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Curriculum: Planning for the Global Urban Agenda

Master Thesis

Design and Modeling of Solar Photovoltaic Systems and Renewable Energy Communities Using Open Source GIS: A Case Study in Liguria

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Abstract

The world needs to switch to renewable and distributed energy systems as soon as possible since climate change and energy security issues become increasingly urgent. Solar photovoltaic technology, especially rooftop PV systems, is vital for this energy shift. Because it is flexibility, low emission, and adaptability to urban environments. At the same time, renewable energy communities (RECs) serve as a decentralized way to regulate energy. They give people opportunities to work together to produce, exchange, and manage local renewable energy.

This study focuses on the Liguria region of Italy, exploring how rooftop solar photovoltaic systems can be effectively integrated into Renewable Energy Communities to enhance energy autonomy, economic efficiency, and environmental sustainability. The study uses open-source geographic information systems (QGIS, ArcGIS Pro) to assess the regional rooftop PV potential, by using high-resolution spatial data and solar radiation simulation techniques. By overlaying building types, roof orientations, and household electricity demand, the study identifies the self-consumption and the sale of surplus electricity.

Building on resource-demand matching analysis, this study further assesses the integration potential of PV systems within RECs, employing a series of energy performance metrics and economic indicators for quantitative analysis. And also evaluating the environmental benefits of PV systems in terms of carbon emissions reduction. Finally, the study proposes policy recommendations for the advancement of RECs. The study provides local governments and urban planners with dual technical and policy support pathways.

Keywords: Solar photovoltaic (PV) systems, Renewable Energy Communities (RECs), Rooftop solar, Open-source GIS, Spatial energy planning

Acknowledgment

As my master's study journey in Italy draws to a close, I can't help but look back on this unique and fulfilling experience. It has not only shaped my academic understanding but also fostered my personal growth. This thesis is the culmination of my learning and exploration, and its realization would not have been possible without the support and accompaniment of many people.

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Finally, I would like to thank myself. Thanks for every early morning and late night, thanks for my persistence and passion. I am proud of the journey I have undertaken.

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Glossary of terms

CO_2	Carbon Dioxide
CEC	Citizen Energy Community
CH_4	Methane
CPV	Concentrated Photovoltaics
DEM	Digital Elevation Model
DG	Diffuse to Global radiation ratio
DNI	Direct Normal Irradiance
DSCC	Dye-sensitized Solar Cells
DTM	Digital Terrain Model
GIS	Geographic Information System
$kWh/m^2/m$	Kilowatt hour per square Meter per Month
LT	Linke Turbidity factor
MAE	Mean Absolute Error
MAPE	Mean Absolute Percentage Error
MCDA	Multi-Criteria Decision Analysis
N_2O	Nitrous Oxide
NPV	Net Present Value
OPI	Over-Production Index
PBT	Payback Time
PSC	Perovskite Solar Cells
PV	Photovoltaic
REC	Renewable Energy Community
SC2	Scenario 2
SCI	Solar-Consumption Index
SSI	Self-Sufficiency Index
T	Transmittance of atmosphere

1 Introduction

1.1 Context and Importance

1.1.1 Climate change and global energy transition

According to the Sixth Assessment Report on Climate Change of the IPCC (AR6), compared to the 1850-1900 base period, the global average surface temperature increased by about 1.09°C between 2011 and 2020, representing the fastest warming in nearly 100 thousand years. (Figure 1-1) shows that this trend was mainly driven by human activities, particularly in unsustainable energy use, land use change and high carbon lifestyles. These activities produce large amounts of greenhouse gases which are the direct cause of climate warming. Among these, fossil fuel burning and industrial emissions contribute the most CO_2, while N_2O, CH_4, and other gases are also increasing. Climate warming has caused a series of chain reactions, including sea level rise, ocean warming, and frequent extreme weather events such as heatwaves, further threatening global food and water security (IPCC, 2023). Therefore, in order to stop greenhouse gas emissions and mitigate climate change, a transition is urgent needed to shift from high-carbon, non-renewable fossil fuels to zero-carbon, clean renewable energy systems.

In addition to climate hazards, the traditional energy system's heavy dependence on fossil fuels such as coal, oil, and natural gas has led to serious energy security issues. On one hand, fossil fuel resources are unevenly distributed, primarily concentrated in a limited number of exporting countries. This makes their supply vulnerable to geopolitical conflicts and market fluctuations, resulting in significant price variability for importing countries. On the other hand, the centralized energy production and long distance transmission model further increases the potential risks of supply interruptions. In contrast, renewable energy has a natural advantage in enhancing energy security. As Azzuni and Breyer point out, renewable resources such as solar and wind energy have the following characteristics (Azzuni & Breyer, 2017). First, in terms of supply availability, they differ from limited resources like oil or natural gas, as they are theoretically limitless. Secondly, renewable energy resources have strong diversity, as they are widely distributed across regions, helping disperse risks and reduce reliance on a single import source. Third, as technology advances, their operational costs tend to stabilize, mitigating the impact of fluctuations in international energy market prices and achieving cost control. Finally, in terms of system resilience, renewable energy can be integrated with energy storage facilities to enhance the ability to respond to unexpected disruptions in energy supply.

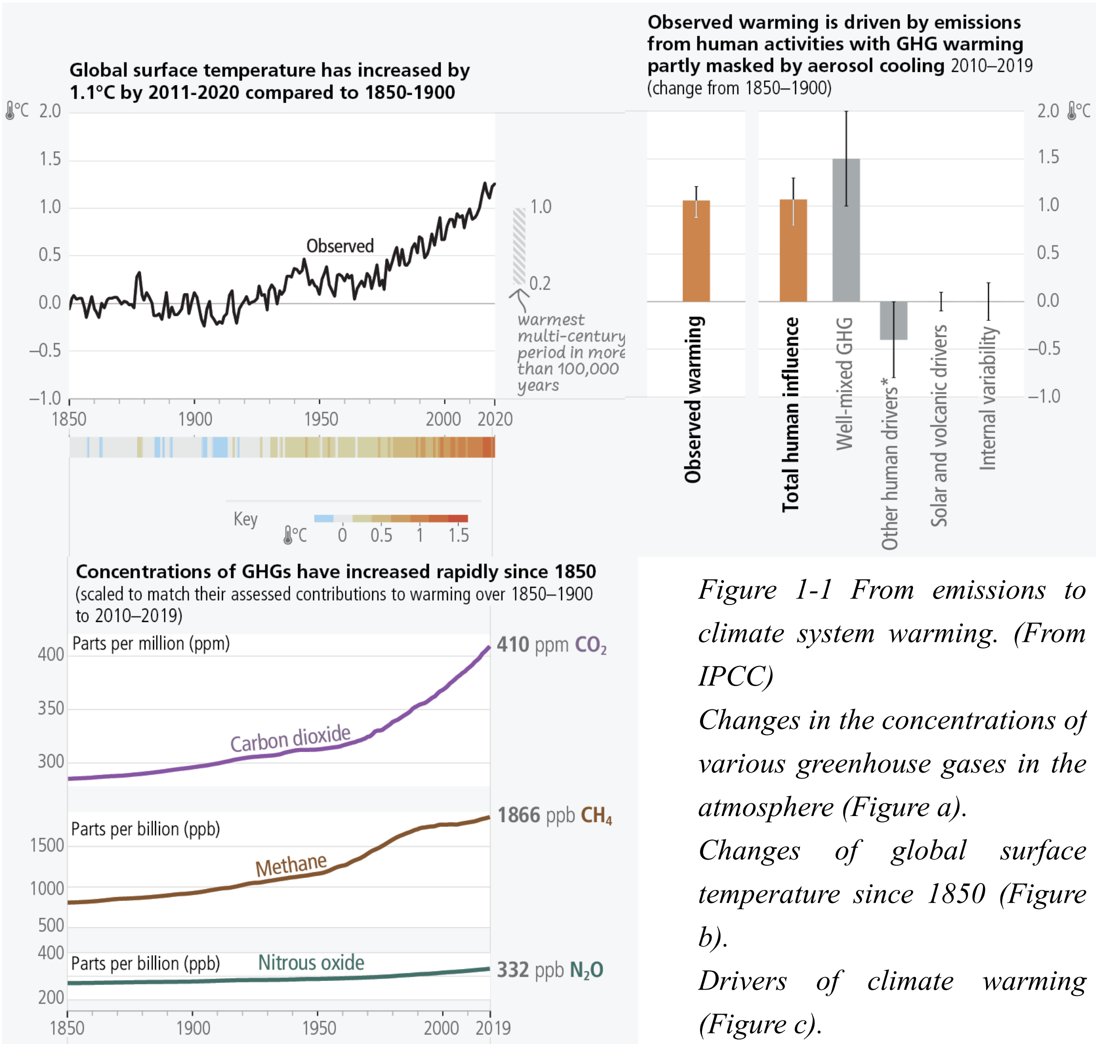

Figure 1-1 From emissions to climate system warming. (From IPCC)
Changes in the concentrations of various greenhouse gases in the atmosphere (Figure a).
Changes of global surface temperature since 1850 (Figure b).
Drivers of climate warming (Figure c).

To address both energy security and climate challenges, the EU has proposed a number of structural reform measures. As a signatory to the Paris Agreement, the EU released the European Green Deal in 2019. It clearly specifies that the EU will reduce greenhouse gas emissions by 55% compared to 1990 levels by 2030, with the goal of achieving net-zero greenhouse gas emissions by 2050 (European Commission, Secretariat-General, 2019). In 2021, the EU proposed the "European Climate Law," which would legally enforce the objectives of the European Green Deal (European Climate Law, 2021). The REPowerEU Plan presented by the European Union in 2022 explicitly proposes to reduce dependence on a single supplier by establishing an EU energy platform for the joint purchase of natural gas, liquefied natural gas and hydrogen. At the same time, it has elevated renewable energy projects to the status of "top public interest", greatly simplified the approval process and accelerated the deployment of projects. It has also launched in-depth cooperation with foreign partners in terms of capital, technology and industrial chain to promote the construction of green energy systems (European Commission, 2022).

In October 2023, the European Union adopted the Renewable Energy Directive (EU) 2023/2413. The regulation raises the minimum target for the share of renewable energy in total energy consumption from the 32% proposed in 2018 to at least 42.5% and aims to reach 45%. The new directive further requires that at least 5% of new renewable energy capacity must utilize innovative technologies, while also standardizing the rules for establishing "renewable energy acceleration zones" and the approval process. New projects in "renewable energy acceleration zones" must be approved within 12 months, while projects in other areas must be approved within 24 months, which significantly increases policy implementation efficiency (Directive (EU) 2023/2413 of the European Parliament and of the Council, 2023).

Global renewable energy deployment has expanded because of policy initiatives and growing investment. Data shows that worldwide energy systems, particularly in Europe, are gradually transitioning to decarbonization, with the EU's electricity carbon intensity steadily declining. Despite the significant rise in fossil fuel prices due to global geopolitical concerns, the overall wholesale electricity prices in the European market have shown a downward trend (Figure 1-2). Between 2021 and 2023, EU electricity consumers saved approximately 100 billion euros in electricity thanks to the additional power generation from newly installed solar photovoltaic and wind power projects

(International Energy Agency, 2023).

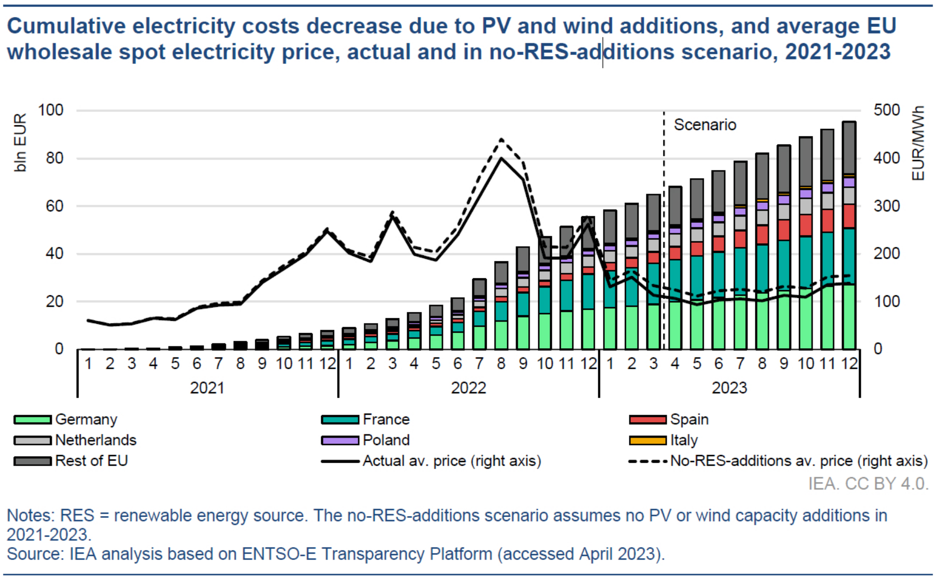

Figure 1-2 EU wholesale spot electricity price and PV & wind installations (From IEA)

1.1.2 Importance and potential of solar energy

Among all the sustainable energy sources, solar energy shows significant advantages due to its wealth of resources, environmental friendliness and technological potential. First, unlike limited fossil fuels, solar energy is a potentially limitless source of renewable energy. As estimated by Ali O M Maka et al., sun rises from the horizon every day, leaving behind about 108 to 1018 kWh of energy (Maka & Alabid, 2022), which is far more than the current human demand for electricity.

Solar energy systems also have outstanding environmental sustainability. Compared to traditional fuels, which cause greenhouse gas emissions and air pollution, photovoltaic power generation has the advantages of higher efficiency and no pollution. Research on the relationship between carbon dioxide emissions, solar energy consumption, and coal energy consumption shows that as solar energy use increases, CO_2 emissions show a clear decrease (Güney & İnce, 2023).

Technological advancements are also contributing to the rapid development of solar energy. So far, the solar market has been mainly dominated by photovoltaic modules made of crystalline silicon. However, new photovoltaic materials are constantly emerging, such as perovskite, organic, and organic-inorganic hybrid materials, which offer higher conversion efficiency and broader application scenarios. At the same time, photovoltaic battery storage technology is gradually becoming more popular, as a solution to address issues such as being unable to run at night or during sandstorms and lower power on cloudy days. In terms of economics, although the initial investment costs for solar energy systems are relatively high, their subsequent operational and maintenance costs are extremely low (Guangul & Chala, 2019). Additionally, photovoltaic modules typically have a lifetime of 10 to 15 years, making them highly economically effective over their entire lifecycle. As technology becomes more mature and the industrial scale expands, the costs of photovoltaic systems have considerably decreased, furthermore, driving the widespread deployment of solar energy (International Renewable Energy Agency, 2024).

According to statistics released by the International Renewable Energy Agency (IRENA) in 2025, 2024 became the year saw the largest increase in life cycle in global renewable energy generation capacity on record. Solar systems accounted for more than 75% of new capacity that year, achieving an annual growth rate of 32.2% (International Renewable Energy Agency, 2025).

In Europe, Italy has actively responded to the European Green Deal and is strongly promoting the development of the photovoltaic industry. According to its National Energy and Climate Plan (PNIEC) submitted to the European Commission, Italy has set five major goals: achieving energy decarbonization, improving energy efficiency, enhancing energy security, improving the internal energy market, and strengthening research and competitiveness (Ministero dell'Ambiente e della Sicurezza Energetica, 2024).

To achieve these goals, Italy has introduced a number of supportive policies and incentive measures. Photovoltaics (PV) are identified as the core of future energy systems in the PNIEC, due to their advantages such as modality and widespread availability of resources. According to the plan, the target for solar power installed capacity will increase from 19,269 MW in 2016 to 52,000 MW by 2030 (Ministero dell'Ambiente e della Sicurezza Energetica, 2024). Additionally, the plan encourages the deployment of renewable energy communities and distributed energy storage systems to enhance the local efficiency of solar systems. The Conto Energia program offers financial incentives for various types of photovoltaic systems and provides rewards for systems that integrate highly efficient energy use (DECRETO 5 Luglio2012 (Quinto Conto Energi), 2012). The 'Reddito Energetico Nazionale' initiative assists low-income households, providing funding for the installation of residential photovoltaic systems (DECRETO 8 Agosto 2023 (DM REN), 2023).

According to a report by the Italian Energy Services Agency (GSE), as of the end of 2023, the cumulative photovoltaic installed capacity in the whole country reached 30.3 GW, with an increase of 5.2 GW added that year, representing an annual growth rate of 21%. Among the new capacity, 69% was distributed systems on building roofs. In this context, the number of photovoltaic systems in Liguria increased by 35% compared to 2022, with distributed systems being the main type, demonstrating the growing importance and application potential of solar energy in the region.

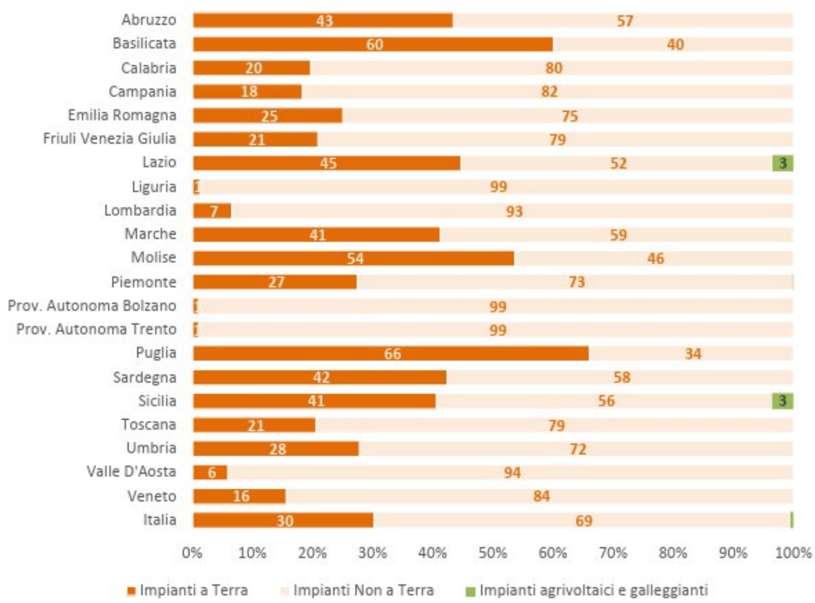

Figure 1-3 Distribution of PV panels in regions at the end of 2023 (From GSE)

1.1.3 Importance of rooftop PV systems

Distributed photovoltaic systems, especially rooftop photovoltaics, are critical in promoting the decentralization and low-carbon transformation of energy systems. By generating electricity locally and using it nearby, these technologies effectively reduce the load pressure on traditional centralized power grids and minimize transmission losses over long distances. Furthermore, when combined with inverters, they enable efficient, stable, and clean power transmission, facilitating smooth integration with dispersed grids and enhancing the overall operational efficiency of the system (Blaabjerg et al., 2017). Additionally, when paired with battery storage technology, distributed PV systems can provide emergency power supply during large-scale power outages or natural disasters, therefore improving grid stability and system resilience.

In urban environments, large-scale centralized renewable energy projects face different constraints due to limited land resources. Building-integrated photovoltaic (BIPV) systems, particularly rooftop PV, utilize existing building infrastructure (such as rooftop surfaces) without requiring additional land (Bernasconi & Guariso, 2021). This spatial utilization is particularly suitable for densely populated, land-limited regions like Italy's Liguria region. In recent years, Italy has had particularly rapid growth in distributed PV systems. Especially in off-ground systems, the proportion of rooftop PV applications has grown significantly. This trend reflects the strategic value of distributed energy in ensuring energy security and increasing system flexibility.

1.2 Research Objectives

This study aims to explore how to promote the effective integration of solar PV systems in renewable energy communities (RECs) through technical assessment and policy optimization, with the goal of enhancing sustainable energy production and energy self-sufficiency levels and driving regional sustainable development.

1.2.1 Assessment of solar PV potential and energy consumption

First, this study will use open-source geographic information system (GIS) tools, such as QGIS and ArcGIS Pro, to conduct a comprehensive spatial analysis of solar resources and available rooftop solar potential in the study area (Liguria, Italy). By processing high-resolution building contour and solar radiation-related data, an annual total solar radiation map of the region will be generated. This will be combined with rooftop orientation and building use data to estimate the solar PV generation potential of residential building rooftops. Then, by comparing solar potential with household energy consumption data, the study will assess the ability to self-consume and sell surplus electricity, to analyze the value of rooftop PV systems to households, communities, and the entire region's energy structure.

1.2.2 Integration of solar PV systems with RECs

Based on the identified match between solar resource distribution and electricity demand, this study further analyzes the integration potential of PV systems within sustainable energy communities. REC is a new type of bottom-up energy governance framework that emphasizes the collective production and sharing of energy among community members. This study will assess the potential for improving energy efficiency and the economic feasibility of the REC model by calculating economic indicators such as Energy Performance Indicators and Net Present Value (NPV). Additionally, the study will quantify the reduction in carbon emissions compared to traditional energy systems and evaluate the environmental benefits of installing solar PV systems in Liguria, Italy.

1.2.3 Provide planning and policy recommendations for implementation.

Lastly, the study will propose targeted policy and planning recommendations to promote the adoption of rooftop PV systems in regional energy communities. The focus will be on incentive mechanism design, localized implementation recommendations, and discussions on technical barriers. The aim is to provide practical, feasible, and scalable implementation plans for energy community development in European cities, particularly in densely populated regions like Liguria.

1.3 Structure of the Thesis

This thesis is divided into six chapters, each exploring a specific aspect of the research topic. Chapter 1, this chapter, provides an overview of the climate change context and the objectives of the renewable energy transition. It also introduces the importance of solar photovoltaic systems, particularly rooftop systems, in energy production and clarifies the research objectives.

