESS50	sdrPR	1002.08	65.20	936.88	6.5%	999.04
		midPR	1002.08	78.80	923.27	7.9%	1207.54
	PV100	sdrPR	1002.08	53.26	948.82	5.3%	816.09
		midPR	1002.08	66.31	935.76	6.6%	1016.18
Nucleus with others or more than 1 nucleusy	PV100/BESS50	sdrPR	715.77	73.77	642.00	10.3%	1130.38
		midPR	715.77	88.98	626.79	12.4%	1363.46
	PV100	sdrPR	715.77	58.74	657.03	8.2%	900.11
		midPR	715.77	72.70	643.07	10.2%	1114.02

Nomenclature

General Terms

REC: Renewable Energy Community

PV: Photovoltaic

BESS: Battery Energy Storage System

EMS: Energy Management System

NPV: Net Present Value

ROI: Return on Investment

QoE: Quality of Experience, a measure of fairness and efficiency.

LCOE: Levelized Cost of Electricity

SDR: Supply-Demand Ratio

TOU: Time-of-Use

FIT: Feed-in Tariff

GSE: Gestore dei Servizi Energetici

NPV: Net Present Value

ROI: Return on Investment

LCOE: Levelized Cost of Electricity

Mathematical Symbols and Variables

$E_{grid,tocomm}(t)$: Grid electricity purchased by the community at time t

$E_{pv,tobess}(t)$: Grid electricity charged to BESS at time t

$E_{pv,togrid}(t)$: PV electricity fed into the grid at time t

$E_{pv,tocomm}(t)$: PV electricity sold within the community at time t

$E_{bess,tocomm}(t)$: BESS electricity discharge to the community at time t

$E_{bess,togrid}(t)$: BESS electricity fed into the grid at time t

WithdrawPR(t): Withdrawal price from grid electricity at time t

FeedinPR(t): Feed-in price of PV electricity at time t

PR_{RD}: Ritiro dedicato price (PV feed-in price)

PR_{zonal}: Prezzo zonale orario (regional hourly price)

PR_{min}: I prezzi minimi garantiti (minimum guaranteed price)

TP(t): PV Trading price of community electricity at time t

TPmid: Mid-market price

TPsdr: Supply-Demand Ratio price

SIt: Saving Incentive factor

P0: Energy consumption threshold

w(P): Weight factor in the Reverse Sigmoid function

W_i: Normalized saving weight factor for household i

σ(T): Standard deviation of savings

95%σ(T): 95th percentile of savings

QoE: Quality of Experience

Indices and Subscripts

t: Time index (hour of the day)

i: Household ID index

sdr: Supply-Demand Ratio

Constants and Parameters

CRF: Capital Recovery Factor

r: Discount rate

T: Project lifetime (years)

α: Weight factor for saving incentive mechanism

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