Doctoral Dissertation.
Interuniversity Doctoral Program in
Urban and Regional Development (38th Cycle)

Post Carbon Cities and Renewable Energy Communities:
Stacked Urban Energy Precincts for low-carbon pathways

Hashem ALSIBAI

Supervisors:
Prof. Egidio Dansero,
Prof. Lavinia Chiara Tagliabue,
Prof. Gilles Desthieux.

Politecnico di Torino - Università degli Studi di Torino
October 31, 2025

I hereby declare that the contents and organisation of this dissertation constitute my own original work and does not compromise in any way the rights of third parties, including those relating to the security of personal data.

Hashem Alsibai Turin, October 31, 2025

Summary

Cities run on energy and trust. One is measured in kilowatts; the other in the willingness of institutions, neighbours, and networks to act together. For a century, we expanded outward, feeding urban life with development and activities that made us prosper and relied on whatever energy source we had. That model is cracking. Grids strain. Prices swing. Climate math tightens. The question is no longer whether cities can generate more clean power, but whether they can organize it to replace the fossil fuel routine.

This thesis offers a tangible path: the Urban Energy Precinct. Think of it as a city's functional unit for decarbonization, an electrically coherent cluster of buildings, managed by an anchor institution, and run on a digital layer that turns solar potential into shared energy. It is where maps meet action, and where policy starts developing. The method is contextualized in a simple path; each step yields something buildable, precinct atlases, cabin-aligned precincts, standard agreements, and an Asset management system that eases in real time.

Two very different cities ground the work. In Turin, university buildings are grouped by primary cabin to form legally valid communities. In Geneva, consolidated ownership (UN district) shows the same logic under other rules, internalizing exchange through ZEV/CEL mechanisms. Together, they synthesize a path to post-carbon cities.

A future to design, one community, one precinct, one city at a time

Acknowledgment

I would like to thank many people who have helped my during my research and thesis writing, in particular, in my Department of DIST Polytechnic University of Turin my supervisor, Egidio Dansero, his guide was an amazing help to me the pillar stone to everything in these three years, and the trust he gave me was something I appreciated a lot and will never forget, the day I approached him was the day my PhD life became a life filled with ambition and I hope I made him proud, there is not a lot of professors who treat their students as friends and built a healthy relationship with them, I'm really thankful that he took me as his student.

From the Department of Landscape, Engineering and Architecture at the Haute école du paysage, d'ingénierie et d'architecture de Genève, which I would like to thank for hosting me during my period abroad, my co-supervisor, Gilles Desthieux, provided his guidance was a major part of how my thesis evolved. I have learned a lot from him, and count myself very lucky to be his student and to have had the pleasure of meeting him at a conference in my second year.

And from the Department of Computer Science at the University of Torino, my co-supervisor Lavinia Chiara Tagliabue, her reviews at the beginning of my PhD were another major part of how my thesis was edited, her comments made me realise how a researcher should approach the audience and always be up-to-date with the literature presented

And above all, I would like to thank God for giving me this opportunity, and to work and expand on something I love. Last but not least, my family for their continued support.

I would also like to thank Marco Santangelo and Lorenzo Mauloni for their help and devotion at the beginning of my journey.

ILLUSTRATIONS AUTHORSHIP

All illustrations are duly acknowledged. Those without an explicit citation have been composed by the author of the thesis.

Dedication

The dedication is very common in some countries, while it is not in other countries.

It is entirely up to you to write it or not and it can have a more colloquial or formal style, again depending on your decision. Just remember that it will stay printed for a very long, long time.

TABLE OF CONTENTS

Table of figures

Table of tables

Acronyms

AMS: Asset Management System

API: Application Programming Interface

ARERA: Autorità di Regolazione per Energia Reti e Ambiente (Italian energy regulator)

BI: Business Intelligence

BIM: Building Information Modeling

CAPEX: Capital Expenditure

CEC: Citizen Energy Community (EU)

CEL: Communauté d'Électricité Locale (Local Electricity Community, CH)

CHP: Combined Heat and Power

CM: Community Manager (anchor institution role)

CMMS: Computerized Maintenance Management System

CO_2 / GHG: Carbon Dioxide / Greenhouse Gas

DER: Distributed Energy Resources

DSO: Distribution System Operator

EC: Energy Community (generic)

EPC: Engineering, Procurement, and Construction

EU: European Union

EV: Electric Vehicle

FIPOI: Fondation des Immeubles pour les Organisations Internationales (Geneva)

FIT: Feed-in Tariff

GIS: Geographic Information System

GSE: Gestore dei Servizi Energetici (Italy)

IEA: International Energy Agency

IEMD: Internal Electricity Market Directive (EU)

IPCC: Intergovernmental Panel on Climate Change

IRR: Internal Rate of Return

IRENA: International Renewable Energy Agency

kVA / kW / kWh / kWp : kilovolt-ampere / kilowatt / kilowatt-hour / kilowatt-peak

KPI: Key Performance Indicator

LCOE: Levelized Cost of Energy

LEn: Loi sur l’énergie (Canton Geneva Energy Law)

MoU: Memorandum of Understanding

MRV: Monitoring, Reporting, and Verification

MTBF: Mean Time Between Failures

NPV: Net Present Value

NT1 / NT2 / NT3 : Network Types / Scenarios (precinct configurations)

O&M: Operations and Maintenance

OPEX: Operating Expenditure

PBP: Payback Period

PPA: Power Purchase Agreement

PNRR: Piano Nazionale di Ripresa e Resilienza (Italy)

PR: Performance Ratio (PV)

PV: Photovoltaic

REC: Renewable Energy Community (EU)

RED II: Renewable Energy Directive (EU)

RCP: Regroupement (de consommateurs) dans le cadre de la Consommation Propre (French term for ZEV)

SCR: Self-Consumption Ratio

SDG: Sustainable Development Goals (UN)

SEC: Sustainable Energy Community

SIG: Services Industriels de Genève (utility)

SLA: Service Level Agreement

SoC: State of Charge (storage)

SPV: Special Purpose Vehicle

SSR: Self-Sufficiency Ratio

TSO: Transmission System Operator

TIAD: Testo Integrato Autoconsumo Diffuso (Italy; ARERA framework)

UEP: Urban Energy Precinct

UNFCCC: United Nations Framework Convention on Climate Change

UniGE: Université de Genève

UniTo: Università degli Studi di Torino

V2G: Vehicle-to-Grid

ZEV: Zusammenschluss zum Eigenverbrauch (Collective Self-Consumption, CH)

2050Today: Geneva climate partnership initiative

Chapter 1

1. Introduction: The Urban Energy Transition Imperative

1.1 Post-Carbon Cities and Energy Use: The accelerating energy demands in global cities

Cities now power most of the world's growth. According to a landmark report published by the United Nations, cities are home to approximately 56% of the world's population in 2021, a proportion projected to grow to nearly 68% by 2050, adding approximately 2.2 billion urban inhabitants (United Nations, 2022). This fast urban growth drives energy demand; the rise comes from steady economic growth, new infrastructure, and a general increase in living standards (Seto et al., 2012). As the International Energy Agency notes, cities already use well over two-thirds of the world's total energy, and that share keeps rising as urban areas spread, most noticeably in developing regions (IEA, 2022). This rapid pace puts real strain on power systems, transport, and housing, turning energy management into one of the toughest hurdles for sustainable development.

This pace makes cities keep changing how they use and produce energy. Historically, energy sources were mostly fossil fuels such as coal, oil, and natural gas, and that alone directly links economic growth with the increase of greenhouse gas emissions (Kennedy et al., 2015). About 75% of the global primary energy is consumed in cities and 70% of energy-related CO_2 emissions, making their role undoubtedly the solution for climate mitigation efforts (Creutzig et al., 2017). This reliance on fossil fuels positions urban areas as keys for intervention and the first in line to adopt a model of reducing emissions, which needs a shift in energy sourcing, infrastructure efficiency, and consumption practices. Without a targeted and well-layered framework for action, urban energy demands could potentially double by mid-century, adding pressures on sustainability and climate stability (Ürge-Vorsatz et al., 2018).

However, the patterns of energy consumption are different between developed and developing regions, especially with diverse socioeconomic contexts, urban forms, and infrastructure. In well-developed economies, energy demand growth has somewhat stabilized due to improved energy efficiency, stricter regulations, and technological development (Ürge-Vorsatz et al., 2018). However, energy consumption per capita remains relatively high due to the current lifestyle, the need for infrastructure, which includes transportation, heating, and cooling demands, and highly extensive building energy use (Bai et al., 2018). In contrast, cities in developing economies keep showing an increase in energy demand, driven by the growing populations, expanding middle-class lifestyles, increased economic activity, and infrastructure development. Often, they rely heavily on fossil fuel-based energy sources, disregarding ofc the environmental effect that would have, and contributing significantly to global emissions trajectories (Seto et al., 2016).

The dilemma here is that urban energy demand effectively requires understanding the spatial characteristics of urbanization itself. Cities that are dense in urban forms tend to have lower per capita energy use, people travel shorter distances, buses and trains have more incentives to be used, and buildings share walls and systems, which cuts heating and cooling losses (Newman & Kenworthy, 2015). But widespread urban areas have a much lower density, suburban developments, and car-dependent infrastructures, which leads to a higher energy consumption, which means higher greenhouse gas emissions per capita (Creutzig et al., 2016).

Therefore, what makes a city able to transition into a post-carbon path is within the domain that makes its spatial characteristics, mainly building density, infrastructure, transportation, and employing underutilized lands(Ramaswami et al., 2016), all of which tell us the city's capacity to transition into a sustainable post-carbon community.

1.2 Energy as the Key Climate Challenge: A Brief overview connecting energy systems explicitly to urban carbon emissions.

Production and consumption of energy are the most significant sources of anthropogenic greenhouse emissions and contribute to about 73% of the global emissions, mainly by the generation of electricity, transport, industry, and building activities (Shukla et al., 2022). Being the consumption hub for about two-thirds of the global energy consumption, cities also contribute to a similar fraction of the total carbon emission, both directly in the combustion of fossil fuels within the city limits and indirectly in the form of imported electricity supplied by the external regions (Keramidas et al., 2023). Hence, the carbon intensity and composition of the urban energy systems hold a determinant role in the attainment of global climate objectives such as the target to restrict the global temperature increase to 1.5°C over pre-industrial levels (Seto et al., 2012).

Perera (Perera et al., 2020) argues the impact of climate change on cities and urban areas and emphasizes the need for a sustainable energy supply in the face of increasing extreme climate events. Climate change influences urban energy use by affecting energy demand, production, systems, and infrastructure (Nik & Sasic Kalagasidis, 2013; Stern et al., 2016), and the generation of renewable energy is also susceptible to these changes, with differences depending on the type of renewable source such as wind, hydropower, or solar (Pryor et al., 2006; Sailor et al., 2008) according to their geographical location (Wang et al., 2014), especially in cities.

In this sense, urban carbon emissions are the result of numerous interconnected driving factors, principally the consumption of fossil fuels for power, heating, cooling, and transport. The combustion of coal, oil, and natural gas adds high levels of carbon dioxide emissions, alongside other pollutants detrimental to both climate stability and human health (Kennedy et al., 2015). Cities frequently rely on centralized, fossil-based electricity grids and combustion-engine vehicle fleets, both of which are primary sources of urban carbon emissions (Creutzig et al., 2017). Additionally, the built environment itself (through inefficient heating, cooling, and lighting systems) represents a growing source of carbon emissions, as urban populations and economies expand (Ürge-Vorsatz et al., 2018). A consequence is that any effective measure to provide climate mitigation in urban settings must give priority to decarbonize the underlying energy systems powering them (Shukla et al., 2022).

In addition to operational emissions, urban regions also emit carbon indirectly in the form of embodied energy in construction material, product manufacturing, and infrastructure construction. The processes involved in manufacturing cement, steel, aluminium, and other construction materials carry highly fossil-fuel-powered processes that escalate the carbon intensity of cities (Hertwich et al., 2020). As urban populations expand, the demand for housing, commercial buildings, roads, and utilities increases embodied energy consumption, often overlooked in traditional energy assessments (Moran, Hasanbeigi, et al., 2018). Mitigating such indirect emissions requires an integrated approach that encompasses planning of urban areas beyond operational consumption of energy to incorporate urban planning strategies, circular economy principles, and sustainable material sourcing in order to minimize the climate effect related to urban growth (Haberl et al., 2017).

1.3 Global Frameworks and Policy Imperatives: Overview of relevant agreements and frameworks

To fully understand and tackle the state of the art on urban energy use and the climate impacts it comes with, coordination of international policy frameworks and there commitments are needed. responding to climate change, multiple global initiatives and agreements came together to unify international actions towards sustainable development and carbon reduction. For instance the Paris Agreement, adopted in 2015 under the United Nations Framework Convention on Climate Change (UNFCCC), addresses and emphasizes nations and asks them to limit global temperature rise below 2°C above pre-industrial levels, with ambitions to restrict it to 1.5°C (UNFCCC, 2015).

And of course the United Nations Sustainable Development Goals (SDGs), specifically Goal 7 (Affordable and Clean Energy) and Goal 11 (Sustainable Cities and Communities), clearly define the role of sustainable energy practices in addressing climate challenges (UN, 2015). These global frameworks act as a guide not only to the national scale but invites local actions towards urban sustainability and energy transition. supporting these global frameworks, regional policies such as the European Green Deal aim to align national and municipal actions with international climate commitments through ambitious targets for renewable energy adoption, emissions reduction, and sustainable urban development (European Commission, 2019b).

The European Green Deal highlights the need to achieve climate neutrality by 2050, promote strategies that effect the large-scale decarbonization of energy systems, enhance energy efficiency, and adopt circular economy principles in urban planning and infrastructure (European Commission, 2019b). likewise, urban initiatives like the Covenant of Mayors tells us how municipal authorities play the main role in translating global and regional climate targets to tangible local action, clearly pinpoints the importance of connection between policy frameworks at various governance levels and practical implementation strategies within cities (Bertoldi et al., 2018).

Despite global significance, the success of these frameworks ultimately depends on the extent to which they are operationalized through national policies and urban-level implementation. Cities, being major energy consumers and emission sources, are increasingly recognized as strategic actors in achieving climate goals (Revi et al., 2014). However, they often face challenges such as fragmented governance structures, limited financial autonomy, and inconsistent access to data and technological resources, which hinder their capacity to align local actions with international agendas (Bulkeley & Betsill, 2013). In light of these enduring warnings and given the lengthy period that climate mitigation has been on the global agenda, it is important to identify and critique key international governance measures that are currently in place and the consequences for implementing low-carbon and inclusive transitions

So, in order to bridge this implementation gap, we clearly require integrated multi-level governance approaches that empower cities with the authority, tools, and funding needed to act effectively within global sustainability frameworks, especially in the areas of energy planning and infrastructure development.

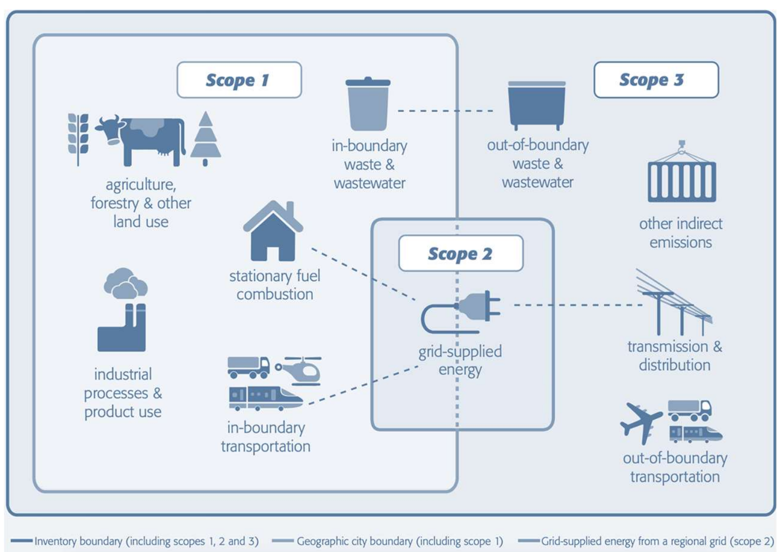

Figure 1.1: A schematic showing scopes 1, 2, and 3 emissions categories in the Global Protocol for Community-Scale GHG Inventories (Source: Global Protocol for Community-Scale Greenhouse Gas Emissions Inventories)

Converting global frameworks into effective, ready-to-go urban climate action requires consistent measurement and reporting of energy and emissions data at the city level. For instance, frameworks such as the Global Protocol for Community-

Scale Greenhouse Gas Emission Inventories (GPC) were developed to classify the emissions and scopes of cities (Figure 1.1), helping them to align with their climate targets that connect them to national and international goals (Wilmsen & Gesing, 2016).

Such tools not only help harmonize urban efforts globally but also facilitate transparency and accountability in tracking progress toward decarbonization. However, there remains considerable variation in data quality and methodological approaches across cities, particularly between developed and developing regions, highlighting the need for enhanced capacity-building and international cooperation in urban climate governance.

1.4 Problem Statement & Motivation:

The brief introduction made us already realise that despite all the global agreement on the need to cut carbon emissions, the efforts to decarbonize urban energy systems still remain scattered and poorly aligned, especially when it comes to local governance. Paris Agreement and the SDGs set direction, but they don't directly or clearly provide cities with the tools or authority to act.

Many municipalities face core issues that obstruct them from even starting, like outdated infrastructure, fragmented data systems, regulatory confusion, and social inequalities that block progress on the ground (Bulkeley et al., 2014). And these core issues or gaps become more evident when it comes to decentralizing renewable energy strategies, especially when technical potential often fails to translate into real deployment or impact.

One of the biggest challenges in making cities more sustainable is putting energy communities into practice. These are local systems where people, institutions, and buildings work together to produce, share, and manage a sustainable energy source. The idea has gained momentum, especially in the EU's Clean Energy Package. But in real urban planning and infrastructure, it's yet to be implemented (European Commission, 2019a). Especially for large institutional campuses, such as universities or international associations, which often possess significant spatial, technical, and social potential for renewable energy deployment, but most don't have the tools or rules to become working examples of energy-sharing systems. So, we miss key chances to test and grow local, connected, digital energy models right in the heart of our cities.

A fundamental disconnect between the spatial and technical modelling of renewable energy potential and the actual implementation of community-based energy systems remains. Most urban sustainability strategies treat energy planning, digital infrastructure, and social governance as separate domains, resulting in fragmented approaches that fail to deliver integrated, place-based solutions (Gouldson et al., 2015). As a result, the chance to design and operate localized energy communities, especially in dense cities as mentioned previously, gets overlooked or approached through purely technical and theoretical feasibility studies, which lack a real-life implementation process that assesses the real feasibility of Solar Energy Communities (SEC) without addressing how spatial, digital, and governance layers interact in practice.

This weak integration and connection limit both the understanding and the policy translation of energy communities as operational tools for post-carbon cities.

So there is a need and a clear gap to be filled for research that not only quantifies renewable energy potential but also embeds it within governance-ready, digitally enabled, and spatially explicit frameworks that cities can actually use.

1.5 Research Questions & Objectives

This thesis prioritizes results from practice and supports its theoretical framework. In doing so, it redefines energy communities as spatially grounded, which focus on precinct-scale solutions, demonstrating how the transition to low-carbon cities can begin, tangibly, in the places where people live, work, and collaborate.

All the complications that come with the issue of urban energy transition require research that is both analytically clear and grounded in real-world contexts. Guided by the gaps and needs identified above, this thesis paves the way to clarify not only how cities can accelerate the shift toward renewable energy but also what practical models and frameworks are needed to make this transformation both effective and replicable.

This research is organized around its hypothesis that centers on a set of interlinked questions and objectives, each targeting a core aspect of precinct-scale energy communities.

1. **What parameters (physical or abstract) limit the adoption of Solar Energy Communities (SEC) in urban areas and districts?**

   a. Using GIS and open-source data, can we overcome these barriers to achieve meaningful energy Self-Sufficiency and sharing?
   b. What rate of applicability makes SEC possible?
2. **What are and how can we establish anchor institutions that compose the SEC together? (Governance)**
   a. What are the financial means and support we have from the Frameworks and governments to make SECs?
   b. How can an Asset management system integrate buildings into SECs?
3. **What concrete strategies, drawn from the Turin and Geneva experiences, synthesize Urban Energy Precincts (UEP)?**

The primary objectives of this thesis are to:

1. **Increasing the self-sufficiency of solar energy communities** that are adopted in dense urban areas
2. **Develop and apply a GIS-based, open-data modelling framework** to assess and optimize solar energy potential at the campus and precinct scale.
3. **Evaluate and pinpoint anchor institutions** for a base model to scalable pilots for urban energy precincts.
4. **Conclude strategies and policies to implement** from case studies conducted in Turin and Geneva, providing practical guidance for cities seeking to accelerate their transition toward sustainability and energy Self-Sufficiency.
5. **Reduce complications** that are mostly linked with governance and bureaucracy
6. **Create systematic typologies** that can be implemented on city scales, reducing bureaucracy and technical complications..
7. **Connect** the stakeholders and precincts' citizens to SECs

Together, these objectives aim to generate both new knowledge and practical tools that support the advancement of sustainable, precinct-scale energy transitions in dense cities.

1.6 Thesis Structure

The remainder of this thesis will outline the research contributions made during the three years of the PhD project (funded from the PNRR) with a predefined topic in more detail. Chapter 2 provides an overview of energy communities and the driving forces behind them, and dives into their envisioned role in both EU and Swiss regulation. Chapter 3 will introduce the relevant framework and methodology of the thesis, before diving more closely into the results and contributions of (chapters 4,6,7). In the same vein, Chapter 4 will look at (RQ1), while Chapters 5 and 6 do this mainly on (RQ2) and touch on (RQ3). The findings and main recommendations of this work will be further developed in up in Chapter 7, addressing (RQ2) and (RQ3), and finally, Chapter 8 will wrap up the conclusions drawn, which will also propose some directions for future work in all 3 research questions and their branches.

1.7 Thesis contribution

This thesis describes the development of Solar Energy Communities (SEC) to address sustainable urban planning. 'Urban Energy Precincts' entail a variety of built environments that have been developed. In this study, the built environment is seen as a resource to be utilized in dense cities to mainly increase solar self-sufficiency in cities. This goal is not just set here, but it has become more prominent for different types of organisations in the knowledge-based economy (e.g., universities, firms, and municipalities). In this view, urban precincts are studied as resources supporting the goal of stimulating connections in multiple organisations. Exploratory research that uncovers and positions "Urban Energy precincts" in a broad theoretical and empirical context that is used to develop such knowledge.

This introductory chapter describes the rationale of the thesis and the ways in which the research has been conducted. First, it will describe the methodology and framework developed, which was used for the work. Then, it shows real-life applications in two selected cities and continues to focus on solutions to accommodate the path that achieves the objectives of the thesis.

The research context of the Ph.D. fellowship aims to fill the lack of adequate investigation in the field of energy planning tools and models in different spatial scales and their integration in territorial governance and spatial plans. The research project refers to the international framework of strategies and policies on climate change:

- The Paris Agreement (United Nations, 2015)
- The 2030 Agenda for Sustainable Development (2015) and the 17 United Nations Sustainable Development Goals
- The Intergovernmental Panel on Climate Change (IPCC).

Chapter 2

2. Literature Review: Energy and the Sustainable Urban Paradigm

2.1 Historical Evolution of Urban Energy Systems

Urban energy systems have improved over the last two centuries, specifically due the industrialization and urban growth. In the 19th century, cities ran on coal. It powered factories and expanded even more, but also locked in high-carbon infrastructure (Smil, 2018). In the 20th century, though, oil and gas took over. They reshaped transport, industry, and heating, pushing centralized energy models that scaled efficiently but increased fossil fuel dependence much more (Fouquet, 2016). By mid-century, large electricity grids shaped cities even. This history built the carbon-intensive urban systems we live with today.

From the late twentieth century onward, urban energy systems began to diversify in response to oil shocks, air quality, and advances in gas, nuclear, and energy-efficient sources, even as centralized electricity grids remained dominant (Smil, 2018; Sovacool, 2016). Since the 2000s, the cost has started to decline, and scaling in wind and solar has accelerated the shift toward low-carbon supply; for instance, the global average cost of utility-scale solar PV fell by roughly 90% between 2010 and 2022 (IRENA, 2022; Shukla et al., 2022). Moreover, cities added rooftop panels, district energy, heat pumps, and electric transport. Smarter controls and demand-side tools started to challenge the old one-way system (IEA, 2017; Shukla et al., 2022). This transition is one of the drives of the research that will be done in this thesis and many other initiatives of reducing carbon emissions and changing to a sustainable energy source.

Cities are rapidly expanding their boundaries and populations, and as noted,

> "From a climatological perspective, human history is essentially the history of urbanization" (Santamouris et al., 2001).

Trends of industrialization and urbanization have significantly increased the number of buildings in urban areas, which in turn has affected energy consumption trends. Moreover, if we look at history alone, the urban population has already grown from 600 million in 1920 to 2 billion by 1986 (Santamouris et al., 2001), then we slowly started to realise that we have done a carbon lock-in.

There are three layers that made us carbon lock-in: physical infrastructure (buildings, district networks, and one-way power grids sized for fossil heat), institutional rules and market designs that privilege centralized supply, and transportation systems that raise energy demand (Seto et al., 2016; Unruh, 2000). Without major changes, existing infrastructure alone could burn through a large part of the remaining carbon budget (S. Davis & Socolow, 2014; Shukla et al., 2022). Breaking lock-in requires interventions at an intermediate, coordinative scale (precinct scale), where shared renewables, thermal networks, storage, and managed loads can be aligned with local planning. Done right, these systems balance local supply and demand and still connect with the wider city grid (IEA, 2021; Shukla et al., 2022).