Chapter 2 reviews the preview research progress, challenges, and outlook of solar photovoltaic technology, and introduces the concept and application cases of Renewable Energy Communities (RECs).

Chapter 3 provides a detailed description of the methods and data framework used in this study, as well as the GIS workflow and performance evaluation indicators related to energy, economy, and environment.

Chapter 4 focuses on the case study of the Liguria region in Italy, first introducing the local context from geographical, climatic, and renewable energy perspectives. Then, GIS analysis is used to assess solar potential, electricity consumption trends, and regional energy community scenarios.

Chapter 5 conducts a comprehensive assessment of energy performance, economic feasibility, and environmental benefits under different scenarios, and explores the potential challenges and opportunities for implementing RECs.

The final chapter summarizes the main research findings and their implications for sustainable energy planning, and proposes policy recommendations and future research directions, providing broader guidance for policymakers and urban planners.

2 Literature Review

2.1 Solar Photovoltaic Systems

2.1.1 History and evolution of PV technology

In 1839, French physicist Alexandre Edmond Becquerel reported his experiments using wet cell units, which first demonstrated the photovoltaic effect (Nag et al., 2022). In a published work, Willoughby Smith and Richard Day investigated the effects of sunshine on selenium, adding to the evidence for this discovery. In the late 1880s, Charles Fritts created a selenium cell with an efficiency of just 1–2%, which looked quite similar to modern solar cells.

However, due to a lack of interest, expertise, or the low cost of fossil fuels, the development of photovoltaic technology remained slow for half a century after its discovery. In March 1905, Albert Einstein published an explanation of the photoelectric effect based on Max Planck's quantum concept, pointing out that if the frequency of photons is sufficient to dislodge electrons, the collision will cause the photoelectric effect. This breakthrough earned Einstein the 1921 Nobel Prize in Physics and laid the theoretical foundation for photovoltaic systems (The Nobel Prize, 2019).

In 1939, Russell Ohl discovered the photoelectric effect in silicon. A year later, he developed the world's first silicon solar cell at Bell Labs, which was then referred to as a photosensitive electronic device and not used as a solar cell. In 1954, the Bell Labs chemist Calvin Fuller and physicist Gerald Pearson improved the efficiency of the photoelectric effect to 6% by doping silicon (Marques Lameirinhas et al., 2022). In 1955, the first solar cell unit was deployed as a power source for a telecommunications network in Americus, Georgia. However, during that time, the solar cell was mainly applied in the aerospace field. On March 17, 1958, the Vanguard-I satellite launched by NASA was the first satellite to carry a solar system, which significantly extends the satellite's lifetime. However, due to immature manufacturing processes and high commercialization costs, its development in public applications was constrained.

Following the oil crisis of 1973, photovoltaic technology began to gain wide attention.

To reduce manufacturing costs, various new technologies have emerged. Monocrystalline silicon has gradually been replaced by polycrystalline silicon and amorphous silicon, and the crystalline silicon photovoltaic cells now have a 26.1% efficiency rate (NREL, 2025). Currently, crystalline silicon cells dominate the worldwide photovoltaic market, accounting for 95%.

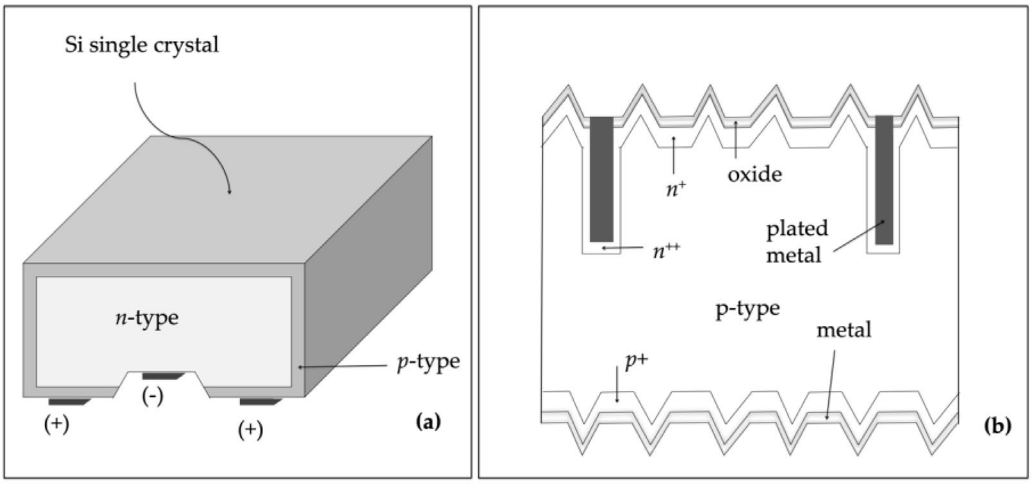

Figure 2-1 modern silicon cell history (From Bosio, Pasini, & Romeo, 2020)
(a) The first modern silicon cell reported in 1954, use single-crystal silicon wafers. (b) A new type of silicon cell with light capture, back reflector, and buried contacts, with an efficiency lose to 27%

CdTe is regarded as an excellent solar cell material, with a theoretical maximum efficiency approaching 30%. Although the first CdTe thin-film solar cell achieved only 6% efficiency in 1972, after years of research, in 2015, CdTe (1− x) (S,Se) x thin-film solar cells reached a world record efficiency of (22.1±0.5)% (Green et al., 2019). In practical market applications, the manufacturing process of this solar cell is particularly suitable for large-scale, entirely automated and live production. Currently, the highest efficiency of commercial modules is 19.7% (First Solar, 2024). However, due to issues such as excessive thickness of the CdTe layer and low stability, CdTe technology currently holds a limited market share globally.

Among the materials used in second-generation thin-film solar cells, Copper Indium Gallium Diselenide (CuInxGa(1−x)Se2) stands out. Based on the all-thin-film solar cell with an efficiency of 5.7% in the 1970s, which used CuInSe2 (CIS)/CdS, the efficiency of polycrystalline CuInGaSe2 thin films prepared by sputtering and selenization were investigated. By continuously adjusting the percentage of Ga added (Rosa et al., 2016), CIGS solar cells achieved a conversion efficiency of 20.3% by 2010. Following further adjustments to materials and processing methods over the years. In 2017, Solar Frontier established a world record efficiency of 23.35% for CIGS solar cells (Solar Frontier, 2019). However, due to the rare and expensive nature of the material indium (In) used in CIGS cells, they have not gained a dominant position in the photovoltaic module market.

To improve economic efficiency, researchers have developed third-generation solar cells, including multiple junction solar cells (MJSC), dye-sensitized solar cells (DSCC), perovskite solar cells (PSC), and concentrated photovoltaics (CPV) (Sharma & Mishra, 2025).

Compared to single-junction silicon solar cells, multi-junction solar cells are composed of multiple layers, resulting in higher power output. GaInP/GaAs/Ge lattice-matched triple-junction cells have been demonstrated to have efficiencies greater than 30%, but due to their complex manufacturing processes and high costs, they are difficult to scale up for widespread application in the civilian market (Li et al., 2021). In 2020, John F. Geisz and colleagues used an inverted cell with six single-junction cells to achieve an incredible efficiency record of 47.1% under direct sunlight at 143 suns concentration (Geisz et al., 2020).

By comparing to traditional silicon solar cells, DSCC can achieve lower material and production costs. However, the stability of the cells and their relatively lower photoconversion efficiency have hindered the commercialization of this type of cell (Tomar et al., 2023). PSCs are based on dye-sensitized solar cells, have received a lot of attention in recent years from the scientific community due to their exceptional photovoltaic properties and low-cost manufacturing methods. In 2009, the first experimental use of perovskite as a coating in solar cells achieved a solar conversion efficiency of only 3.8% (Park, 2015), by around 2020, efficiency had surpassed 25% (Bati et al., 2023). However, these cells also face challenges related to stability and environmental impact (Aldamasy et al., 2021).

CPV have numerous benefits, including low cost, high efficiency, a small footprint, and environmental friendliness. However, they also have issues such as sensitivity to temperature (Ejaz et al., 2021).

With the ongoing breakthroughs in modern technology, fourth-generation batteries based on two-dimensional materials are also under study. Their efficiency can reach up to 47.6% in laboratory environments, while the highest efficiency of commercial batteries is 26.7% (Fluxim, 2024).

2.1.2 Role of solar PV technology in energy transition

With the advancement of renewable energy and solar energy policies, as well as the development of solar photovoltaic technology, solar PV has become one of the primary energy sources for achieving the 2050 Sustainable Development Goals. As demonstrated by P. J. Verlinden, the solar photovoltaic industry has the capacity to meet all required needs, with photovoltaic power generation capacity projected to increase by up to 70 TW by 2050 (Verlinden, 2020).

Technological advancements have continuously improved the efficiency of photovoltaic modules while significantly reducing production costs. According to research by Yifeng Chen et al., C-Si exhibits higher learning efficiency, reaching up to 24.2%, and costs decrease at a faster rate. By 2030, the manufacturing cost of C-Si is projected to fall below 0.2 USD/W (Chen et al., 2018). In addition to standard photovoltaic modules, current developments indicate there is further potential for innovation. Single axis tracking solar systems enhance power generation by tracking the sun, while double-sided solar cells can convert irradiance from both sides of the panel into electricity. Combining these technologies can achieve highly competitive costs in most regions worldwide (Rodríguez-Gallegos et al., 2020).

In addition to the electricity system, solar photovoltaic power generation can also help to reduce carbon emissions in other industries. Rooftop photovoltaics can power electric vehicles, thereby decreasing the need to strengthen the distribution grid.

Electric vehicle batteries provide short-term storage that works synergistically with photovoltaic power generation, simplifying the daily balancing of solar power generation (Kaufmann et al., 2021). Solar power can not only provide heating and water heating with the assistance of electric heat pumps but also meet cooling needs, contributing to the decarbonization of residential and commercial sectors. Additionally, low-cost solar power can be used to generate electrolytic hydrogen as an alternative to hydrogen produced via steam methane reforming. This can cut emissions related to agriculture ammonia production and fertilizers and enables green methanol as a new bulk chemical to span the entire chemical sector (Breyer et al., 2015).

However, intermittency is the primary constraint of solar energy, but energy storage systems are the preferred solution to address these challenges. Storing electricity generated during the day using battery packs can effectively handle the constraints during periods when solar panels cannot generate electricity. However, solar panels typically generate surplus electricity compared to the energy the load requires. As a result, excess electricity is often transmitted to the grid via connection to the public grid rather than stored in batteries (Hayat et al., 2018).

As photovoltaic technology integrates with energy storage, the grid, and other renewable energy technologies, its role in the energy system continues to grow, becoming an essential component in achieving a low-carbon, smart, and sustainable energy future.

2.1.3 Integration opportunities and challenges for rooftop PV system

Rooftop photovoltaics are an important type of distributed PV power generating as compared to typical centralized power generation technologies, since they offer advantages such as flexible deployment and the flexibility to use local resources. As technology advances, distributed photovoltaic systems have emerged as a crucial strategy for boosting the pace of renewable energy in future power systems, playing an increasingly vital role in the development of renewable resource dominated power systems (Muneer et al., 2011).

Globally, the major distributed PV policies currently in place in key countries primarily include pre-installation subsidies, operational incentives, and the purchase of excess electricity from users. These policies collectively minimize user investment costs, driving the development of rooftop PV systems and promoting the decarbonization and sustainable development of energy systems (Nadeem et al., 2023). The collaborative operation model of distributed PV and energy storage can also potentially provide higher economic benefits by enhancing users' operational autonomy and economic efficiency (Li, Wang, et al., 2021), becoming an important future development model for distributed energy. As distributed PV and energy storage systems grow in popularity, the reduced reliance on the upper-level grid will fundamentally transform the system's power supply and demand structure.

However, rooftop PV systems still face numerous challenges. From a technical perspective, intermittent power generation can cause voltage fluctuations, reverse power, and other grid stability issues (Gürtler & Paulsen, 2018). High-frequency harmonics introduced into the grid have negative effects on grid-connected equipment, leading to reduced operational efficiency, early aging, and potential damage (Torquato et al., 2016). These issues require regulation through energy storage systems and smart inverters (Parag & Sovacool, 2016).

Economically, even as PV costs decline, users may still hesitate due to initial investment costs and tax issues (Xue et al., 2024). Households may also avoid rooftop solar PV systems due to overly long payback times (PBT), which can exceed the 20–25-year lifecycle of solar panels (Agdas & Barooah, 2023).

From a policy perspective, outdated regulatory and regulatory practices may struggle to keep pace with the rapidly changing energy market. Additionally, RECs offer socioeconomic advantages, including reduced energy costs, increased employment opportunities, and significantly enhanced social capital and civic rights. This encourages citizens to work together and enhances their responsibility for sustainable consumption (Akizu et al., 2018). As new energy technologies like energy storage, smart grids, and demand response systems are adopted by energy communities, REC also gives them a place to test. This helps the EU reach its goal of faster technical progress and encourages innovation in sustainable energy (Damato et al., 2022).

To achieve the efficient integration of rooftop PV systems, collaborative efforts are needed across technological innovation, policy support, business model optimization, and public engagement to build a smarter, more efficient, and sustainable distributed energy system.

2.2 Renewable Energy Communities (RECs)

2.2.1 Concept and benefits of RECs

Renewable Energy Directive (RED II) (Directive (EU) 2018/2001, 2018) first introduced the concept of Renewable Energy Communities (REC), which aimed to promote the production, consumption, storage, and sale of locally available renewable energy. The Internal Electricity Market Directive (Directive (EU) 2019/944, 2019) introduced the concept of Citizen Energy Communities (CECs), with the goal of establishing a structural framework to facilitate the full participation of producer-consumers in the electricity market. Both CECs and RECs emphasize the participation and autonomy of citizens, local authorities, and small businesses. In the transition toward sustainable development and renewable energy utilization, both types of communities play a crucial role in supporting individuals. However, REC places greater emphasis on the utilization of renewable energy and has geographical scale limitations. In Italy, the RED II Directive introduced the notion of collective self-consumption and renewable energy communities through (Ministero dello Sviluppo Economico, 2020). The regulatory framework for shared electricity in RECs is defined in (ARERA, 2020), with GSE (Energy Services Agency) acting as the technical support unit. In December 2020, GSE issued technical rules specifying the essential requirements, access procedures, standard contract templates, and the timing for providing incentive measures, which were updated on April 4, 2022.

By using local resources, RECs not only increase community members' participation but also encourage them to be more active in investment, energy ownership, and economic incentive mechanisms. As local communities change, residents are starting to shift from being just energy consumers to consumer-producers, taking on additional responsibilities such as investing in energy, energy management, and sharing energy with community members (Akizu et al., 2018).

By incorporating renewable energy projects into “communities,”, renewable energy communities not only replace fossil fuel-based electricity supply, driving decarbonization and energy independence, but also reduce air pollution, improve local air quality, and serve as a key tool for advancing the energy transition. Additionally, RECs offer socioeconomic advantages, including reduced energy costs, increased employment opportunities, and significantly enhanced social capital and civic rights. This encourages citizens to work together and enhances their responsibility for sustainable consumption. As new energy technologies like energy storage, smart grids, and demand response systems are adopted by energy communities, REC also gives them a place to test. This helps the EU reach its goal of faster technical progress and encourages innovation in sustainable energy (Damato et al., 2022).

2.2.2 Global case studies of REC implementation

Currently, there are approximately 2,500 RECs (REScoops) in Europe, primarily focused on solar energy, with the majority located in Northwest Europe.

Denmark had a history of wind energy cooperatives even before the concept of energy communities emerged. In the mid-1980s, the implementation of tax exemptions for wind power generation and feed-in tariff subsidies, coupled with the promotion of decentralization, facilitated the development of wind energy cooperatives. By 2002, the national wind power installed capacity had reached 2,897MWh, accounting for 22.9% of Denmark's total electricity generation, with approximately 150,000 households participating in wind power cooperatives. However, by the late 1990s, as the political system changed, incentives for wind power feed-in tariffs were significantly reduced, and public interest in community energy also declined (Mey & Diesendorf, 2018). After 2009, Denmark once again encouraged public investment in wind power, but due to regulations favoring large offshore wind farms, few new energy communities emerged. Nevertheless, some innovative cooperatives that transcend local boundaries have emerged, such as the most well-known offshore wind cooperative in Copenhagen, Middelgrunden Vindmøllelaug I/S, which owns 10 wind turbines with a total capacity of 20 megawatts (Middelgrunden Vindmøllelaug I/S - Få Hele Historien, 2021).

Compared to the fluctuating development of wind energy, the growth of district heating systems has been more stable, resembling the structure of RECs. While producers are primarily local energy companies, citizens have a voice in energy choices and ownership, effectively reducing heating costs and enhancing citizen participation.

Figure 2-2 German REC study (From ‘Klimakommune Saerbeck’, 2023）

Unlike Denmark, Germany has both photovoltaic and wind energy facilities in the construction of energy communities, due to differences in climate and environmental conditions. Germany's energy communities, also known as energy cooperatives (Energiegenossenschaften), emerged in the late 19th century and was important in the process of electrification (Holstenkamp, 2015). After the 21st century, with the promotion of renewable energy policies, energy cooperatives became active again, and by 2020, there were approximately 896 energy cooperatives nationwide (DGRV, n.d.). A key factor contributing to this development is the long-term stability and attractiveness of feed-in tariffs/subsidies, which help mitigate investment risks. Additionally, this has created a favorable market environment for small-scale, local renewable energy producers. Bottom-up power production plans have faced increased hurdles in recent years as political framework conditions have changed, particularly after 2017, when Germany gradually replaced feed-in tariff support programs with competitive bidding procedures (Krug et al., 2022). While this shift benefits large corporations, it has resulted in a decrease in the number of newly established energy communities. Nevertheless, the German ‘Klimakommune Saerbeck’ (Figure 2-2) has become a typical success story for RECs. Initiated by residents and led by the mayor, the community has implemented a sustainable energy strategy, with most households installing photovoltaic systems on their roofs. The town also features public wind, solar, and biomass power generation and storage facilities, achieving local power generation and storage (Klimakommune Saerbeck, 2023).

In 2020, Italy's first certified REC was established in Cuneo, Italy. This REC generates electricity from a photovoltaic system on the roof of a town hall, which is shared among eight participants, including three households. The total annual electricity generation is expected to be 24,198 kWh/year, meeting nearly 50% of the community's electricity demand (Ghiani et al., 2022). In the following years, many more RECs were established. Unlike renewable energy community regulations in many countries, Italy imposes geographical restrictions on RECs, requiring members within a community to be under the same Point of Delivery (POD). While this creates certain barriers to the promotion of sustainable energy communities, it also offers new opportunities for consumer, business, and institutional participation.

2.2.3 Key factors influencing REC success

Based on the above experience, it can be concluded that the success of RECs depends not only on the technical capabilities of distributed renewable energy generation and grid connectivity but also on a bottom-up governance system and active cooperation from community members. The participation of stakeholders plays a crucial role in establishing RECs, and the sustainable development of RECs also relies on the collective efforts of community members and fair decision-making. In situations of energy surplus, sharing the produced energy among participants can effectively enhance the utilization efficiency of renewable energy within the community. Additionally, consumers transitioning into producer-consumers can further enable RECs to achieve self-sufficiency (Herenčić et al., 2022). The sustainable development of RECs relies on government policy support. For example, incentive mechanisms such as feed-in tariff subsidies significantly reduce the cost of energy systems and enhance public participation enthusiasm in some projects, local municipal authorities play a key role in promoting decentralized energy systems. Their support in empowering communities, assisting with permitting procedures, and addressing local issues can effectively address local challenges and stimulate resident participation.

2.3 Role of GIS in Renewable Energy Assessments

2.3.1 Use of GIS for evaluating solar energy potential

A Geographic Information System (GIS) is an integrated platform (Figure 2-3) used for collecting, managing, analyzing, and visualizing spatial data. Its core components include geographic spatial data, data collection, data management, data exploration, and spatial analysis capabilities. GIS can process both vector and raster spatial data. By integrating spatial and time information, it provides effective support for energy system planning. Common GIS software such as QGIS, GRASS GIS, and ArcGIS provides important technical tools for site selection, potential assessment, and policy support in renewable energy development (ESRI, 2024).