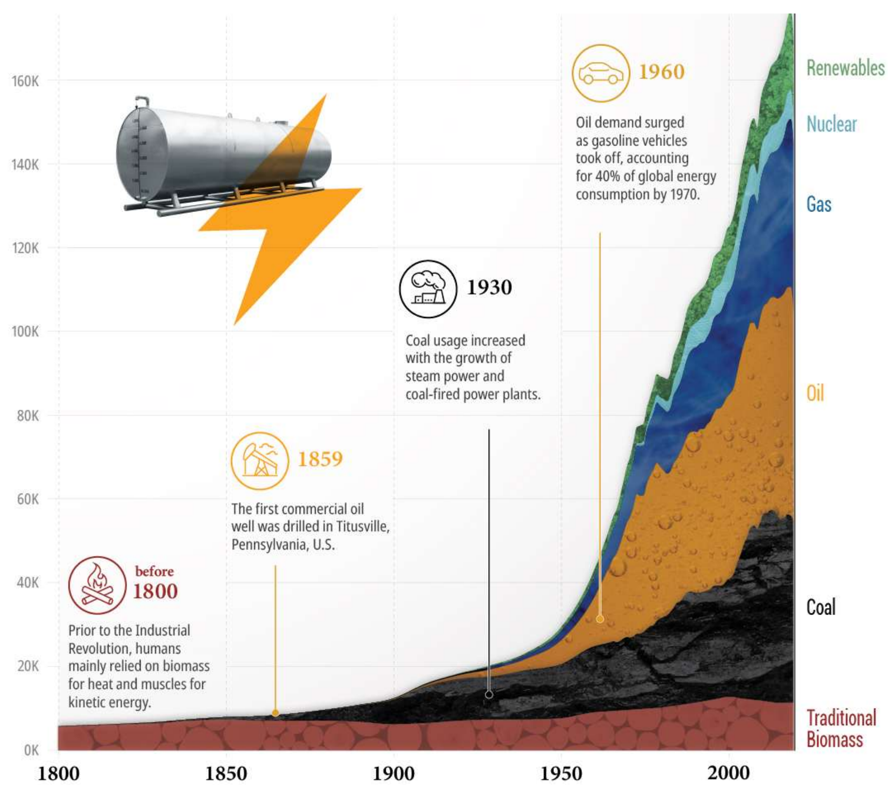

Figure 2.1: Parallel timeline with four tracks(1) dominant fuels, (2) infrastructures, (3) urban form, (4) policy/economy, highlighting the recent opening for precinct-scale coordination. (Source: Vaclav Smil (2017) and WE statistical review of the World Energy references)

If we look at each new energy system, we see that they have raised the carbon footprint of cities (Figure 2.1). Coal created dense, stationary emissions. Oil-powered transport stretched urban boundaries and ramped up mobility-related emissions. Natural gas lowered some intensities but locked in combustion-based heating. And today's electrification shifts a large share of emissions upstream to the grid, making the carbon intensity of electricity a decisive factor for urban mitigation (IPCC, 2022).

2.2 Energy Systems in Cities

Within the urban footprint, buildings and transport typically dominate operational demand, with trajectories shaped by how quickly we transition into a sustainable energy source, how spaces in the cities are utilised, and how carbon-intensive electricity is (Ramaswami et al., 2016; Ürge-Vorsatz et al., 2018), as shown in Figure 2.2. Taken together, these dynamics point to a coherent mitigation agenda: cut demand through efficiency and changing into a sustainable source, turning potential surfaces of the city into resources, and decarbonize the power supply, priorities repeatedly identified across quantitative assessments and multiple scenario analyses (Creutzig et al., 2017; S. Davis & Socolow, 2014; Grubler et al., 2018).

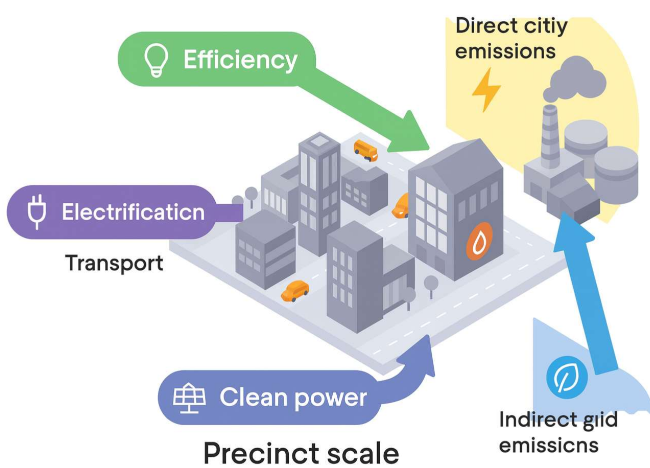

Figure 2.2: city emissions from (a) direct on-site combustion (buildings, transport, industry) and (b) indirect grid electricity/heat

Operational emissions are high in buildings and transport. Comparative inventories across global cities show building energy (electricity and fuels) as the largest contributor, with transport being the second; the balance shifts with climate conditions, density, income, and modal split (Creutzig et al., 2018; Kennedy et al., 2015). The core drivers are: buildings, area per capita (utilised and not), building insulation, heating and cooling needs, and appliance use; In transport: trip length, car ownership, street layout, and the carbon intensity of fuels (Creutzig et al., 2018; Ürge-Vorsatz et al., 2018). These drivers align with a concise set of precinct-scale levers: Reduce energy usage and make buildings energy efficient, employe under utilsed surface for Solar PV (rooftops, facades, and any other surface deemed possible), and redesign transport access and freight to shorten trips, shift to cleaner modes, and cluster EV charging on a low-carbon grid (however, this thesis focuses on the first part of drivers) (S. J. Davis et al., 2018; Grubler et al., 2018). Taken together, the sustainable urban precinct emerges as the scale at which demand reduction, energy production, and clean supply can be co-optimized in space and spread out through usage time.

Current urban emissions are misaligned with the decisions we need to make. City-level emissions don't fully account for the indirect emissions, like the carbon footprint of goods produced elsewhere but consumed in the city**,** (e.g. imported cement, steel, electronics, clothing) and they don't all follow the same rules when reporting emissions (Kennedy et al., 2015; Moran, Kanemoto, et al., 2018; Peters et al., 2011; Wiedmann & Minx, 2008). These inconsistent methods make it hard to:

- Compare one city's emissions with another's
- Know where to focus action (buildings? transport? imported goods?)
- Set clear, effective priorities for decarbonization

So, the result is a mismatch between the emissions data we have and the decisions cities need to make.

Not having clarity on such a topic makes cities and policymakers struggle to synchronize the three main pillars of decarbonization. If responsibilities and impacts aren't clear and transparent across these pillars, the transition momentum slows down:

- **Reducing the Demand**: lowering the amount of energy and materials needed.
- **Creating alternatives to sustainable energy sources**: shifting end uses (heating, transport, industry) from fossil fuels to electricity.
- **Clean supply chain**: decarbonizing the electricity that we originally used and the material supply chain.

2.3 Solar Energy as a Path to Current Sustainability Frameworks & International Commitments

The shift in population and scale mismatch that accommodates this shift affected energy trends in buildings. In a report by the IEA (Garde & Donn, 2014), the average annual growth in energy demand for buildings has been slightly over 1%. In 2022, there was an almost 1% increase in energy demand compared to 2021. Electricity constituted approximately 35% of total building energy use in 2022, marking a rise from 30% in 2010. Despite a shift towards alternative energy sources like electricity and renewables, the use of fossil fuels in buildings has been steadily increasing at an average annual growth rate of 0.5% since 2010 (Garde & Donn, 2014). Yet rising solutions like Solar technologies hold significant potential for generating sustainable energy in cities that mainly rely on the amount of solar radiation available (Šúri & Hofierka, 2004).

This city scale mismatch is between where energy is used, where renewables can be placed, and where networks can be created between them. Rooftop PV potential clusters spatially, but distribution imposes local hosting constraints; without coordination of PV, storage, and flexible hourly demand, projects take a lot of time and increase in cost (Good et al., 2015). At the same time, urban models rarely exploit open geospatial data and 3D building stock models to target surfaces like roofs, façades, and thermal synergies at the district scale (Nouvel et al., 2017). And when they do, the result is technically a feasible potential that remains practically inaccessible.

Adding to this, urban energy transitions are slowed by fragmentations in multi-layered governance, split incentives (owner, tenants), and market rules that were built for centralized systems (Geels, 2011). Even the best community models face equity and access risks if capital costs and tariff design exclude lower-income households (Carley & Konisky, 2020). These frictions show that even the technically sound projects lack a viable pathway from analysis to adoption.

So to reflect on what was said before, because buildings and transport dominate urban energy use, and because carbon lock-in resides in stocks and urban form, the highest-impact moves combine demand reduction, making a sustainable energy source as the end use, and integrate a sustainable infrastructure model into the existing one on a precinct scale. However, they must be co-optimized in space and coordinate using time (Creutzig et al., 2016; Grubler et al., 2018; Ürge-Vorsatz et al., 2018). The precinct is the actionable scale at which cities can align siting of PV and storage, make heat-pump retrofits with energy infrastructure where viable, and cluster EV charging with flexible loads (for transportation), creating a replicable pattern that scales up in the city (Ramaswami et al., 2016).

From this literature up until now, we can make a small remark: the current complexities of a city are not easy to tackle, and the global framework and goals set by the world are good, but there is no clear practical way to achieve them yet, which makes research currently a perfect laboratory to explore such endeavours.

However, these three levels do not deliver equally in all places or at all times. Electrification of heating and mobility cuts emissions most where electricity is already low-carbon; where grids remain carbon-intensive, it's better not to reduce emissions immediately but instead improve efficiency and then control how sustainable energy should be supplied at hours of high carbon-intensive supply (Creutzig et al., 2016; S. J. Davis et al., 2018; Jenkins et al., 2018). Without that alignment, we risk (Seto et al., 2016; Ürge-Vorsatz et al., 2018):

- Locking in outdated systems
- Creating stranded assets
- Wasting the chance for real carbon cuts.

Without a clear plan that says what to do, where, and when, cities slip into three traps. (i) **Lock-in happens** when old fossil equipment is replaced with the same or new gas heating; these choices set the emissions path for decades and make later change expensive (S. Davis & Socolow, 2014; Seto et al., 2016; Unruh, 2000). (ii) **Stranded assets** will eventually occur when investments that seemed sensible lose value quickly, especially when utilizing space in such dense areas that make rules tighten, which forces early retirement (Mercure et al., 2018). (iii) **Muted gains** occur when good ideas are done in the wrong place or order: heat pumps in poorly insulated buildings, electric cars charged when electricity is still very carbon-intensive, or solar PV is added where the local network cannot absorb it or does not take the time of sharing as a factor (Jenkins et al., 2018; Szinai et al., 2020; Ürge-

Vorsatz et al., 2018). The way around these risks is to plan by neighbourhood (precinct): map where energy use is highest (Figure 2.3), where buildings are easiest to fix, where electricity is cleanest (or soon will be), and where there is room on the lines, then roll out insulation, heat pumps, solar and charging in that order and in those places. This "right measure, right place, right time" logic turns climate targets into projects that work. This thesis takes inspiration from this visualization and reflects it on targeting areas with high solar potential and area with a potential of coordination.

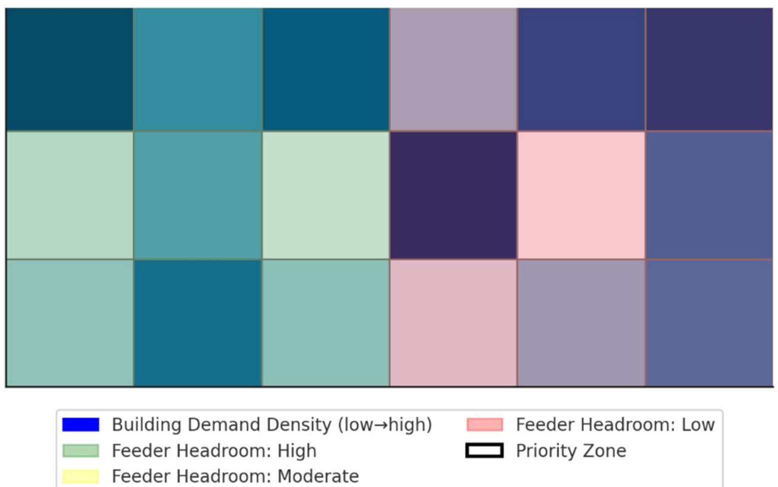

Figure 2.3: A spatial, precinct-scale view, precinct map concept overlaying building demand density with feeder headroom to illustrate where to electrify first, illustration by the author based on Ürge-Vorsatz et al. (2018); Seto et al. (2021).

And as stated previously this thesis works on achieving global sustainability frameworks that set the pace and direction for what they define urban decarbonization to be. The Paris Agreement's temperature goals imply rapid declines in energy-related emissions this decade, near-complete decarbonization of electricity by the 2030s–2040s, and net-zero CO_2 around mid-century to keep 1.5 - 2 °C within reach (Intergovernmental Panel on Climate Change (IPCC), 2022; IPCC, 2018; Rogelj et al., 2016) Figure 2.4 shows CO_2 pathways aligned with the Paris temperature goals. Current national pledges fall short of these trajectories, which elevates the importance of sub-national action, especially in cities where electrification of heating and mobility, coupled with clean power, is decisive (Creutzig et al., 2018; Rogelj et al., 2016). Running with this goal are specifically Sustainable Development Goals 7 and 11, which anchor an agenda (universal access to modern energy and sustainable, resilient urban development), creating a combined mandate for cities to reduce demand, electrify end uses, and align with rapidly decarbonizing grids (Nilsson et al., 2016).

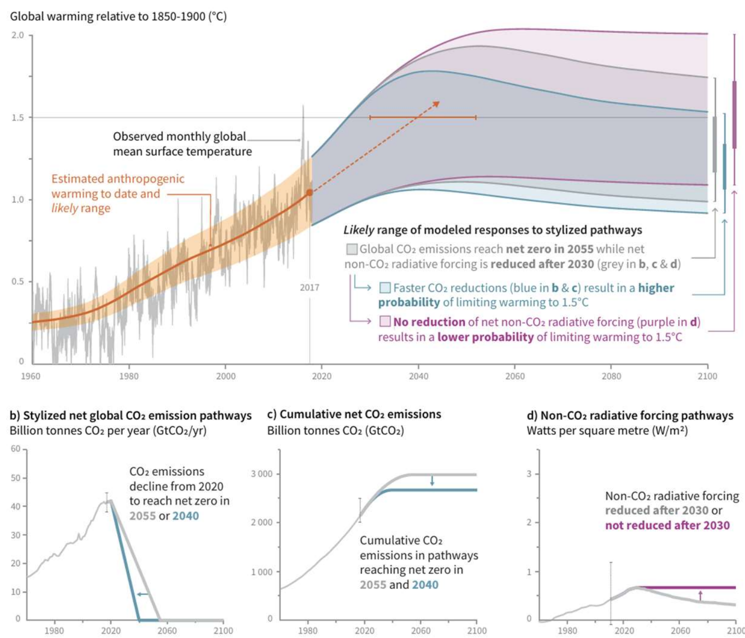

Figure 2.4: Illustrative CO_2 pathways aligned with the Paris temperature goals, highlighting steep near-term reductions and net-zero around mid-century. Source: IPCC (2018).

Translating global goals into local action depends on how each city measures emissions and what boundaries it uses. Community-scale standards such as the Global Protocol for Community-Scale Greenhouse Gas Inventories (GPC) clarify Scopes 1–3 for cities and align accounting with national targets, improving comparability and tracking over time, which include scope 1 as emissions from within a city, scope 2 includes indirect emissions from purchased energy, and scope 3 includes indirect emissions from supply chains (ICLEI et al., 2014). Many cities ignore consumption-based emissions in the city, especially when it comes to embodied emissions in construction materials and traded goods, and shift priorities away from the most effective interventions (Kennedy et al., 2015; Moran, Kanemoto, et al., 2018; Peters et al., 2011; Wiedmann & Minx, 2008) Europe suffer much less from emission outside the cities compared to cities in Asia or Africa, However there is still a lot of renovations that need to happen to make buildings more efficient (Filimonova et al., 2022; Lützkendorf & Balouktsi, 2022).

Adding this knowledge, this thesis will focus its efforts on what constitutes a post-carbon city within its boundaries, focusing on employing Solar PV, and emphasizing the weight of Sustainable Development Goal (SDG) 7, which becomes very important. The fast installation time and low levelised cost of Rooftop Solar photovoltaics (RTSPV) can aid in mitigating the problem of energy access in cities by making citizens or communities a prosumer (Joshi et al., 2021). The prosumer can generate and consume electricity as per their need without depending on a centralized grid infrastructure. As the fastest deployable energy generation technology with the highest year-on-year growth rate (IEA, 2020), solar PV technology is projected to supply 25–49% of the global electricity needs by 2050 while employing up to 15 million people between 2018 and 2050 (IRENA, 2019a). Out of this, RTSPV alone will contribute up to 40% of the total solar PV-derived electricity generation by 2050.

Nearly 20% of the global potential lies in the high-density areas where the deployment of RTSPV can aid in displacing fossil fuel-derived electricity with less polluting electricity generation, thereby reducing carbon emissions. It's important to note that 55% of the global RSTPV potential is spread across low-density areas. So, providing cost-effective and fast deployable electricity can be realized in rural areas within a city as well (Joshi et al., 2021)

Despite the studies of Joshi's limitations and shortcomings, their current assessment is still the state of the art and provides researchers with global analysis datasets. These methods and datasets have been peer-reviewed and are of the highest quality currently available. They mark a major step forward compared to those used in earlier studies, knowing this RTSPV will be considered as the base model for technical application in the case studies conducted here, and establish the indicators that will steer this thesis.

To steer investment where it delivers most, these indicators should be mapped by neighbourhood, for example, high demand spots, roofs with high solar yield, and places where the local grid has room for new loads or RSTPV, so that targets, budgets, and projects line up synchronise (Bai et al., 2018; Bertoldi et al., 2018).

Taken together, all of the above frameworks and methods become actionable when they are translated into clear visual maps that are scheduled at the precinct (neighbourhood) scale. Recalling the literature and the most relevant sources to finalise this section, identifying where demand is highest, where roofs can deliver solar power, and where the local grid can accept new loads, then sequencing measures accordingly.

Planning at this scale aligns sector goals with urban form and infrastructure, avoids lock-in and stranded assets, and converts climate commitments into prioritized, buildable projects (Creutzig et al., 2018; Grubler et al., 2018; Kennedy et al., 2015; Ramaswami et al., 2016; Seto et al., 2016).

2.4 Energy Communities and Local Governance:

Energy communities connect households, institutions, and local people to co-produce, share, and manage energy services. Recategorizing people from passive consumers to active owners and managers of their own energy supply and demand (Parag & Sovacool, 2016; Walker & Devine-Wright, 2008). Energy communities add a lot of advantages (Bauwens, 2016; Wierling et al., 2018) like inducing Greater public acceptance of renewable energy, adding job opportunities, creating flexible energy demand, and enforcing stronger participation in neighbourhood decisions.

Relying less on technology, community services, and more on governance. Entities that can join, invest, and share the energy surplus usually shape the outcomes of how an energy community can be established (Bauwens, 2016). Having said so, good governance can turn energy communities into long-term tools for urban decarbonization. Poor design leaves them as one-off pilot projects with little impact (Wierling et al., 2018). In a study conducted across 24 diverse community energy projects throughout Europe, the main drivers for participation in community energy initiatives were identified as (Caramizaru & Uihlein, 2020):

- Investment in sustainable infrastructure (80%),
- Production of green heat and electricity (72%)
- Financial motives (52%)
- Social and environmental sustainability (48%)
- Self-sufficiency (32%).

2.4.1 What are Renewable Energy Communities (RECs) and how do they work

Renewable Energy Communities (RECs) are open, voluntary, and non-commercial entities that produce, share, and consume renewable energy. (Soeiro et Dias, 2020; Campos, 2020). They are collaborative initiatives where individuals, businesses, and organizations come together to produce, manage, and share energy resources, typically focusing on renewable sources such as solar, wind, or hydropower (Roberts, 2019). These communities show the local stakeholders the opportunity not only to manage and create their own energy needs, but also to promote sustainability goals and put their cities into the global framework (Caramizaru & Uihlein, 2020). By hosting collective ownership and decision-making processes, energy communities prioritize the interests of their members and contribute to local economic development (Kooij et al., 2018).

Additionally, they enhance energy independence and security by producing energy locally, which minimizes transmission losses and vulnerability to external supply disruptions (Hewitt et al., 2019). Despite their benefits, they face challenges, such as technical and financial, so they need supportive policies and access to funding to see and reach their full potential (European Commission, 2019a).

In Europe, they engage citizens by relying on the local energy transition, local authorities, and businesses in the joint production and management of renewable energy resources (Caramizaru & Uihlein, 2020). The European Union's Renewable Energy Directive II emphasizes the critical role of such communities by providing a supportive legal framework and recognizing the role of Renewable Energy Communities (RECs) in achieving sustainability goals (European Parliament, 2018a).

Solar energy communities (SECs) are basically under the umbrella of EU-recognised energy communities that centre on photovoltaic (PV) generation, collective self-consumption, and local energy sharing. In EU law, the umbrella concepts are (RECs) in the Renewable Energy Directive (RED II) and *Citizen Energy Communities* (CECs) in the Internal Electricity Market Directive (IEMD). This combination formalises the community-owned entities, whether it's open, voluntary participation and member control (European Commission, 2019a; European Parliament, 2018a). SECs manage these provisions specifically for solar electricity, like shared PV assets, peer-to-peer exchanges, and neighbourhood-level allocation, linking technical arrangements for metering and settlement with participatory governance (Caramizaru & Uihlein, 2020).

In general, PV is the most utilized technology across European energy initiatives. Comparative studies show that cooperatives and community-based entities have contributed to PV deployment, social acceptance, and local investment, while considering the policy instruments that are induced, such as feed-in tariffs (Wierling et al., 2018). Through a comparative study between the Spanish, Italian, and Swiss contexts, Poletti et al. (2025) emphasized that the successful implementation of SECs depends on strong integrated governance and the effective coordination of energy planning tools and stakeholder engagement across local, regional, and national levels.

Foundational work done on Renewable energy communities pinpointed that these initiatives require attention to both the process (ownership, control, participation) and outcomes (economic benefits), which is a current standard in REC design and appraisal (Walker & Devine-Wright, 2008).

Like many initiatives, there are always implementation barriers. Regulatory analyses from different countries show that there are some recurring challenges around grid access, metering, settlement for energy sharing, tariff design, and the evolving role of distribution system operators (DSOs), all of which complicate neighbourhood-scale PV exchange and collective self-consumption (Campos et al., 2020). Policies on mobility of RED II highlight that enabling frameworks must be coupled with clear operational rules and citizen participation, alongside financing models resilient to declining export remuneration (Hoicka et al., 2020).

REC in cities mainly have two main roles, for the way they are designed, energy communities usually have members that produce more electricity than needed, and some others to consume more than they produce. The first ones are called *prosumers* as they both produce and consume electricity at different times of the day, sharing the surplus of energy within the community, while the second ones are called *consumers*, as they are not able to share the surplus of energy (Luthander et al., 2015; Parag & Sovacool, 2016).

They are fundamental to any type of RECs, as they only work if some of their members can share their surplus with members who need it (Brummer, 2018; Caramizaru & Uihlein, 2020). Making communities more efficient themselves and avoiding drawing electricity from the grid. Moreover, RECs are now designed to receive an economic incentive for each MWh of energy shared within the community in Italy; specifically, an incentive is paid per kWh of shared energy (European Parliament, 2018a; MASE, 2022). So the more energy produced, the more economic incentive received. In this context, the shared energy is defined, on an hourly basis, as the minimum between the amount of electricity fed into the grid by the production plants and the amount of electricity drawn from the grid in the same energy market area.[1]

Accordingly, the closer the amount of energy produced with respect to the energy consumed, the higher the amount of energy shared and the economic incentive received, which is one of the main goals of increasing self-sufficiency (SF).

The main point here is to illustrate how energy communities offer an alternative to the current energy production and distribution model. When comparing it to centralized systems, Renewable Energy Communities (RECs) make three major types of benefits possible, which are outlined in Directive 2018/2001/EU:

1. **Environmental benefits**
   RECs generate electricity without emitting CO_2., and they reduce energy through the grid.

2. **Economic benefits**

   RECs earn incentives based on the amount of energy shared within the community. The members can then reinvest in another public REC or reinvest revenue into better services. In case it's a private REC, people can use the savings and sell them to other members, lowering energy bills across the board.

3. **Social benefits**

   RECs give communities control over their own energy. This strengthens local independence and can also stimulate the local economy by creating jobs. In this way, the energy transition isn't just about cutting carbon; it's a tool for building energy equity and resilience where people live and work.

Setting up energy communities in cities isn't straightforward. In rural areas, it's usually easier because we often deal with single owners and tighter social networks. Cities, on the other hand, face split incentives, high tenant turnover, and messy legal or technical issues in multi-owner buildings (Gui & MacGill, 2018; Koirala et al., 2018).

---

[1]The definition of "shared energy" is given by the Legislative Decree 199/2021, Art.2 (f). The full text in the original version is available at the following link: file:///D:/geen%20office/CER/doc/d.lgs%20199_21_decretomilleproroghe.pdf

People in apartments usually don't have roof access or control over shared infrastructure. Utilities add limits with metering, billing, and grid rules, which makes sharing energy across buildings harder (Lowitzsch et al., 2020). This is why governance matters. Several studies suggest that successful community-energy or commons-based projects often rely on an institutional organization (for example, a city authority, cooperative organization, or university) that can coordinate participants and manage collective benefits (Bauwens, 2016; Kalkbrenner & Roosen, 2016).

Making a small remark on the above, we can see that Projects that succeed often have a strong anchor that can hold things together and manage the complexities that come with densifying cities, making energy communities a path that grows into this gap. Filling the gap of what communities can do and what they demand.

As stated in the previous sections, given that cities are dense, they make energy communities hard. Tenants move out fast, buildings have split ownership, and shared spaces like rooftops aren't easy to use (Gui & MacGill, 2018; Koirala et al., 2018). Even if the tech works, rules and grid limits block energy sharing across properties (Lowitzsch et al., 2020). Without a plan, cities risk small pilots that go nowhere, or worse, bad designs that waste money and get stuck. Without solid support, energy communities fall short, technically, financially, and socially (Bauwens, 2016).

If we take a step back and look at their beginning with rural cooperatives in the mid-20th century, where locals pooled resources to bring electricity to areas that national grids hadn't reached (Walker & Devine-Wright, 2008). In Europe, a second wave emerged in the 1990s. Market liberalization and growing concern over environmental impacts sparked new models (Seyfang et al., 2013). Since then, approaches have multiplied.

In cases like Courant d'Air in Belgium, Coopernico in Portugal, and Zuiderlicht in the Netherlands, we see how governance shapes outcomes. Whether the model is state-driven, cooperative, or market-hybrid, the rules and context decide whether energy communities can grow or not (Petrovics et al., 2024). Milan's Chiaravalle district tested virtual energy sharing within existing laws. The team had to combine technical design, social engagement, and energy modelling to make it work in a real urban setting (Ferroni et al., 2024).

All of these points to the same conclusion: collective ownership still works, but in cities, structure is everything. Without the right mix of governance, regulation, local coordination, and public buy-in, it doesn't scale.

2.5 The Italian context

Italy has seen a wave of energy community pilots, especially in urban and peri-urban areas. Some show real promise, others reveal what still holds the system back. In Magliano Alpi, one of the country's first pilots, modelling with Mixed-Integer Linear Programming (MILP), which is a mathematical optimization method used to find the most cost-efficient energy-system design or operation when some decisions are discrete (e.g., build or not build) and others are continuous (e.g., power flows), showed that prosumer participation and capacity expansion can stay economically viable if incentives are well designed (De Santi et al., 2022).

In Reggio Calabria, a building-level PV system tied to the grid brought clear energy and financial gains. It also proved that shared systems work better when investments are coordinated (Marino et al., 2024). Naples tested a district-scale model. Local PV production could meet nearly all electricity demand, but only with long-term planning and a solid governance setup (Aruta et al., 2024).

On a national scale, analyses show most energy communities in Italy still operate at a small scale. They often lack diverse actors, and many run into regulatory grey zones and bureaucratic delays (Brunoro et al., 2024). Which means that technical potential isn't enough, energy communities need a bigger overview of the policies implemented from a national to a local scale, with well-designed incentives, and planning that ties into district-level frameworks.

Italy's energy communities didn't appear on their own. They came out of EU legislation, mainly Directive 2018/2001 (RED II), which formally recognized "renewable energy communities." Italy brought this into national law with Law 8/2020, which allowed groups of prosumers on the same low-voltage substation to share power (Caramizaru & Uihlein, 2020; European Parliament, 2018b).

The Milleproroghe Decree and ARERA Resolution 318/2020 listed the tariff rules and outlined how to share surplus energy inside communities (ARERA, 2020). Later, Legislative Decree 199/2021 updated the framework again. Aligning the Italian law with RED II and RED III raised the limit to 1 MW per production unit and opened up participation to municipalities and public bodies (GSE, 2022).

The system, however, is still complicated, incentives aren't always clear, and grid operators are still the dominant force on the market. So even with strong political support, regulation hasn't yet translated into action, especially in cities (Brunoro et al., 2024).

2.5.1 Renewable Energy Community in the Italian regulation framework

Renewable energy communities were introduced in Europe by the 2018/2001/EU Directive, known as the Renewable Energy Directive (RED II).[2] In Italy, this Directive was initially transposed by Decree Law 162/19[3], afterwards by the Legislative Decree 199/2021[4] and the Legislative Decree 210/2021.[5] In January 2023, the ARERA (The Italian Regulatory Authority for Energy, Networks and Environment) Resolution, better known as *Testo Integrato per l'Autoconsumo Diffuso* (TIAD), was adopted, which regulates the modalities, requirements, and procedures needed for the establishment of a REC.

According to this resolution, RECs can be established under two main conditions (ARERA, 2023):

1. Members of RECs must belong to the same primary cabin[6].
2. RECs' power plant must be lower than 1 MW.

Furthermore, on 22 November 2023, the European Commission approved the Italian decree regarding the economic incentive for renewable energy self-consumption, which establishes the economic incentives a REC can obtain. According to this decree, two kinds of incentives are provided: the *Incentivo in Tariffa* and the *Contributo a Fondo Perduto* (MISE, 2023). Both these incentives can be applied to all renewable energy technologies, such as photovoltaic, hydroelectric, wind power, and biomass.

---

[2]The full text of the 2018/2001/UE Directive in the original language version is available at the following link: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L2001;
[3]The full text of the Decree Law 162/19 in the original language version is available at the following link: https://www.gazzettaufficiale.it/eli/id/2019/12/31/19G00171/sg;
[4]The full text of the Legislative Decree 199/2021 in the original language version is available at the following link: https://www.gazzettaufficiale.it/eli/id/2021/11/30/21G00214/sg;
[5]The full text of the Legislative Decree 210/2021 in the original language version is available at the following link: https://www.gazzettaufficiale.it/eli/id/2021/12/11/21G00233/sg;
[6]The primary cabin is the high voltage cabin, i.e. an electrical system that has the function of transforming high voltage energy into medium voltage energy.

The *Incentivo in Tariffa* is a 20-year fixed incentive issued to the RECs on Italian soil that applies to them within 120 days from the entry into operations of the power plants. This incentive is calculated on the amount of MW of energy shared within the community, for a maximum threshold of 5 GW until 2027. The Incentivo in Tariffa is made up of two parts: a fixed part, which depends on the size of the energy plant's power, and a variable part, which depends on the geographical area in which the plant is located (i.e., North, South, and Centre of Italy)[7]. For example, a CER located in Turin (Piedmont) with a power plant of 600 W will receive an economic incentive of 60€ for each MWh of energy shared within the community (i.e. fixed part of the incentive) and an additional 10€ for each MWh of the same energy shared (i.e. the variable part of the incentive) because it is situated in a north Italy region.

The *Contributo a Fondo Perduto*, instead, is an economic incentive addressed to RECs located in municipalities with less than 5.000 inhabitants. It can cover a maximum of 40% of the eligible costs incurred for the establishment of the REC, and it can be provided for plants with a minimum power of 2 GW only (MISE, 2023).

RECs in Italy depend on targeted incentives, the most important is the (Tariffa Incentivante) from GSE, which is about €110 per MWh of shared electricity, guaranteed for 20 years, on top of market revenues (GSE, 2022). Made to shorten payback times and make collective self-consumption financially viable.

The Recovery and Resilience Plan (PNRR) backed this further, with a total of €2.2 billion to support at least 2,000 new RECs, focusing on towns under 5,000 residents (MASE, 2022). Other tools, like Conto Termico, also contribute to national energy savings. ENEA reports them annually in its Rapporto sull'Efficienza Energetica, though their impact on ECs remains small due to complex rules and limited eligibility (ENEA, 2022). Still, there's a catch. Studies show that shifting rules and regulatory uncertainty continue to slow down wider adoption (Brunoro et al., 2024). Incentives work, but only when they're clear, stable, and backed by governance that makes them easy to use.

Permitting and grid connections pose an issue for small players, making many pilot projects never scale up (Candelise & Ruggieri, 2020). Recent projects

[7]This part of the incentive was introduced to compensate for the different sun exposure between the north, south and middle regions of Italy.

highlight two recurring issues: admin complexity and an unclearly defined business model, both of which make replication harder (Tatti et al., 2023).

Rolling out renewable energy communities in Italy depends on several key institutions, each handling a different part of the system:

- ARERA sets the rules. Through the Testo Integrato Autoconsumo Diffuso (TIAD), it defines how shared energy is measured, priced, and compensated (ARERA, 2022).
- GSE runs the incentives. It checks project eligibility, manages payments under the tariffa premio, and oversees funding from PNRR grant programs (Bollino, 2009).
- ENEA supports on the technical side, offering guidance and publishing annual reports on programs like Conto Termico and Superbonus. But its role in energy communities is still limited (ENEA., 2022).

Currently, Municipalities act as both facilitators and early participants, with no single point of coordination it leads to grid connection delays, useless bureaucratic steps, and variations of local capacity (depending on the area). All of this shows the lack of connections between agencies and municipalities (Brunoro et al., 2024; Candelise & Ruggieri, 2020). Until these points are addressed directly, institutional complexity will keep limiting the pace and reach of energy communities in Italy.

Decreto CACER (MASE n. 414/2023) (GSE, 2025a) outlines the financial incentives for Italian energy communities. The main tool is the tariffa premio (TIP), paid by GSE for shared renewable electricity. It has two parts: a fixed base and a variable bonus tied to the zonal electricity market price (Pz).

- Systems ≤ 200 kW: 80 €/MWh fixed + up to 40 €/MWh variable (cap: 120 €/MWh)
- 200 kW to ≤ 600 kW: 70 €/MWh fixed (cap: 110 €/MWh)
- 600 kW: €60/MWh fixed (cap: 100 €/MWh) (GSE, 2024a).

Photovoltaic systems also get regional incentives classified as 10 €/MWh in Northern Italy and 4 €/MWh in Central Italy, to account for the lower solar yield (GSE, 2024b). For the TIP, it is locked in for 20 years from commissioning, and RECs in municipalities with fewer than 50,000 residents could get a capital grant that covers up to 40% of eligible investment costs through PNRR funding (GSE, 2023). But if they decode to take the grant, the TIP gets reduced proportionally (Regione Emilia-Romagna, 2024).

Table 2.1 Tariffs in Italy

Plant Size (kW)	Fixed TIP (€/MWh)	Variable TIP (€/MWh)	Maximum Total TIP (€/MWh)	Geographic Bonus	Incentive Duration	Capital Grant (PNRR)
Less than 200	80	Up to 40	120	+10 €/MWh (North) +4 €/MWh (Center)	20 years	Up to 40% of <50,000 residents (with TIP reduction)
Between 200 and 600	70		110			
Bigger than 600	60		100			

All these regulations above are made to establish financial feasibility across different project sizes. Noting that, the technical rules, caps, and overlapping conditions can still be hard to navigate, especially for small initiatives, without institutional support. The main tariffs that would be used for calculation are: P (self consumed), which is between 0.18-0.22, and P (sold to the grid), which is 0.12, and TIP (shared)=0.115

2.5.2 How the Italian Electric Grid Operates

In Italy, both collective self-consumption (within a single building) and renewable energy communities (across buildings and actors) use the public distribution grid (not private wires) to share energy (ARERA, 2022). For RECs, all production and consumption points (PODs) must be under the same cabina primaria (a high/medium-voltage substation). GSE's interactive map in Figure 2.5 shows where these boundaries fall, and they define the geographic limits for urban projects (GSE, 2025b).

Currently, only smaller plants with a capacity of up to 1 MW per unit have the ability to access TIP incentives and support from the PNRR. The premium (TIP) is paid solely on shared energy, which is calculated on an hourly basis: essentially, the minimum amount determined by what member plants inject into the grid and what members consume during that same hour through self-consumed energy (ARERA, 2022; GSE, 2025a).

This arrangement influences city planning to maximize returns from shared energy and:

- Keep loads and PV under the same primary cabin,
- align operating hours so that daytime office demand matches PV output.

- Use storage or shift demand to raise the hourly shared energy minimum.

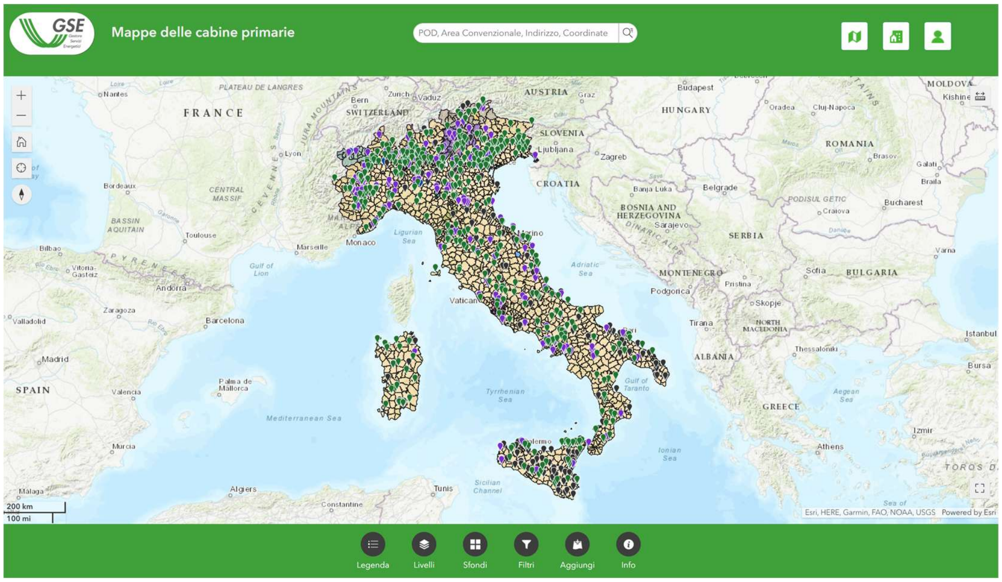

Figure 2.5: Interactive map of the cabins in Italy (GSE, 2025b)

An energy community must be run by its members and exist mainly to deliver local environmental, economic, or social benefits, not to maximize profit (Directive (EU) 2018/2001 availabile in Appendix B, art. 22; Directive (EU) 2019/944, art. 16). In practice, Italy has different legal form, depending on open participation and community control. The Common legal forms are:

- **Association (associazione):** community-driven for small pilots, neighbourhoods, and early engagement.
- **Cooperative (cooperativa)**: one-member-one-vote, built for shared ownership.
- **Consortium or SPV/S.r.l. (special-purpose vehicle)**: a company created just for the assets.
- **Municipal-anchored hybrid (association and municipality)**: a great choice for using public roofs, speeding permits, and credibility with GSE.

GSE's Regional Operative (CACER) outlines the technical and economic rules for membership (based on meter/share) and incentive distribution, irrespective of the chosen legal entity. The choice of entity will mainly influence factors such as voting rights, contracting parties, liability allocation, etc(GSE, 2024).

Table 2.2: Legal forms for Italian energy communities (CER/CEC)

Legal form	Finance & bankability	Admin burden	REC compliance fit	Typical urban use-case	Pick this when
Association (Associazione)	Low; relies on grants, member fees; lenders may require a partner/SPV	Very low (fast to start)	High (easy to show community purpose & open participation)	Street/block pilots; condo clusters; early engagement	**speed, inclusion, and trust-building** before large investments
Cooperative (Cooperativa)	Medium: better credibility with banks; can raise member equity	Medium (audits, boards, reporting)	Very high (aligns with "community benefit" test)	Multi-building REC under one cabina primaria; mixed households/SMEs	want fair governance and long-term participation with some bankability
SPV / S.r.l. (Special-purpose company)	**High**; familiar to banks; clean asset/risk ring-fencing	Medium	Medium (ensure open participation & local benefit in statutes)	Larger rooftop/parking-canopy PV; storage; third-party stakeholders	need project finance and stakeholders
Consortium (Consorzio)	Medium; depends on members' strength	Medium–high (coordination overhead)	Medium–high (good for multi-actor local value chains)	Campus/district with multiple owners (e.g., SMEs + municipality)	need peer coordination without creating a new company
Municipal-anchored hybrid (e.g., Co-op/Assoc. + Municipal SPV/PA)	**High** (access to roofs, credit, grants)	Medium–high (public procurement, compliance)	**Very high** if community control is explicit	City halls, schools, and social housing as **anchor loads/roofs**	need public assets, faster permitting, credibility

In this thesis, the case study will focus on the last 2, consortium and municipal hybrid, to create a new type of governance that reduces their limitations.

2.6 The Swiss context

The literature consistently calls for implementation-ready SEC models that integrate (i) REC/CEC legal provisions with PV-focused collective self-consumption mechanisms; (ii) participation pathways extending beyond early adopters to ensure equity, scale, and community participation; and (iii) business models under changing policies that prioritise on-site use and local exchanges (Caramizaru & Uihlein, 2020). These gaps motivate the present study's focus on how an SEC can be designed and governed within a concrete legal and market setting.

Switzerland now recognises two complementary instruments that enable local sharing of solar electricity:

- **Self-consumption** (Regroupement pour la Consommation Propre) (RCP, German: ZEV) allow groups within one or more buildings to jointly produce and consume PV power through a dedicated physical microgrid and settle internally (based on the Energy Act, EnG, and Energy Ordinance, EnV) (SFOE, 2023; SFOE, 2022). From 1 Jan 2025, a virtual form (RCPv / vZEV) was introduced: the DSO's existing low-tension connection lines and smart meters can be used to aggregate meters virtually, easing implementation without rewiring (SIG, 2025c; Swissolar, 2024; valfor, 2025).

- **Local electricity communities** (CEL / Communautés Electriques Locales, German: LEG): a market design that, from 2026, permits trading locally produced electricity via the public grid within a neighbourhood in the limit of the municipality border, widening the spatial scope beyond building parcels (SFOE & DETEC, 2024). These CELs are expected to improve the utilisation of available roof/façade area for PV.

So why does this matter for SECs? Together, RCPv lowers transaction/installation frictions for collective self-consumption, while CEL enables local exchange over the public grid at the district/municipal scale, precisely the design space needed for a solar energy community in Geneva's UN district. These instruments operationalise EU-style community energy principles in Swiss law while remaining tailored to Swiss grid governance (SFOE, 2024; SFOE, 2023).

2.6.1 Renewable Energy Community in the Swiss regulatory framework

A key market change arrives from January 1st, 2026: remuneration for injected renewable electricity will follow the quarterly average market price at the time of injection, with minimum tariffs introduced for small/medium PV to guard against very low market prices (especially in high-PV seasons) (EnergeiaPlus & Swiss Federal Office of Energy (SFOE), 2024; SFOE & DETEC, 2024; Swissolar, 2024). This shift increases the value of self-consumption and local exchange relative to uninstructed exports, particularly in summer mid-day periods when market prices can sag (Groupe E, 2025).

Moving on a more local scale, Geneva has positioned solar PV as a central pillar of its energy transition. Energy Master Plan of Geneva 2020–2030 (PDE) sets the canton's pathway to 2030/2050 and explicitly prioritises reducing fossil demand while optimising local renewable resources, including rooftop and façade PV (Cantonal Energy Office (OCEN), 2020). One of the targets of this Master plan is to reach a total solar PV capacity of 300 MWp by 2030. This policy thrust is operationalised through cantonal instruments, notably the solar cadastre that quantifies site-specific PV potential and supports project pre-feasibility for buildings across the Grand Genève (Desthieux & Thebault, 2024; Thebault et al., 2022).

Although enabling conditions have improved, solar remains under-deployed relative to technical potential. The solar cadastre estimates 1,600 MWp of rooftop potential across the agglomeration (Thebault et al., 2022), while installed PV capacity in the canton was reported at only 146 MWp in 2024 (SIG, 2025b), which represents only the halfway of the cantonal target (300 MWp) This discrepancy underscores the importance of mechanisms that increase self-consumption and local exchange, especially under evolving remuneration schemes that will lower export values from 2026 (Federal Council, 2025).

In this Thesis, for a SEC in the UN district and UniTo Campuses, the best path is therefore: (i) maximise the self-consumption of solar energy within the producers' building, (ii) maximise the self-sufficiency (SFOE & DETEC, 2024; Swissolar, 2024).

2.6.2 How the Swiss Electric Grid Operates

As mentioned in the literature, the global energy system is shifting to decarbonization, decentralization, and digitalization. The current infrastructure we have (the central grid) is a large-scale, centralized power generation and long-distance transmission to consumers (International Energy Agency (IEA, 2022). While effective in scaling energy access, this model is vulnerable to outages, carbon intensity, and a lack of local resilience.

In order to adapt, the microgrid and the virtual grid came to be. A microgrid is a localized energy network that integrates Distributed Energy Resources (DERs) such as solar photovoltaic systems, combined heat and power units (CHP), and energy storage. It is capable of operating both in connection with and independently from the main grid through a process known as islanding (Lasseter, 2002). Microgrids have resilience and efficiency, especially in an infrastructure setting like campuses, hospitals, and remote communities. However, their limits include high capital costs, technical complexity, and fragmented regulatory frameworks.

Meanwhile, virtual grids, also referred to as virtual power plants or virtual energy communities, make use of digital infrastructure to sell energy among their members without the need for a physical connection. These systems enable geographically dispersed prosumers have the ability to join in collective self-consumption models (International Renewable Energy Agency (IRENA, 2019b). Such virtual grids offer a potentially low-cost way to connect urban areas, but that depends on data governance and flexibility in sharing data regularly.

To better understand the practical distinctions between the main grid, microgrid, and virtual grid, we need to compare their core characteristics across technical, operational, and regulatory dimensions (IRENA, 2019b).

While all three models aim to deliver electricity, they are different in terms of infrastructure requirements, control mechanisms, ownership structures, and resilience capabilities. The main grid lacks the flexibility and local Self-Sufficiency that microgrids and virtual grids offer. While microgrids provide physical energy independence and resilience, they still demand higher capital investment and complex system integration.

Table 1 presents a structured comparison of the three mentioned grid models to highlight their respective advantages, limitations, and use-case scenarios.

Table 2.3: Comparison between the grid connections

Feature / Aspect	**Virtual Grid**	**Microgrid**	**Main Grid**	**References**
Definition	Digital energy sharing using the main grid	Local grid with generation, storage, and control	Centralized national or regional grid	IRENA (2020), IEA (2021)
Physical Infrastructure	No physical connection; relies on the existing grid	Own infrastructure (DERs, cables, inverters)	Large-scale centralized infrastructure	Lasseter (2002), IEA (2021)
Energy Exchange	Via billing credits and virtual metering	Physical local exchange	Centralized, one-directional	IRENA (2020)
Ownership	Distributed among users; utility-based accounting	Community, municipal, or private	State or private utilities	IRENA (2020)
Operation Mode	Always grid-connected	Grid-connected or standalone (islanded)	Always grid-connected	Lasseter (2002)
Energy Source	Off-site renewables (e.g., solar farms)	On-site renewables, CHP, storage	Centralized fossil, nuclear, and large renewables	IEA (2021)
Control	Platform-based digital tracking	Local smart controllers	Centralized dispatch and SCADA	IRENA (2020)
Resilience	Dependent on the main grid	Can function during grid outages	Vulnerable to large-scale blackouts	IEA (2021)
Flexibility	Flexible contracts, not operations	High technical flexibility	Low end-user flexibility	IRENA (2020)

Use Cases	Distributed communities, apartment prosumers	Eco-villages, campuses, islands	Cities, regions, national grid	IEA (2021)
Costs	Low initial cost	High investment, long-term savings	Tariff-based, shared by all	IRENA (2020)
Technology Dependence	Smart meters, software	Batteries, inverters, control systems	Bulk systems, grid automation	Lasseter (2002)

In this thesis, the existing urban energy infrastructure serves as the baseline. The scenarios developed in Chapter 3 build on this framework. They work with the rules that both Geneva and Turin currently depend on, using the central grid to sell excess energy. A separate scenario introduces a microgrid model, allowing local energy sharing at lower costs.

2.7 The Effect of Ownership on REC

Ownership makes energy communities both easier and harder to implement. If one entity owns all the buildings, like a municipality, campus, or developer, we can avoid most legal obstacles. This also enables us to make one capital decision and follow one governance model. That setup allows microgrids to be installed with private cabling, shared storage, and local controllers (European Parliament & Council of the European Union, 2019; IRENA, 2019b). This way, load sharing, maintenance, and billing directly, can be managed directly to make technical and legal work simpler.

When many owners are involved (homeowners, businesses, or housing cooperatives), the process becomes harder. Facing disputes over property lines, privacy, shared investments, and compliance (Inês et al., 2020; Sousa et al., 2019). In these cases, virtual grids make more sense. They let people share energy digitally through the public grid, using virtual net metering or peer-to-peer trading (IRENA, 2020). But success depends on strong rules and the right digital infrastructure (Caramizaru & Uihlein, 2020).

In Switzerland, single-owner energy communities work more efficiently compared to a collective one. When there are Multiple owner setups start facing tougher rules. The 2021 Swiss Energy Act revision enabled self-consumption associations (ZEVs), on the condition that all buildings must be connected to one transformer (SFOE, 2023a). In Geneva, that creates a bit of a problem, since there are a lot of dense neighbourhoods that often means they have fragmented ownership with a shared infrastructure, but lacking a manager. Even when properties are in the same area, they still need DSO approval from SIG, which slows things down (SIG, 2024).

Virtual sharing models (peer-to-peer or virtual net metering) were outside federal law until the new virtual models of RCPv CEL were introduced in Switzerland. Some pilots that were done during that time, for example, like Quartierstrom in Walenstadt (Ableitner et al., 2020), but without legal backing, communities can't scale. Cantonal authorities in Geneva have started testing flexible interpretations of grid rights, yet broader reforms are needed. Without them, most new projects will stay limited to single-owner microgrids instead of larger community models (Caramizaru & Uihlein, 2020). Table 2 shows a comparison.

Table 2.4: Comparison of implementing EC according to ownership

Aspect	Single Owner (e.g., Housing Cooperative, Municipality)	Multiple Owners (e.g., Private Apartments, Mixed Buildings)
Legal Simplicity	High – One entity can contract, invest, and manage directly	Low – Requires agreements between co-owners or a legal entity
Regulatory Barriers	Lower – Easier to meet the Swiss ZEV criteria for internal energy sharing	Higher – Limited by building boundary rules and DSO approval
Infrastructure Sharing	Feasible – Can build a private microgrid or internal cabling easily	Complicated – Often cannot justify or legally connect across properties
Virtual Models (e.g., P2P)	Not essential – Physical sharing is possible	Often the only option, but currently not legalized in Swiss law
Investment Coordination	Simple – Centralized planning and funding	Complex – Multiple stakeholders, financing disputes
Governance & Decision-Making	Centralized – Fast, unified management	Decentralized – Slower due to consensus and legal structures
Support from SIG/DSO	More direct coordination is possible	Requires case-by-case negotiation and approval
Example Technologies	Microgrids, collective PV, battery storage	Virtual net metering (not yet legal), rooftop PV per building
Ideal Use Case	Public housing, campuses, business parks	Apartment complexes, city districts with individual ownership
Current Feasibility (Geneva)	High – Aligned with ZEV policy and SIG guidelines	Medium to low – Needs legal reform or innovative policy mechanisms

2.8 Key Takeaways from the frameworks

Energy communities have emerged across Europe as instruments to democratize energy production and accelerate local decarbonization. Yet, their operationalization depends heavily on national transpositions of EU directives and domestic energy governance traditions. This chapter critically compares Italy, Switzerland, and the EU's overarching framework to highlight how regulatory design, incentive mechanisms, and institutional capacity shape the real feasibility of collective self-consumption and community-based energy systems. Through this lens, the chapter situates the Turin and Geneva case studies within broader policy dynamics that either enable or constrain post-carbon urban transitions.

The main references are the EU Clean Energy Package (2019), RED II (Directive 2018/2001), IEMD (Directive 2019/944), and REPowerEU (2022). which defined Renewable Energy Communities (RECs) and Citizen Energy Communities (CECs), emphasizing citizen participation, with a non-profit orientation, and local control, to promote shared energy through the grid.

Looking at Italy, it has Fast Regulatory Adoption, Complex Execution, with the main pillars being :

- RED II via Legislative Decree 199/2021 and ARERA 727/2022.
- Institutional actor, which is Gestore dei Servizi Energetici (GSE), manages tariff incentives and data flow.
- Incentive mechanisms, which are Tariffa Premio (TIP), and PNRR investment support.
- Using the main grid, within the same primary cabin boundaries.
- Strong top-down regulation, but it still has fragmented governance on a local scale.

On the other hand, Switzerland has Slow Legislative Evolution, but a Stronger Local Autonomy.

- Independent from EU law, with the key framework being *the* Energy Strategy 2050 and Energy Act (EnG).
- Instruments: ZEV (Zusammenschluss zum Eigenverbrauch) and CEL (Collective Energy Label).
- Operating on private grid or parcel connections, which would exclude most public-grid sharing.
- Incentives, feed-in tariffs,
- Barriers such as limited scalability beyond neighbourhood boundaries and high capital costs without subsidies.