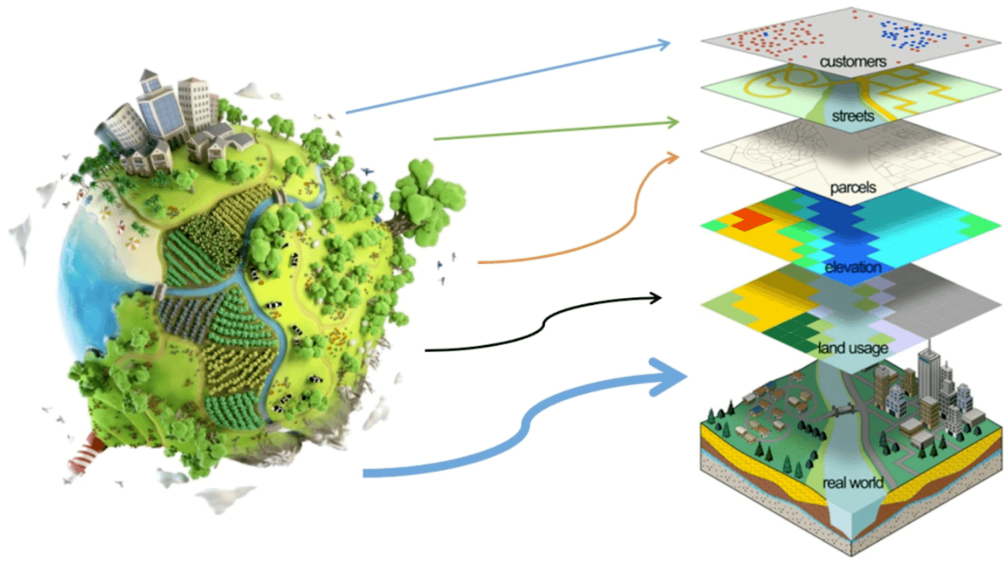

Figure 2-3 GIS layers model (From GEO University, 2025)

In the field of renewable energy research and utilization, GIS tools are widely employed to assess resource availability and development potential across various scales. For instance, (Zambelli et al., 2012) applied GRASS, QGIS, and PostGIS to combine terrain morphological characteristics with forest sources technical capabilities, for calculating the energy potential of woody biomass in the Italian Alps.(Ouchani, Jbaihi, Alami Merrouni, Maaroufi, & Ghennioui, 2021) utilized GIS technology to assess the power generation capacity and economic potential of solar photovoltaic systems in Morocco under different scenarios. (Mary, 2022) analyzed the site suitability and power generation potential of photovoltaic systems across Ghana, discovering that approximately 85% of the land is suitable for deploying solar systems.

During the deployment of renewable energy systems, spatial constraints must always be taken into account. For example, (Martínez-Martínez, Dewulf, & Casas-Ledón, 2021) used a GIS-based multi-criteria decision analysis (MCDA) method, combined with ecological constraints, to assess the suitability of various renewable energy projects. The results indicated that approximately 44% of the areas were suitable for solar energy development. David Severin Ryberg et al. further explored the constraints faced in land use in Europe, analyzing their weights of exclusivity, overlap, and independence (Ryberg, Robinius, & Stolten, 2018), providing a foundational basis for the constraints on future renewable energy deployment.

Furthermore, GIS is widely used for site selection optimization of renewable energy facilities. When evaluating the location of a new biomass anaerobic digestion plant, researchers used buffer zone analysis to assess the distance to existing infrastructure (Valenti, Parlato, Pecorino, & Selvaggi, 2023). Pea Sanchez et al. used the Geospatial Land Availability Evaluation System (GLAES) to compare the potential of open-field PV and rooftop PV in Mexico. The results indicated that although open-field PV has more limits, its power generation potential is significantly higher than that of rooftop PV systems (E. Sánchez, Severin David Ryberg, Heinrichs, Detlef Stolten, & Robinius, 2021). Livio De Santoli et al. conducted an in-depth analysis of future photovoltaic power plant site selection based on the distribution of existing renewable energy facilities and energy consumption covers (de Santoli, Mancini, & Astiaso Garcia, 2019).

In the above spatial analysis of solar energy and other renewable energy sources, the main methods employed include proximity analysis and overlay analysis. Proximity analysis is used to identify the relevant areas based on the locations of existing renewable energy facilities. Overlay analysis combines multiple layers to extract spatial areas that meet multiple criteria. These spatial analysis methods provide strong support for the precise deployment and scientific planning of energy systems.

2.3.2 Strengths and limitations

GIS software provides significant advantages in renewable energy assessment. It can evaluate the potential of renewable energy across multiple scales, dimensions, and study scopes (Benalcazar, Komorowska, & Kamiński, 2024). Additionally, the ability to merge different types of data and models helps users comprehend and visualize spatial and temporal information, as well as the structural relationships between them (Alhamwi, Medjroubi, Vogt, & Agert, 2017). Furthermore, many researchers and institutions develop or integrate GIS-based processing and analysis tools and provide a wealth of open-source data and software, which increases flexibility for GIS analysis.

However, GIS also has some limitations. For example, open-source software (such as QGIS and GRASS GIS) is less functional than commercial purchased software (such as ArcGIS), limiting user operations, especially when compared to many professional commercial alternatives, which require more manual data processing. Open-source data also has the issue of slow updates. This is why many researchers develop their own instruments.

2.4 Gaps and Opportunities

2.4.1 Gaps of the preview literature

Although numerous studies have been conducted to assess the potential of solar energy resources at urban or wider scales, many of these studies have not to adequately utilized high-resolution spatial data, such as high-precision DEMs or building contour data, which can have an impact on the precise analysis of urban energy systems.

Although there have been technical or economic analyses of photovoltaic systems. Research on how to effectively integrate them into RECs, particularly in urban environments, is still inadequate.

Furthermore, existing research is mostly focused on single-dimensional technical or economic evaluations, absent an integrated assessment framework that includes into account solar power generation systems, REC operational models, and economic environmental effect elements. This gap restricts our comprehensive understanding of urban energy system sustainability and scientific decision-making assistance.

2.4.2 Opportunities of the research

Future research can be further expanded in the following directions:

High-precision solar potential assessment: Use high-resolution DEM, building geometric data, and localized solar radiation data to develop detailed spatial analyses based on GIS, mapping high-precision distribution maps of photovoltaic resource potential in urban areas.

REC shared energy model analysis: Integrate photovoltaic power generation systems with REC sharing mechanisms to simulate and evaluate the electricity demand coverage and economic returns of photovoltaic systems under different community structures, improving energy communities' internal coordination efficiency.

Development of an integrated assessment model: Combining technical performance, economic feasibility, and environmental impact to systematically assess the sustainable energy capacity of different models in the Liguria region of Italy, providing a scientific basis for future policy formulation and infrastructure deployment.

3 Methodology

3.1 Research Design

3.1.1 Overview of the Research Design

This study aims to establish a comprehensive urban building energy assessment model based on GIS technology and energy modeling methods. This model will be used to analyze photovoltaic (PV) power generation potential and building energy consumption, and further evaluate its economic and environmental benefits. The entire research process is divided into several interconnected phases: pre-modeling, energy modeling and validation, result analysis and final scenario assessment.

During the pre-modeling phase, geometric and non-geometric data are obtained from multiple sources, including primary and secondary data. These raw data is preprocessed, including data cleaning, integration and spatialization, followed by solar radiation simulation. A spatial database is then established using the GIS platform for convenient management, which lays the foundation for energy modeling and spatial analysis.

After completing the solar radiation simulation and validation, the core energy modeling phase begins. In PV system power generation modeling, the available roof area and orientation of buildings are considered to estimate the power generation potential of each residential roof. In energy consumption modeling, the volume of individual buildings is calculated, and the number of households living in the buildings is estimated in proportion. This enables a more accurate estimation of energy consumption for each building. The modeling process considers the temporal dimensions of energy demand and production, enabling dynamic analysis for building-level energy balance scenarios.

Finally, different scenarios are designed for multi-dimensional assessment considering the perspectives of energy efficiency, economic benefits, and environmental impact. Two modes are simulated: independent project of individual buildings and with the construction of Renewable Energy Communities (RECs) to achieve energy sharing between buildings.

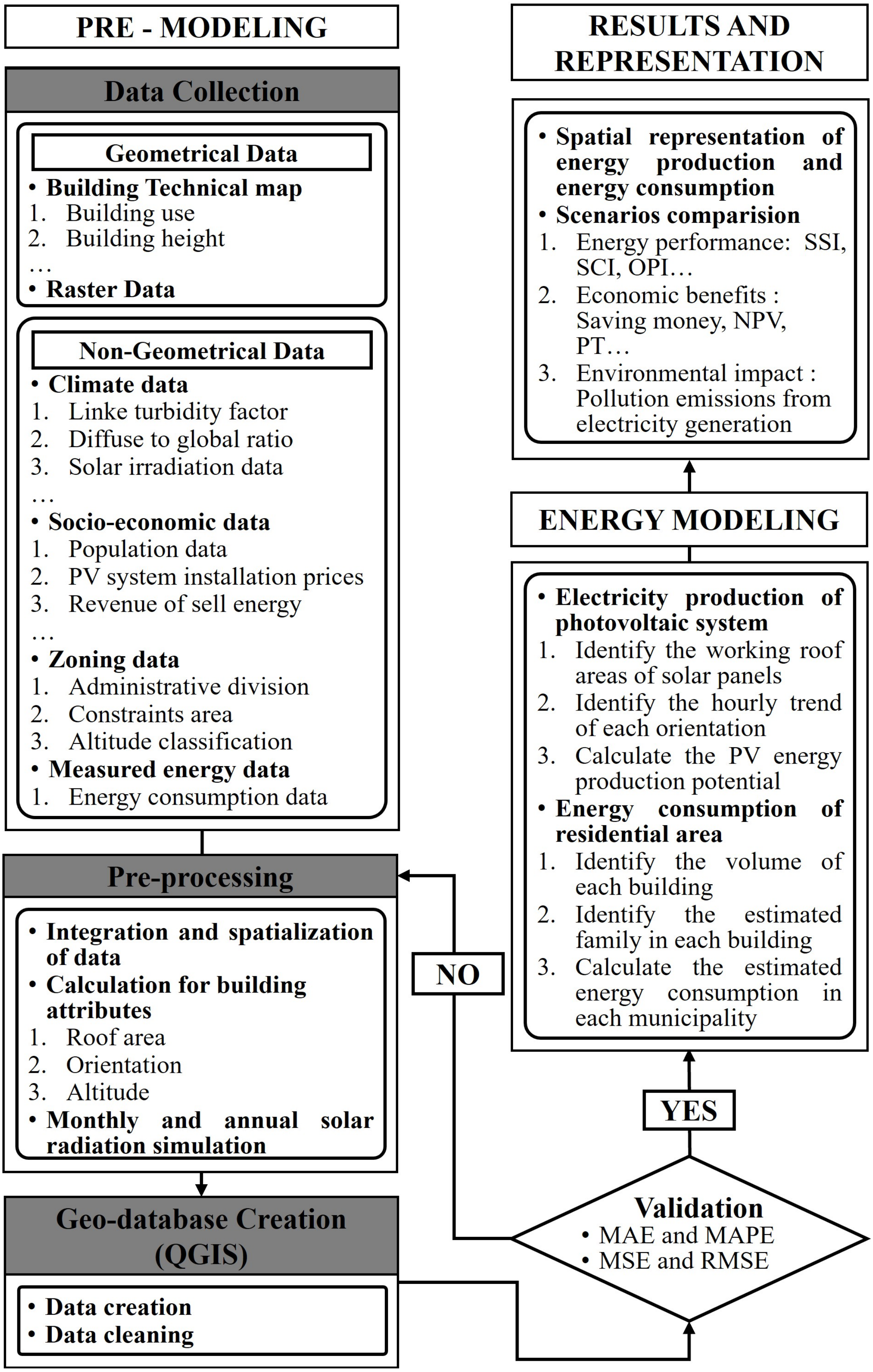

Figure 3-1 Research Design (By Author)

3.1.2 Theoretical Basis

Energy Modeling: This is the core component of this study, aimed at quantitatively analyzing the energy demand of buildings and the potential power generation in urban spaces. The study is based on building geometric information, climate irradiation data, and roof identification technology to establish a time-series model for PV power generation at the building level. Roof area and orientation are geometric factors that determine the installed capacity of PV panels and the amount of incident radiation. Roofs with different orientations exhibit significant differences in the timing and intensity distribution of incident radiation. Through accurate building models and GIS spatial analysis functions, the theoretical maximum PV power production potential under optimal orientation can be calculated for each roof area.

Building energy consumption modeling aims to predict the amount of energy consumed in buildings. Residential energy consumption is a complex system influenced by climate conditions, building structure, and population density. This study employs the volume allocation method combined with census statistical population data to estimate the number of households in each building, thereby calculating the energy consumption per building unit. This data is then analyzed on an hourly time series scale and aggregated from the single-building level to the community and city levels.

Geographic Information System (GIS) Technology: This serves as the technical support platform for this study, providing robust spatial data integration, processing, and visualization capabilities. This study integrates raster layers, vector layers and attribute table data through the QGIS platform to establish a standardized data management framework. In ArcGIS pro and QGIS, spatial analysis tools such as "Area Solar Radiation," "Join attributes by location," and "Join attributes by field value" are used to align and visualize the photovoltaic power generation potential with energy demand. Thematic maps and comparison maps are generated to ensure the model results are intuitive, operational, and regionally adaptable, providing data-driven decision-making support for urban planners, policymakers, and investors.

3.2 Data Collection and Preprocessing

3.2.1 Data sources

In order to construct a reliable urban energy model, this study systematically collected and integrated various types of data, including Geometrical Data, Climate Data, Socio-economic Data, Zoning Data, and Measured Energy Data. The data sources include national and regional authoritative institutions, remote sensing platforms, and statistical databases, ensuring high authority and timeliness.

Table 3-1 Data Sources (By Author)

Input Data	Source	Time	Link
Classification: Geometrical Data			
Building technical map	Regione Liguria	2007/2013	Carta Tecnica Regionale 1:5000 - Edificato
DTM 20m resolution	OpenDEM	2020	DTM 20m
Classification: Climate Data			
Linke turbidity factor	Meteonorm 8	average of 2000-2019	Meteonorm 8
Diffuse to global ratio	PVGIS	average of 2016-2020	Ratio of diffuse to global radiation
Actual monthly solar irradiance	PVGIS	average of 2016-2020	Monthly irradiation data
Actual hourly solar irradiance	PVGIS	average of 2005-2020	Daily data
Hours of daylight	ENEA	average of 2006-2020	Tabelle e diagrammi della posizione del Sole
Emissions from electricity generation	LowCarbonPower	2024	Carbon Intensity
Classification: Socio-economic data			
Elevation of each city center	Gazzetta ufficiale	2011	Tabella dei gradi/giorno dei Comuni italiani raggruppati per Regione e Provincia
Number of family of each census	ISTAT	2021	Attributi territoriali delle sezioni di censimento 2021
PV system installation prices	GSE	2023	National Survey Report of Photovoltaic Power Application in Italy
GSE's incentive tariff for REC	Decreto CER	2023	The table provided in Annex 1 of the Decreto CER
Revenue of Electrical Energy injected to the network	GSE	2024	Prezzi medi mensili 12/2024

Cost of Electrical Energy withdrawn from the network	ARERA	2024	Prezzi applicati ai clienti domestici nel mercato libero 2024
PV System lifetime	IEA	2021	PV Module Design for Recycling Guidelines 2021
PV O&M cost	IRERA	2021	RENEWABLE POWER GENERATION COSTS IN 2021
Classification: Zoning data			
Administrative division of Liguria	ISTAT	2024	Confini delle unit à amministrative a fini statistici
Renewable Energy Communities Boundary	GSE	2023	Mappa interattiva delle cabine primarie
Historical buildings	Regione Liguria	2008	Vincoli architettonici, archeologici, paesaggistici- Vincoli Architettonici
UNESCO sites	UNESCO	1997, 2006	World Heritage properties
Altitude classification	ISTAT	1958	Le geografie e le classificazioni territoriali
Classification: Measured energy data			
Hourly energy consumption per month per residential customer	ARERA	2022	Prelievo medio orario dei clienti domestici
Actual energy capacity	GSE	2021	ATLAIMPINATI

Geometrical Data: mainly used to describe the morphological characteristics of buildings and their surrounding spaces, this data serves as the foundation for PV system installation and modeling of building energy consumption spatial distribution. The Buildings technical map, with a scale of 1:5000, provides detailed building boundaries that accurately reflect building locations and contours. These data can be used to extract roof area, orientation, and volume. The DTM model with a 20-meter resolution provides ground elevation information for the study area, used to analyse terrain variations and the impact on solar radiation.

Climate Data: provides essential environmental parameters for PV power generation simulations, covering solar radiation, meteorological conditions, and solar position information. Includes the Linke turbidity factor (LT), hours of sunshine, and the ratio of diffuse to global radiation (DG), providing key parameters for estimating solar radiation. Monthly irradiation data and daily data are critical for conducting detailed analysis of daily power generation fluctuations and model validation. Carbon intensity is used to assess the carbon emissions from traditional electricity production, thus measuring the environmental benefits of replacing traditional energy sources with photovoltaic power generation.

Socio-economic data: reflects the energy consumption capacity of building users and the energy policy context, which provides a foundation for assessing the economic feasibility of energy projects, and analyzing their social impacts. This includes 2021 census district data, which is used to estimate indicators such as the number of residents and household in each building, and as input for building energy consumption modeling. The Renewable Energy Communities (REC) incentive tariff published by GSE is an important parameter for assessing the economic benefits of shared power.

Zoning Data: defines the administrative boundaries and protected areas within the study area, which is key to ensuring that energy planning complies with local regulations and cultural heritage protection requirements. The REC boundary is defined by GSE based on the location of power substations within the area. This is an important consideration for assessing the grid connection capacity of photovoltaic power generation, power sharing, and identifying potential grid constraints.

Measured energy data: directly reflects residents' electricity consumption fluctuations at different times. It can be combined with the number of households in a building, to assess the demand profile of a single building. With the support of the spatial data software QGIS, these data will be categorized and processed. They are used as input for multi-level models, enabling detailed management and visualization of the municipalities’ energy system.

3.2.2 Data preprocessing steps

To ensure the consistency and usability of input data for the model, the collected raw data is preprocessed, including format conversion, cleaning, and integration, to meet analysis requirements and generate key attributes for subsequent modeling.

First, data from different formats and sources are spatially integrated and visualized, unified within a GIS platform, enabling overlay and analysis in a geographic context. Then, to address the issues of varied data sources and inconsistent formats, all spatial data are converted to the coordinate system (EPSG:32632 - WGS 84 / UTM zone 32N) used in the study area, ensuring the accuracy of spatial overlay analysis.

The building layer is then cleaned to remove any buildings with unusual areas or heights. When combined with building limitation zone information, buildings under cultural protection or lacking development potential are removed, leaving only those suitable for photovoltaic deployment. Furthermore, some basic data is overlay and merged for analysis, laying the foundation for energy modelling.

Before evaluating photovoltaic power generation potential, climate data and building geometric information were used to simulate solar radiation for 12 months and the entire year on urban areas and building roofs in a GIS environment. This study used DTM 20m as a reference for terrain topography and shading, and then applied the Area Solar Radiation tool in ArcGIS Pro to dynamically predict roof solar conditions. Given the huge volume of data in Liguria, the region was divided into three typical elevation zones based on the central elevation of municipalities. In each zone, the representative municipality with the middle elevation is selected for irradiation simulation.

The input climate parameters include DG parameters from PVGIS, which is the average of 2016 to 2020 to enhance accuracy. During the simulation process, atmospheric transmittance (T) was also considered, calculated using the formula:

$$T = \left(\frac{DNI}{Solar\ Constant}\right)^{\frac{1}{LT}}$$

where,

DNI is direct normal irradiance, i.e., the intensity of solar radiation per unit area perpendicular to the sun's rays on the Earth's surface.

Solar Constant is 1367 W/m2, i.e., the average intensity of solar radiation received per unit area perpendicular to the sun's rays outside the Earth's atmosphere.

Through the above data preprocessing, this study constructed a highly integrated multi-source energy modeling dataset. Subsequent calculations of PV power generation potential, energy consumption modeling, and scenario assessments will be conducted based on this dataset.

3.3 Solar Potential and GIS Analysis

3.3.1 Overview of GIS analysis

This study integrates Geographic Information Systems (GIS) with energy modeling techniques to conduct a comprehensive assessment of solar power generation potential, building energy consumption demand, and their economic and environmental benefits. GIS serves as the core platform, integrating data preprocessing, energy supply and demand calculations, and result presentation, ensuring spatial accuracy and clear visualization of the analysis.

During the data preprocessing stage, multi-source heterogeneous data is collected, cleaned, integrated, and spatialized. Extract by location, Join by location, and Minimum bounding geometry are tools for extracting essential properties including building area, orientation, and residential population. It is also used to remove miscellaneous metadata, identify and mark buildings unsuitable for photovoltaic system installation. These attributes serve as the main input data for subsequent photovoltaic power generation potential and energy consumption estimation, while also ensuring the regulatory compliance of subsequent analyses.

Then, using Area Solar Radiation to input data impact solar radiation, to simulate the distribution of solar radiation for each grid cell in Liguria across different months, resulting in a localized solar resource map. Raster to Point and Join by Location tools are used to transform the monthly solar radiation raster map into vector data, which is then spatially combined with the building vector data. This assigns each building an average monthly sun radiation property and creates a dataset.

To ensure the reliability of the model results, the study also compares and validates the simulation results with actual statistical data. Common metrics include the Mean Absolute Error (MAE) and Mean Absolute Percentage Error (MAPE) to ensure the accuracy of the radiation simulation data.

Based on this, the study further calculated and matched the solar power generation potential with electricity consumption. The monthly power generation estimation is calculated on a standard power generation model, combing the radiation values of building roofs with PV conversion efficiency, installation area and other parameters. Subsequently, to enhance the accuracy of hourly power generation estimates, dynamic weighted corrections were applied to hourly power generation capacity. This was achieved by overlaying the hourly solar radiation data provided by PVGIS for each orientation to generate fluctuations in daily power generation. This ensures the spatial granularity and temporal precision of solar power estimates.

In terms of energy consumption modeling, the study incorporates hourly household electricity consumption data provided by ARERA of each province, with household information of each building, to estimate total electricity consumption for buildings. By comparing it with energy production data, the energy performance of each building is further assessed

In the final scenario simulation phase, energy supply and demand balance analysis and scenario design are conducted within the specific geographic boundaries of RECs. Using GIS tools such as "Join attribute by location", scenario visualization is achieved across multiple dimensions including energy performance, economic benefits, and environmental impact. They provide data-driven decision support for policy-making and community energy planning.