- The governance model is currently decentralized, cooperative, and often initiated by property owners or cooperatives.

Table 2.5: Comparison of implementing EC according to ownership

Dimension	**European Union (Framework)**	**Italy (National Transposition)**	**Switzerland (Domestic Framework)**
Legal Definition	REC & CEC under RED II and IEMD	REC under D.Lgs. 199/2021	ZEV/CEL under EnG (non-EU)
Grid Connection	Public distribution grid (DSO-managed)	Public grid under the *cabina primaria* constraint	Private grid or shared parcel only
Governance Model	Cooperative/non-profit entities	GSE supervision	Based on the cantons
Incentive Mechanisms	General renewable support via market integration	TIP (€/MWh) + PNRR grants (≤40% CAPEX)	tariffs 2025 tariffs 2026
Participation Scope	Open to citizens, SMEs, local authorities	Limited to building inside the same cabin	Limited to buildings inside the same district
Administrative Complexity	Medium (guidance but flexibility)	High (bureaucratic, multilayered approval)	Medium (autonomous but fragmented)
Scalability Potential	High across regions	Medium, limited by DSO boundaries	Low beyond district scope
Main Barriers	Uneven transposition	Bureaucracy, grid sharing, DSO	Legal restrictions on grid sharing
Main Strengths	Harmonized goals and rights	Strong financial incentives	Strong autonomy and grid control

While all three frameworks aim to empower prosumers and decentralize energy production, their institutional architectures diverge. The EU's model prioritizes harmonization, striving for communities that can have flexibility and renewable energy across borders. Italy, although aligned with this vision, has operationalized it through a highly centralized system managed by GSE, which has some rigidity that delays local projects. In contrast, Switzerland's approach reflects its federal governance and liberalized energy ethos, focusing on self-sufficiency over coordination, which reduces cooperation.

This divergence shows a knowledge gap: current frameworks don't quite capture how governance structures, incentive design, and infrastructural boundaries meet to shape actual energy-sharing performances at the precinct scale. Treating legal and technical dimensions separately, overlooking the connection between policy architecture, spatial configuration, and Technical feasibility.

Bridging this gap requires a clear conceptual framework, one that links institutional governance to spatial and technical parameters of energy sharing. Such an approach must move beyond national policy comparison toward an integrated understanding of how energy communities perform under real spatial, regulatory, and operational conditions.

The forthcoming chapter 3 develops this framework to enable an empirical exploration of how the contrasting Italian and Swiss governance systems translate into measurable differences in self-consumption, self-sufficiency, and economic viability using institutional entities such as UniTo and the United Nations in Geneva.

Through this methodological bridge, the thesis advances from literature to quantitative evidence, showing how to shape the potential of post-carbon energy communities in European cities.

Chapter 3

3. Conceptual Framework and Methodology

This thesis approaches the post-carbon cities through the concept of "Urban Energy Precients", which integrates multi-layered renewable energy generation, primarily solar photovoltaics, with geospatial analysis leveraging GIS and extensive open-source datasets. These precincts contain anchor institutions that function as concentrated nodes where spatial solar potential is assessed and optimized to promote local energy production and sharing. While BIM and digital asset management systems (AMS) are applied in specific case studies (University of Turin), the core methodology centers on scalable, open-data GIS tools that facilitate replicable urban energy modeling. These technical insights gain real-world impact when embedded within "Urban Energy Precincts" spatially defined urban areas where governance structures, community participation, and localized policies enable effective energy self-sufficiency and SEC. Together, these concepts bridge the technical assessment of renewable energy potential with the socio-political mechanisms necessary to realize sustainable, equitable urban energy transitions.

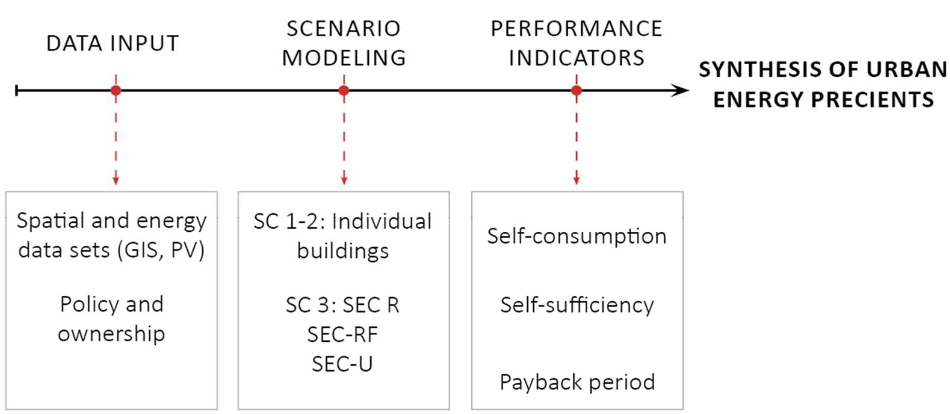

Figure 3.1: General Methodology of the thesis

3.1 Research Design and Approach

This research is grounded in a thematic priority of Italy's National Recovery and Resilience Plan (PNRR), which follows the direction set by global climate frameworks: the Paris Agreement (COP21, 2015), the 2030 Agenda and its 17 Sustainable Development Goals (UN, 2015), and IPCC scientific assessments. These global frameworks define the climate targets that national energy strategies (including energy communities) must align with.

Italy and Switzerland were selected not as comparative cases but as complementary case studies, stressing the fact that this thesis is not trying to compare different applications, but complement them with each other, as they reflect two different policy pathways under shared global commitments.

Italy, as an EU member, is tied to RED II and other directives and was one of the first to incorporate RED II into national law, introducing incentives for collective self-consumption and creating ECs. But as mentioned in the literature, it is currently slowed down by local complexity; even strong incentive systems fall short with no local coordination (Candelise & Ruggieri, 2020; De Franco et al., 2023).

Switzerland offers a different model. It's not part of the EU, but aligns with the Paris Agreement through its Energy Strategy 2050 and cantonal policies like Geneva's Plan directeur de l'énergie. Projects here rely on local governance and strong utilities rather than EU-wide rules. This makes Switzerland a useful counterpoint; it shows how energy communities can emerge from institutional leadership at the local level, even without a harmonized EU framework (Cantonal Energy Office (OCEN), 2020; SFOE, 2023b).

The complementary analysis between them reveals whether energy communities depend on EU regulation only, or if they can grow on their own through local governance. Using a case-study approach, the thesis dives into the nature of energy communities where technical and financial models look for an anchor that binds them. The thesis manifests most of its work in the case study of Geneva's United Nations district, analysing the ownership, institutional strength, and climate ambition of the city.

The research is built on three main pillars:

- **Policy and Governance Review**

  Analysis of EU directives, Italian legislation, and Swiss frameworks to identify what enables or blocks energy communities.

- **Scenario-Modelling**

  Quantitative testing of Scenarios (first, Second, Third), using indicators like self-consumption, payback time, and self-sufficiency.

- **Urban deployments and financial analysis**

  Forecasting what can be implemented within realistic, tangible results.

Policy sets the rules that communities must follow, and modelling quantifies what's possible, with an institutional analysis that deems it possible. Together, they create a clear structure to follow and create typologies to adapt, and create a solar energy community

Energy communities don't happen on their own. They exist only when national and local laws allow people to share energy, connect through public infrastructure, and access the grid. At the EU level, RED II and the Electricity Market Directive gave legal backing to citizen energy communities, but national implementation varies widely (Ahmed et al., 2024a).

Italy has strong incentives, but also complex rules. Municipalities, DSOs, and national agencies don't coordinate, and permits take time while tariffs are still evolving. Local projects take a lot of time because they lack coordination with governance; even though there is funding, this specific uncertainty makes funding and development hesitate (De Franco et al., 2023; Gruber et al., 2021).

Switzerland follows a different path, since there is no EU pressure, cantons like Geneva are experimenting with energy sharing and variable tariffs depending on the season. But still, most projects depend on a one-time deal with DSOs and utilities, making long-term planning difficult (Neij et al., 2025).

This pattern repeats across Europe. Pilot projects start strong, but scaling them hits the same walls: vague rules, missing data, and unclear grid access. Local momentum isn't enough without a clear, stable framework. The projects that succeed are usually led by a single institution that takes charge and cuts through the red tape (Corasaniti et al., 2025) (chapter 2).

This analysis focuses on three core tasks: Mapping potential across the EU, national, cantonal, and municipal levels. Clarifying possibilities across urban precincts, energy cabins, and DSO. Integrating the SEC while addressing fragmented authority. Together, these define the boundary conditions, the legal and institutional limits, within which technical and financial models can work.

The second part of the method builds energy scenarios tailored to the local context. Each scenario, as shown in Figure 3.2, tests how different solar PV configurations affect self-consumption, payback, and CO_2 reduction. The system expands in layers:

- Rooftops (base case)
- Rooftops + façades
- Urban integration: Parking sheds, green areas, railway land (any surface usable for solar investment)
- Solar Energy Community (SEC)

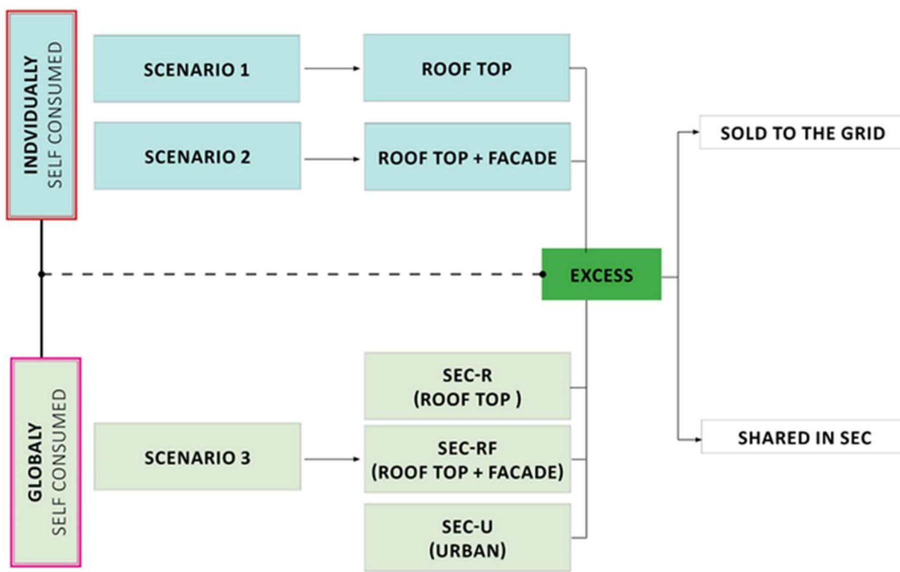

Figure 3.2: Technical Framework of the case studies roadmap map

The study uses real energy consumption data collected from the anchor institutions for each case study (United Nations, UNITO). It combines this with PV production estimates and known tariff structures according to each country's regulations.

Scenarios are all conducted with the use of GIS and the translation of that data into a structured Excel model for both technical and financial calculations. It includes investment, maintenance, incentives, and payback, with each scenario tested for the evaluation metrics that will be explained further on in this chapter.

To conclude this section, the goal isn't really to forecast the possible solutions but rather to show what's possible now (using real inputs and current policies). The focus will always remain on what can actually be built while thinking about the context-specific environment of the case study and its current governance capabilities.

Geneva's UN district shows this clearly; it includes several buildings, but most are managed by a single institutional owner: FIPOI. This central control reduces legal friction and makes coordination easier. In more fragmented districts, ownership is split between private and public actors, and project delivery slows down (chapter 2.4).

These 2 case studies can be emphasized even more when looking at them on a European scale. Each one has specific attributes, yet they are very similar to neighbouring European cities; their differences make them an ideal choice for a complementary pilot project conducted in cities

3.2 General Framework

Technicality, governance, and financial means with a single, multi-layered framework, that is the aim of the framework in a sentence. Developed to address a recurring problem in energy communities, the gap between technical feasibility and institutional implementation.

It reveals how actors (municipalities, universities, DSOs) interact across systems they are currently operating. It's a compound layered method that guides complex decisions in the urban energy transition, applied across two main case studies :

1. **The city of Torino**: UniTo campus precinct, applies the method to a live case with full modeling, and focuses more on implementation constraints
2. **The city of Geneva:** United Nations precinct, tests transferability under a different legal context but shared climate goals, and focuses more on institutions and policies

Together, these case studies define and create the pilot projects for a pathway for identifying viable energy community models in real urban conditions and a post-carbon city.

3.3 Data sources

Both qualitative and quantitative data are needed, drawn from primary and secondary sources. Each dataset supports a specific layer of the analytical framework (policy, technical, financial, or institutional). The scope includes national regulations, building-level energy profiles, solar simulations, incentive schemes, and spatial planning documents.

Policy data includes EU directives (RED II), Italian national laws (e.g., Legislative Decree 199/2021, ARERA TIAD 2023), and Swiss cantonal strategies such as Geneva's Plan directeur de l'énergie, from GSE and MASE (Italy), and from SFOE and OCEN (Switzerland), covering self-consumption rules, incentive access, and grid constraints (Cantonal Energy Office (OCEN), 2020; GSE, 2022; SFOE, 2023b).

Technical and spatial data were collected through GIS and BIM-based software. The Turin case study, inputs included building geometries and terrain models from public sources (Geoportale Piemonte, PVGIS, ENEA). Then the solar radiation raster is generated from QGIS and GRASS GIS, with the use of the (r.sun.insoltime) module for solar potential estimation (Šúri & Hofierka, 2004). Noting that BIM models were developed and integrated into the university's Asset Management System (AMS) to evaluate PV siting under planning and fire code constraints (Alsibai et al., 2024).

Energy consumption data were collected from electricity distributors (IRETI, e-distribuzione) and UniTo's green office, which includes annual profiles across 23 university buildings. In Geneva, yearly building-level demand and solar potential data were obtained through SIG (Services Industriels de Genève) and 2050 Today.

Financial data for investment and operational costs, and incentives were based on official sources. Italian parameters were taken from GSE guidelines, including fixed and variable TIP (Tariffa Incentivante Premio) values and the (Contributo a Fondo Perduto). Swiss estimates followed SFOE standards for PV and grid resale pricing. All values were cross-checked against actual project quotes and market offers to ensure accuracy (GSE, 2024; SFOE, 2023).

Governance data were in Turin UniTo's administrative structure and building ownership, while in Geneva, it was the United Nations district with a focus on the buildings in agreement with 2050 Today. Local master plans and energy strategies were also reviewed to assess how energy communities could start in their specific urban precincts within the existing governance systems.

Table 3.1: Data collected and sources

Data Type	Source	Use in Framework	Tools / Notes
Policy & Regulation	EU RED II; Legislative Decree 199/2021; ARERA TIAD (2023); Plan directeur de l'énergie; GSE, MASE, SFOE, OCEN	Defines legal rules, eligibility, and grid access	Legal review, regulatory comparison
Spatial & Technical	Geoportale Piemonte; PVGIS; ENEA; SoDa; Solargis	PV potential, system sizing, urban integration	QGIS, GRASS GIS (*r.sun.insoltime*), GIS workflows
BIM & Asset Management	UniTo BIM models, campus fire codes, and architectural plans	PV siting, regulatory feasibility	Autodesk Revit, AMS integration (UniTo)
Energy Consumption	IRETI; e-distribuzione; UniTo internal monitoring; SIG, 2050Today	Demand profiles for scenario modeling	monthly, annual resolution
Economic & Financial	GSE tariff data; SFOE BiPV pricing guidelines	Investment and maintenance modeling, payback, incentive logic	Excel models, incentive calculators
Institutional & Governance	UniTo structure; FIPOI ownership roles; masterplans; energy strategies, 2050 today	Embedding scenarios in real governance systems	Stakeholder mapping, planning document review

3.4 Scenario Design and Comparative Application

3.4.1 Rooftops (R)

R represents the baseline scenario, in which PV deployment is limited exclusively to building rooftops. Rooftops are the most straightforward surfaces for solar integration: they do not compete with other land uses, require relatively simple permitting, and are already the focus of most incentive schemes across Europe. In policy terms, R aligns with the "low-hanging fruit" of the energy transition.

R provides the most realistic and common type of PV, which, as mentioned in the literature, is the RTSPV, requiring minimal institutional coordination and delivering measurable benefits. However, its limitation is that it typically covers only 20–30% of demand, leaving a gap between technical potential and energy Self-Sufficiency.

3.4.2 Rooftops + Façades (RF)

RF integrates building façades, essentially embedding PV into the vertical surfaces of the buildings, to produce more solar energy. Unlike rooftops, façades expand capacity is not really determined by the plot area exactly, but more of a design strategy that aligns with the sustainability goals of building renovation projects.

This scenario was implemented in the Geneva UN zone. On the other hand, many façades in historic university buildings in Italy were excluded due to protection under Italian cultural heritage law (Legislative Decree 42/2004), so it wasn't considered for Torino.

RF represents the full potential a building can have when using solar PV on it. It's the next step to reach higher self-sufficiency. While BiPV can theoretically raise energy output in modern or less-constrained buildings, its costs are relatively higher and efficiency lower than rooftops due to orientation and angle, which is when smart architectural design employs itself. Still, RF makes planners and policymakers address and incentivize façade PV, and align it with building renovation cycles.

3.4.3 Urban (U)

U is the most ambitious scenario between them. It combines rooftop, façade, and the collective spaces around within the urban precinct (parking sheds, railway surfaces, and selected open areas), suitable for PV installation. This scenario shows the maximum technical potential of a precinct. U is more about showing the upper boundary of what a comprehensive energy community could achieve, even though it might be complicated to do under current governance rules.

This scenario was only used in the Geneva case study (UN), under scenario 3, with the existence of a dominant institutional owner (2050Today) and the collaboration of the Services Industriels de Genève (SIG), they created the conditions to link surfaces that in other contexts would be difficult to coordinate. This underlines how governance structure determines whether SEC-U remains an abstract scenario or a viable strategy.

SEC-U is not the most likely pathway in the short term, but it serves as a benchmark. Defining the outer limits of PV deployment clarifies what is technically possible and how far actual governance frameworks are from enabling it. It also forces a broader discussion about urban space of including car parks or railways, to be mobilized for energy production, and put them under institutional arrangements.

From a theoretical view, SEC-U is an example of technical modelling and institutional governance meeting together and expanding. But without strong coordination, the costs, planning requirements, and multi-owner negotiations make SEC-U unrealistic. Yet in governance settings where ownership is concentrated, such as the Geneva UN zone, SEC-U can be the exact reason why governance should be employed to make it happen.

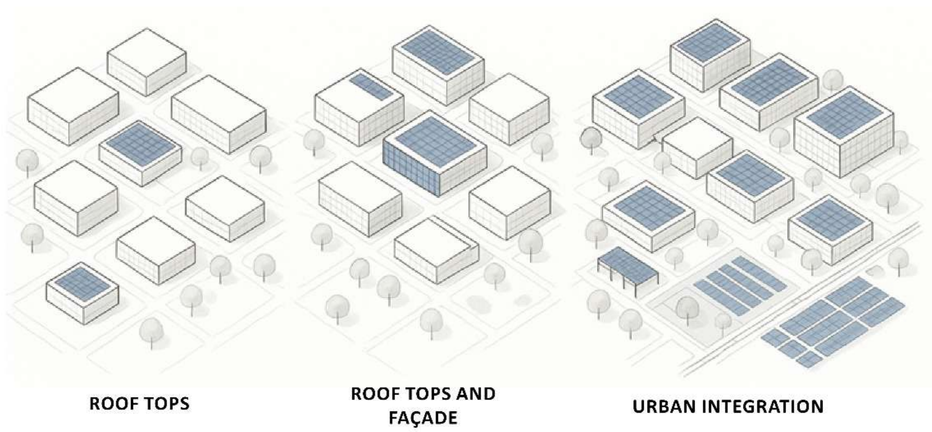

Figure 3.3: The three main types of solar PV Integration

3.5 Evaluation metrics

Evaluation metrics turn the analytical framework into real, trackable results. To compare each scenario not only by energy output, but also by how well they perform across three key dimensions: technical, financial, and governance.

3.5.1 Global Energy Metrics

These indicators assess how well each SEC or Scenario produces and uses electricity on-site:

1. **Self-consumption** (**SC**): How much of the solar power gets used locally.

$$\text{Self-consumption} = \frac{\text{PV electricity consumed}}{\text{PV electricity generated}} \quad (1)$$

2. **Self-sufficiency** (**SS**): How much of the total demand is covered by the system.

$$\text{Self-sufficiency} = \frac{\text{PV electricity consumed}}{\text{Total electricity consumption}} \quad (2)$$

These metrics were applied in all the case studies and set as the primary indicators for assessing the potential for creating an energy community. Because these metrics quantify how much of the energy is produced and used locally (versus needing the external grid), they help judge how autonomous an energy community can be.

3.5.2 Economic and Financial Metrics

These indicators evaluate project costs, returns, and market compatibility:

1. **Investment**: Upfront cost of the solar system, only a one-time expense.
2. **Maintenance**: Ongoing maintenance and management costs are accounted for annually.
3. **Payback Period (PBP)**: How many years it takes to recover the investment.
4. **Net annual gains**: The long-term value of the project, using a 3% discount rate.
5. **Incentives**: Includes Italy's *Incentivo in Tariffa* and *Contributo a Fondo Perduto*, and Swiss incentives.

In Geneva, resale tariffs like the CEL (around 0.14 CHF/kWh) were included to reflect local pricing. All figures follow GSE (2024) and SFOE (2023) standards (chapter 2.4).

3.5.4 Governance Metrics

Even the best technical system fails without strong governance. These metrics evaluate:

1. **Ownership (one actor, two, or multiple)**
2. **Assigning an anchor institution**: Whether a dominant actor (like UniTo or FIPOI) can manage planning and coordination.
3. **Regulatory fit**: How easily the project aligns with national and cantonal rules.

Together, they guide the comparison in the different scenarios in Figure 3.3. The calculation of the financial part is presented in Appendix 1 for more details, and presented in Table 3.2 briefly

Table 3.2: Equations used

Dimension	Metric	Formula / Definition	Unit	Data source & method
Technical	PV generation (E)	From GIS/BIM sizing and irradiance: $E = PR \cdot Hs \cdot S \cdot \eta$	kWh/yr	r.sun / PVGIS (GIS), BIM module counts, PR & η from specs
	Self-consumption rate (SCR)	PV used on site ÷ PV generation	%	Interval demand + PV profile matching
	Self-sufficiency rate (SSR)	PV used on site ÷ total demand	%	Same as above
	Excess Energy	PV generation − PV on-site use	kWh/yr	-
Economic / Financial	Investment	Installed cost per kWp × sized capacity	€ or CHF	
	Maintainance cost	Annual 1% of investment	€/CHF/yr	
	Payback (PBP)	Appendix I	years	From tariff structures + bill savings
	NPV (3%)	Σ (net cash_t ÷ (1+0.03)^t) − CAPEX_net	€ or CHF	Cashflow model, 3% discount

	Incentives	Italy: Incentivo in Tariffa + Contributo a Fondo Perduto; CH: BiPV/utility schemes	€/CHF/kWh	GSE/MASE (IT), SFOE/utility (CH)
	Resale tariff	Price for exported kWh	€/CHF/kWh	ARERA/GSE (IT), SIG/CEL (CH)
Governance / Institutional	Ownership concentration	Single coordinating owner vs many	index	Stakeholder mapping

3.6 Limitations

This analysis focuses strictly on electricity from photovoltaic (PV) systems in campus or district-scale energy communities. It doesn't include thermal networks, heat pumps, electric vehicle fleets, or storage systems (except for brief notes on sensitivity). The goal is to test technical and economic feasibility under current policies, to model one of the paths to decarbonization.

At the city scale, open-source GIS raster data were used combined with building footprints, while at the precinct scale, energy consumption load data were obtained when available, but when there was not available, standard profiles were used. There were some inconsistent metering formats (e.g., hourly vs monthly intervals), incomplete legacy records, and mismatched time bases, which were addressed by cross-checking values against utility summaries.

Solar radiation was modelled and extracted using GIS with standard parameters like Linke turbidity and typical PV performance ratios, with conservative losses for shading, dirt, and temperature effects applied. While r.sun provides reliable estimates, it's still a sky model, with seasonal conditions that can affect and cause local deviations (Šúri & Hofierka, 2004).

Not all surfaces are usable. Fire codes, safety zones, parapets, and heritage protections reduce available PV areas. These constraints were mapped directly in GIS/BIM models, based on current regulations. However, local authorities interpret rules differently (especially when it comes to façades under NT2), so the deployable area varies by building (Alsibai et al., 2024b).

Self-consumption and self-sufficiency depend on how well PV output matches actual demand. Where we lacked sub-hourly data, we downscaled monthly values using typical daily profiles. This introduces uncertainty (especially for buildings with unusual schedules).

Investment and maintenance costs reflect current market quotes and benchmark values, with net annual gains using a 3% discount rate. Incentives are modelled as constant fractions, so prices or grid charges are treated as fixed scenario inputs (GSE, 2023; SFOE, 2023a).

The SEC can be applied elsewhere, but the results are context-specific. Urban layout, heritage rules, grid tariffs, and institutional strength differ between Turin and Geneva. This comparison shows what's needed to scale up (not a one-size-fits-all model) (empirical analysis I II III IV). The thesis work incorporated all these limitations in its essence.

Chapter 4

4. EMPIRICAL ANALYSIS I: Geospatial Analysis for Solar Energy

4.1 Introduction

Modeling solar radiation in urban areas is more challenging than in open spaces due to the complex shading created by varying building heights, densities, and roof slopes. To estimate the energy that solar technologies can produce in cities, two key factors must be taken into account: (Tehrani et al., 2024): the urban solar availability, i.e., the total incident irradiation on building roofs and facades, and the utilization factor that assesses the area suitable for installation as well as technical characteristics, in this case the focus will be on Rooftop Solar photovoltaics (RTSPV) technology.

Different urban environments make techniques like spatial interpolation with data from meteorological stations unreliable (Tovar-Pescador et al., 2006). While also worth mentioning is that satellite imagery processing is usually not as effective in cities due to its low resolution, which is typically 1 km or more (Anselmo et al., 2024).

As a result, modeling has become the primary method for obtaining solar radiation data at an urban scale, with various approaches depending on how buildings are represented (Köker et al., 2025). There are two main methods: raster digital elevation models (DEM) and vector-based computer-aided design (CAD) data. A DEM consists of a grid where each cell has an elevation value and is often integrated into a geo-information system (GIS) environment to leverage geospatial data storage and analysis. Models that use CAD vector data are more labor-intensive and generally less accessible (Köker et al., 2025).

While determining the total roof or façade area is straightforward with both DEM and vector representations, obstructions like antennas and chimneys are often excluded. To account for this, correction factors are applied to reduce the total area to the usable area. These factors include shading coefficients (considering shade from trees, etc.), roof pitch coefficients (adjusting for installations on one side of a double-pitched roof), and feature coefficients (adjusting for areas occupied by windows, chimneys, etc.) (H. X. Li et al., 2019).

Additional criteria are also applied, such as the minimum available area, slope restrictions, aspect suitability like avoiding north-facing surfaces, and solar radiation thresholds (Bergamasco & Asinari, 2011; Jakubiec & Reinhart, 2013).

To determine solar potential, there are two tools used: one is developed by Fu and Rich (Fu & Rich, 1999), and (r.sun), which is based on the work of Šúri and Hofierka (Šúri & Hofierka, 2004). Both of them require a DEM as an input, with the addition of atmospheric transmissivity and the diffuse ratio. However, a major limitation is that they don't consider solar radiation reflected from the ground and nearby surfaces, which is important in urban settings, yet in cities like Europe, it can be less important since all buildings have a building code.

The 'r.sun' model is integrated into the open-source 'GRASS GIS' (Neteler & Mitasova, 2002) environment. In addition to a DEM, 'r.sun' requires other parameters, which can either be internally computed or user-defined, such as Linke atmospheric turbidity, ground albedo, beam and diffuse components of the clear-sky index, and the sampling density for evaluating raster cell visibility. A key feature that sets 'r.sun' apart from other models is its ability to spatially distribute input parameters and define them through a series of raster maps, allowing for the modeling of large areas with varying climatic conditions. Other tools that use DEMs to calculate solar radiation include 'Solar Energy from Existing Structures' (SEES) and 'SHORTWAVE' (Kumar et al., 1997).

This study tries to assess the GIS methodology based on DEM and (r.sun) while considering the need and fill the gap of development in solar radiation models that integrate a wider variety of factors such as atmospheric conditions, urban morphology, and material properties (e.g., albedo) to better reflect the unique characteristics of urban environments.

4.2 Solar Assessment Framework

The study begins by developing a database that starts from the regional level and focuses on the city level, which mainly includes the Digital Terrain Model (DTM) and the Digital Surface Model (DSM) as a starting point. By plugging in this data into QGIS, the solar potential for Torino, Italy, in this specific study is then calculated. The accuracy of the database significantly influences the study's results, as solar potential is closely tied to the geographical characteristics of the area (Jonsson et al., 2012). Integrating satellite images into numerical values is also essential. Figure 4.1 provides a conceptual map outlining the steps involved in the overall process.

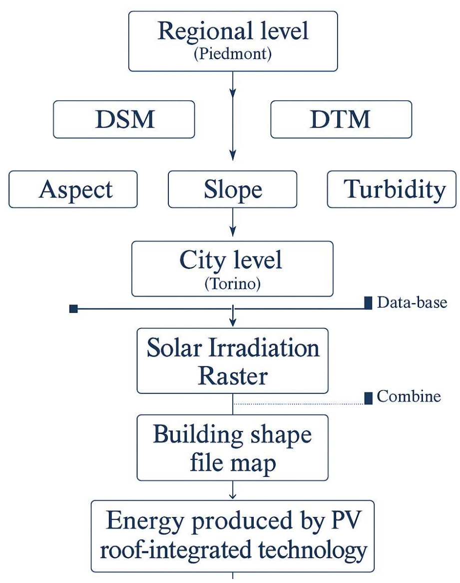

Figure 4.1: Methodology of creating the database of the study.

4.3 Geographical data (Database)

4.3.1 Slope and aspect

The first step is the conversion of the image. The output obtained is the DTM, a raster file (in .tif format) where every cell is associated with the altitude value (meters above sea level, m a.s.l.). Figure 4.2 shows the DTM of the piedmont region.

In Geographic Information Systems (GIS), slope and aspect are two fundamental concepts used to understand and analyze terrain, (Chang & Tsai, 1991; Grohmann, 2015) showed that the accuracy of slope and aspect decrease as a DEM resolution decreases (coarsens), and that the larger slope differences occur in areas of steep relief, while larger aspect differences are in low relief areas. The slope is the steepness or the degree of incline of a surface. It represents the rate of change of elevation for each digital elevation model (DEM) pixel, measured in degrees. Slope can be expressed either in degrees or as a percentage (Y. Li et al., 2021).

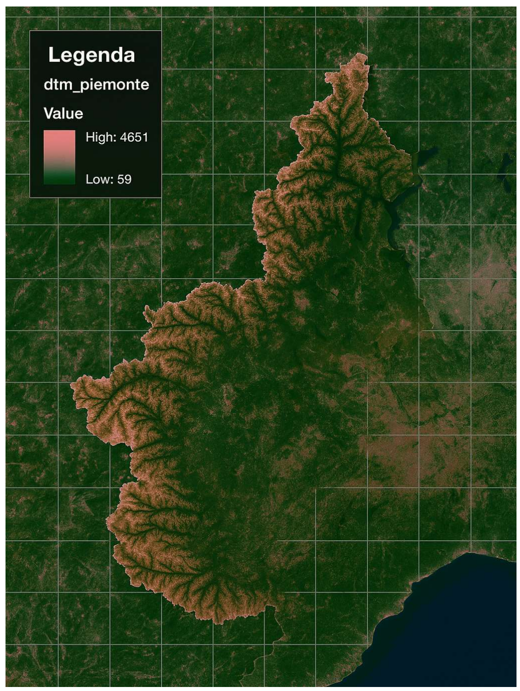

Figure 4.2: Digital Terrain Model (DTM) with a 50-meter x 50-meter detail with an elevation reaching 4651m.

Aspect, on the other hand, is the orientation of the slope, measured clockwise in degrees from 0 to 360, where 0 is north-facing, 90 is east-facing, 180 is south-facing, and 270 is west-facing (Y. Li et al., 2021). Aspect identifies the downslope direction of the maximum rate of change in value from each pixel to its neighbors.

Using this raster, the slope can be generated, which is an algorithm that calculates the angle of inclination of the terrain from an input raster layer, expressed in degrees. Then, combined with the aspect, it calculates and generates a raster layer that contains values from 0 to 360 that express the slope direction: starting from North (0°) and continuing clockwise (Figure 4.3).

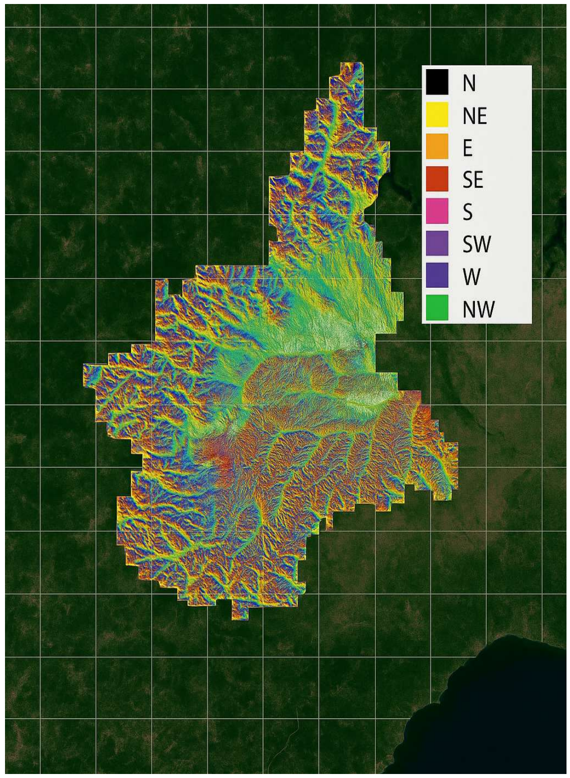

Figure 4.3: Aspect layer reclassified of the Piedmont region.

4.3.2 Turbidity factor

The Turbidity Linke factor (TL, for an air mass equal to 2) is a very convenient approximation to model the atmospheric absorption and scattering of solar radiation under clear skies. It describes the optical thickness of the atmosphere due to both the absorption by the water vapor and the absorption and scattering by the aerosol particles relative to a dry and clean atmosphere (Ineichen & Perez, 2002). The larger the TL, the larger the attenuation of the radiation by the clear sky atmosphere. It is a convenient parameter to summarize the turbidity of the atmosphere. It is a key input to several models assessing solar irradiance under clear skies, which has always been used by several communities in the fields of renewable energies, climatology, agro-meteorology, and atmospheric pollution (Kasten, 1996; WMO, 1981).

To generate the radiation data, it needs various aspects, which are mainly the average day of each month, diffused global radiation, link turbidity data, and the diffused part of the global radiation (D/G ratio). Table 4.1 provides the data types along with their sources.

The data is extracted taking into account the region of study, in this specific case, it is the Piedmont region containing the city of Torino.

Table 4.1. Data sources required for the solar Irradiance simulation

Data	Source
Average Day	(Duffie & Beckman, 2013; Klein, 1977)
Diffuse to global radiation ratio. UNI 10349-1 (2016)	(ENEA Renewables, 2006)
Linke Turbidity data raster	(MINES ParisTech & Vaisala, 2014)
Link sky diffuse radiation coefficient raster (D/G)	(World Bank Group, 2019)
Digital Terrain Model	(Regione Piemonte, 2015)
Building shape files	(OpenStreetMap contributors, 2015)
Slope	Generated using QGIS
Aspect	Generated using QGIS

4.4 Solar Energy Production Calculation

Incoming solar radiation (insolation) originates from the sun, is modified as it travels through the atmosphere, is further modified by topography and surface features, and is finally intercepted at the earth's surface as direct, diffuse, and reflected components. Direct radiation is intercepted unimpeded, in a direct line from the sun. Diffuse radiation is scattered by atmospheric constituents, such as clouds and dust. The reflected radiation is reflected from surface features. The sum of the direct, diffuse, and reflected radiation is called total or global solar radiation (Muneer et al., 2007).

As previously mentioned in the literature, the solar geometry incorporated in the model is derived from the research conducted by Krcho (Krcho, 1990), which was later enhanced by Jenčo (Jenčo, 1992). The model’s equations, which describe the position of the Sun-Earth and the interaction of solar radiation with the atmosphere, are primarily based on the formulas proposed by Kittler and Mikler

(Kittler & Milker, 1986). Significant updates to this model were made following the recommendations and findings of the working group led by Scharmer and Greif (Scharmer & Greif, 2000). The current model calculates all three components of global radiation (beam, diffuse, and reflected) under clear sky conditions, without accounting for the spatial and temporal variations of clouds to quantify RTSPV accuretly.

4.4.1 Simulation Parameters

The simulations are done on the average days of the 12 months (r.sun.insoltime). Processing will be done 12 times, changing the average day indication and the Linke turbidity factor raster data (one for each month of the year). Table 4.2 for the locality Lat=45°04' Long=7°41' is provided to understand how the calculation works in the specific month and which day to take :

Table 4.2: Average days in each month for diffuse to global radiation (Duffie & Beckman, 2013)

Day	17-Jan	16-Feb	16-Mar	15-Apr	15-May	11-Jun	17-Jul	16-Aug	15-Sep	15-Oct	14-Nov	10-Dec
Cumulative avg day	17	47	75	105	135	162	198	228	258	288	318	344

Since the number of days is variable for each month, it is considered useful to calculate the monthly data. The value of the radiation monthly derives from the product of the previously obtained values relating to daily radiation and the exact number of days of the month considered:

$$Global\ Radiation\ January\left[\frac{kWh}{\frac{m^2}{month}}\right] = Global\ Radiation\ January\left[\frac{kWh}{\frac{m^2}{day}}\right] \times 31 \qquad (3)$$

Both steps were performed using a specific QGIS software tool that performs calculations based on the raster pixel values entered into the project, called “Raster Calculator”. Then we can extract the twelve solar radiation raster layers (one for each month) in the assigned municipality to have an in-depth look. The global solar radiation of the Piedmont region is determined and depicted in Figure 4.4.

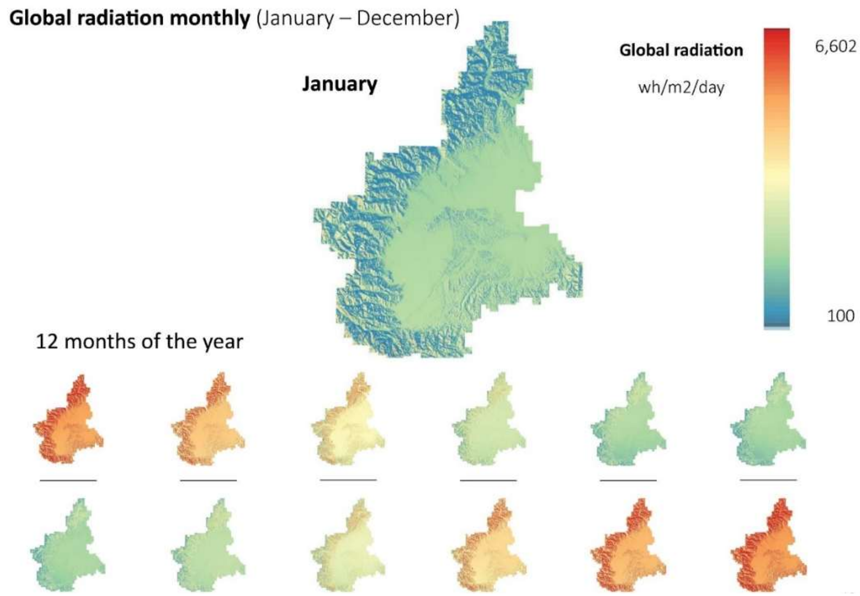

Figure 4.4: Monthly global radiation from January to December.

The resulting rasters will be converted to monthly rasters using equation 4, which are expressed in Wh/m2/month. Dividing it by 1000 will convert it to kWh/m2/month, and finally, with this information, the global radiation can be calculated using the following formula:

$$Global\ Radiation\ Year\left[\frac{kWh}{\frac{m^2}{month}}\right] = Global\ Radiation\ January\left[\frac{kWh}{\frac{m^2}{month}}\right] + Global\ Radiation\ Year\ Febuary\left[\frac{kWh}{\frac{m^2}{month}}\right] + etc \quad (4)$$

The software facilitates the transformation of raster values into points by converting pixels into corresponding points. Each point retains the exact value of its originating pixel. The process and results of this conversion are depicted in Figure 4.5. Upon completion of the shape file, it can be integrated with the building data. This allows for the assessment of each building's value and solar potential in Turin.

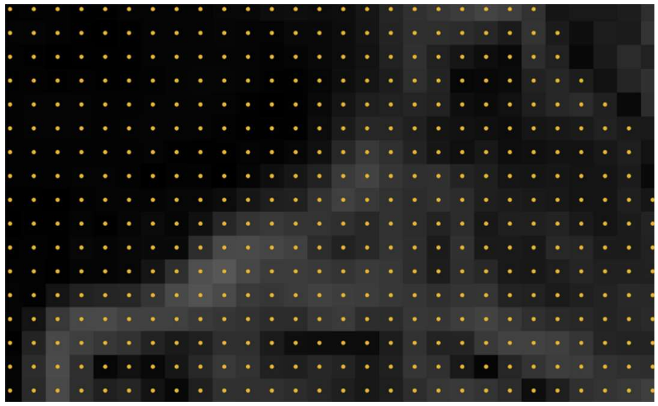

Figure 4.5: The raster layer was converted to points 1m x 1m.

Using this layer and cutting out only the city of Torino will result in a map showing the solar potential of Torino presented as points, as shown in Figure 4.6. The solar potential in Torino is mostly the same throughout the city, which makes sense since the elevation levels are the same. However, including the mountains on the east side of the city, the values range from 900 to 1900 kWh/m2.

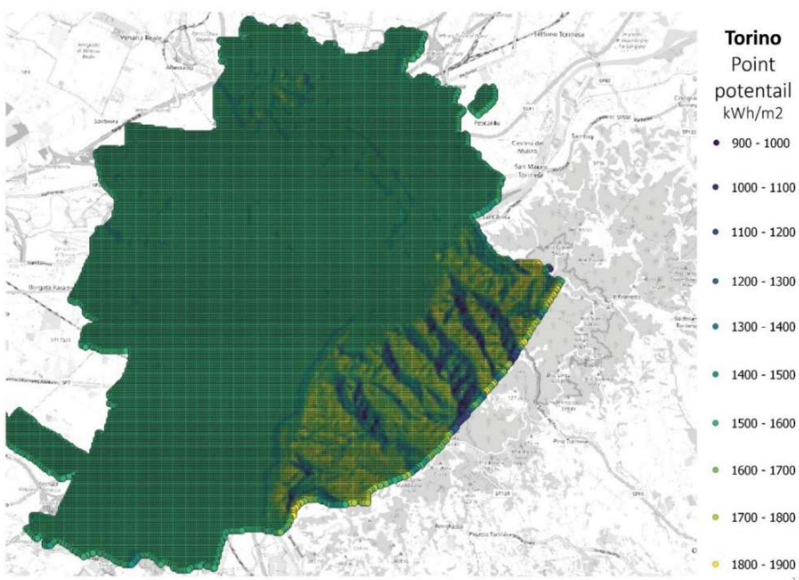

Figure 4.6: Torino solar potential, represented as points with a grid of 1m x 1m

To utilise this data, the building shape files of Torino will be integrated with the process of interpolation; this way, solar potential data can be recorded on each building inside the city of Torino. However, because it is mostly flat, the variation of values is low. Figure 4.7 shows the integration of the point layer with the building layer to make the final map.

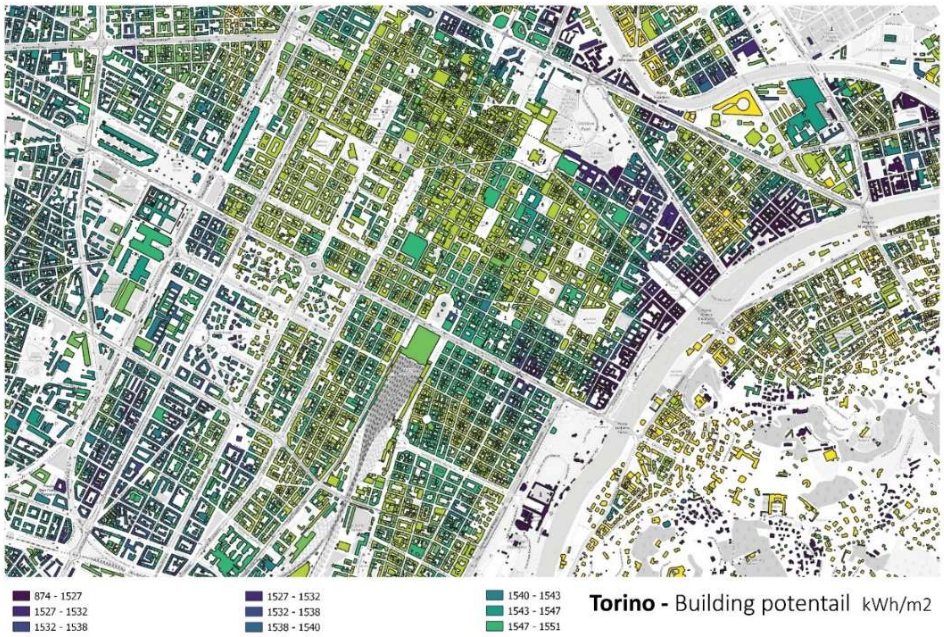

Figure 4.7: Torino's building potential

4.5 Results

The building potential of Turin ranges between 874 and 1551 kWh/m2, with this information, solar production can be calculated using the following equations (Suri et al., 2008) :

$$E = PR \times Hs \times S \times \eta \qquad (5)$$

Where:

- E is the electrical energy produced by year [kWh/y];
- PR is the performance index of the system (≈ 0,75);
- Hs is the solar potential (cumulative annual solar radiation) [kWh/m2/y];
- S is the working surface of the panel [m2] (about 30-40% of the roof area)

ɳ is the conversion efficiency, that is, the ratio of incident solar energy to produced energy:

$$ɳ = Wp \frac{Wp}{S \times Istc} \tag{6}$$

Wp is the peak power of the panel (equal to 1 kWp, which corresponds to about 6-8 m2 of PV surface).

To maintain the authenticity of the findings, 40% of the available area is utilized, assuming that the roofs on the south side are only taken into account, and 10% for movement space. Assuming crystalline silicon technology, a total installed peak capacity of 281 kWp, and 15 percent system losses (aligned with Italian performance ratio standards of at least 85%), the system was modeled as roof-integrated (BiPV). The tilt angle was set to 21°, representing the dominant roof plane, and the azimuth to 42° west.

Figure 4.8 shows the overall RTSPV energy production using all of Torino's building stock, ranging from 143.00 to 390,000.00 kWh/Y Y. This 3D visualization shows the overall potential of the city, to emphasize how hard it is to transition the energy needs to a sustainable source.

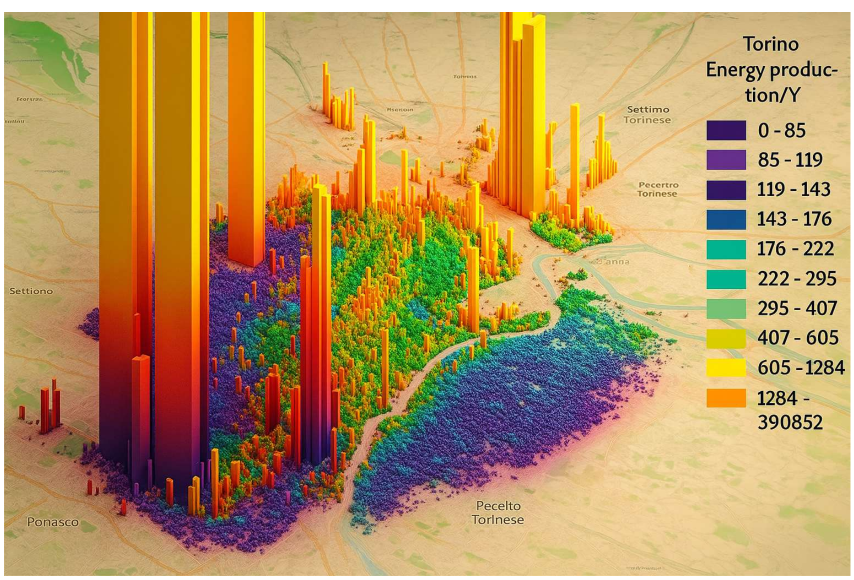

Figure 4.8: Torino RTSPV energy production KWh/y.

4.6 Discussion & Conclusion

The total amount of RTSPV energy produced in Torino using 40% of the roof surface area amounts to 20.642 Gwh, putting that into perspective, the total annual electric consumption of Torino is 79.6 GWh (Jarre et al., 2017), the main variable that makes all the difference is the area, the rural areas are the highest due to the availability of roof surface area, which also confirm the finsing of (Joshi et al., 2021) in his study on Solar production using roof tops.

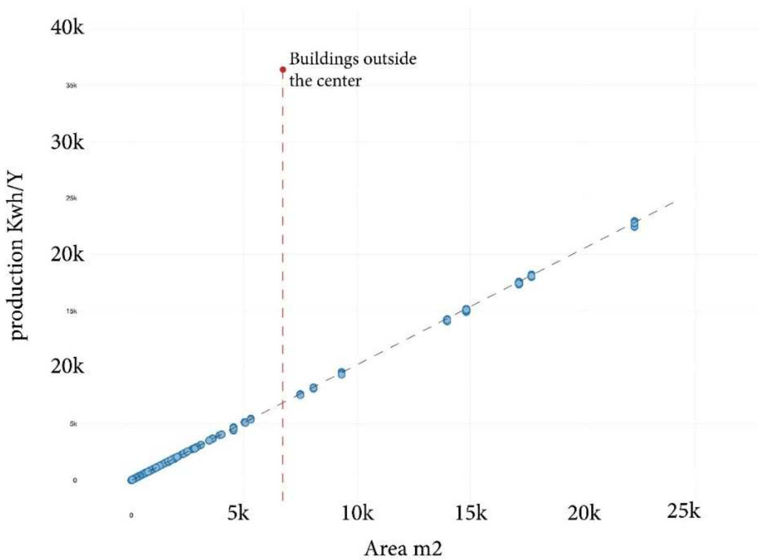

Figure 4.9: The correlation between Area and PV Production.

After rounding all the values of solar PV production using rooftops, Figure 4.9 shows an evident direct correlation between the area and production, which is logical considering that larger areas provide more space for the installation of solar panels. This also accounts for the higher production values in areas outside the city center, with much fewer constraints when it comes to policies.

Considering the information above, Torino can theoretically cover 25% of its electric energy consumption using RTSPV technology. However, that is only abstract. The means of creating a sustainable city is not achieved in this way per se; there are many factors to take into account, as discussed in the literature in chapter 2, such as governance and grid connection. However, this technical aspect constitutes a main pillar for the creation of Solar Energy Communities (SEC).

In conclusion, creating sustainable cities using RTSPV technology is one of the main sources that is economically and operationally tangible. The analysis showed how to assess the solar irradiance of a city by combining GIS and satellite imagery and producing more accurate results that can be translated into numerical values and illustrated visually on maps.

The study employed geoinformation systems (GIS) in conjunction with satellite imagery to investigate the potential rooftop solar energy production in the city of Turin, in the context of assessing solar radiation reaching the Piedmont region. By leveraging GIS technology, more accurate measurements of solar exposure are obtained, serving as an input for subsequent energy production calculations due to the separations of the values on a grid 1m x1m as mentioned in the methodology section.

The results show the exact numerical values of solar irradiance reaching a specific point on the surface of the Earth, and in this case, the rooftop values. After applying the calculation, the results show the value of energy production using solar PVs, utilizing 40% of the available surface area, taking into account the south-facing side of the rooftops. This study provides insight into the complex relations between energy, cities, and sustainable development on a city scale. However, it's only part of a bigger scope of the possible future that cities can prosper into.

Chapter 5

5. EMPIRICAL ANALYSIS II: Campuses of UniTO as a leading Energy community

5.1 Introduction

Recalling the literature, Renewable Energy Communities (RECs) are open, voluntary, and non-commercial entities that produce, share, and consume renewable energy. They are associations of local citizens, small and medium enterprises, public administrations, territorial government agencies, etc. (Soeiro et Dias, 2020; Campos, 2020). For the way they are designed, energy communities require some of their members to produce more electricity than needed and some others to consume more than they produce. Reasonably, the first ones are called *prosumers*, as they both produce and consume electricity at different times of the day, sharing the surplus of energy within the community, while the second ones are called *consumers*, as they are not able to share the surplus of energy in the grid.