The entire GIS workflow emphasizes the importance of spatial data as the foundation for analysis. Through precise geometric processing, solar radiation simulation, attribute association, and spatial aggregation, to apply complex physical and economic models in specific urban environments. The results of the research are presented in an intuitive spatialized form, providing scientific support for urban energy transition.

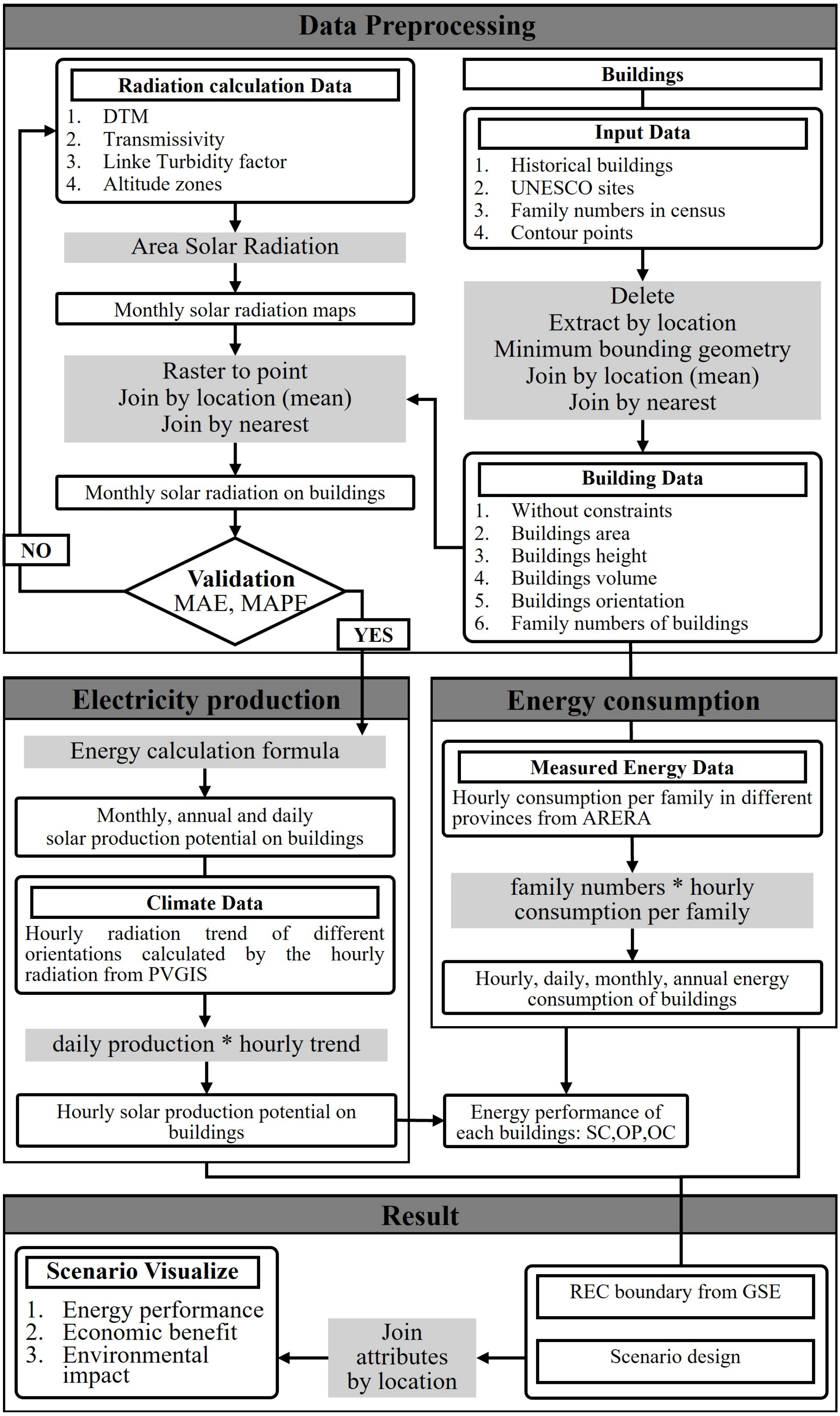

Figure 3-2 GIS Analysis Flowchart (By Author)

3.3.2 Data validation and calibration

Data validation and calibration are key steps in ensuring the reliability and accuracy of the model. This is achieved by comparing the simulation data with actual statistic data and to optimize and adjust the model based on the comparison results. This study mainly uses the following indicators:

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|Simulate\ Value_i - Actual\ Value_i|$$

$$MAPE = \frac{100}{n}\sum_{i=1}^{n}\left|\frac{Simulate\ Value_i - Actual\ Value_i}{Actual\ Value_i}\right|$$

$$MSE = \frac{1}{n}\sum_{i=1}^{n}(Simulate\ Value_i - Actual\ Value_i)^2$$

$$RMSE = \sqrt{MSE}$$

where,

Mean Average Error (MAE) is the average absolute difference between the simulated and actual values, the lower the MAE value, the more accurate is.

Mean Absolute Percentage Error (MAPE) is the average of the absolute percentage differences between the model's simulated and actual values.

Mean Squared Error (MSE) is the average of the squared difference between the simulated and actual values

Root Mean Squared Error (RMSE) is the square root of MSE

3.3.3 Energy modeling techniques

This section will provide a detailed explanation of the specific techniques and processes used in the study to assess the photovoltaic power generation potential and estimate energy consumption.

The assessment of photovoltaic power generation potential is a multi-step technical process aimed at converting solar radiation into electrical energy output:

i. Identification of photovoltaic module working area. Based on architectural limits and system installation specifications, the study assumes that 30% of the total roof surface is an effective area available for photovoltaic installation. The PV modules with an inclination angle of 30° to optimize solar collection. This parameter serves as the basis for subsequent power generation estimates:

$$S_{PV} = \frac{S_e}{cos\theta}$$

where,

S_e is the effective area (m2) for PV installation, 30% of the total roof area

$\theta = 30^{\circ}$, is the best inclination angle of the PV modules from the roof plane,

ii. Calculation of photovoltaic power generation potential. Power generation depends not only on solar radiation but also on the performance of the photovoltaic system itself. The model applies standard energy calculation formulas, considering various system losses such as system performance ratio and photovoltaic material conversion efficiency. And to calculate the photovoltaic power generation potential on a daily, monthly, and annual basis:

$$E_{day,i} = \frac{E_{month,i}}{number\ of\ days\ in\ i\ month}$$

$$E_{month,i} = PR * I_{month,i} * S_{PV} * \eta$$

$$E_{annual} = \sum_{i=1}^{12} E_{month,i}$$

where,

PR is the performance of the system, set as 0.75

$I_{month,i}$ is the monthly irradiation per square meter ($kWh/m^2/m$) of the i month

η is the conversion efficiency of incident solar energy to produced energy, this time use the monocrystalline silicon efficiency = 0.23

iii. Hourly global horizontal radiation data from PVGIS are used in this work to produce a more detailed hourly power generation curve. Use this information to calculate the power generation fluctuations of solar systems with different orientations during the day. More properly reflects the dynamics of photovoltaic energy generation.

iv. In order to obtain a more detailed hourly power generation curve, this study use hourly global horizontal radiation data from PVGIS. Use this information to calculate the power generation fluctuations of solar systems with different orientations during the day. More accurately reflects the dynamic of photovoltaic energy generation:

$$E_{h,i} = E_{day,i} * \frac{G_{h,i}}{G_{day,i}}$$

where,

$\mathbf{G_{h,i}}$ is the global horizontal irradiance (Wh/m²) at h in month i, from PVGIS

$\mathbf{G_{day,i}} = \sum_{\mathbf{h=1}}^{\mathbf{24}} \mathbf{G_{h,i}}$ is the total daily irradiance (Wh/m²) in month i.

In the demand-side modeling of energy consumption in residential buildings, a bottom-up approach is adopted. Combining the number of households in each building obtained during the preprocessing stage with actual energy consumption data, the hourly energy consumption of each building is calculated:

$$C_{h,i} = Family\ numbers\ of\ the\ building * C_{f,h,i}$$

where,

$C_{f,h,i}$ is the recorded energy consumption data for each household group iat h in month i, sourced from ARERA.

Hourly energy consumption data is aggregated to obtain daily, monthly, and annual energy consumption data at the building level:

$$C_{day,i} = \sum_{h=1}^{24} C_{h,i}$$

$$C_{month,i} = C_{day,i} * number\ of\ days\ in\ i\ month$$

$$C_{annual} = \sum_{i=1}^{12} C_{month,i}$$

3.4 Results Indicators

3.4.1 Energy performance indicators

This study evaluates the performance of various buildings and regions in terms of energy self-sufficiency and system efficiency by constructing a set of energy performance indicators. The core indicator calculation formula is as follows:

$$SC_t = \min(E_t, C_t)$$

$$OP_t = E_t - \min(E_t, C_t)$$

$$OC_t = C_t - \min(E_t, C_t)$$

where,

Self-consumption (SC) is the actual local energy consumed generated by PV system at t time.

Over-production (OP) is the excess electricity generated by PV systems not consumed locally at t time.

Over-consumption (OC) is the amount of local demand exceeding the electricity produced by the PV system at t time.

E_t is the total energy generated locally by PV system at t time (kWh).

C_t is the total electricity energy consumed locally at t time (kWh).

Based on the above indicators, the following performance indices are further calculated:

$$SSI_t = \frac{SC_t}{TC_t}$$

$$SCI_t = \frac{SC_t}{TP_t}$$

$$OPI_t = \frac{OP_t}{TE_t}$$

where,

Self-Sufficiency Index (SSI) is the ability of local energy supply to meet demand.

Solar-Consumption Index (SCI) is the proportion of electricity supplied by PV.

Over-production Index (OPI) is the proportion of potential waste of system capacity.

TC is the total local energy consumption at t time (kWh)

TE is the total local PV system energy production at t time (kWh)

3.4.2 Economic benefit

To assess the economic feasibility of PV systems for buildings or communities, this study uses quantitative modeling based on the following four dimensions. The main parameters used in the calculations are shown in the table below:

Table 3-2 Main techno-economic parameters used in PV-battery system (By Author)

Parameter	Value	Cash flow
PV system installation prices of different PV systems in 2023	Peak power< 6kW, 2000 €/kW; 6 kW<=Peak power<=20 kW, 1600 €/kW; 20 kW<Peak power, 1000 €/kW	**Initial Investment**
Revenue of Electrical Energy injected to the network	0.14821 €/kWh	**Revenue**
GSE's incentive tariff for REC based on self-consumption	Rated power< 200kW, 120€/MWh, 200kW <=Rated power< 600kW, 110 €/MWh, 600kW <=Rated power, 100 €/MWh, Liguria region +10€/MWh, 20years	
Cost of Electrical Energy withdrawn from the network	0.33 €/kWh	**Cost**
PV System lifetime	20 years	
PV O&M cost	2%/y (of Inv. cost)	
Emissions from electricity consumption	310.092 gCO2eq/kWh	**Pollution reduction**

Saving Money measures the total savings from reduced energy costs and additional income earned:

$$Saving\ Money = saving\ cost\ of\ buy\ energy + revenue\ of\ sell\ energy + incentive\ tariff$$

Net Annual Income (NAI) measures the net financial benefit that a PV system provides to the user of a year:

$$\text{NAI} = \begin{cases} 0 & , Annual\ Revenue < Annual\ Cost \\ Annual\ Revenue - Annual\ Cost, & Annual\ Revenue \geq Annual\ Cost \end{cases}$$

The Payback Time (PBT) calculated based on Net Annual Income, which is the time required for the PV system to recover its initial investment. It directly reflects the liquid risk and recovery speed of the investment:

$$\text{PBT} = \begin{cases} 0, NAI \leq 0 \\ \dfrac{Initial\ Investment}{NAI}, NAI > 0 \end{cases}$$

Net Present Value (NPV) is a more comprehensive investment evaluation method that reflects the time value of money. If NPV is positive, it indicates that the project is economically feasibility and can generate returns exceeding the investor's minimum required return:

$$\text{NPV} = \sum_{i=1}^{n} \frac{NAI_i}{(1+r)^i} - Initial\ Investment$$

where,

r: the required rate of return per period (e.g. 2%).

n: the life of the project in years, i.e. 20.

3.4.3 Environmental impact

The environmental benefit assessment focuses on analyzing the greenhouse gas emission reduction effects caused by the replacement of traditional energy sources. This study uses the average carbon intensity coefficient of Italy (310.092 gCO2eq/kWh), to estimate the CO_2 emissions reduced per unit of electricity generation (g CO2eq) and the CO_2 emissions that would still be emitted (g CO2eq):

$$Emissions\ reduction = E_{annual} * \text{carbon intensity}$$

$$Emissions = OC_{annual} * \text{carbon intensity}$$

4 Case study: Liguria

4.1 Regional Context

4.1.1 Major geographic features

Figure 4-1 Geographical characteristics of Liguria (From Blue Green Atla)

Liguria is in the northwestern part of Italy, forming a narrow coastal region. It borders Tuscany to the east, France to the west, and the Ligurian Sea to the south. Its unique semi-circular south-facing terrain, combined with the mountainous environment formed by the Alps and the Apennine Mountains, gives it significant potential for renewable energy. The region has valuable offshore wind energy resources and mountain ridges suitable for installing wind turbines. Additionally, its borders with France and Monaco facilitate cross-border energy cooperation. Ports also provide convenient transportation and installation for offshore wind energy equipment.

However, the region's rich and complex mountainous terrain also poses challenges. Limited flat land restricts the development of large-scale grounded renewable energy systems, but rooftop and small-scale solar installations remain viable. Complex geological conditions also hinder transportation, leading to higher costs for grid construction and maintenance. Furthermore, extensive ecological and historical protected areas limit the development and utilization of renewable energy.

4.1.2 Climatic and socio-economic characteristics

Liguria is located in the mediterranean climate zone, with average winter temperature ranging from 7–12°C and summer temperature between 23–28°C (Cedar Lake Ventures, Inc, 2025). The mild and stable climate is beneficial for ensuring the efficiency of solar panels. Mediterranean sea winds and mountain-sea wind circulation also create local wind energy potential. Compared to other regions in northern Italy, Liguria has abundant solar radiation resources, with an average daily solar irradiance of 4.0–4.6 kWh/m²/day (Regione Liguria, 2022), making it highly suitable for the development of solar power generation.

However, increased cloud cover and rainfall during the autumn and winter seasons lead to seasonal variations in solar photovoltaic output power. Increased precipitation may also result in extreme events such as heavy rainfall, which could impact the safety of PV and wind power facilities. High humidity and sea salt fog in coastal areas can also damage PV equipment and increase maintenance costs.

Figure 4-2 Global Horizontal Irradiation of Italy (From Global Solar Atlas)

According to data from Istat (2025), coastal cities in Liguria are densely populated, with tourism dominating the local industry. The dense urban structure makes rooftop solar energy particularly promising for enhancing local energy self-sufficiency. Green energy initiatives, including energy communities, can enhance the region's sustainable tourism image. However, tourism also has requirements for landscape protection, which often conflict with the visual and spatial impacts of renewable infrastructure.

4.1.3 Current status of renewable energy and solar PV adoption

With the support of national policies and incentives, Italy's deployment of renewable energy, particularly solar PV, has seen significant growth. In 2023 alone, Italy added 5.2 GW of new PV capacity, bringing the total installed capacity to 30.3 GW. Residential systems were the primary driver of this growth, accounting for 94% of the new installed capacity (Tilli et al., 2024).

Despite these advancements in the Liguria region, its renewable energy production remains relatively low, with only 9.1% of electricity generated from renewable sources (GSE S.p.A., 2023). This lag may be attributed to the region's complex terrain, requiring strategic planning and investment to fully realize its sustainable energy potential.

4.2 Data Preprocessing and Cleaning

4.2.1 Preliminary analysis of buildings

To ensure the accuracy and consistency of spatial and energy-related assessments in the Liguria case study, the study undertook a thorough data preprocessing and cleaning phase. This phase included standardizing the building dataset, classifying building types, calculating orientation indicators, integrating demographic and altitude data, and managing solar radiation input parameters.

Figure 4-3 shows the classification of building functions and land use codes based on the Liguria Regional Geographic Database "CARTA TECNICA REGIONALE".

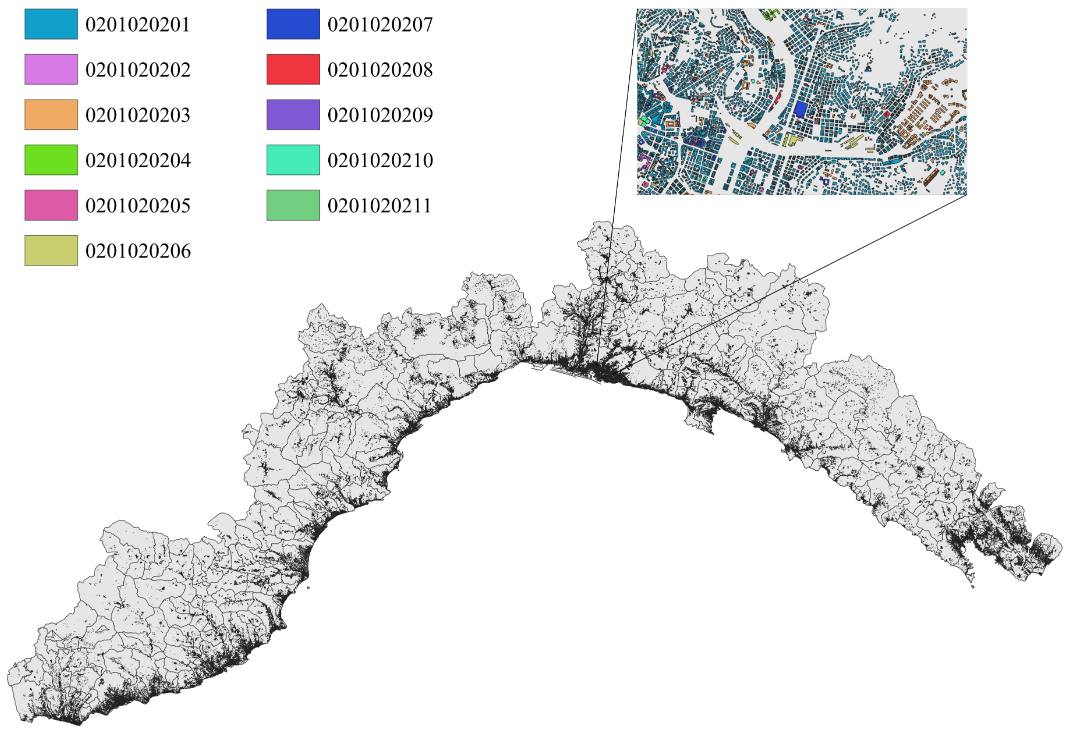

Figure 4-3 Classification of Ligurian buildings (By Author)

To simplify the analysis, zoning codes were reclassified into six major categories: residential, service buildings, commercial and entertainment buildings, industrial, agricultural, and mixed-use (Table 4-1). This classification supports a differentiated analysis of solar photovoltaic potential based on building type. For example, residential buildings are typically suitable for rooftop photovoltaic installations, while commercial and industrial buildings typically offer larger, flatter surfaces that are ideal for installing solar panel arrays.

Table 4-1 Classification of architecture(By Author)

Zoning Code	Using	Category
0201020201	residential	Residential
0201020202	administrative	Service buildings
0201020203	public service	
0201020204	military	
0201020205	place of worship	
0201020206	transport services	
0201020207	commercial	Commercial & entertainment buildings
0201020210	recreational	
0201020208	industrial	Industrial buildings
0201020209	agricultural	Agricultural buildings
0201020211	other	Mixed-use & other buildings

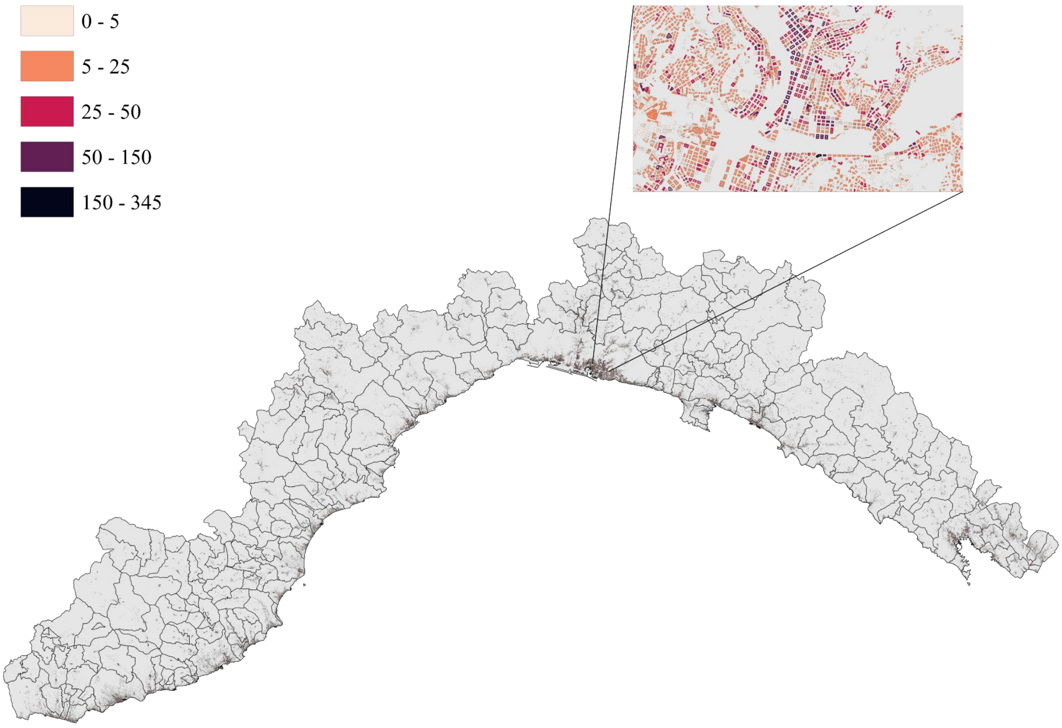

Figure 4-4 Liguria family number in each building (By Author)

In addition to classification, Figure 4-4 shows the number of households living in each building, based on municipal census data. This demographic overlay map identifies areas with high residential density, which are prioritized for community-scale photovoltaic power generation deployments.