When their members can share their surplus of energy with members who need it, the community optimises the use of energy within itself and avoids drawing electricity from the grid. Moreover, RECs are designed to receive an economic incentive for each MWh of energy shared within the community; thus, the greater the amount of energy shared, the higher the economic incentive received. Under Italian regulation, shared energy is calculated on an hourly basis and set as the minimum between the amount of electricity fed into the grid by the production plants and the amount of electricity drawn from the grid in the same energy market area.[8]

Accordingly, the closer the alignment between energy production and consumption within the community, the greater the volume of shared energy and, consequently, the higher the economic incentives received.

This brief overview highlights that energy communities represent a compelling alternative to traditional energy production and distribution systems. According to Directive (EU) 2018/2001, Renewable Energy Communities (RECs) deliver three key categories of benefits:

1. Environmental benefits. Within CERs, electricity is produced in an environmentally responsible way as it comes from renewable sources, without emitting CO2. At the same time, electricity is consumed conscientiously as it is locally managed and distributed, reducing current leakages in the grid.
2. Economic Benefits. Energy communities receive economic incentives for the amount of energy shared within the community itself. Members of RECs can decide how to use and invest these revenues, according to the social purpose they set in their statutes. For example, if a REC is composed of public entities like a school, a hospital, or a sports center, its revenues might be used to improve facilities' functioning. Otherwise, if a REC is made up of private citizens, revenues might be distributed among its members, resulting in significant savings on utility bills.
3. Social Benefits. Energy communities are designed to facilitate the energy independence of a territory, by giving the possibility to their members to manage their electricity. They can develop the local productive sector too, creating new jobs for the community. This demonstrates the social role of the energy transition process, for which green energy is not just economically and environmentally advantageous but also a way of ensuring energy equity and security.

Moreover, Renewable Energy Communities (RECs) promote responsible energy usage, as each member actively manages their individual consumption.

---

[8]The definition of "shared energy" is given by the Legislative Decree 199/2021, Art.2 (f). The full text in the original version is available at the following link:

https://www.gazzettaufficiale.it/eli/id/2021/11/30/21G00214/sg

Additionally, local electricity distribution contributes to grid stability and reduces transmission-related costs.

5.2 Scope and context

The University of Turin (UniTo) stands out as a prominent academic and research institution at both regional and national levels within Italy, playing a pivotal role in promoting innovation, education, and socio-economic development (University of Turin, 2024; AlmaLaurea, 2024). With approximately 83,000 students enrolled in the academic year 2024/2025, including a significant international presence (7%) and substantial female representation (62%). UniTo represents a major educational hub (University of Turin, 2024). It employs around 2,000 academic staff and 1,900 administrative personnel, operating within approximately 120 buildings strategically distributed throughout the city of Turin and across Piedmont (University of Turin, 2024). Among its facilities is the Campus Luigi Einaudi, a seven-building complex of more than 45,000 square meters designed by architect Norman Foster, which hosts faculties including Law, Economics, and Political Science (Camera di Commercio delle Marche, 2023). UniTo further consolidates its regional impact through decentralized branch campuses that support over 5,000 students outside Turin, fostering educational accessibility and regional cohesion (Corriere Torino, 2024). Its 27 academic departments offer comprehensive educational pathways, comprising 71 undergraduate degrees, 87 master's programs, and numerous doctoral and specialization courses (University of Turin, 2024). Moreover, UniTo serves as a key reference point for public institutions, third-sector associations, and private enterprises, significantly contributing to local economic growth, technology transfer initiatives, and workforce development through thousands of graduates annually entering various professional sectors (AlmaLaurea, 2024).

Unitos Renewable Energy Communities represent one of the latest energy-related innovations. Recently, they have had great success in academia and the research sector, as they are changing the paradigm of energy shared and consumed between citizens (Ahmed et al., 2024b). The Renewable Energy Communities represent one of the last energy-related innovations. To understand how they work, the University of Turin began to research REC through the dedicated entity of UniTo Green Office. And in the last months, an internal debate arose about the possibility of fostering the development of a REC within the territory. The idea is to make the University of Turin the main promoter of energy within the communities they are in (the university’s buildings and local stakeholders). A university-promoted REC, in addition, would be a symbolic role, as it could raise awareness of the existence of RECs themselves and their functioning within the social community.

In the previous section, we have seen that one paramount requirement for the development of a REC is that its members are connected to the same primary cabin. In order to understand which primary cabins UniTo buildings belong to, we mapped the university buildings using GIS. To see how each building connects to the main cabins, we compared the current map with one showing the main cabins in the Metropolitan Area of Turin. The building asset of Unito is present in the Piedmont region of Italy. The mapping of the electric cabins that contain the buildings is shown in Figure 5.1. Moreover, the city of Turin is divided into 11 primary cabins that cover different areas of the City.

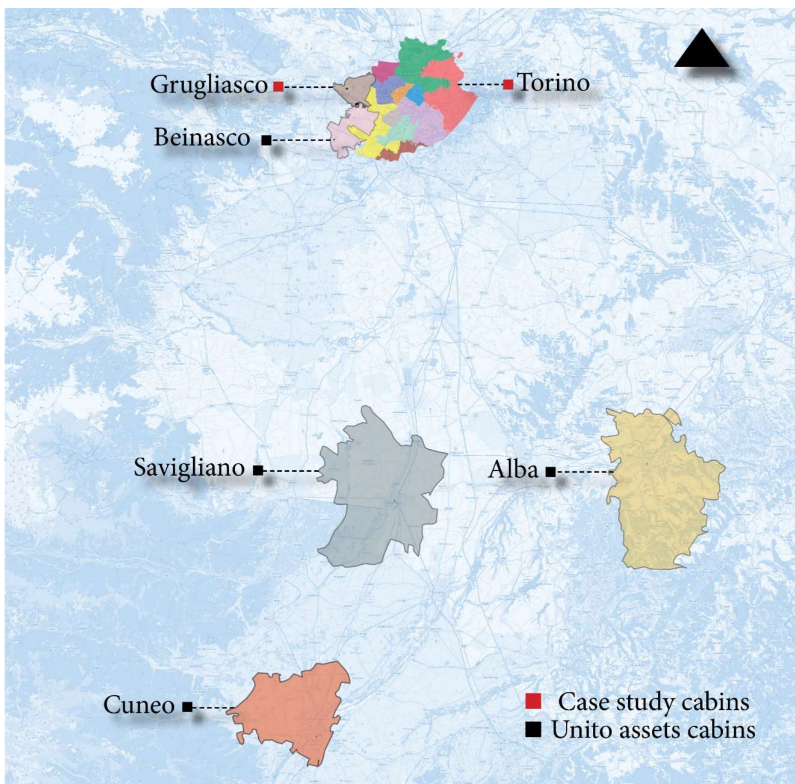

Figure 5.1: Map of Unito primary cabins and the surroundings.

5.3 Methodological approach

To test the feasibility of the development of a REC promoted by UniTo, the study will start with a technical preliminary study that aims at understanding if UNITO could be a prosumer and make use of university buildings that can produce more electricity than consumed, to share this surplus within the community. For this purpose, we analyze the actual electricity consumption of university buildings and the amount of renewable electricity these buildings could produce.

The overall track of the study can be summarized in Figure 5.2. The aim is to test the feasibility of a REC promoted by UniTo and understand if UNITO could be a prosumer, in other words, if it could produce more electric energy, mainly from photovoltaic panels, than it consumes, to share this surplus within the community. Hence, three main aspects act as filters for selection: the consumption data, the production of electric energy, and surface availability (mainly roofs).

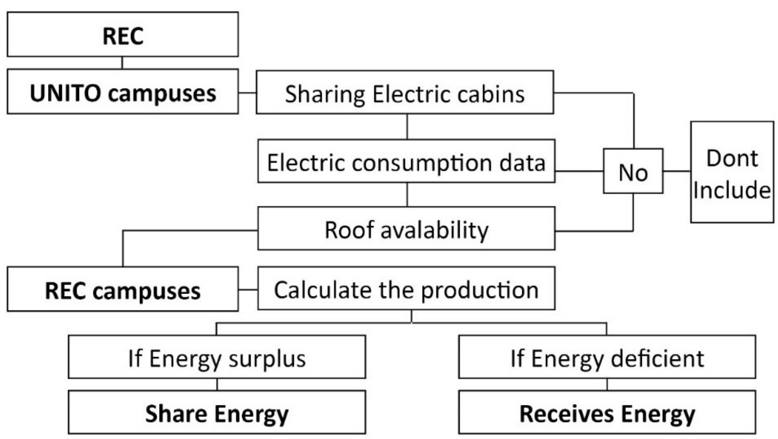

Figure 5.2: The track of the Torino case study

Focusing on the metropolitan area of Turin, we can see that the UniTo buildings are located in 7 of the 11 cabins shown in Figure 5.3, and most of them are concentrated in the three central areas. In the three main cabins, the buildings are identified with the ID numbers summarized in Table 5.1.

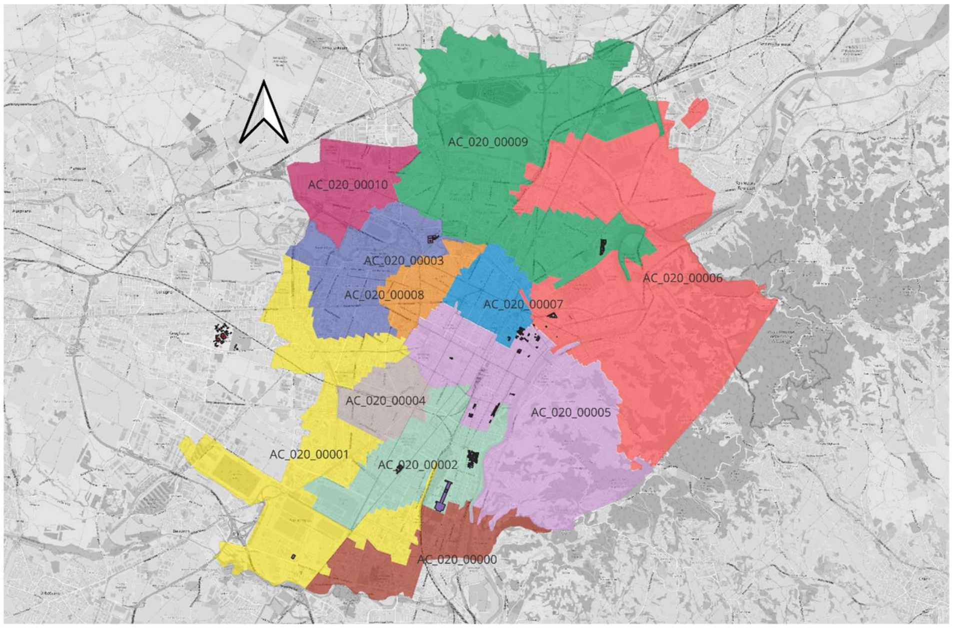

Figure 5.3: Map of Unito primary cabins in the metropolitan area.

5.3.1 Data collection

In the next paragraphs, we estimate the amount of electricity that could be generated by UniTo buildings if solar panels were installed on them. The analysis is conducted using energy produced by solar panels, which are the most common devices used to generate renewable electricity in urban environments.

In order to understand how much energy production we can achieve, we must first calculate how much solar potential or solar irradiance we can get. The solar energy potentials and the solar energy production estimates are respectively described in paragraphs 2.3 and 3. The tool used for the simulations in both these sections is the QGIS software.

Table 5.1: Building ID divided by primary cabin zones.

Zone Name	CODE (distributors)	ID
buildings in Centro	AC_020_00005	22, 37, 18, 14, 34, 38, 35, 42, 41, 36, 20, 2
buildings in Arbarello	AC_020_00007	3, 9, 1
buildings in Stura	AC_020_00006	27, 48, 50, 45

The previous study simulated the solar potential of Torino (chapter 4), done through QGIS and the mapping of UnitO buildings (fig. 3). With these foundational steps completed, the study continues with the second phase, which involves calculating the energy production of specific buildings and finally comparing it with their consumption to understand how much energy surplus can be achieved. This will help in identifying the specific buildings that can contribute to paving the way for an energy community.

Figure 5.4: Map of UniTo buildings in the metropolitan area of Turin.

Since only the buildings with full hourly consumption were included, only 23 buildings made the final selected list. The complete list is given in Table 5.2.

Table 5.2: List of UniTo buildings with completed consumption data.

ID	Name	Energy supplier
01	Rettorato	IRETI
02	Palazzo degli Stemmi	IRETI
03	Cavallerizza	IRETI
09	Palazzo Campana	IRETI
014	Ex Caserma Podgora	IRETI
018	Palazzo Venturi	IRETI
020	Palazzo Aldo Moro	IRETI
021	Palazzo Nuovo	IRETI
022	Ex Calandrino Cairoli	IRETI
027	Dipartimento di Scienze Giuridiche	IRETI
034	Orto Botanico	IRETI
035	Inrim - Ex Galileo Ferraris	IRETI
036	Dipartimento di Fisica	IRETI
037	Chimica e Farmacia	IRETI
038	Dipartimento di Anatomia Patologica	IRETI
041	Scuola di Biotecnologie 1	IRETI
042	Scuola di Biotecnologie 2	IRETI
044	Lingotto	IRETI
045	Ospedale Molinette	IRETI
048	Ex Irve	IRETI
050	Ex Edilscuola	IRETI
055	Ospedale San Luigi	e-distribuzione
056	Ex Centro Sperimentale Agraria	e-distribuzione

5.3.1 Horly balance analysis

The buildings were selected based on the availability of comprehensive data (the primary focus of our analysis). To fulfill the first rule of making EC in the same cabin, the study will focus on the purple cabin (AC_020_00005) section as the prime model to expand on in later studies.

Looking closely at the bar chart in Figure 5.5, the potential for solar energy is highest during July and August, and lowest in January and December. This is mainly due to the cloud factor, which prevents the sun's solar waves from reaching the earth's surface."

This analysis provides an overview of the data, highlighting trends, variations, and summary statistics for energy potential among different entities. Further investigation and analysis are necessary to draw more specific conclusions or make informed decisions based on this data. Upon database creation, the study will narrow its focus to the campuses situated in the metropolitan areas of Turin and Grugliasco Campus. This selection is driven by the comprehensive availability of data, specifically the annual consumption data.

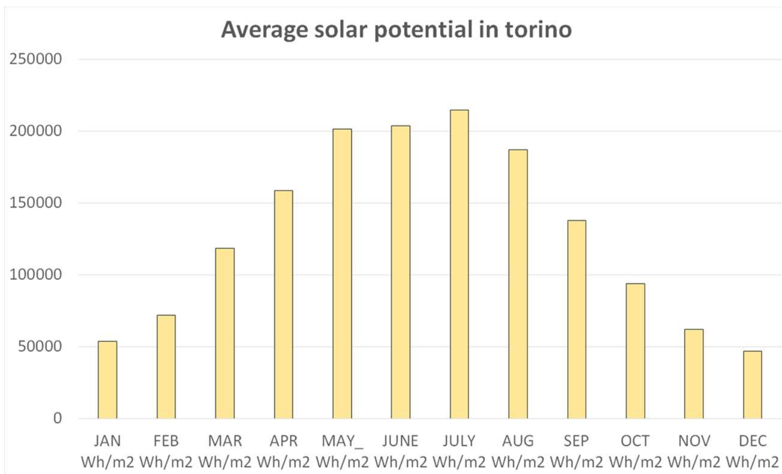

Figure 5.5: Energy potential in Torino for each month.

The University of Turin owns 56 buildings of different dimensions, located within the Metropolitan Area of Turin and the Province of Cuneo. The analysis is done on all the buildings, which are managed by two energy suppliers, i.e., *IRETI* and *e-distribuzione.*

For each building, a quarter-hour and daily consumption data were extracted for the period from 1st May 2022 - 1st May 2023.

For the consumption, the analysis begins with a preliminary qualitative evaluation of the electricity consumption data of the buildings listed in Table 3. For each one, we analyze the daily electricity consumption data of each month of the period considered, and we graphically represent the consumption data with a vertical bar diagram. This helps in understanding the development of energy consumption during the days of each month and in figuring out if there are days in which consumption is higher or lower than others. We also highlight Saturdays and Sundays of each month in red, for the purpose of understanding if energy consumption is less during the weekend with respect to the weekdays.

Three parameters are considered as mentioned in the framework of the thesis: the energy metrics, which are Self-sufficiency, self-consumption, and the financial metrics, which mainly is the payback period.

As an example, it is shown the case of Biotecnologie 1 (Figure 5.6) is shown: during the weekend ends, there is a recurrent and detectable reduction in consumption.

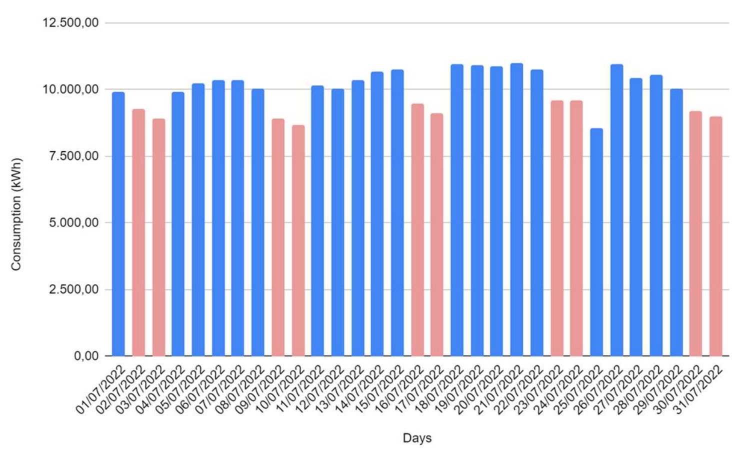

Figure 5.6: Daily electricity consumption data of Scuola di Biotecnologie 1, July 2022. In red the week-ends and in blue the working days.

On a monthly scale, the minimum and maximum values of energy consumption and the average electricity consumption of the period are shown in Table 5.3.

The energy consumption of the buildings listed in Table 5.1 was analyzed using data from the IRETI and e-distribuzione platforms. Both platforms offer customer portals where we can enter a building's POD (Point of Delivery) number to access and download detailed quarter-hour consumption data.

Table 5.3: Minimum, maximum, and average electricity consumption of the Scuola di Biotecnologie 1 building for the period 05/01/2022 - 05/31/2023.

Month	MIN (kWh)	MAX (kWh)	Avg Consumption (kWh)
May 2022	7,189.16	10,215.48	8,981.90
June 2022	8.262,76	10.781,32	9.517,63
July 2022	8.534,68	11.006,16	9.986,51
August 2022	8.215,24	10.761,96	9.394,57
September 2022	6.885,56	9.670,32	8.595,94
October 2022	6.979,28	9.100,96	8.209,12
November 2022	6.296,40	8.273,76	7.443,16
December 2022	5.924,60	8.250,88	7.074,19
January 2023	5.832,20	7.881,28	7.029,85
February 2023	6.051,32	7.575,92	7.057,03
March 23	5.592,40	5.592,40	7.130,92
April 2023	5.974,32	8.080,60	6.937,39
May 2023	6.500,12	8.672,40	7.832,37

Some buildings lacked data for a few months; others had no usable data at all. In most cases, this likely resulted from missing updates on the utility platforms. For each building with available data, the full set of quarter-hour readings was analysed, and daily consumption was calculated by summing each day’s (results were rounded to two decimal places.

5.4 Case Study: Unito Campuses in Torino

To recall the overall entities, UniTo buildings are in 7 of the 11 cabins shown in Figure 3**,** and most of them are concentrated in the three central areas. In the three main cabins, the buildings are identified with the ID numbers, which are summarized in Table 5.1.

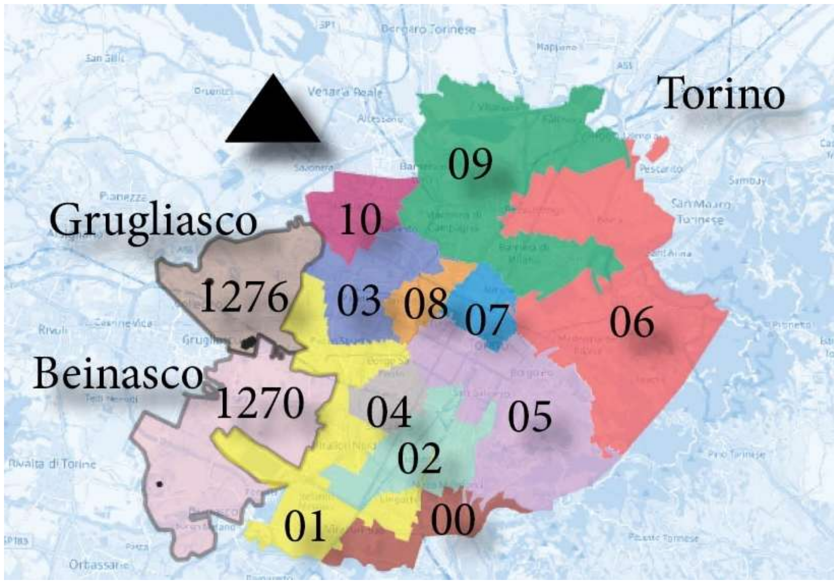

Figure 5.7 (3): Map of Unito primary cabins, Grugliasco and Beinasco.

The potential for solar energy is highest during July and August, and lowest in January and December (figure 5.5), about a quarter compared to summer months.

The study emphasizes that the work is done on cabin 05 (purple). The number of panels that can be placed on the roofs is the surface area divided by the area of a typical panel (1.0m x 1.70m). Only 40% of the roof was considered, and another 10% for maintenance space and roof windows, following the logic and conclusion obtained in chapter 4.

5.4.1 Global Energy Balance Analysis

In this section, the energy analysis will be shown for scenario 1, with solar PV mounted on the roofs only, and Sec-R, the key indicators, are the self-sufficiency and the self-consumption. We will analyse the results at three levels: yearly, monthly, and hourly. This helps us see both the global and individual impact of solar energy production over time.

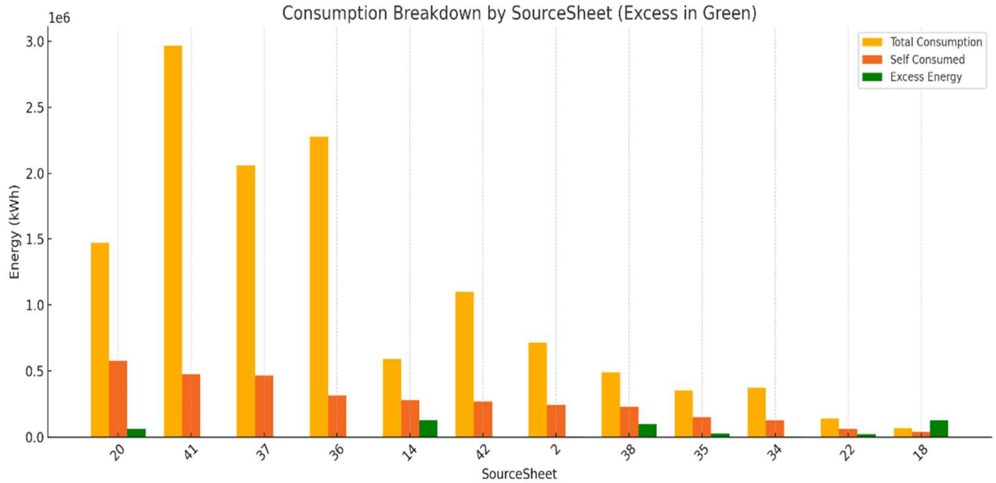

Figure 5.8: Total consumption, production, and self-consumed energy for buildings inside cabin 05.

The graph represents the total amount of energy consumed for each building compared with its production and excess energy under scenario 1. For this setup, buildings operate alone (Figure 5.8); they don't share energy, and energy produced is self-consumed within the building. If there is any excess energy, it is sold to the grid (chapter 3). Across all buildings in cabin 05, RTSPV production covers only a small percentage of each building's demand. Buildings like 41, 36, and 37 use the most energy, yet they still rely heavily on the grid.

Looking at this graph is the start to understand the scope of the buildings in the cabin, even though their total energy demand shows that it's very high, the story might be very different when we look at the hourly scale. Nevertheless, a better view of this is the SF and SC.

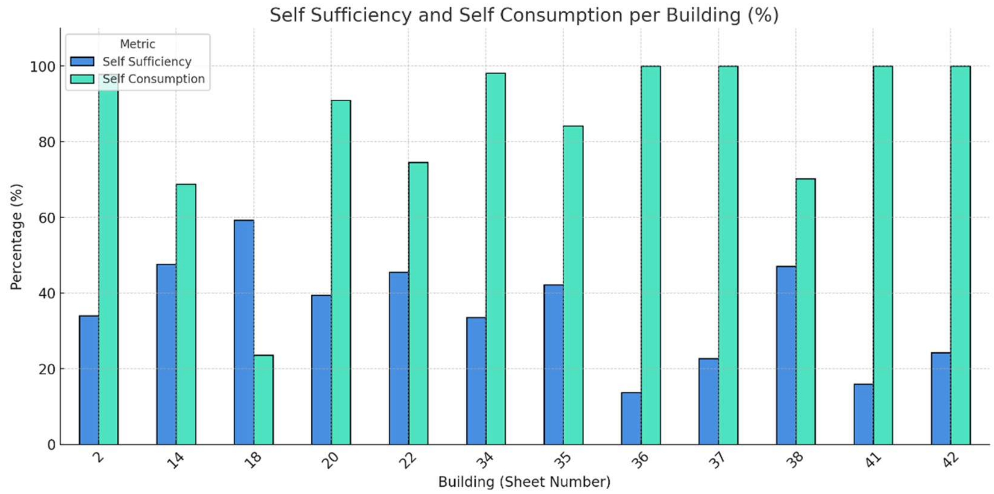

Figure 5.9: Self-consumption and Sufficiency, for buildings inside cabin 05.

The figure shows the self-sufficiency and self-consumption levels of the 12 selected buildings in cabin 05. Self-consumption levels are consistently high (often exceeding 90% and reaching 100%), which means that most of the energy produced is self-consumed. But self-sufficiency values, on the other hand, vary significantly, ranging from around 15% to 60%, with buildings like 36, 41, and 42 showing near total self-consumption and very low self-sufficiency; they consume everything they produce and get the rest of their energy needs from the grid.

Buildings 18, 22, and 38 have more stable levels, showing moderate self-sufficiency and strong self-consumption, having energy surplus at certain hours, where they would be able to share if they were in a SEC, or sell it to the grid.

These results serve as a baseline for evaluating alternative scenarios, such as SEC-R, where collective systems and added PV surfaces are deployed to improve self-sufficiency overall, coordination, and economic returns. Results in SEC-R are formed from an hourly aggregate of the data, pinpointing a specific hour a building has energy demand or energy surplus.