In addition, a key spatial parameter in solar potential analysis is roof orientation. Using QGIS analysis tools, each building was classified into four main orientation categories: east-west, north-south, southeast-northwest, and southwest-northeast (Figure 4-5). This classification is useful for modeling directional irradiance in subsequent simulation

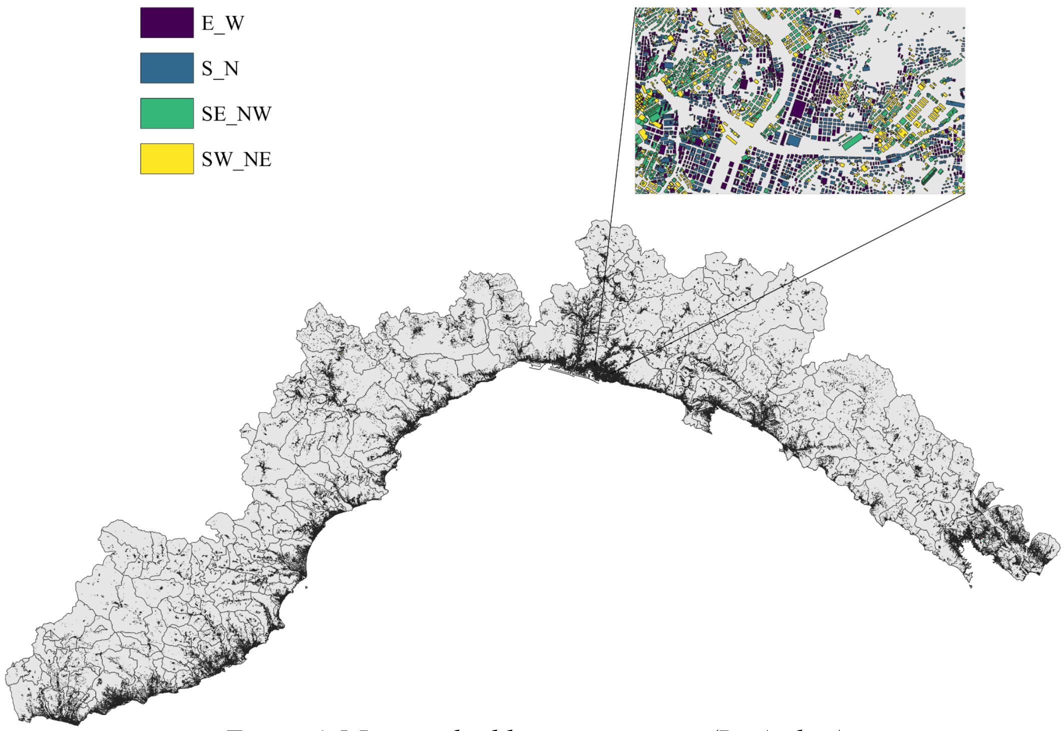

Figure 4-5 Liguria buildings orientation (By Author)

steps, especially for analyzing the orientation most favorable for solar PV performance.

4.2.2 Preparation for solar radiation estimation

Due to atmospheric extinction and shadow effects, solar radiation is sensitive to altitude. Therefore, as shown in Figure 4-6, municipalities are divided into three altitude zones based on the altitude of their administrative centers: plains (0-300 m), hills (300-600 m), and mountains (>600 m). This layered approach enables the association of climate and solar radiation data with corresponding geographical conditions.

For each elevation zone, three key parameters were extracted to support monthly solar radiation modeling: the Linke turbidity factor (LT) represents atmospheric transparency; the diffuse-to-global ratio (DG) is the proportion of diffuse light relative to global irradiance; and transmittance (T) is the proportion of solar radiation reaching the Earth's surface.

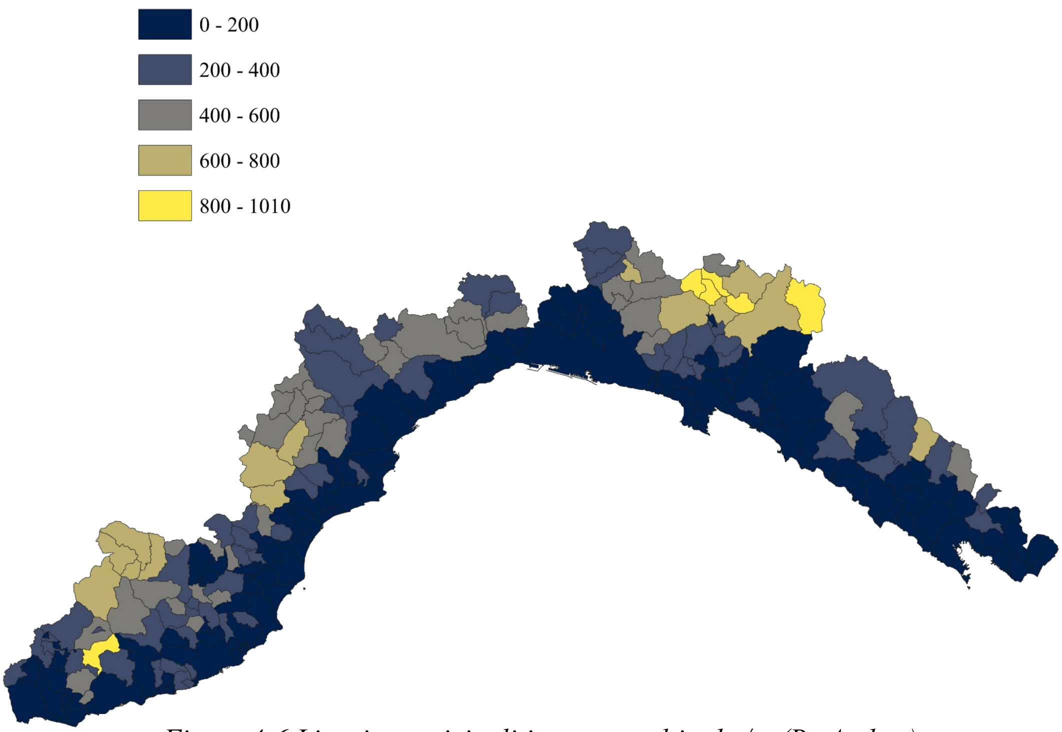

Figure 4-6 Liguria municipalities center altitude /m (By Author)

These values are summarized in Table 4-2, which lists representative cities for each altitude zone (e.g., Calice Ligure for the plains, Sassello for the hills, and Cosio d'Arroscia for the mountains).

Table 4-2 Monthly metrics for solar radiation calculation(By Author)

Altitude zone	Represent city	Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
plain	Calice Ligure	LT	2.8	3.0	3.5	3.9	3.9	3.9	3.8	3.7	3.5	3.4	3.1	2.8
		DG	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.5	0.5
		T	0.4	0.5	0.6	0.6	0.6	0.7	0.7	0.6	0.6	0.5	0.4	0.4
hilly	Sassello	LT	2.7	2.9	3.3	3.7	3.7	3.7	3.6	3.5	3.3	3.3	3.0	2.7
		DG	0.4	0.5	0.4	0.4	0.5	0.4	0.4	0.4	0.4	0.5	0.6	0.5
		T	0.4	0.4	0.5	0.6	0.6	0.6	0.6	0.6	0.6	0.5	0.4	0.3
mountain	Cosio d'Arroscia	LT	2.7	2.9	3.4	3.8	3.8	3.8	3.7	3.5	3.4	3.3	3.0	2.7
		DG	0.4	0.5	0.4	0.4	0.5	0.5	0.5	0.4	0.5	0.5	0.5	0.4
		T	0.4	0.5	0.6	0.6	0.6	0.6	0.6	0.6	0.5	0.5	0.4	0.4

4.3 GIS-based Solar Analysis

4.3.1 Solar irradiation simulation and validation

To assess the solar potential of Liguria, this study first used the “Area Solar Radiation” tool in ArcGIS Pro to conduct a comprehensive GIS-based solar radiation simulation. After format conversion, the simulation results were output as the annual solar radiation (Wh/m²) on the roofs of buildings in the region, as shown in Figure 4-7. The spatial distribution shows that areas with higher altitudes and south-facing orientations tend to receive higher radiation values, making them more suitable for PV installation.

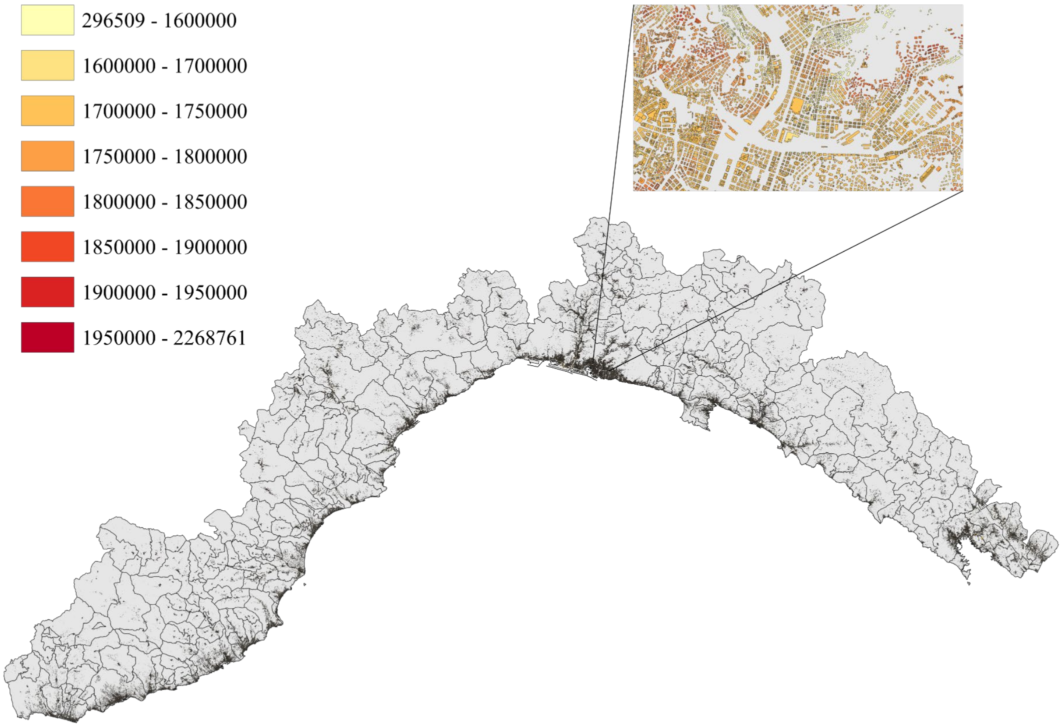

Figure 4-7 Liguria Annual Solar Radiation Simulation on Building Roofs (Wh/m2) (By Author)

In order to ensure the accuracy and reliability of the simulated solar radiation data, the results of the ArcGIS Pro simulation were compared and validated against the actual observed values from PVGIS datasets. Table 4-3 shows the comparison results, including the monthly radiation values and their corresponding absolute errors. Calculations show that the model's MAPE is 4.68% and RMSE is 1.24%, indicating that the simulated values are highly consistent with the observed values. This validates that ArcGIS Pro simulations can accurately represent the actual solar radiation on building roofs in Liguria. This validation step enhances the credibility of the simulated data and confirms its suitability for subsequent energy production potential estimates.

Table4-3 ArcGIS pro simulation and PVGIS actual data comparing (By Author)

Months	ArcGIS pro simulation radiation (kWh/m^2)	PVGIS actual radiation (kWh/m^2)	Absolute error (MAE)
Jan	0.517	1.735	1.219
Feb	1.620	2.524	0.904
Mar	4.118	3.746	0.372
Apr	7.046	5.224	1.823
May	8.677	6.183	2.494
Jun	9.328	7.531	1.797
Jul	9.002	8.539	0.463
Aug	7.628	7.090	0.538
Sep	4.828	4.925	0.097
Oct	1.916	2.835	0.919
Nov	0.956	1.709	0.753
Dec	0.376	1.467	1.091
Annul	4.668	4.459	1.039

4.3.2 Estimation of solar energy production potential

Based on verified solar radiation data, the potential energy production of building roofs in Liguria was estimated. Figure 4-8 shows the spatial distribution of annual rooftop solar energy production (in kWh) across the region. By aggregating building-level production data to the municipal level (Figure 4-10), a broader overview of the solar potential across Liguria's administrative communities was provided. Municipalities with higher total production potential are key areas for large-scale deployment of PV power generation and the coordination of REC programs.

To explain the differences caused by roof orientation, we applied an orientation index obtained from Genoa PVGIS data (Figure 4-9). This index reflects the hourly power generation curves of solar production for different orientations, and this time analysis is crucial for understanding the timing of energy production. For example, south-facing roofs typically reach peak output at midday, east-facing roofs at morning, and west-facing roofs at afternoon. This temporal alignment is critical for designing self-consumption strategies within renewable energy communities.

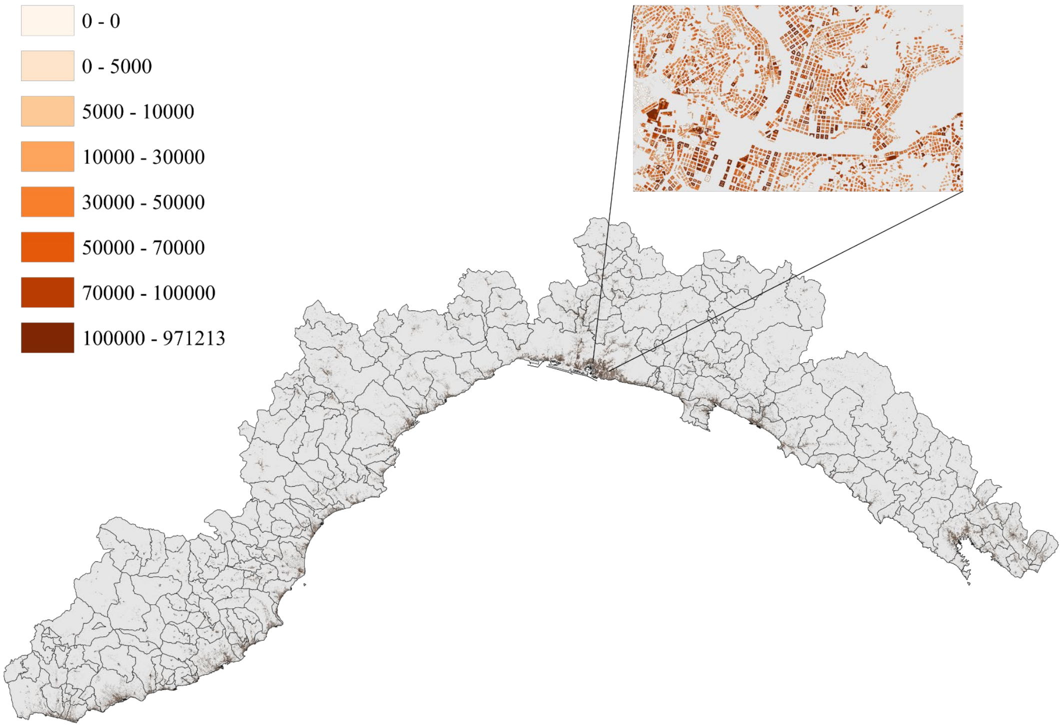

Figure 4-8 Annual solar production on building roofs (kWh) (By Author)

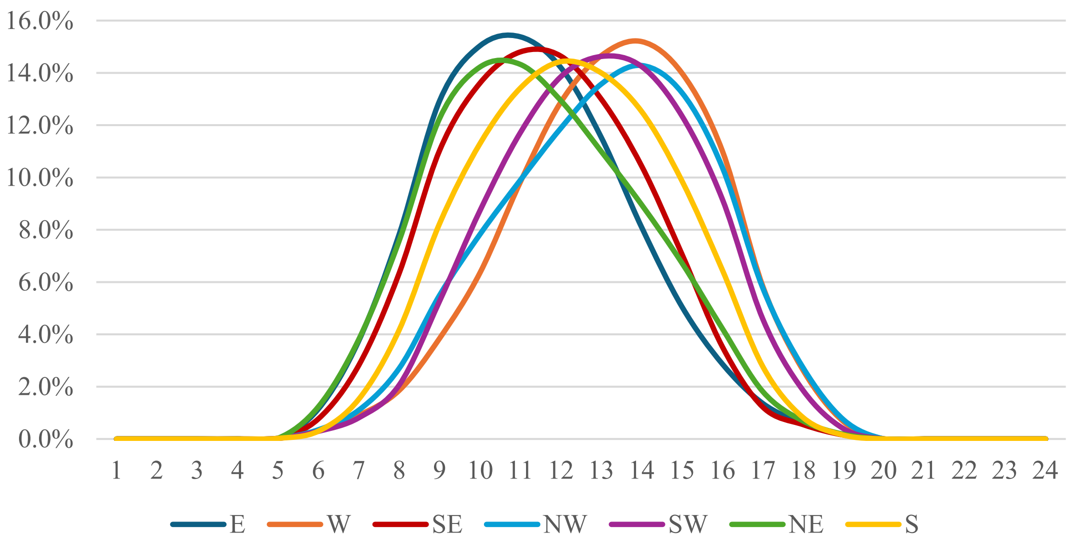

Figure 4-9 Annual solar production on building roofs (By Author)

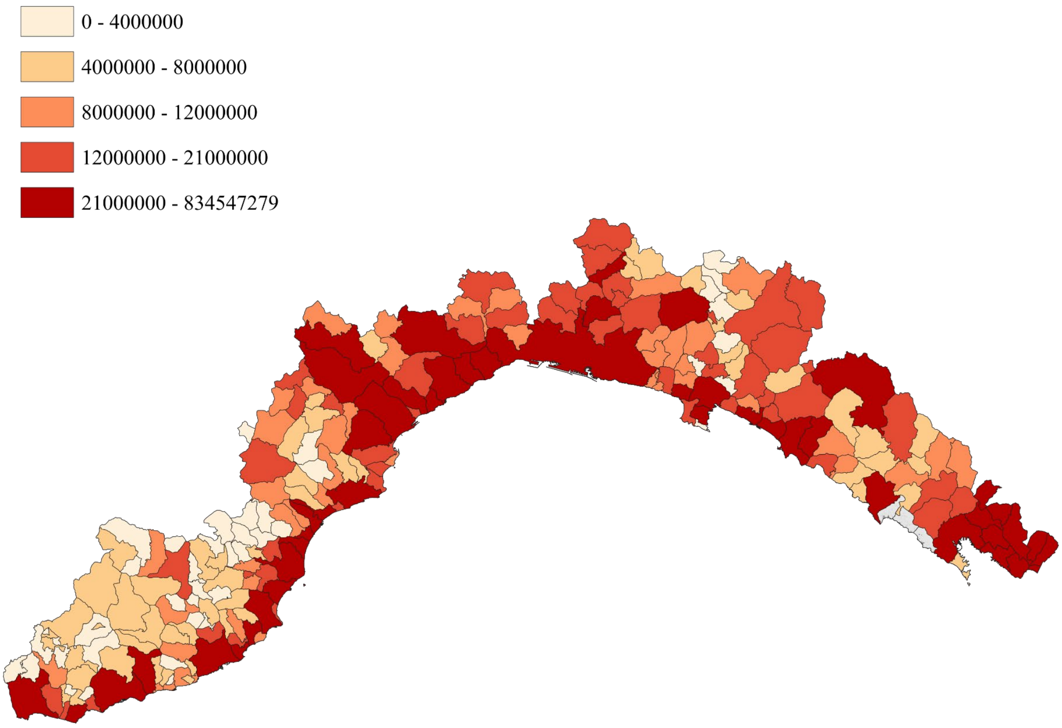

Figure 4-10 Annual solar production of each municipality (kWh) (By Author)

4.3.3 Electricity consumption patterns

A comprehensive analysis of solar potential requires not only an understanding of energy production, but also electricity consumption. This helps to assess self-sufficiency and plan the scale of PV systems appropriately.

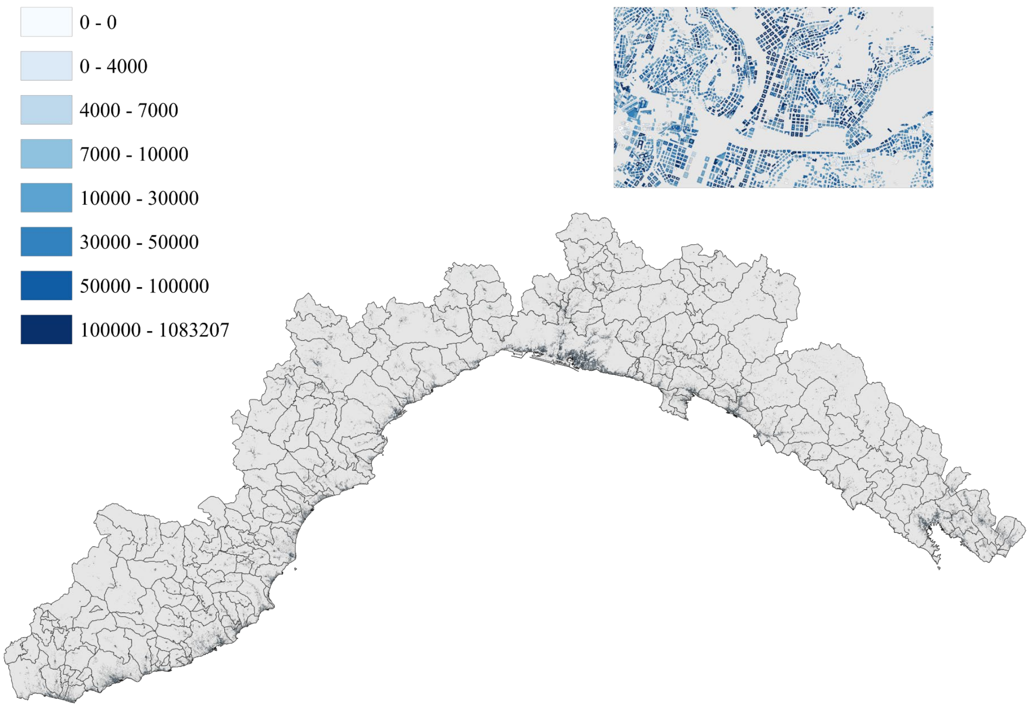

Figure 4-11 Annual energy consumption demand in buildings (kWh) (By Author)

Based on provincial electricity consumption statistics, the annual electricity demand per building in Liguria was analyzed (Figure 4-11). Areas with high energy demand were highlighted, where implementing renewable energy generation in these areas could reduce dependence on the grid.

Aggregating building-level consumption data to the municipal level (Figure 4-12) provides a macro view of energy demand across the entire Liguria region. Comparing this with the municipal solar production map (Figure 4-9) shows that areas with higher population density and energy demand also have greater solar potential.

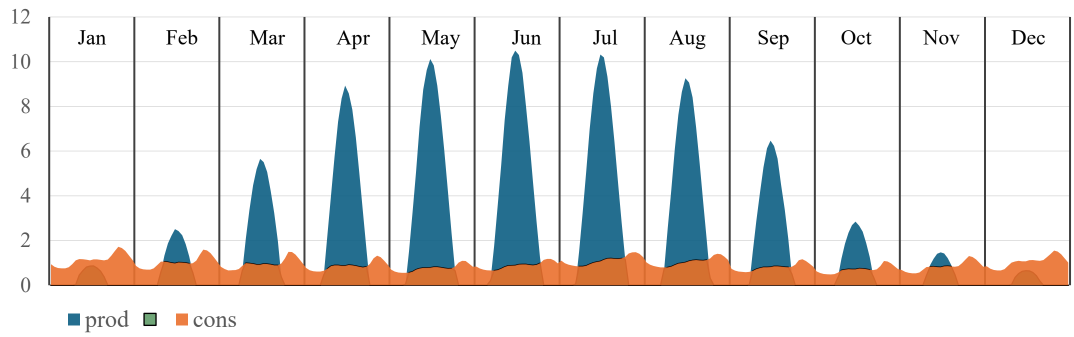

Figure 4-12 Hourly solar production compared energy demand (kWh) (By Author)

Comparing monthly energy consumption with estimated production per building (Figure 4-13) indicates that spring and summer are most favorable for energy independence, but additional power purchases from the grid are to be needed in winter. This is critical for designing efficient and equitable systems for energy sharing.

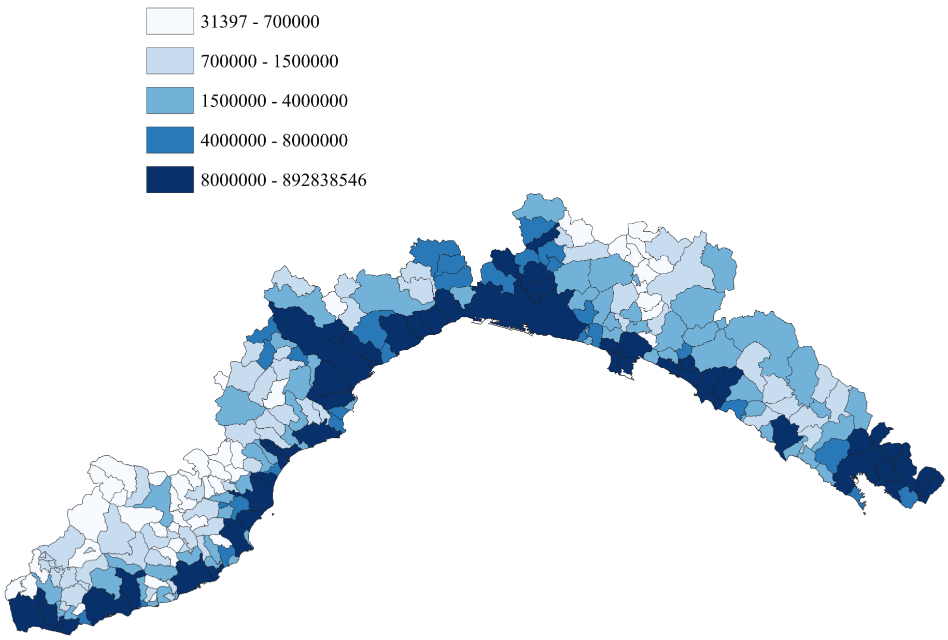

Figure 4-13 Annual energy consumption demand of each municipality (kWh) (By Author)

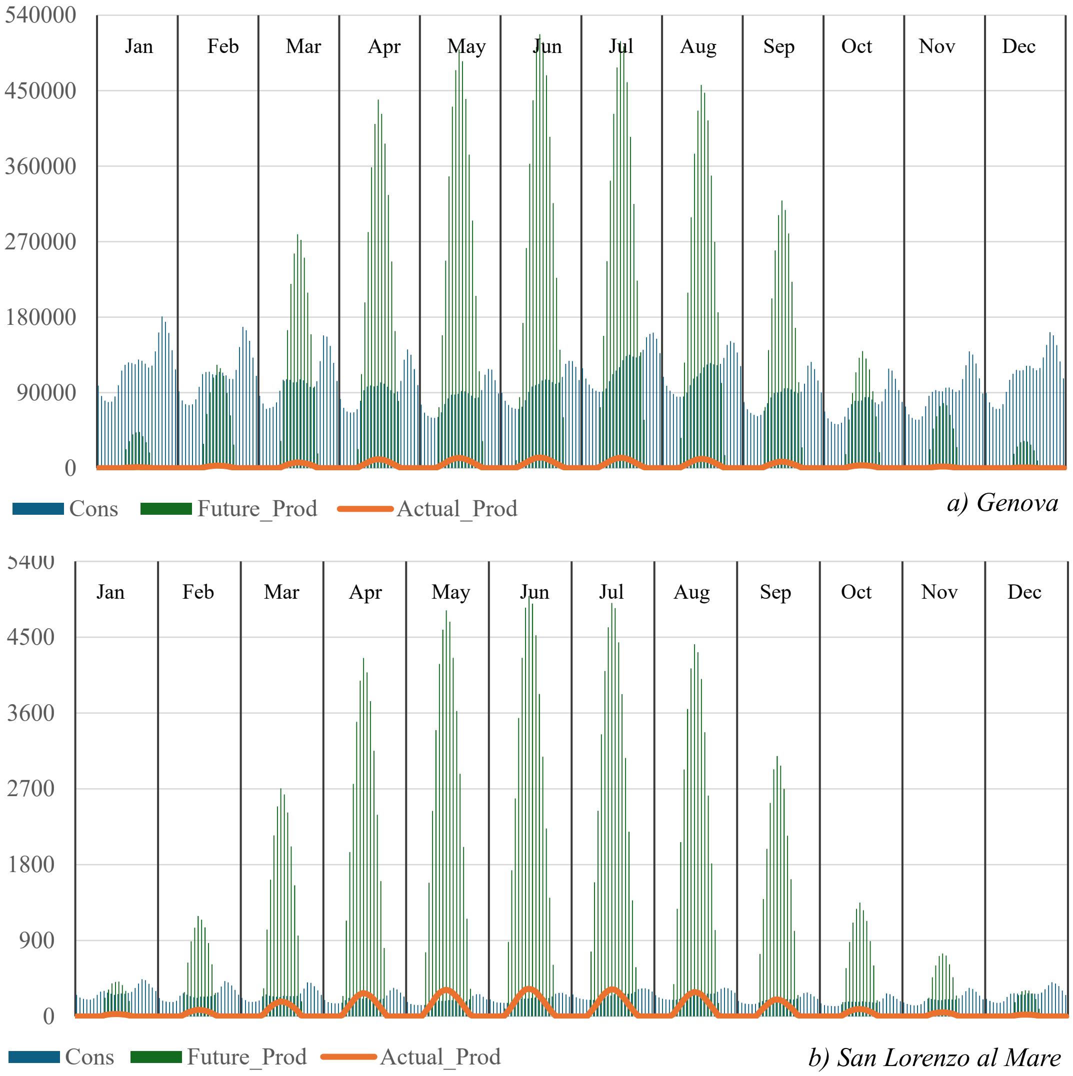

Figure 4-14 Actual production and future planning production of municipalities (By Author)

Figure 4-14 compares and analyzes the difference between electricity consumption and PV generation capacity in two representative cities of Liguria. One of them, Genova, as a large city with extensive rooftop coverage, shows a significant potential for PV installations. However, its high density urban structure is also followed by a greater demand for energy consumption. Therefore, a more advanced energy management system is needed to maximize self-consumption and sharing. In contrast, as a small city, San Lorenzo al Mare has a much lower average daily electrical load than Genova. Although its absolute generation potential is lower due to the limited rooftop resources, that are available for the deployment of PV systems. It has a similarly limited energy demand, which makes it easy to achieve higher PV penetration rates. This characteristic gives small cities a good capacity for energy contribution and sharing in RECs.

However, the actual PV generation in both municipalities is significantly lower than their future potential generation. This trend reflects the current underdeveloped PV potential and emphasizes the urgent need for policy support and investment guidance. Especially in large cities, the future activation of their potential resources will significantly improve the efficiency of renewable energy integration and RECs in the whole area.

4.4 Scenario-based Solar Potential Analysis of REC

4.4.1 REC Site Selection

To determine feasible locations for Renewable Energy Communities (RECs), this study used the REC eligibility boundaries defined by the Italian Energy Agency (GSE). They are based on the distribution of major substation areas and the distribution network infrastructure, as shown in Figure 4-14. This map helps to visually show the areas where RECs can be established from a legal and technical perspective, thereby guiding the selection of specific areas for detailed scenario analysis.

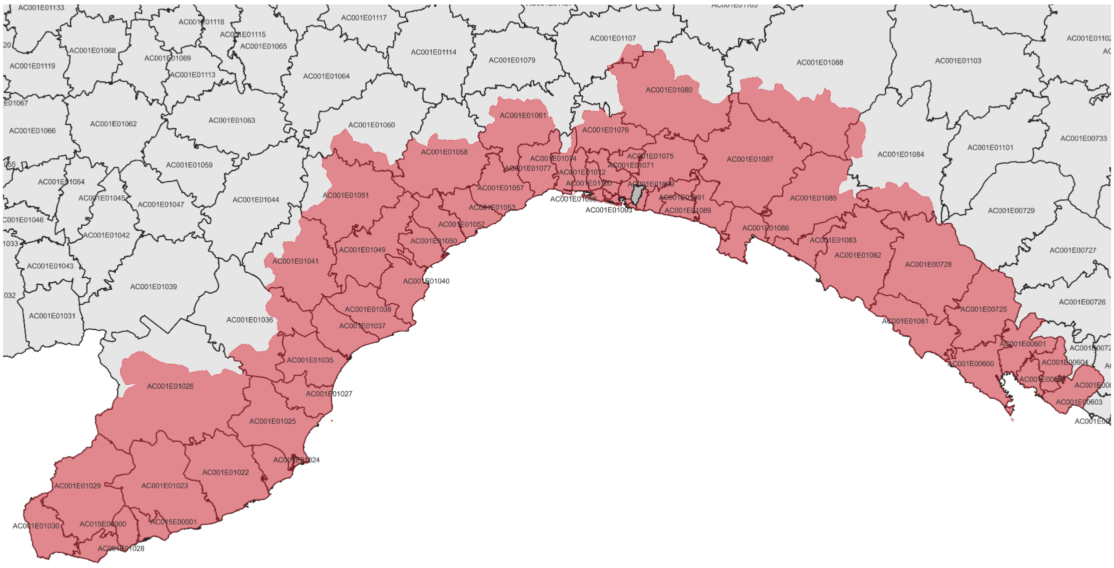

Figure 4-15 REC boundary support by GSE (By Author)

4.4.2 Scenario design

To comprehensively evaluate the integration effectiveness of PV systems under REC configurations, three different scenarios were designed in this study. Each scenario represents a unique operational mode and interaction with the grid.

SC1 - Individual Self-Consumption: Buildings generate and consume electricity individually and do not share energy and therefore do not qualify for REC incentives. All generated energy is only for self-consumption, emphasizing the resilience and independence of self-generated power, which is highly suitable for remote or isolated settlements.

SC2 – Integrating REC with Optimized Energy Sharing: The building is connected to the public grid and participates in the REC program to share excess electricity within the community. REC members primarily consume locally produced renewable energy, with excess energy exported to the grid for revenue. And the energy gap can be addressed by importing energy from the grid. This approach allows for more flexible balancing of supply and demand and enhances the economic viability of the REC program through grid incentives for excess energy.

SC3 - Reducing PV System Deployment: Aims to limit excess PV installed capacity to avoid insufficient utilization and higher system costs. This scenario prioritizes cost-effectiveness and aligns energy production with actual demand and grid integration capacity.

These scenarios enable a comparative analysis of the technical feasibility, economic viability, and energy self-sufficiency potential of RECs in Liguria.

5 Results and discussion

5.1 Energy Performance in Liguria

5.1.1 Solar energy potential and electricity demand

To assess the match between the renewable energy potential and energy consumption, this study first analyzes the annual energy demand of renewable energy communities (RECs) in Liguria. As shown in Figure 5-1, the annual energy consumption of different RECs exhibits a clear geographic distribution. RECs that are located in densely populated coastal areas, especially around major urban centers, tend to have an annual energy demand of more than 20,000 to 50,000 MWh. In contrast, inland mountainous RECs have relatively low consumer demand, typically below 12,000 MWh per year.

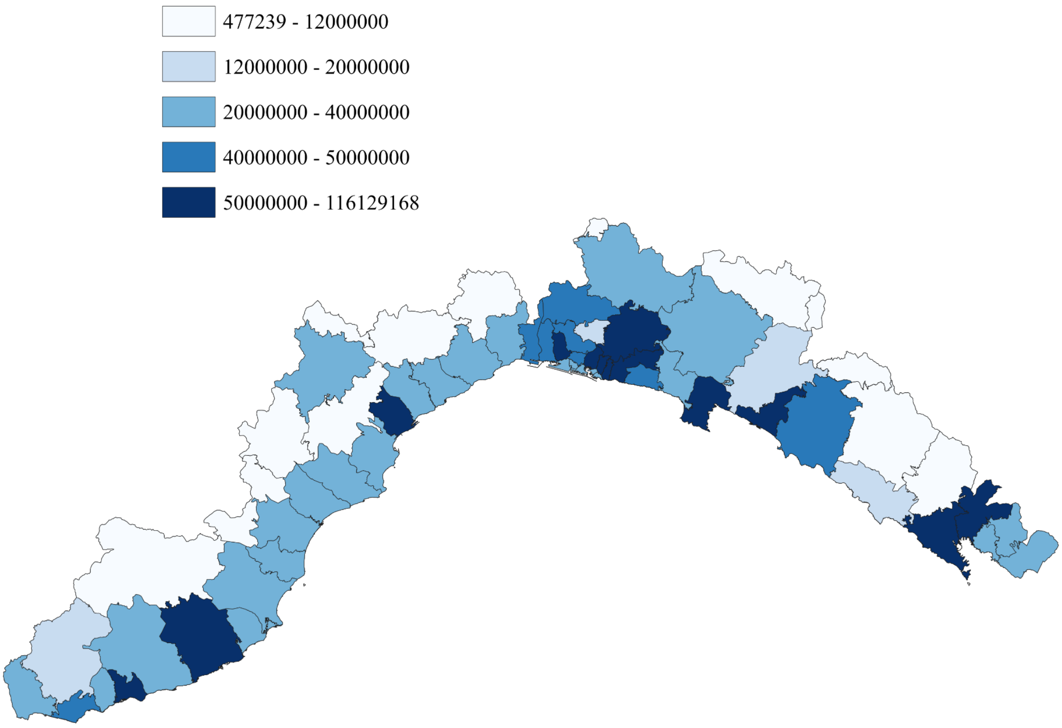

Figure 5-1 Annual energy consumption demand of each REC (kWh) (By Author)

Figure 5-2 shows the annual self-consumption values for two different scenarios. In Scenario SC1, the building operates in an individual mode, the electricity produced is consumed entirely within the building and is not shared at the community level. This results in significant spatial heterogeneity, with many RECs not fully utilizing their production capacity. Self-consumption rates in some communities are only 20-30% due to the timing gap between generation and demand. In contrast, in Scenario SC2, there is a significant increase in local self-consumption of energy through energy sharing at the community level. The self-consumption rate has reached 40-50% in many communities. This suggests that energy sharing is effective in mitigating the mismatch of production and electricity consumption between different buildings.

5.1.2 Energy performance index

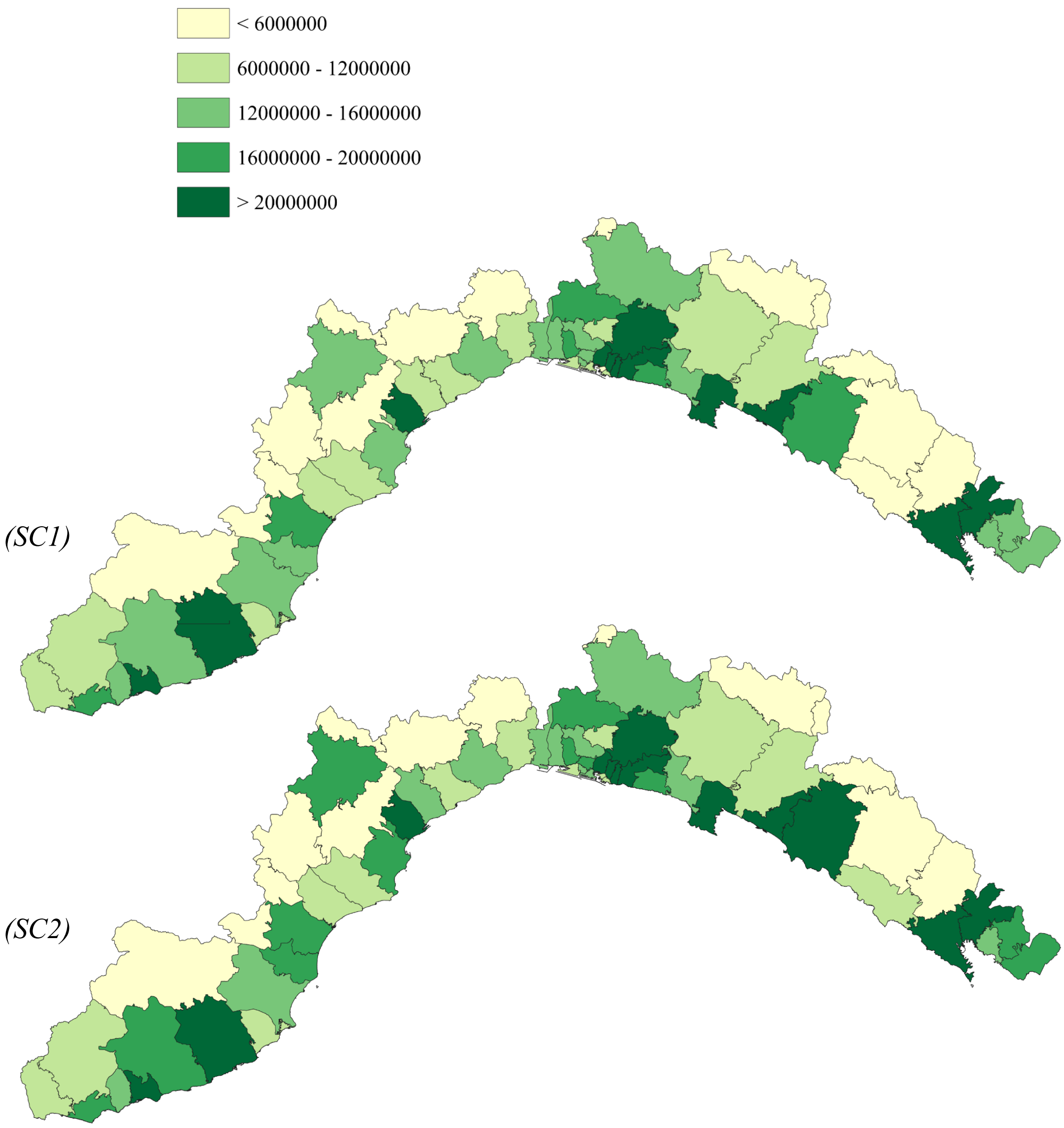

Figure 5-2 Annual self-consumption of each REC in different scenarios (kWh) (By Author)

The comprehensive energy performance assessment presented in Table 5-1 provides quantitative indicators to assess the effectiveness of different REC scenarios in Liguria. The analysis covers the energy production capacity, SSI, SSI, the overall performance index and the amount of shared energy.