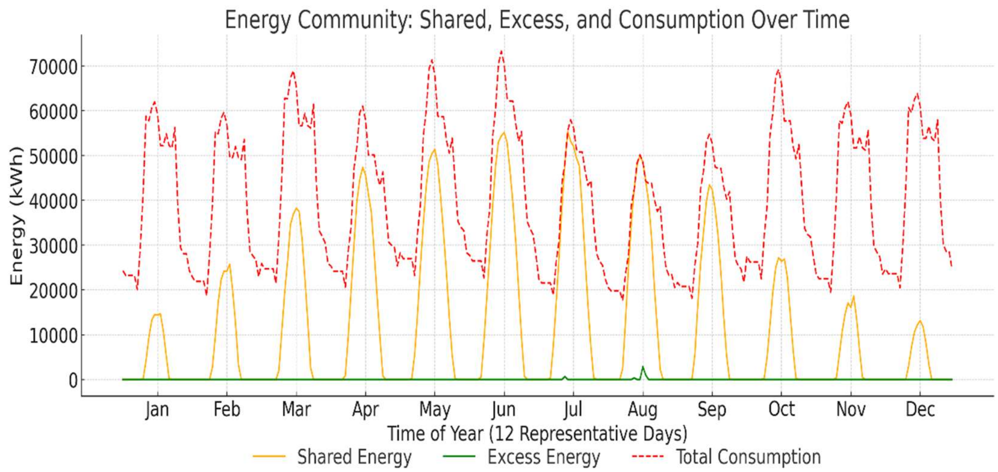

Figure 5.10: SEC of UNITO, showing the shared energy, excess, and total consumption

Figure 5.10 presents the SEC-R modelled as a single entity, depicting Shared Energy in yellow (locally generated energy and consumed within the community), Excess Energy (green) which is the energy surplus exported to the external grid, and the Total Consumption (red) representing the Combined demand of all buildings within the community, all represented on an hourly scale, the total consumption remains dominant here with some hours in July and august managing to have a surplus.

The total consumption of the SEC is 11,502 MWh, and the total production is 3,427 MWh, with an excess energy of 4,384 kWh. The total self-sufficiency from SER-R is 30%, making use of the excess energy in each hour, whether it is shared with other members (considered self-consumed in this case) or sold to the grid. This collective coordination adds a lot of value on an hourly basis, special when comparing it to scenario 1 where every building operated alone.

As mentioned in the literature, SECs qualify for financial benefits. Working together lets communities rely less on the grid (especially during months with high solar output). This improves energy security, reduces stress on the public grid, and supports long-term goals for decarbonization and decentralization. Treating multiple buildings as one energy system pays off. Shared consumption improves renewable use, increases financial returns, and helps meet energy targets. The data shows that energy communities aren't just technically sound, they're practical, scalable, and aligned with future energy systems. If we look at it in other terms, it's not really producing energy; it's producing resilience.

5.5 Economic and Financial Balance Analysis

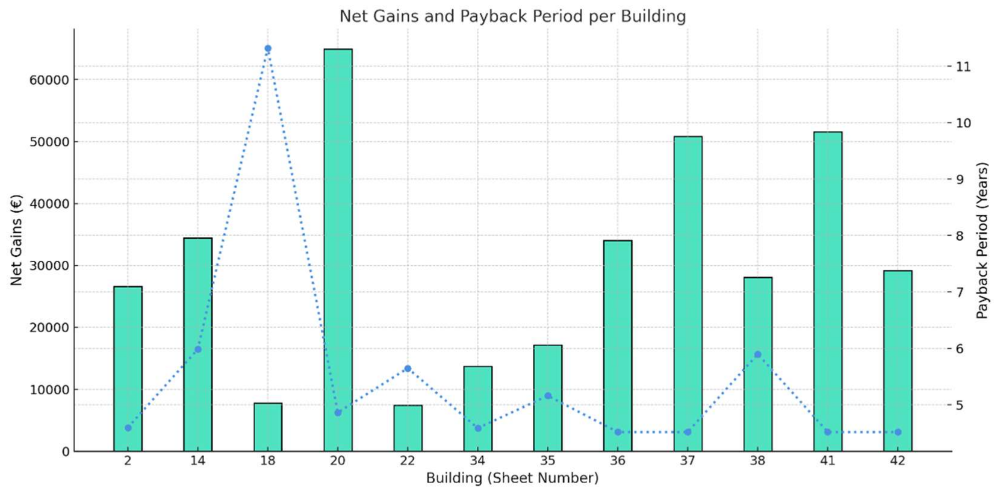

Figure 5.11: Energy community of UNITO, showing the shared energy, excess, and total consumption

To complete the analysis, the final perimeter to assess is the financial part. In scenario one, where every building acts as a prosumer, the annual gain doesn't cover the capital to make such an investment,

Most buildings show a positive net gain, and the photovoltaic systems deliver clear financial returns. Buildings 20, 37, and 41 perform best, suggesting a good match between system size, energy prices, and demand patterns. Payback periods range from 4.5 to 6 years, except for Building 18, which extends beyond 11 years due to lower gains.

Reflecting on self-sufficiency as a third variable gives more context. Across the portfolio, self-sufficiency stays below 60%. Buildings 18 and 22 reach higher levels, showing a stronger balance between production and demand. Some buildings earn strong financial returns despite low self-sufficiency, meaning they use most of what they generate, even if it does not cover total demand. Both economic and energy indicators are needed to judge system performance.

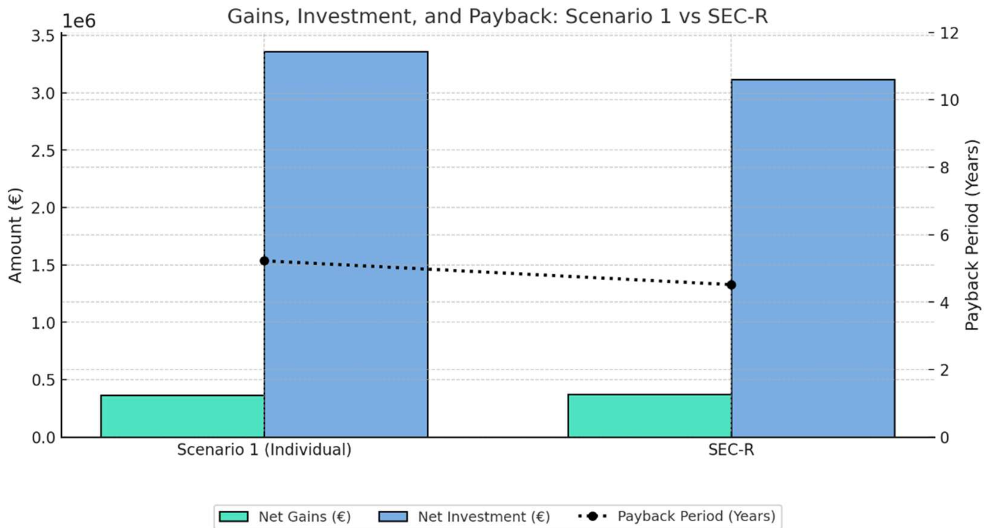

Figure 5.12: Financial return for the energy community of Unito

The SEC-R scenario had annual gains nearing 685,000 €, while scenario one is 373,000 €, which is considered a long-term value path, with a payback period of just 4.5 years, making it a highly efficient project that should be invested in, particularly for its scale. When comparing it to individual buildings, SEC-R accelerates cost recovery and maximizes energy value, due to optimized energy sharing, resource pooling, and reduced redundancy.

Although they both require similar investments of about 3.1 million euros, SEC-R delivers higher net gains and a faster payback. The payback period drops to 4.5 years in SEC-R, considering that the average payback period for scenario 1 is more than 6 years. SEC-R clearly has quicker capital recovery and better financial efficiency, making it a more sustainable financial and energy configuration.

The net cost figure accounts for incentives in Italy mentioned in Chapter *2*, and the annual gains combine savings on energy bills with feed-in revenues, with the application of 3% discount rate.

SEC-R elaborates on cooperative infrastructure planning and highlights its efficiency and its reduced reliance on the grid. These results alone justify why we should have stronger regulatory and financial support for ECs, inducing policies that emphasize energy sharing and coordinated public investment. If governments aim to accelerate the energy transition, precinct-scale ECs should be a central pillar (bankable, resilient, and built for long-term returns).

5.5 Discussion and conclusion

This comparative study evaluated two distinct photovoltaic deployment strategies within a university campus context: Scenario 1, where each building operates independently, and SEC-R, a collective energy community relying on shared rooftop installations. The analysis focused on three primary indicators: SF, SC, and payback period.

Although both scenarios involved a comparable total investment of approximately €3.1 million, the SEC-R configuration demonstrated better financial performance. With a higher net gain of (373,500€) than the aggregated gains from individual buildings, and a shorter payback period of 4.5 years, compared to a weighted average of over 6 years in the individual scenario.

Centralizing PV production under a collective scheme reduces redundancy and makes energy sharing and operation viable. Sharing of production across buildings enhances self-consumption as a community, which in turn limits excess energy exports, saving a lot of capital. Finally, administrative and maintenance costs are lower when they run under a single energy community structure.

Individual buildings have low self-sufficiency and scattered investments, which result in fragmented benefits and delayed financial returns. SEC-R, by contrast, delivers a more balanced energy and economic profile, leveraging the connection made between members of the community.

The results of this analysis support the Creating a SEC, specifically the SEC-R configuration, as a more efficient pathway for precinct-scale energy transition. With a similar capital expenditure, SEC-R offers faster payback, greater energy coordination, and higher gains when compared to a decentralized, single building.

Post-carbon urban strategies require a clean energy supply; this case study provides evidence for institutional stakeholders to create a collective investment. Future research should extend this comparison to include SEC-RF (roof + façade) when applicable by the government and SEC-U (urban-scale with sheds and façades) configurations, for a more comprehensive transition roadmap to an Urban Energy Precinct which will be seen in chapter 7.

Chapter 6

6. EMPIRICAL ANALYSIS III: Digital Governance Tools for SEC Management

6.1 Introduction

The previous part (Chapter 5) evaluates electricity-sharing communities across multiple buildings. In this chapter, we will discuss how to integrate the management system for the anchor institution, taking the University of Torino as an example.

The University of Turin (UniTo) has the scale and institutional credibility to lead the pilot project of a SER-R, since it has a lot of campuses widespread throughout the city and within the same primary electric cabin, with more than 50 buildings spread throughout Turin and its surroundings, and it already manages its own energy network theoretically. This is all the more reason to be the candidate to not only become a prosumer, but a central coordinator for local energy production and sharing, following the footsteps to become the anchor institution in its urban precinct.

By bringing together municipalities, schools, hospitals, public utilities, and private citizens, UniTo can build and connect a network of stakeholders with aligned energy goals. Being academic adds another layer of research-innovation, data, and policy analysis. Rather than passively joining RECs, UniTo could step into the role of a precinct's energy orchestrator, fulfilling the energy demand of its community and facilitating its energy production, ensuring transparent governance, and guiding long-term energy transition strategies.

Which is the first step to fill the gap mentioned in Chapter 2, emphasizing Italy’s fragmented energy landscape, where legal implementation takes a lot of time due to unclear jurisdiction between municipalities, DSOs, and regulators.

With Legislative Decree 199/2021 now in place (Chapter 3), UniTo can bridge these gaps and create the SECs that are technically feasible, financially viable, and institutionally possible. By leading its own campuses and scaling outward, the University could model a replicable pathway to a locally energy Self-Sufficient urban precinct and a path to carbon neutrality.

The first step in this case study, after entering the data from Chapters 2 and 3 and applying the framework from Chapter 4, made one thing clear: there's a big difference between applying an energy community and actually building one. The road to sustainable cities isn't about installing solar panels; it's about fixing past mistakes. That means creating a new kind of infrastructure. Not one defined by what can be seen on the ground, but by how well it supports the transition to post-carbon cities. A network using UniTo as both the source and the governor shows how even a small, contained case (limited to a few campus buildings) can become not just energy efficient, but financially viable. It proves that with the right structure in place, energy communities can scale from concept to impact.

Using this remark, the university campuses of Unito will slowly transform the city of Turin into a sustainable urban precincts that form a grand network.

6.2 Asset Management

Managing large and diverse property portfolios such as university campuses is complex. Buildings differ in geometry, age, typology, technical systems, and user needs, creating a constant flow of heterogeneous data that complicates decision-making. The difficulty increases when information is stored across fragmented, document-based systems that are hard to access or integrate, often delaying maintenance and planning actions. To address these inefficiencies, universities are adopting digital asset management systems (AMS) grounded in information management principles to improve operational decisions, reduce costs, and limit waste in line with the Sustainable Development Goals. However, a fully integrated AMS that can connect data from multiple sources, ensure accuracy, and support decisions across the asset life cycle is still missing (Moretti et al., 2021; Vivi et al., 2019). Developing such a system would help overcome current management limits and enable scalable approaches applicable to other public property portfolios such as schools, hospitals, and social housing(Qian & Papadonikolaki, 2020).

The term *campus* is commonly understood as "the collection of buildings of a university or college, including the land around it" (Oxford, 2022). Yet this definition feels limited, particularly when viewed through the lens of sustainable urban development and the wider transition toward greener practices. In contemporary discourse, the idea of a *smart* or *technology campus* (Heijer et al., 2012) extends far beyond the physical boundaries of a university. It brings together the built environment with the fields of urban planning, regional development, business, and technology, creating a more integrated and dynamic framework.

Only a few campuses have been examined through this broader perspective, where they are treated as complex real estate systems analyzed across strategic, financial, functional, and physical dimensions (Heijer et al., 2012; Hoeger & Christiaanse, 2007). The smart campus concept adapts principles from smart city thinking, using digital and information technologies to improve management efficiency and environmental performance (Dong et al., 2020). In doing so, it lays the foundation for what is increasingly described as a *sustainable campus*, one that leverages data and technology to guide informed and responsible decision-making.

Although there is no specific definition that exists, Dong et al. (2020) identified six characteristics that make such campuses: context-aware, data-driven, forecasting, immersive, collaborative, and ubiquitous. These features show the central role of data and its interpretation within its context in supporting sound decisions and long-term investments (Vivi et al., 2019). In reality, the smart campus represents a shift from managing physical assets to actually managing its own knowledge, an evolution that only draws inspiration from and toward digital and sustainable urban systems.

For this purpose, the availability of updated and accessible data on the building and its surroundings is core, providing effective digital AMS development with complete and shared knowledge, useful for more sustainable decisions on multiple aspects such as environmental comfort, energy consumption, maintenance, and efficiency measures, optimisation of space use, etc. The use of static and dynamic data, representing the basis for smart campuses, can support the execution of automated tasks, improving efficiency and reducing the time to respond to emergency issues. However, integrating and processing diverse data from heterogeneous sources to support asset managers is still rather challenging.

BIM (Building Information Modelling) and GIS (Geographical Information Systems) play a central role in understanding assets across multiple spatial and technical scales. Combined with Business Intelligence (BI) tools, they provide complete and reliable information that supports university asset management systems (AMS) (Bao et al., 2023; Moretti et al., 2021). In other words, their integration enables the creation of a multi-level database based on clear information standards, ensuring consistent data collection, aggregation, and updating.

To improve data comparison, interpretation, and sharing among stakeholders with diverse expertise, the University of Turin (UniTO) developed a dedicated AMS (Di Giuda et al., 2023). The system integrates BIM and GIS within BI tools, allowing data on buildings, locations, space use, energy demand, and occupancy flow to be processed and displayed through interactive dashboards. Each dashboard is tailored to specific management needs. BI tools connect different data sources, combining BIM models with GIS maps to deliver both geographic and detailed insights into individual buildings and their components.

The UniTO AMS evaluates the current condition of university assets and supports management decisions through data analysis and visualization within a web application (Di Giuda et al., 2023). A specific section dedicated to Energy and Sustainability, recently developed, demonstrates how the system can integrate and analyse information on energy consumption and solar potential to guide the campus toward decarbonization.

Energy, economic, and spatial data of the University of Turin were collected to estimate the available surface area for photovoltaic installation and assess the potential use of renewable energy, processed, and compared using two main approaches: one based on GIS and the other on BIM.

The research combines BIM, GIS, and BI tools to provide clear, accessible, and comparable information to support informed decisions by the university itself. The analysis and visualization dashboards reveal opportunities for improvement and optimization, to take clear and effective actions.

6.3 Methodological framework

The methodology developed for evaluating university energy and sustainability policies focused on three core aspects: solar potential, building energy consumption, and photovoltaic (PV) energy production. Two distinct approaches were applied to carry out the analysis, using GIS (Chapter 4) and BIM to generate the required data and Business Intelligence (BI) tools for visualization. The following sections describe in detail how each technology was used.

The main goal here is to identify which method can obtain better results when it comes to assessing the solar potential a building can have, mainly by installing RTSPV, yet it is worth noting that these two methods can also complement each other by using each one at a different scale.

To validate the process, the study defines and applies a replicable methodology through a pilot case study: Palazzo degli Stemmi. This building, located in the historic city center, was selected due to its architectural, regulatory, and technical characteristics, which are representative of more than 40 percent of UniTO's active building stock. These buildings are currently protected under national or international heritage regulations, as defined by Legislative Decree 42/2004.

Palazzo degli Stemmi is a six-floor historic building located in the center of Turin, housing several university administrative offices. This building was selected as a case study due to the typical characteristics of its roof, which are redundant in local historical structures. The research uses this case to apply and test the proposed methodology, focusing on identifying roof areas suitable for photovoltaic installation, taking into account technical constraints, regulatory requirements, and architectural features.

Recalling the method in Chapter 4, it uses the same solar radiation data and GIS functions to calculate solar potential by processing large numerical datasets related to solar exposure. This helps in pinpointing areas with high solar potential and plan accordingly for the effective placement of rooftop photovoltaic systems in dense urban areas.

The datasets include information such as the representative day for each month, global diffuse radiation, Linke turbidity values, and the direct-to-global radiation (D/G) ratio, as shown in Table 6.1 with the list of data types and their sources.

Table 6.1: Data extracted from open-source platforms

Data	**Source**
Avg Day	Klein 1977
Diffuse to global radiation ratio - UNI 10349-1 (2016)	ENEA 2024
Linke turbidity data	SoDa (Linke Turbidity Factor,2024)
DG_ratio	Solargis 2024

Figure 6.1: Turin Roof Solar Potential [kWh/m2]

Figure 6.1 shows the solar potential for the city of Turin. Covering the entire roof with solar panels represents an ideal but unfeasible scenario. In reality, constraints such as the need for maintenance access reduce the usable surface. This study adopts a standard approach by limiting the exploitable area to 40 percent of the total roof surface, balancing technical feasibility with sufficient solar output based on typical photovoltaic (PV) panel specifications.

To test the validity of the proposed methodology, data from Palazzo degli Stemmi were extracted and compared with the results from the second method, which works more on the building scale, with energy production calculated using Equation (4) and compared to real energy consumption data obtained from UniTO green Office.

In parallel with the GIS-based territorial method, the study developed a BIM-based process to assess PV potential at the building level. Following the approach outlined by Di Giuda et al. (2023), researchers modeled UniTO buildings using data from the AMS platform. Roofs were recreated in 3D using BIM software, capturing key geometric features such as slope, height, and potential obstructions. Thin virtual layers were used to represent regular, dimensionally consistent sections of the roof. Elements such as skylights, dormers, gutters, and ventilation shafts were excluded to define realistic PV coverage areas. The model also included a one-meter buffer around fire protection devices and vertical compartment elements, in line with Italian fire safety codes (Ministero dell'Interno, 2022). Local regulations required flush-mounted panels on pitched roofs to preserve building profiles and reduce wind loads. Although national guidelines (Italian National Standardization Body, 2022)(CEI 82-25, 2022) recommend south-facing panels to maximize solar exposure, architectural constraints often force non-optimal orientations. Nearby shading elements further affected potential output. These technical limitations directly influence energy yield and project economics by increasing cost per kilowatt-hour and extending the return on investment.

To model roof tops with each having specific characteristics, costume created parameters were implemented on Revit to account for that, which include its slope in degrees, the orientation wither its facing N, S, E, W, or a combination of them, pitch type (flat, inclined, curved), its material like clay tile, concrete, membrane or metal, and the total available surface area. Using these parameters, we can calculate and model the number of solar panels that could be installed.

The BIM-based analysis of Palazzo degli Stemmi shows how a simple rooftop can have a very complex roof geometry, with dimensional constraints that limit suitable spaces for PV installation. From a total rooftop area of 2,451.20 m², only 1,724.68 m², approximately 30 %, can realistically host RTSPV. Panels were placed digitally, with each modelled panel type added based on high-efficiency commercial products with dimensions of 2120 x 1052 x 40 mm and a rated peak power of 465 Wp under Standard Test Conditions (STC).

Based on the information above and taking into account all the constraints of the rooftop, using RTSPV would amount to a total of 605 installable panels, with a combined peak capacity of 281,325 kWp.

Energy production depends on several variables, in line with CEI 82-25 (2022). These include:

- The solar radiation reaching the module surface, influenced by site latitude, surrounding surface reflectance, panel tilt and orientation, and any shading or soiling.
- outdoor temperature;
- module characteristics such as peak output and temperature sensitivity;
- system losses from mismatches or partial shading;
- and the overall performance of the Balance of System (BOS), including inverter efficiency and wiring losses.

To verify the solar potential, the study considered data from UNI 10349, which offers monthly average daily radiation values by province. However, for greater precision, it used the PVGIS Solar Atlas developed by the European Research Centre. PVGIS allows location-specific calculations using roof tilt (α) and azimuth (γ) inputs from the 3D model. It estimates daily solar irradiance per square meter, based on satellite data (PVGIS-SARAH2), and reflects real site conditions more accurately than static tables. For the coordinates of Palazzo degli Stemmi (45.0685°N, 7.6905°E), the annual in-plane solar irradiation was estimated at 1,624.03 kWh/m² for the year 2020.

With a total installed peak capacity of 281 kWp, and 15% system losses (aligned with Italian performance ratio standards of at least 85%), roof-integrated (BiPV) systems were modelled with a tilt angle of 21°, representing the dominant roof plane, and the azimuth to 42° west.

Using PVGIS data, the total RTSPV energy production amounts to 326 MWh. Using Equation (3) to make a more exact estimation and reference, with performance ratio PR = 0.85, irradiation Hs = 1,624.03 kWh/m², surface S = 605 panels × 2.23 m² = 1,349.15 m², and panel efficiency η = 0.2085 (derived from 465 W / 2.23 m²), the total energy production would be 388 MWh. By comparing the two estimates, PVGIS is16 % lower, since it was a more site-specific data rather than general assumptions, making PVGIS and BIM a better estimate when it comes to the building scale.

The trick here is to understand which method to use first. GIS thrives in urban scale assessment, especially when trying to pinpoint the best area, while BIM-based methods should be implemented when making a detailed study of a building; both of these methods complement each other

As part of the broader AMS methodology (Di Giuda et al., 2023), the georeferenced BIM model was integrated into the UniTO AMS application. It supports customized dashboards focused on Energy and Sustainability; these visualizations are presented and discussed in the following section.

The comparison between the BIM-based and PVGIS-based methods highlights the trade-offs between geometric accuracy and computational simplicity. As shown in Table 6.2, the BIM-based approach offers greater spatial precision by modeling real roof constraints and simulating the actual placement of photovoltaic panels. This leads to a higher estimated energy yield, but requires more time, detailed input, and modeling expertise. In contrast, the PVGIS-based method provides a faster estimation using location-specific solar data, though it lacks sensitivity to building-specific morphological constraints. The 16% gap in estimated production between the two approaches reflects these methodological differences. While both methods remain valid, their combined use strengthens decision-making by aligning detailed asset information with realistic energy forecasting.

Table 6.2: Data extracted from open-source platforms

Parameter	BIM-Based Method	PVGIS-Based Method
Surface considered	Modeled panel area: 1,349.15 m² (605 panels × 2.23 m²)	GIS-calculated usable roof area: 1,724.68 m² (approx. 30% of roof)
Data source	BIM 3D model (Revit), AMS platform	PVGIS Solar Atlas (SARAH2 satellite data)
Panel specs	2120 × 1052 mm, 465 Wp, 20.85% efficiency	Same panel specs assumed
Tilt (γ)	21° (from 3D model)	21° (input to PVGIS)
Azimuth (α)	42° West	42° West
Performance ratio (PR)	0.85 (15% system losses, per Italian regulations)	0.85 (same assumption)
Irradiation source	UNI 10349 + Equation (2)	PVGIS database (2020 satellite-based estimate)
Annual irradiation (Hs)	1,624.03 kWh/m² (input value)	1,624.03 kWh/m² (automated via PVGIS)
Estimated annual energy (E)	388,310.62 kWh	326,084.17 kWh
Difference	Reference calculation (Equation 2)	Approx. 16% lower than the BIM-based estimate
Advantages	Higher spatial detail, realistic panel placement, 3D geometry	Faster, location-based, uses dynamic solar data
Limitations	More complex setup and modeling effort	Less responsive to building-specific geometry and constraints

6.4 Results and Discussion

To compare the outcomes of the two methodologies, Business Intelligence (BI) tools were used to process and visualize data from the BIM model of the case study, including solar radiation, energy consumption, and estimated energy production. The resulting values were displayed in customized dashboards, allowing direct visual comparison between the two methods. Figure 6.2 presents one such dashboard, which reports the building's annual energy consumption and illustrates monthly estimates of solar radiation, energy output, and projected energy savings.

Method 01, which uses GIS (shown in blue), and Method 02, based on BIM (shown in red), display similar monthly trends but differ in absolute values.

During the summer months, there is a 12 to 20 percent difference in the estimate between the two methods. Interestingly, in winter, the gap becomes bigger with a 30 to 52 percent variation, with all cases having Method 02 resulting in a higher estimate for both energy production and monthly savings. These results clearly show that while both approaches follow a consistent seasonal pattern, the BIM-based method produces higher outcomes, because it accounts for detailed modelling of roof geometry and installation constraints.