In SC1 scenario, due to the isolated operation of the buildings, Liguria region as a whole has a low SSI and a medium SCI, highlighting the limitations of an isolated energy system in enhancing regional energy autonomy. When energy sharing mechanisms are integrated, in contrast, both indicators gain some overall improvement.

To further assess the impact of PV deployment level on the sharing effect, the study set up three PV configuration scenarios: 45%, 70% and 90% retention. The results show that the lower the configuration level, the lower the SSI of the REC, which reflects the energy independence at the community level. At the same time, the increase in power sharing within the RECs was attributed to the increased energy demand of each building, and excess energy within the community could be distributed and utilized more efficiently.

Table 5-1 Total energy performance of RECs for each scenario in Liguria (By Author)

Scenarios	Energy production (kWh)	SSI	SCI	OPI	Sharing energy (kWh)
SC1	4790438928.703	0.1849	0.3751	0.8151	0.000
SC2	4790438928.703	0.2001	0.4059	0.7999	72732827.849
SC3	2155697517.916	0.3785	0.3455	0.6215	82822174.340
SC4	3353307250.092	0.2681	0.3808	0.7319	75672246.378
SC5	4311395035.833	0.2184	0.3989	0.7816	73554531.052

Figure 5-3 further shows the trend of SSI and SCI with the percentage of PV deployment. It is shown that SSI is positively correlated with the increase in the proportion of PV deployment, which rises from about 0.35 to 0.42 as the proportion of deployment increases from 45% to 100%. This trend suggests that higher PV penetration is contributing to the increase in of SSI within the REC. On the contrary, the SCI tends to decrease with the increase in the percentage of PV deployment, from about 0.38 at 45% deployment to 0.22 at 100% deployment. This inverse relationship suggests that while a higher percentage of PV deployment increases the overall energy production, the excess energy production is not adequately consumed locally, which in turn reduces the SCI. This mismatch between supply and demand is further supported by the stabilization of shared energy.

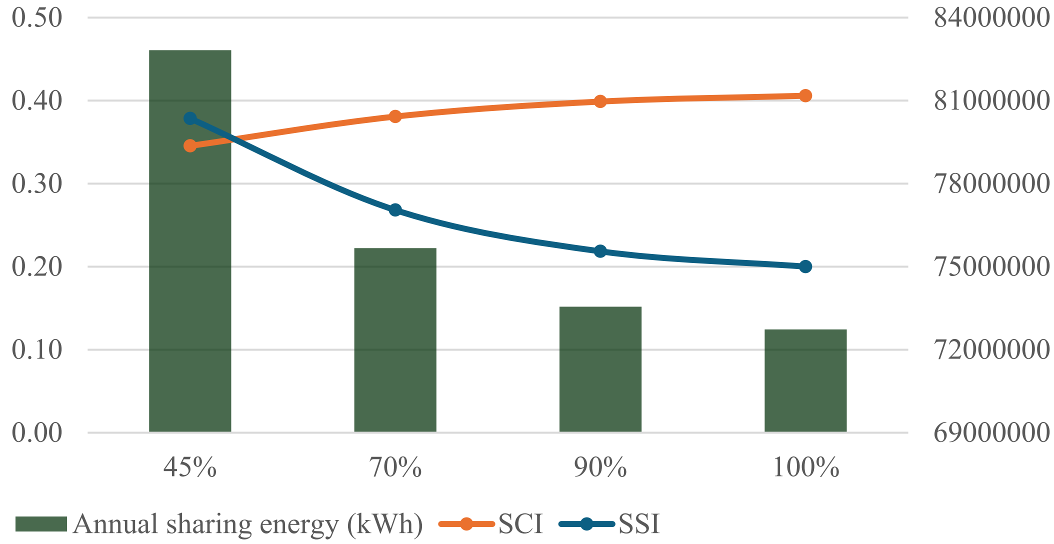

Figure 5-3 Total SSI and SCI of RECs on different PV deployment (By Author)

Considering the trends of SSI and SCI together, it can be found that the decline rate of SSI is significantly higher than the increase rate of SCI. This implies that the loss of self-sufficiency exceeds the gain of self-consumption at a higher deployment situation. Therefore, a 45% PV configuration is better able to achieve a balance between these two.

The energy sharing analysis shown in Figure 5-4 illustrates the annual shared energy capacity of each REC. The value of shared energy varies widely among communities, with some communities able to share more than 1 million kWh of energy per year, while others contribute less energy based on their production and consumption balance. In general, most RECs share the highest amount of energy under 45% energy allocation conditions and share basically the lowest value of energy at 90% energy allocation. This emphasizes the importance of appropriate allocation and the internal redeployment mechanisms within the community.

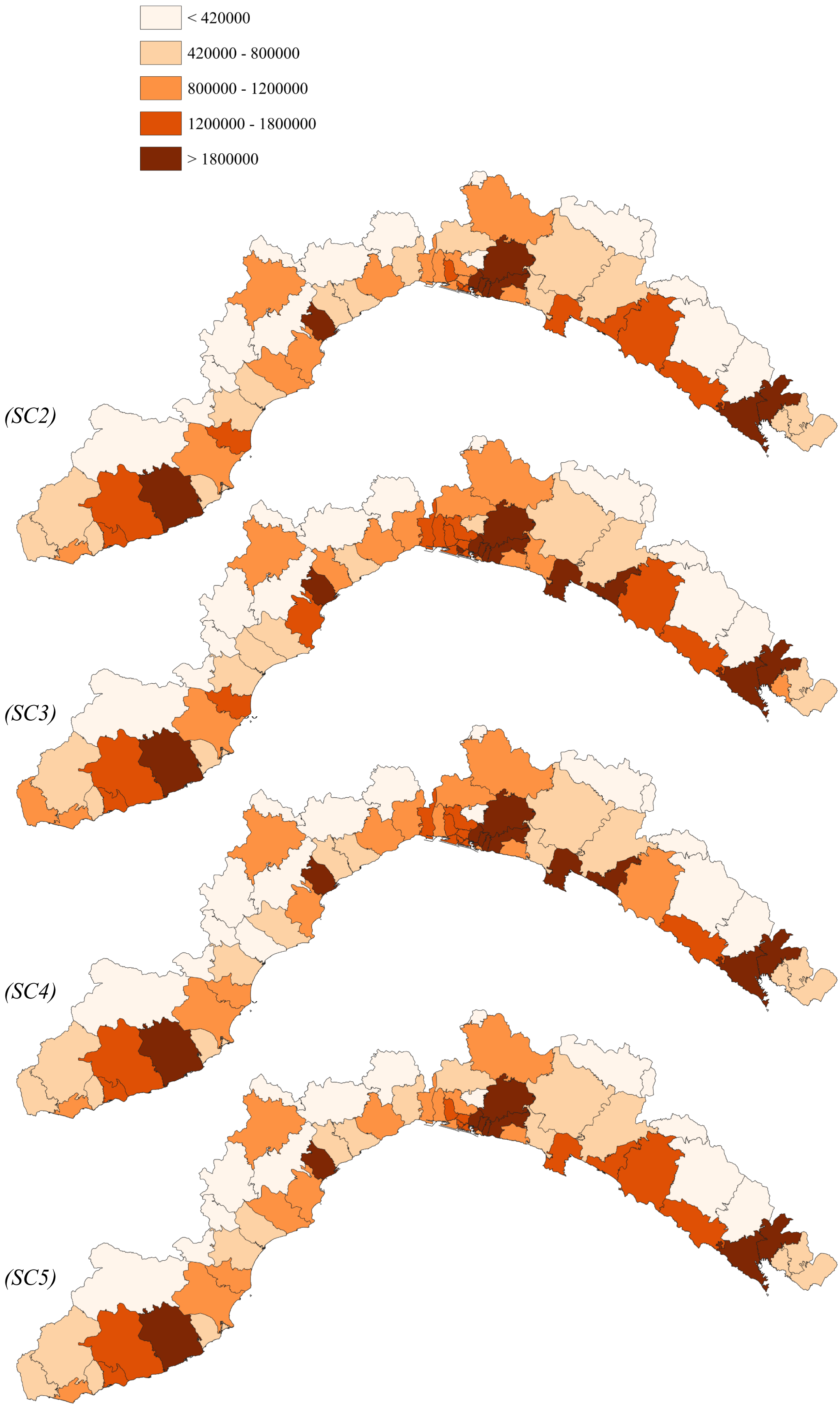

Figure 5-4 Annual sharing energy of each REC in scenarios (kWh) (By Author)

5.2 Economic and Environmental Benefits

5.2.1 Analysis of economic indicators

This study provides a systematic assessment of the economic feasibility of renewable power generation under different scenarios. This covers key financial indicators such as annual revenues, annual costs, annual net income, payback time (PBT) and net present value (NPV), and the results are shown in Table 5-2.

Table 5-2 Total economic benefits of RECs for each scenario in Liguria (By Author)

SC	Annual revenue (k€)	Annual cost (k€)	Annual net income (k€)	Saving money (k€)	PBT	NPV (k€)
SC1	578729.26	559277.37	169219.21	870992.66	1419.75	-13486.47
SC2	577404.80	535275.54	177435.46	893670.03	22.71	-11353.97
SC3	209345.54	547866.90	13219.19	478576.36	44.24	-26639.98
SC4	373563.56	537490.46	61006.15	670293.04	85.75	-27826.11
SC5	508970.05	535225.51	133433.08	819763.42	27.66	-18392.19

Because more electricity is sold in SC1, the annual revenue is larger than in SC2. However, the lack of a sharing mechanism leads to higher annual expenses, resulting in a lower annual net income than in SC2. Although SC5 has the lowest annual cost, it does not realize a shorter payback period due to a larger drop in the overall revenue. Most RECs have negative NPVs, indicating that long-term financial returns are not yet sufficient to cover initial investment under current policy and market conditions. High capital expenditures limit cost-effectiveness, especially in areas with saturated demand.

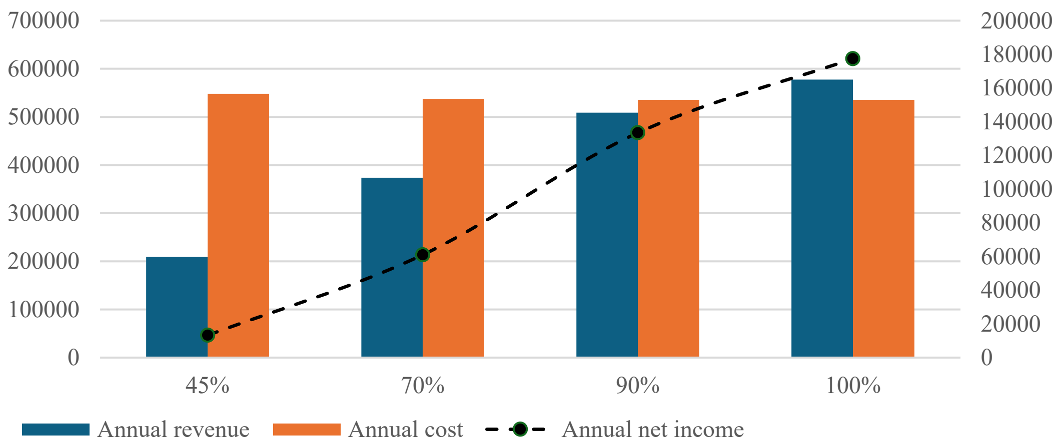

Figure 5-5 Annual income of RECs for each scenario in Liguria (k€) (By Author)

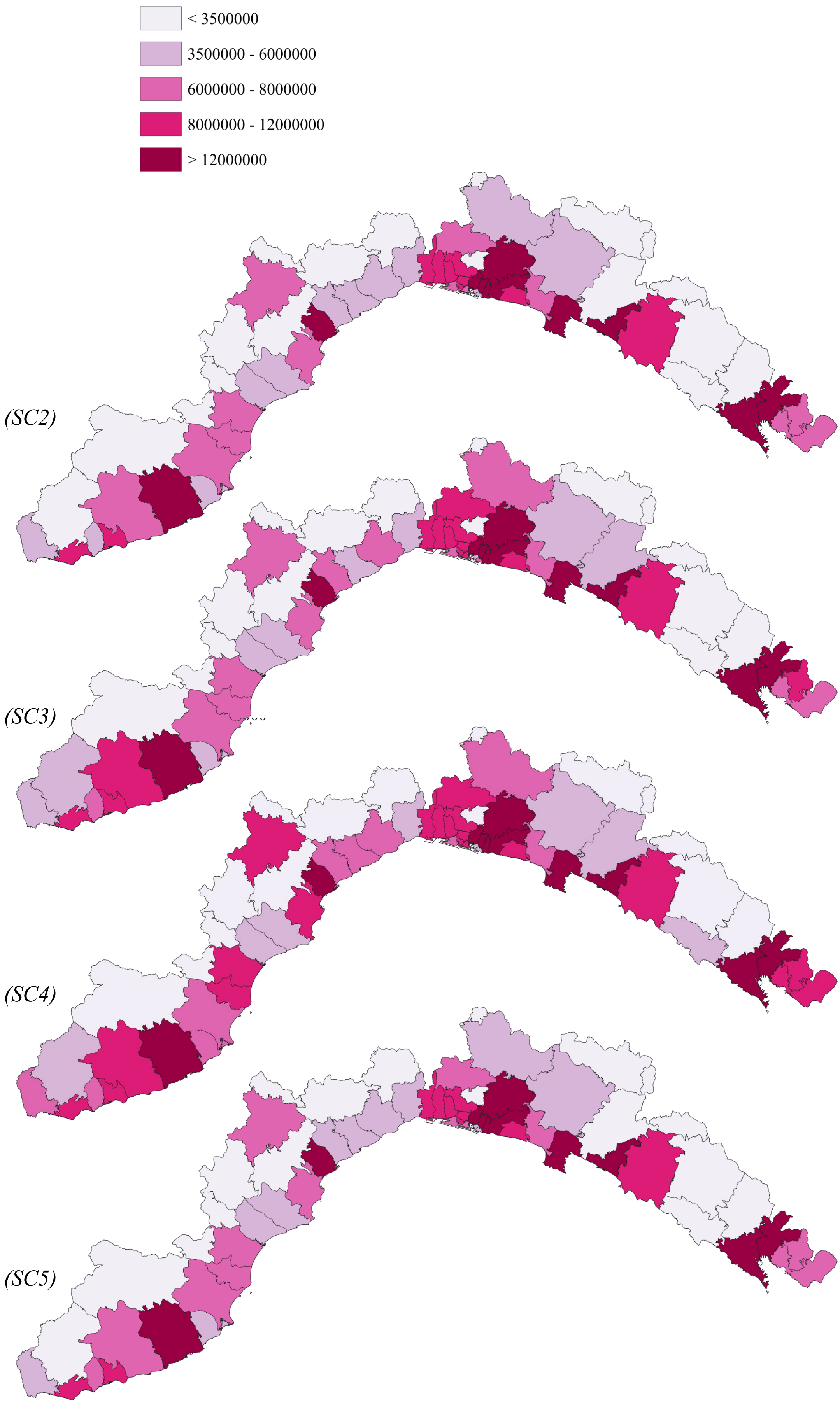

Figure 5-6 Annual cost of each REC in different scenarios (€) (By Author)

Figure 5-6 shows the distribution of annual costs of each REC under each scenario. It can be seen that the annual costs for SC5 and SC2 are closely aligned. Additionally, due to the large scale of the system and the complexity of the infrastructure, the center city REC has the highest cost, which highlights the need for targeted financial planning.

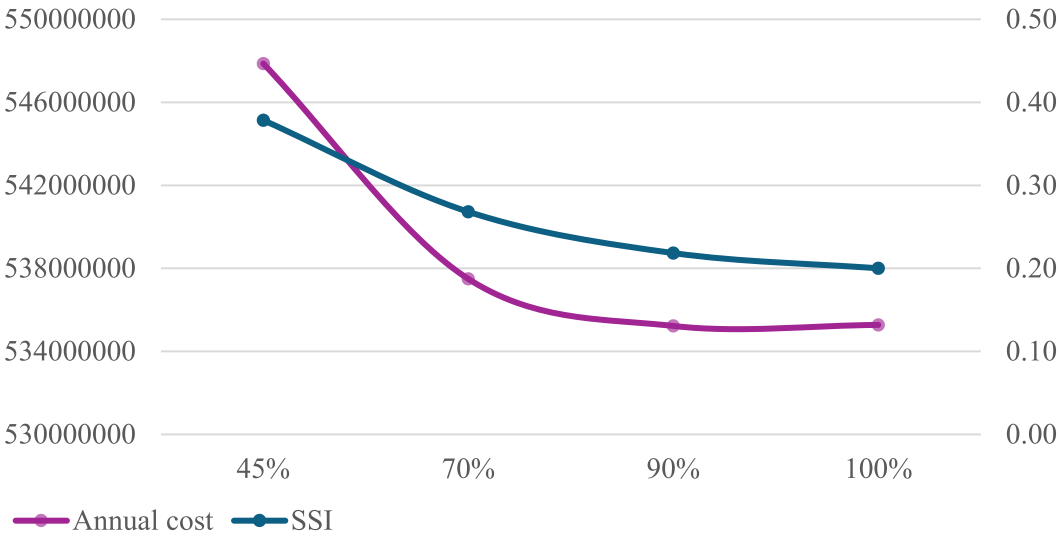

Figure 5-7 Annual cost (€) and SSI in different scenarios (By Author)

The relationship between annual energy costs and PV penetration is further analyzed in Figures 5-7. It can be observed that the total annual cost of energy decreases steadily as the proportion of renewable energy increases and reaches its lowest point at 90%, after which it rises slightly. This indicates that the marginal economic benefits tend to decrease after a high proportion of renewable energy is deployed. At the same time, SSI has a slight downward trend between 90% and 100%. When the trends of SSI and cost are considered together, the case of 90% PV installation can be considered as an optimization. This scenario not only achieves annual cost savings, but also is close to achieving the goal of energy self-sufficiency, demonstrating a cooperative optimization between technology-economy-sustainability.

5.2.2 Analysis of environmental impact

The environmental impact assessment quantifies the carbon footprint reduction potential of REC under different scenarios. Using the traditional grid emissions as the baseline, Table 5-3 presents the CO_2 emissions, emission reduction, and renewable energy penetration for each scenario. In the SC2 scenario, the renewable energy share reaches 40.59% due to the dense deployment of PV and the community sharing mechanism. At the same time, it has the largest absolute CO_2 reduction, which fully reflects its carbon reduction potential.

Table 5-3 Total environmental effects of RECs for each scenario in Liguria (By Author)

Scenarios	CO_2 emission (tons)	CO_2 reduction (tons)	Share of renewable energy
SC1	457568.830	1485476.788	37.51%
SC2	435014.961	1485476.788	40.59%
SC3	479211.917	668464.555	34.55%
SC4	453372.171	1039833.752	38.08%
SC5	440156.715	1336929.109	39.89%

Figure 5-8 visually illustrates the spatial impact of emission reductions. Areas with high initial demand and adequate rooftop potential will gain the most from REC integration. Coastal zones generally show better environmental performance due to better solar radiation conditions compared to inland mountainous areas with limited renewable energy resources.

Figure5-9 shows the relationship between CO_2 emissions and the percentage of renewable energy deployment. It can be seen that CO_2 emissions decrease significantly when PV penetration increases. The annual cost profile fits the trend of CO_2 at lower PV configurations, but also shows a smooth flow around the 90% deployment ratio. If CO_2 and cost are used as dual optimization objectives, the optimal scenario points to the 100 % PV option. This scenario maximizes the environmental benefits, while the costs are close to the minimum. Therefore, the 100% deployment scenario is the most environmentally and economically efficient option in the pursuit of long-term environmental sustainability and carbon neutrality.

Overall, the widespread deployment of RECs in the Liguria region will contribute to a significant reduction of the regional carbon footprint and support national and international climate commitments. This analysis provides strong evidence for the environmental viability of RECs as a foundation stone for a sustainable energy transition strategy.

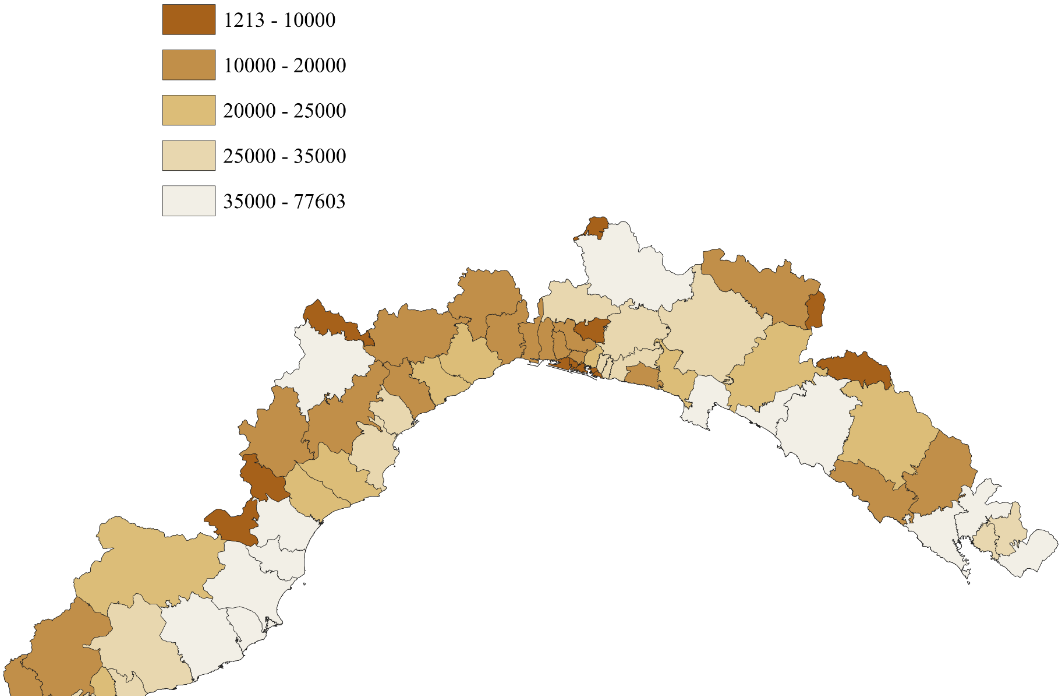

Figure 5-8 Annual CO2 emission of each REC under SC2 (tons) (By Author)

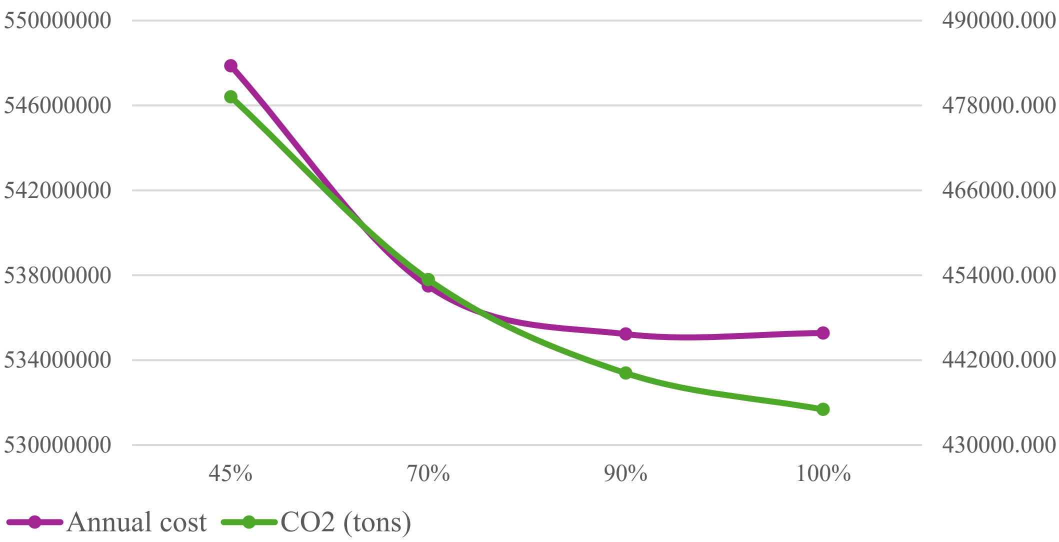

Figure 5-9 Annual CO2 emission (tons)and Annual cost (€)of different scenarios (By Author)

5.3 Renewable Energy Communities: Opportunities and Challenges

5.3.1 Benefits of RECs

A comprehensive analysis of the REC implementation in Liguria reveals its multiple benefits in economic, environmental and social dimensions. The quantitative results show that REC represents a transformative approach to energy system optimization, demonstrating its great potential as a new paradigm for energy system optimization.

Improved energy efficiency and autonomy: The incorporation of energy sharing (SC2-SC5) in REC significantly improves SCI and SSI, leading to more efficient utilization of local solar resources. By redistributing excess energy within the community, it effectively reduces the peak load on the grid and enhances energy resilience at the local level.

Economic savings and positive cash flow: Properly deployed PV systems (SC2 and SC5) can increase net income, shorten PBT, and enhance financial sustainability. This is evidenced by higher savings and more competitive NPV figures. The distributed characteristics of the RECs reduce the reliance on expensive grid infrastructure. In addition, revenue sources are expanded through energy trading and certificate systems.

Enhanced environmental benefits: RECs make a significant contribution to CO_2 emissions reductions, especially in areas where renewable energy penetration is high and sharing mechanisms are optimized. In some cases, the total share of renewable energy will increase to more than 40%, in support of regional decarbonization targets.

Promoting energy localization and social cohesion: RECs promote the democratization of energy, empowering the population to participate in energy governance, which leads to improved social cohesion. At the same time, a localized energy system reduces dependence on external supply chains. It also decreases the risk of exposure to external supply disruptions and price fluctuations, and improves energy security and resilience.

5.3.2 Challenges of RECs

While RECs have clear advantages, a number of technical and regulatory challenges must be addressed to ensure their long-term viability and scalability.

High initial investment and return uncertainty: While full PV deployment boosts electricity generation, as shown in SC2, high capital costs usually lead to negative NPV. In the context of decreasing returns at the margin, high initial investment may reduce the attractiveness of the project. Market movements in energy prices and REC values also create ongoing financial risks for REC participants.

Regulatory and administrative barriers: The establishment of RECs typically requires coordinated action by multiple stakeholders (households, municipalities, utilities) and is limited by changing policy frameworks and incentives. There are also cross-regional coordination challenges when RECs cross multiple administrative boundaries.

Social challenges of energy sharing: Differences among community members in terms of energy consumption patterns, financial capacity, and environmental priorities can cause conflict and reduce the effectiveness of cooperation. In addition, the technical complexity of the system may also inhibit active participation by residents, impacting the long-term quality of REC operation and governance.

5.3.3 Recommendations for REC implementation

In order to maximize the performance and sustainability of REC, the following strategic recommendations for communities, government agencies, utilities and technical services are proposed:

Enhance flexible infrastructure: Deployment of community-level energy storage systems should be considered based on local consumption patterns and renewable energy generation. This can enhance energy scheduling capabilities and respond to load and production fluctuations.

Optimize financial incentives: Innovative financing mechanisms should be developed to decrease the initial investment barrier to participating in RECs. At the same time, establish risk sharing mechanisms to protect communities from market fluctuations and technical failures. To increase incentives for environmental and social performance.

Encourage community participation and education: Effective REC implementation relies on the active participation of residents, local authorities and energy suppliers. Governance mechanisms should be built to promote democratic decision-making. In addition, public education and technical training will be provided to locals to increase their feeling of identification and duty, as well as ensure long-term participation and the system's sustainability.

6 Conclusion and Outlook

6.1 Major Outcomes

6.1.1 Summary of solar potential in Liguria

Liguria located on the Mediterranean coast of northwestern Italy, has huge but underutilized solar energy potential. Based on the analysis of climatic and geographic conditions, the average annual total solar irradiation in the region is generally at a medium-high level. Especially along the coastal strip, where solar energy resources are particularly rich. Although the region's mountainous terrain and narrow coastline limit the development of large-scale ground-mounted PV systems, they also provide significant opportunities for rooftop solar deployment, especially in densely populated urban centers.

This study highlights the spatial variability of solar potential in Liguria through GIS analysis and spatial modeling. Coastal and south-facing hillside areas have the best PV potential. At the building scale, south-orientated roofs and buildings located on higher elevations generally have higher annual radiation levels, which are ideal for PV installation. Comparing the estimated solar generation with regional electricity consumption patterns indicates a clear seasonal trend. PV generation is generally higher than electricity demand during summer while winter shows a lack of supply. In addition, roof orientation plays a key role in shaping the daily generation profile. East-facing roofs reach the peak in the morning, west-facing roofs have higher capacity in the afternoon, and south-facing roofs peak at noon.

But the spatial aggregation of solar generation can significantly reduce fluctuations in the overall system, which provides an advantage for load matching in the framework of local energy sharing. However, realizing this full potential still requires careful planning to address topographical constraints, seasonal variations, and grid infrastructure limitations.

6.1.2 The performance of REC in Liguria

A comprehensive performance analysis of RECs scenarios in the Liguria region shows that they are better than traditional energy systems in terms of technical, economic and environmental dimensions. Multi-scenario modeling reveals the key to optimize the implementation strategy and identifies the main performance drivers for the successful integration of RECs.

The technical performance evaluation of five different scenarios (SC1-SC5) demonstrates that energy sharing mechanisms fundamentally change the economics and effectiveness of distributed renewable energy systems. SC1 scenario represents an isolated, unshared, building-level energy system, which exemplifies the limitations of deployments that lack sharing mechanisms. The arrangement of RECs as represented by SC3, on the other hand, significantly improves the local renewable energy utilization and overall energy efficiency, and achieves a balanced performance. It is shown that a well-designed REC framework can overcome the inherent challenges of renewable energy integration and at the same time maximize the local resource use. However, when PV penetration increases, SSI decreases, suggesting that too much renewable energy capacity can lead to excess generating capacity. This finding suggests that REC designs need to balance between generation capacity and local consumption patterns. In the 45% deployment profile, although the total amount of electricity produced decreases, the amount of shared energy is conversely higher. This is because of the increased reliance of users on community energy, which enhances community cohesion. In contrast, excessive deployment (e.g., 90% or 100%) is easy to cause over-generation and potential power abandonment in the absence of adequate regulation mechanisms. And also reducing the efficiency of energy self-consumption. Therefore, a model that combines medium deployment with efficient sharing can show the best overall performance.

From an economic perspective, the SC2 and SC5 scenarios achieve higher annual net income and shorter payback periods, confirming the potential of RECs to enhance return on investment. The economic sustainability of RECs is expected to be further enhanced, especially with policy support and well-designed sharing mechanisms. By minimizing dependence on the grid and optimizing infrastructure utilization, enhancing renewable energy integration, RECs create significant economic value for community participants.

The environmental impact assessment shows that the REC promotion makes a significant contribution to the regional decarbonization goals. These emission reductions represent significant regional and national progress towards meeting climate commitments, while demonstrating the scalability of energy community based emission reduction strategies. The optimal deployment, with more than 40% of energy supplied from renewable sources, achieves the highest carbon reduction performance.

6.1.3 Importance of REC

This study further emphasizes that renewable energy communities (RECs) are not only a technological or economic innovation, but also a deep change in the existing energy governance structure. RECs optimize the deployment of local resources and enhance efficiency by promoting decentralization and localization of energy. It enhances the participation of all stakeholders in the energy system, can address the multiple challenges facing the contemporary energy system, and provides institutional and social support for the achievement of green transformation.

Although it is currently facing barriers such as high investment thresholds, complex policies, and difficulties in mobilization. REC has the core potential to build a sustainable energy system in the future. The importance of RECs is not only reflected in the optimization of technology and cost savings, but also in their profound impact on the transformation of the energy structure, institutional innovation and social co-governance.

6.2 Future Research Directions

6.2.1 Improving GIS models

This study has validated the core role of Geographic Information Systems (GIS) in renewable energy power planning and optimization. Furthermore, it has shown methods for improving models and increasing analysis precision in order to handle the complicated spatial-temporal dynamics of community energy systems and support more accurate optimization strategies.

Improving spatial resolution: The roof geometry data and solar irradiance data currently in use are limited in accuracy, such as slope and roof shading. Future research should focus on developing integrated high-resolution spatial models to more accurately capture renewable energy potential and community energy dynamics. Spatial models should incorporate advanced satellite imagery, LiDAR data, and drone sensing technologies. Building-level energy modeling should integrate Building Information Modeling (BIM) data to precisely assess integrated photovoltaic potential and supply-demand analysis.

Incorporate dynamic climate data: This study is based on typical climate year data and does not consider interannual fluctuations or climate change trends. To more accurately reflect the temporal variability of solar energy potential, real-time data flows from weather stations, satellite monitoring systems, and ground sensors should be integrated. This would enable dynamic updates to spatial models to optimize energy sharing strategies and predict system performance under different weather conditions.

Develop MCDA for site selection: Future research should incorporate multi-dimensional parameters such as building structural adaptability, grid accessibility, and socioeconomic indicators. A multi-objective GIS decision-making framework can be built to achieve “technology + society” optimization site selection analysis, and promote more equitable and efficient REC deployment.

Machine learning and advanced spatial analysis integration: The development of machine learning-enhanced GIS models is a critical frontier in advancing the spatial analysis capabilities of renewable energy research. AI algorithms can identify complex spatial patterns and relationships beyond the traditional GIS analysis methods. By incorporating convolutional neural networks (CNNs), they demonstrate unique potential in identifying optimal locations for renewable energy generation. Additionally, they can assess renewable energy potential and forecast system performance (Žalik, Mongus, & Lukač, 2024). Integrating historical performance data, climate data, and socioeconomic indicators can enhance prediction modeling abilities, enabling the development of predictive models for renewable energy generation performance used in risk assessment.

Through these improvements, GIS models will play a more precise supporting role in technical planning, policy formulation, and community engagement, further advancing the implementation and sustainability assessment of REC projects.

6.2.2 Expanding REC studies

Currently, research on RECs remains in its early stages, with a lack of systematic comparisons across climate zones and national contexts.

Future research could expand REC analysis to different climate zones to understand the general applicability of community energy systems and identify key research topics for optimizing demand in specific environments. By comparing southern Italy, France, Germany, Eastern European countries and others, it is possible to explore the performance differences of RECs under different climates, social structures, and electricity market mechanisms. Such research not only helps identify universal patterns but also reveals localized adaptation strategies, driving the widespread adoption of RECs across Europe and globally.

This study focuses on technical and economic dimensions, but the success of RECs highly depends on public participation and the governance structure of organizations. Future research should include field studies, behavioral modeling, and participatory simulations to explore residents' preferences regarding energy sharing and revenue distribution mechanisms. It should also examine community satisfaction with participation in renewable energy generation, to propose more inclusive design strategies.

Future research should also pay attention to the potential for promoting RECs among marginalized groups, such as low-income communities or rural areas, to assess their actual contributions to addressing energy poverty and enhancing energy equity.

6.2.3 Integration of other technologies

The successful experience of solar renewable energy generation in the Liguria region has established a foundation for researching the integration of other renewable energy technologies with advanced energy management systems.

Multiple renewable energy integration: This study considered only solar power generation and sharing, but in a real renewable energy system, wind power also plays a significant role. Solar-wind hybrid systems can be used to take advantage of the temporal complementary nature of solar and wind energy resources to provide a more stable energy supply. Additionally, small-scale hydraulic power systems offer potential for REC integration in regions with adequate water resources. The integration of biomass and methane will help deploy RECs in agricultural communities while addressing organic waste management challenges.

Advanced energy storage systems: The introduction of battery energy storage systems can effectively mitigate the time mismatch between PV power generation and electricity consumption, while improving self-consumption and self-sufficiency. Future research should focus on the optimal scale of energy storage systems, control strategies, and revenue distribution mechanisms.

Thermal system integration: Heat pump integration enables renewable energy power generation systems to provide heating services while utilizing renewable electricity. Future research should explore heat pump technology and its integration with renewable energy systems. Integrating multi-energy systems such as electricity and heat can significantly enhance the overall efficiency of energy systems, as well as their potential to reduce total community energy waste.

The integration of these technologies will drive RECs from “single-energy collaboration” toward “multi-energy collaborative governance,” truly achieving the goals of decarbonization and decentralization of energy systems.

6.3 Broader Implications

6.3.1 Role of this research

This study has developed a community analysis framework for renewable energy that applies to diverse geographical and social contexts, providing a repeatable, interdisciplinary, and multi-scale approach for global sustainable energy transition. By integrating GIS spatial analysis, scenario simulation, and performance evaluation, this study offers a standardized method. This method can be used as a reference for designing renewable energy strategies.

Beyond previous research that focused on conceptual and institutional analysis, this study employs a data-driven approach. This is to quantitatively analyze the energy, self-sufficiency, economic benefits, and carbon reduction effects of RECs. The goal is to enhance the evidential credibility of renewable energy objectives and closes the gap between theory and practice. The study also provides a locally adaptable pathway for the EU's “Clean Energy Package,” driving the transition from strategic vision to implementation.

Overall, this study not only deepens academic understanding of RECs but also provides practical guidance for local governments, energy companies, community organizations, and others, which promotes the transition from vision to action.

6.3.2 Policy implications

The research findings provide important implications for the formulation of energy policies across multiple scales, from local community support programs to national renewable energy strategies. The empirical evidence on the feasibility and performance of RECs provides a solid foundation for policy arguments. This supports community energy programs, and also identifies specific policy promotion to enhance their impact. To maximize shared economic benefits, flexible electricity prices and incentive structures should be designed to enable participants to earn profits during periods of mismatch between electricity generation and demand. Risk mitigation mechanisms are important for supporting community investment in REC, especially considering the long investment PBT and technical complexity of these systems. The policy framework should include insurance plans, performance guarantees, and technical support services. The government should encourage internal community cooperation by supporting small and medium-scale local PV projects, such as through the establishment of community energy funds. This will simplify REC registration and management processes, and subsidies for users with low and middle incomes. Local governments should act as promoters and coordinators of REC projects, providing platform support and technical guidance to energy communities, and leading the development of standards and processes tailored for local conditions.

Policy formulation should avoid isolating RECs and should integrate them into broader policy frameworks such as urban renewal, building energy efficiency upgrades, and carbon net-zero pathways to achieve systematic benefits. Spatial analysis results provide references for regional energy planning and infrastructure investment prioritization. The policy framework should align REC development with broader energy infrastructure planning to maximize system benefits and minimize costs. The environmental benefits of RECs support the argument for incorporating them into national climate action plans and carbon reduction strategies. International cooperation and knowledge-sharing mechanisms should also be considered to encourage learning and transferring best practices between regions and countries. Supporting collaborative research and technology transfer will help establish a global institutional framework for REC.

Policy support is not only a guarantor of REC development but also the key to guiding it from a “pilot project” to a “mainstream mechanism”. If collaboration can be achieved across institutions, economics, technology, and society, RECs will play an important role in future energy transitions.

6.3.3 Urban planning in energy transition

In the context of an increasingly decentralized and decarbonized energy system, the role of urban planning has extended beyond the traditional tool of physical spatial layout. It is now a key policy instrument for the energy transition, which enables to integrate distributed energy systems into the urban fabric.

Firstly, land use planning ensures the spatial integration of energy systems with different urban functions, such as residential, commercial, and public uses, to avoid isolated energy installations or bottlenecks in energy supply. Through scientific planning of land use, architecture, transportation network and infrastructure layout, urban planning can effectively promote the integration of distributed energy systems with urban space. This can promote energy systems to serve urban development more efficiently and equitably. At the same time, potential areas for renewable energy deployment should be maximized and identified, such as setting up multi-functional urban areas that can operate as an integrated energy community.

In addition, placing renewable energy facilities in coordination with green infrastructure (e.g., green roofs, urban green belts, etc.). This not only enhances the overall environmental benefits of the system, but also helps to support the city's sustainable development strategy. In areas with rich cultural heritage, urban planning must also balance energy transition with historic preservation. This requires the development of sensitive design approaches that take into account both built heritage and energy transition.

In the future, municipalities need to be more focused on integrating energy considerations into their long-term spatial strategies. This includes enhancing infrastructure accessibility, such as planning the distribution of grid connections and energy storage facilities in urban and peri-urban areas to ensure system operational efficiency. At the same time, cities should promote a shift in the role of residents from “energy consumers” to “energy producers-managers”. The local community should be effectively involved in energy planning and management to enhance social acceptability and optimize system design. Finally, the design of energy equity should take into account socio-economic data, which can help to increase the participation and benefit of low-income groups in the energy transition and realize a truly inclusive energy system.

By viewing energy as an element of the urban system rather than an external service, planners can help cities realize the full potential of renewable energy while creating more resilient, equitable and sustainable communities.

6.3.4 Energy platforms for decision-making support

In order to achieve the integration of urban planning and energy transition, Digital Twin System or Urban Energy Platform is gradually becoming an important tool for urban energy management and decision support. By integrating GIS, remote sensing, AI and other technologies (Koirala et al., 2024), the entire lifecycle of the energy system can be fully understood, analyzed and optimized. Instead of relying on static analysis and periodic assessments, the digital energy platform enables continuous monitoring, self-adaptive management, and evidence-based decision-making in real time. Here are the key features and benefits:

Accurate identification of resource potential: The platform can analyze high-resolution remote sensing imagery and geographic data with the help of AI algorithms, integrated with GIS. These systems can assess the potential of solar, wind and other renewable energy sources in different scales and environments, which provides a scientific basis for the effective deployment of urban energy planning.

Dynamic prediction of system performance: By fusing historical energy consumption records, climate data, and resident behavioral patterns, the platform can build spatial-temporal prediction models. By simulating the performance of the energy system under different development scenarios, the platform can provide data support for the community and planners to formulate strategies.

Multi-objective optimization decision-making: The platform can use advanced multi-objective optimization algorithms to identify the optimal REC configuration strategy. It improves payback and equity by considering technical efficiency, economic feasibility, environmental impact and social acceptance.

Multi-party collaboration and public engagement: The visualization platform presents planning scenarios and makes the complex energy data accessible to different stakeholders. This will support public feedback and collaboration with stakeholders in the city's energy planning process. By increasing the transparency of information, the public will be more willing to accept and participate in the energy community.

Decision support function: The digital twin can simulate the effects of different policies such as incentives, dynamic tariffs, and energy sharing rules. This kind of policy simulation can predict the path of energy community development and potential risks, and support policy makers to make more prospective analysis and adjustments (Maiullari et al., 2024).

Digital energy platforms are becoming the “smart brains” of cities to realize the energy transition, and will drive the evolution of cities from traditional planning paradigms to data-driven and dynamic decision-making mechanisms. From evaluating the sites, to monitoring their implementation, and to simulating future scenarios, the use of digital energy platforms will significantly improve the ability of cities to address climate change and promote the energy transition.

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