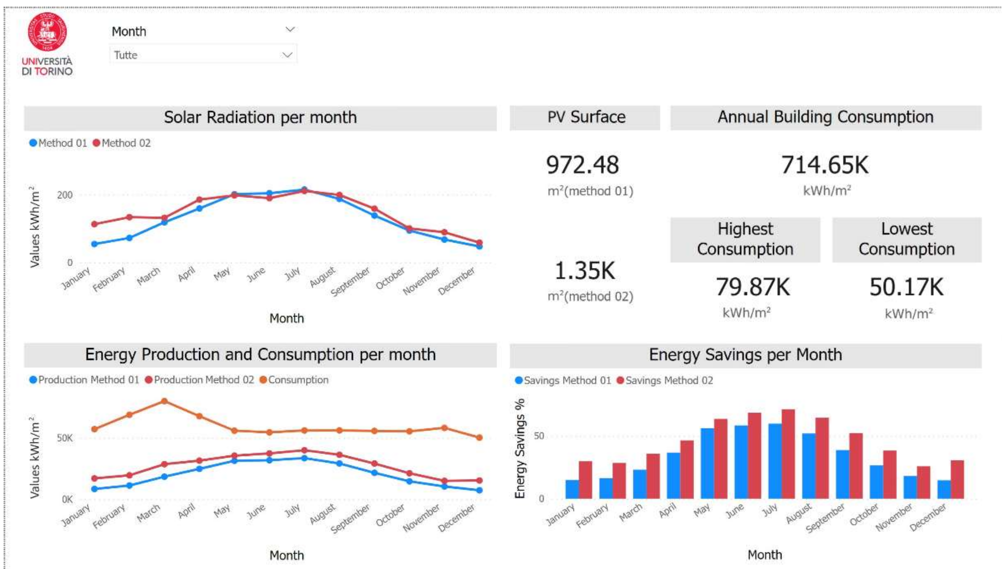

Figure 6.1: BI dashboard showing a comparison of the two methods

With the use of RTSPV, the total energy production can partially meet the building’s energy demand, as shown in Figures 6.1 and 6.2 (orange line). These finding supports Unito's decision-making processes and help find alternative solutions that fulfil strategic goals and technical constraints. Figure 6.2 displays part of the software dashboard with the 3D BIM model shown. Users can select individual roof pitches and get detailed information about their geometry, orientation, and construction type. The dashboard also presents key building data, including total net area, number of rooms, and user occupancy, along with general or pitch-specific information based on the selection.

Based on the entire inclined brick-tiled roof, which has a surface area of 2,451 m², the analysis confirms that PV panels can be placed on 1,725 m². Figure 2 shows the actual area covered by the installed panels, amounting to 1,350 m². This corresponds to 55 percent of the total roof surface and 78 percent of the area previously identified as suitable for installation. When selecting individual pitches, the dashboard provides slope and exposure data. It also reports monthly values of energy production and consumption derived from Method 02, confirming the method's accuracy in estimating building-scale PV performance.

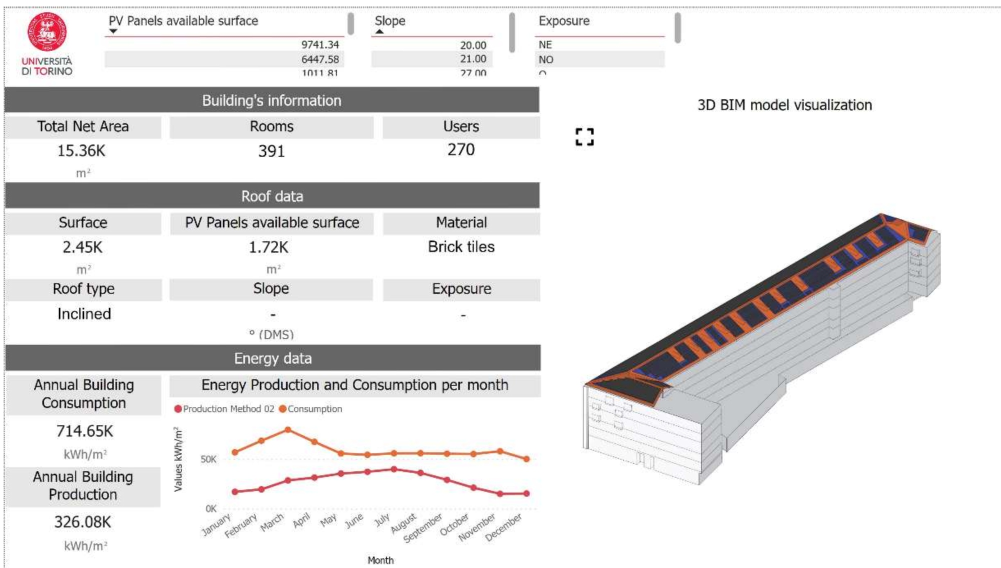

Figure 6.2: BI dashboard displaying information derived from the AMS BIM-based method

The BIM-based approach (Method 01) estimates higher and more stable solar energy production values compared to the GIS-based method (Method 02). Each method, however, has its advantages depending on the context. The GIS method uses open-source data, provides broad, scalable estimations suitable for urban-scale energy analysis, especially in preliminary stages. On the other hand, the BIM method uses detailed, building-specific models with more accuracy in calculating usable solar surface areas.

While GIS remains efficient for large-scale solar potential studies, BIM proves more reliable at the building level due to its dimensional precision and integration capabilities. Combining both approaches creates a balanced framework, pairing the spatial coverage of GIS with the geometric detail of BIM. This dual-method strategy supports more informed decisions on solar energy deployment, helping to optimise both energy output and resource allocation.

Introducing a BIM-based method or something that mirrors it is essential for asset-level management. Decision-makers can use it to evaluate technical feasibility and cost-effectiveness based on real-life data. Since implementing RTSPV a design factors need to be taken into account, and a real-life model needs to be available to optimise the usable surface areas and minimise the shading on the PV, which in turn affects panel efficiency, performance ratios, balance-of-system elements, and roof integration techniques.

AMS can integrate into its system energy metering as well, PV production forecasts, load profiles, and the use of the main grid. Showing real-time, data-driven decisions, especially when unito becomes more than just a set of individual prosumers, but an anchor for a solar energy community (SEC),

AMS would make administrative coordination easier, follow national energy regulations (substation restrictions and hourly load obligations), and promote fair distribution of pooled energy incentives as explained in Chapter 3. Being an integrated system, the AMS ensures that all information concerning energy and asset flows is available to UniTo, which remains at the same time an operating and an institutional center of the REC. This will facilitate member coordination, overcome technical obstacles, and ensure a just distribution between members.

Using AMS creates an opportunity for an institution like UniTo to anchor and manage Solar Energy Communities (SEC) across Turin, making use of its widespread campuses, leading a posta carbon transition in Torino.

Chapter 7

7. EMPIRICAL ANALYSIS IV: Energy community of the United Nations in Geneva: Analysis, connections, and establishment under policies

7.1 Introduction

Crossing back a bit on chapter 2, the global shift toward renewable energy and sustainable climate solutions is advancing rapidly across various sectors and levels of society. Yet, the challenge of meeting the escalating demand for electricity remains a significant hurdle in this transition. As highlighted by the International Renewable Energy Agency (IRENA, 2023), electricity is projected to become the dominant energy source, accounting for over half of total final energy consumption by 2050. This increase is primarily fueled by the widespread adoption of technologies such as heat pumps, electric vehicles, and advanced cooling systems. Consequently, the pressure on power grids is intensifying, raising concerns about potential shortages and instability in a world already marked by uncertainties and successive crises.

By leveraging locally producible renewable resources, solar energy can be used to become the most resilient energy supply in cities (chapter 2), especially since solar photovoltaic (PV) systems have surged, particularly following the energy crisis induced in Europe by the war in Ukraine. According to the International Energy Agency (IEA, 2023), PV capacity reached 1,100 GW globally in 2023, with 220 GW installed in 2022 alone. Projections forecast that PV capacity will exceed 2,500 GW collectively by 2030, making solar energy the biggest source of renewable energy worldwide (IEA, 2024).

However, the rapid growth in solar PV deployment presents risks such as overvoltage and curtailed energy production if grid integration is not effectively managed (Mehta & Tiefenbeck, 2022; Manzolini et al., 2025). Currently, curtailed wind and solar PV generation remains relatively low, ranging between 1.5% and 4% in major renewable energy markets, but this figure is anticipated to rise as renewable capacities expand (IEA, 2024). Urban PV systems, predominantly installed to maximize roof space, have typically been designed for single-use applications, often reselling excess production to Distribution System Operators (DSOs) at attractive tariffs (Pena-Bello et al., 2023; Gautier & Jacqmin, 2020). On average, approximately 60% of PV generation is exported to the grid, reflecting a low self-consumption rate of just 40%.

Solar energy can increase self-sufficiency to a rate of 70% especially when there is limited solar output in winter, while adding a hybrid system that uses solar and wind can even increase the rate higher (Pena-Bello et al., 2019). These findings encourage the adaptation of a more integrated approach when it comes to renewable energy solutions, helping cities address seasonal production variability and stabilize grid operations.

Using solar energy communities to make the global energy transition a reality depends on many factors, like strategic planning and flexible strategies to optimise renewable energy systems and ensure their compatibility with urban infrastructure. By prioritizing hybrid systems and focusing on self-consumption rates, urban-scale projects can slowly become energy independent.

7.2 Scope and context

Solar PV installations account for a relatively small fraction of the canton’s energy mix compared to other renewable sources (Swiss Federal Office of Energy, 2024). The reliance on imported energy and traditional sources underscores the need to expand solar initiatives to enhance energy independence and sustainability (Cantonal Energy Office (OCEN), 2020).

Solar energy sources have made a lot of progress in the energy mix of Switzerland. In the past few years, it increased from 3.8% in 2018 to 11.3% in 2024 (Swissolar, 2024). These numbers forecast the goal of the Swiss government, prioritizing the shift of its energy mix to sustainable sources

Common barriers to solar energy adoption include regulatory complexities, high initial investment costs, and limited public awareness (analyses of BIPV systems and renewable energy commercialization challenges) (Kishore et al., 2025). Addressing these challenges requires strengthening policy support, simplifying administrative processes, and increasing financial incentives specifically targeted at solar development (Cantonal Energy Office (OCEN), 2020).

To have a concrete implementation of solar ECs in Geneva, the following gaps need to be addressed:

- Make RCPv/CEL workable in practice. There is still a lack of tested steps for meter aggregation, allocation keys, billing, data sharing, and DSO interfaces in dense districts (Inês et al., 2020; SFOE & DETEC, 2024; SIG, 2025c).
- Model the new economics. From 2026, seasonal tariffs vary by season in the year. (SFOE & DETEC, 2024; Swissolar, 2024).
- Broaden participation**.** Many designs still suit early adopters. A simple membership, fair benefits, and inclusion of vulnerable groups is a way to go (Caramizaru & Uihlein, 2020; Hoicka et al., 2020; Koukoufikis et al., 2023).
- Scale beyond pilots**.** There is a clear need for mapping methods (potential vs. feeder limits), standard contracts, and integration with Geneva's subsidies.

By bridging this gap, Geneva can advance toward its energy and climate objectives, reducing greenhouse gas emissions and promoting sustainable urban development (Cantonal Energy Office (OCEN), 2020). A promising approach to achieve the city's goals, making it a base model for other cities seeking to transition into the path of a post-carbon city.

7.2.1 Geneva Setting

Support programmes are designed to reduce barriers. At the federal level, Pronovo administers the Rétribution unique (PRU) subsidy (pronovo, 2023). Locally, Geneva maintains complementary cantonal/SIG incentives, including the Prime solaire SIG, set at 20% of the federal PRU in 2025, and the GEnergie catalogue, which consolidates subsidy access for building owners and developers (Canton of Geneva & OCEN, 2025a, 2025b, March 26). These instruments are specifically aligned with national provisions such as RCPv and CEL (chapter 2), to encourage self-consumption and neighbourhood-level exchange rather than relying solely on exports.

Two non-solar precedents are worth noting but remain context only for this paper's solar focus. First, the éco21 programme (run by SIG) is an energy-efficiency and engagement initiative that has established protocols for verifying savings and illustrates Geneva's tradition of citizen and actor mobilisation (SIG, 2024). Second, GeniLac is a hydrothermal district energy network that uses Lake Geneva's deep water to deliver low-carbon heating and cooling, serving as an example of a thermal energy community rather than a solar one, but still demonstrating Geneva's institutional capacity for large-scale, multi-actor energy projects (House of Switzerland, 2021; SIG, 2021a).

Geneva contains multiple areas (Figure 7.1), each is under the same Policy support, provided by the Cantonal Energy Law (LEn), which promotes sustainable energy use by setting ambitious targets for reducing energy consumption and increasing renewable energy production (Cantonal Energy Office (OCEN), 2020). Key provisions include building regulations that mandate high energy efficiency standards for new constructions and major renovations, and incentives such as financial subsidies and tax incentives for energy efficiency measures and renewable energy installations (Cantonal Energy Office (OCEN), 2020). Financial incentives like the Geneva Renewable Energy Subsidy offer grants covering a portion of the costs of installing renewable systems (Cantonal Energy Office (OCEN), 2020). Furthermore, public-private partnerships and community engagement involve collaborations with entities like SIG and cooperatives to implement large-scale energy initiatives (SIG, 2021b).

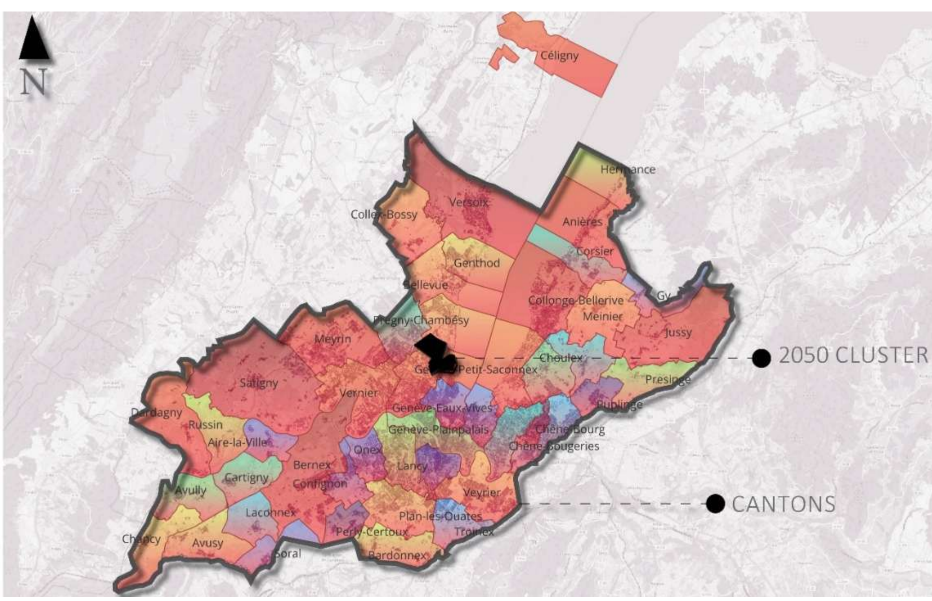

Figure 7.1: Map of Geneva with the different neighborhoods

Despite the various initiatives and policies promoting renewable energy in Geneva, the use of unsustainable energy is still the main source (Swiss Federal Office of Energy, 2024). The potential for photovoltaic (PV) solar energy is still being explored to reach a total installed solar PV capacity of 300 MWp by 2030. The total installed capacity in 2024 was 146 MWp, which means, double the amount should be installed over the next 5 years. Therefore, greater effort should be made to speed up the installation in Geneva (SIG, 2025b).

Chapter 2 examined how ownership structure directly affects the ability to implement energy communities (European Parliament & Council of the European Union, 2019; Inês et al., 2020). Explaining that single-owner models (like university campuses or municipalities) fit well within Switzerland’s ZEV framework. On the other hand, multi-owner districts remain a legal challenge that relies on the government's coordination ability. So they often rely on virtual sharing setups and avoid dealing with bureaucracy that still lacks firm support in the Swiss context. Returning to this comparison is key to understanding the governance choices made in this Chapter 7.

To address the underutilization of solar energy in Geneva, the 2050 Today initiative is spearheading the development of a Solar Energy Community (EC) within the United Nations zone, focusing on a select group of buildings committed to sustainability and aligned with 2050 climate objectives. This initiative aims to establish a scalable model for localized renewable energy solutions, with a primary emphasis on solar PV systems.

The 2050Today Climate Action Forum has over 70 institutions united to reduce greenhouse gas emissions through measurement, by implementing shared solutions, and applying research. The initiative is a partnership of the Swiss Confederation, the Canton and City of Geneva, the University of Geneva, and Geneva’s Industrial Services (SIG). These five main institutions make up 2050Today and compose its Committee of the Parties, under a Collaboration signed in 2022 and renewed in 2025.

The SEC that will be created for this case study makes use of the institutions tied by 2050today, and takes advantage of having a governing body that links different owners, making them have a shared responsibility for energy production and demand, and inducing participation with a sense of ownership among them, to reduce reliance on external grids, in efforts to achive Geneva's Energy Strategy 2050.

Situated in the northwest of Geneva, the United Nations zone hosts institutions and buildings like the UN headquarters, governmental buildings of foreign countries, and corporate offices. This dense area, which will be referred to in this study as the "United Nations Zone," provides unique elements that form it, making it an ideal setting for creating an urban enrby prcent that makes a complex multi-layered precinct into a simple coordinating SEC that leverages its diverse stakeholder base and commitment to environmental goals (Figure 7.2).

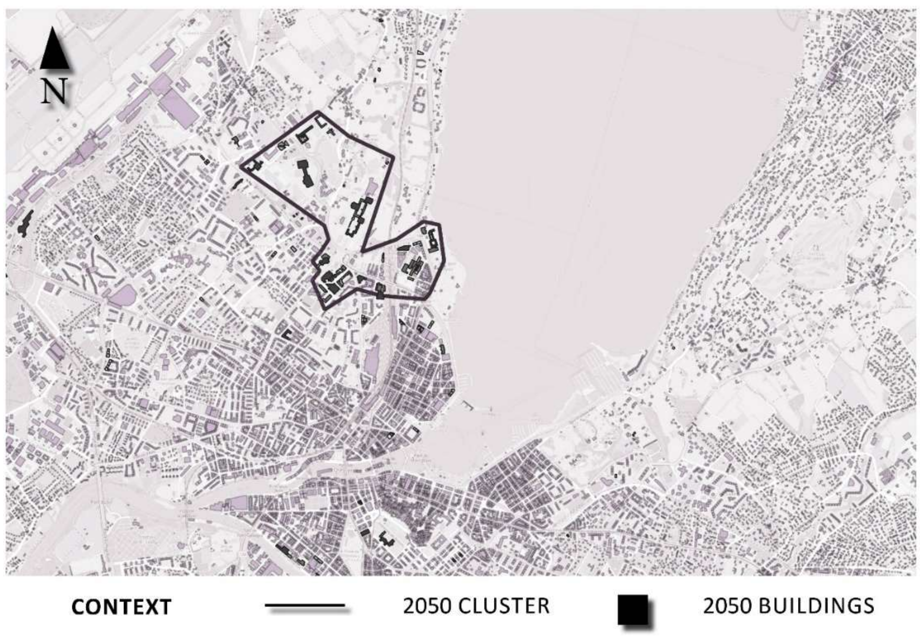

Figure 7.2: Map of the study area in Geneva

The map shows a section of an urban area near the lake, a specific zone, delineated by bold black boundaries and labelled as 2050 Cluster, which contains the UN Zone and the focus of the study. This area concentrates on several members of 2050 Today. Black-filled blocks represent buildings or projects prioritized by "2050Today". The map offers a general spatial framework for understanding the current status and the association's vision.

7.3 Methodological Approach

The first assumption is to create a SEC connecting the 2050Today members (buildings inside the study area). Further connections with additional neighbour buildings and solar energy production (parking and green areas sheds) will be considered to enlarge the SEC and improve energy independence.

The methodology of this study follows three main phases:

1. Hourly solar balance approach with solar production and load profiles
2. The individual and Global contribution of each type of solar installation for a self-sufficient neighborhood (rooftop, facade, green, railway, new buildings), showing the energy balance at a yearly, monthly, and hourly scale, to increase its self-sufficiency
3. Financial analysis with different scenarios to increase profitability

The initial step is focused on identifying buildings in the specified zone. The process then bifurcates into two main pathways: the left path emphasizes collaboration with the "2050Today" initiative, which involves identifying usable rooftop areas for solar implementation and extracting solar irradiance data. Meanwhile, the right path involves obtaining consumption data from the Service Industriels de Genève (SIG), followed by the calculation of energy production, and ultimately determining the level of energy Self-Sufficiency, as shown in Figure 3.

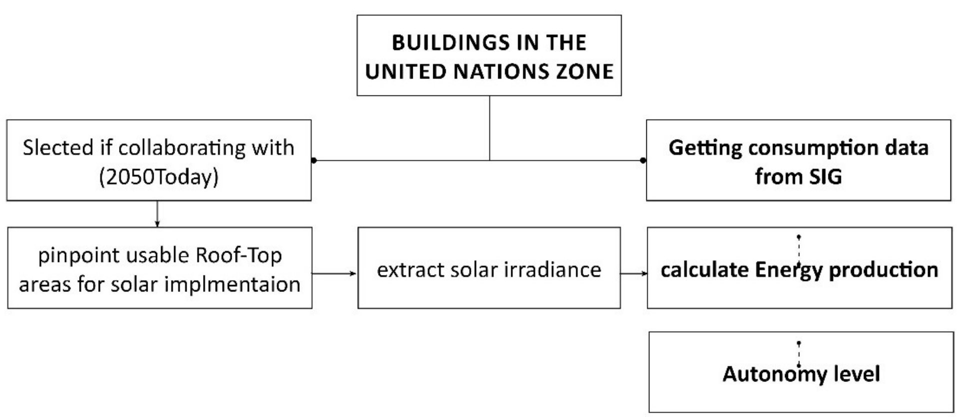

Figure 7.3: Setting up the data of the study

7.3.1 Data collection

The data was collected thanks to the 2050today association and the University of HEPIA in Geneva. In total, there are 70 buildings, some of which belong to a single building block. With the base data ready, the PV solar energy potential was provided by the solar cadaster of Geneva as an open source data (Table 7.1).

The five main areas where development could happen are the roofs, building facades, sheds of parking areas, sheds on green areas, and finally, the coverage of the railway in the main station of Geneva, using the solar irradiance. The calculation of the solar production is performed under the conditions that allow for utilizing these surfaces.

Table 7.1: Data collection and sources

Data	Source
Solar cadastre	(State of Geneva, 2024)
Shapefiles	(State of Geneva, 2024)
Consumption data	SIG
Solar Production	Calculation using the sola cadaster and equation number (4)

The energy consumption data is provided by SIG for all buildings on an annual basis. However, due to privacy concerns, only the aggregated energy consumption figures could be displayed. The total number of buildings within the block is 70, along with their total consumption reaching 84,494 MWh.

7.3.2 Horly balance analysis

A key objective in expanding solar energy use is to increase the share of photovoltaic (PV) electricity within the overall energy mix. One effective approach is to promote local consumption of the electricity produced, referred to as self-consumption, which is especially relevant in urban areas where individual buildings can both generate and consume energy.

Self-consumption can reduce grid stress by limiting ramp rates and reverse power flows, and it can improve the economic value of solar installations. Moreover, it enables users to consume local, renewable energy, reinforcing a sense of personal contribution to the energy transition (Luthander et al., 2015).

An hourly analysis quantifies the balance between solar production and demand, determining for each hour the self-consumed portion and the shareable surplus. Demand is modeled with Schneider's reference load profiles (Schneider et al., 2017) (one profile per building type, eg, commercial, residential, etc) while the PV production profile derives from the solar cadastre. This setup yields hour-by-hour values of self-consumption and excess generation available for community sharing.

The annual electricity consumption data for most buildings is provided by SIG (Services Industriels de Genève), the sole energy provider in the Canton. To derive hourly consumption values, this yearly data is disaggregated using load profiles representative of over 80 building typologies (e.g., residential, single-family homes, apartments, restaurants, etc.) (SIA, 2016).

As previously explained in the methodology, hourly profiles were used for solar production and hourly load for electricity consumption according to the building category use (SIA, 2016). The hourly values of both production and consumption are in percentages, which are multiplied by the yearly value (total production, total consumption). Hence, by hour we can calculate the solar self-consumed share and the surplus resold to the grid. And then aggregate them to show the monthly and yearly balance. Table 7.2 shows the residential type as an example of its usage percentages during the year.

And finally, for the hourly analysis, another set of re-standardization hourly percentages will be used. This Data will be analysed for one day each month, with percentages adjusted based on building usage. In total, 12 days are studied across the year, amounting to 288 hours of analysis.

Table 7.2: percentages of electric consumption each month (SIG)

Month	Consumption standard
January	0.082
February	0.077
March	0.092
April	0.077
May	0.082
June	0.085
July	0.083
August	0.080
September	0.082

October	0.083
November	0.089
December	0.083

Building on the hourly balance, hourly values are aggregated to annual totals for self-consumption and solar excess. Based on the total yearly consumption and production, we calculate the main indicators. The following equations mentioned in Chapter 3 are applied:

$$\text{Self-consumption} = \frac{\text{PV electricity consumed}}{\text{PV electricity generated}} \quad (1)$$

$$\text{Self-sufficiency} = \frac{\text{PV electricity consumed}}{\text{Total electricity consumption}} \quad (2)$$

In this study, we don't consider the total solar energy produced, even if one part is sold to the grid, which makes the building not autonomous, so we focus on the self-consumed energy instead, which would make the buildings self-sufficient.

In the next sections, we will first analyse the potential of each type of solar installation individually and its contribution to self-sufficiency. Then, we calculate the overall energy balance based on the total contribution of solar installations, also highlighting the excess solar energy that can be shared within the SEC. Finally, we compare different scenarios on technical and financial bases: single use of solar energy by buildings and sharing of solar energy within the SEC.

7.4 Individual contributions to the energy balance of each type of solar installation

To maximise self-sufficiency at the community level, the potential for solar energy production should be maximised. Solar PV panels will be carried out on rooftops, facades, parking areas, green spaces, railway, and the top 20 solar-producing buildings in the zone outside the 2050today association, as an additional potential intervention for energy production, each one with a different probability of implementation according to the association (Table 7.3), they are based on the meetings with the 2050Today asscoation.

Table 7.3: Intervention Probability of Implementation

Scenario	Score	Probability of implementation
Roof tops	1	high
Parking	2	high
Green area	3	low
Façade	1	mid
Train way	2	mid
Top 20	2	mid
Railway	2	mid

The table points to two primary options: rooftop and façade PV. These are the only measures physically tied to a building, so they should first serve the host building's demand. Other surfaces, parking canopies, open areas, and similar act as shared generation assets for the community rather than building-specific supply. The self-sufficiency rate is then calculated using Equation 1.

7.4.1 Rooftops

A comprehensive analysis of the solar energy potential was conducted on 70 buildings using the solar cadaster of Geneva, as mentioned earlier. The annual energy production was calculated to be 15,518 MWh, of which 14,281 MWh was self-consumed by each building, leading to a surplus of 1,253 MWh per year.

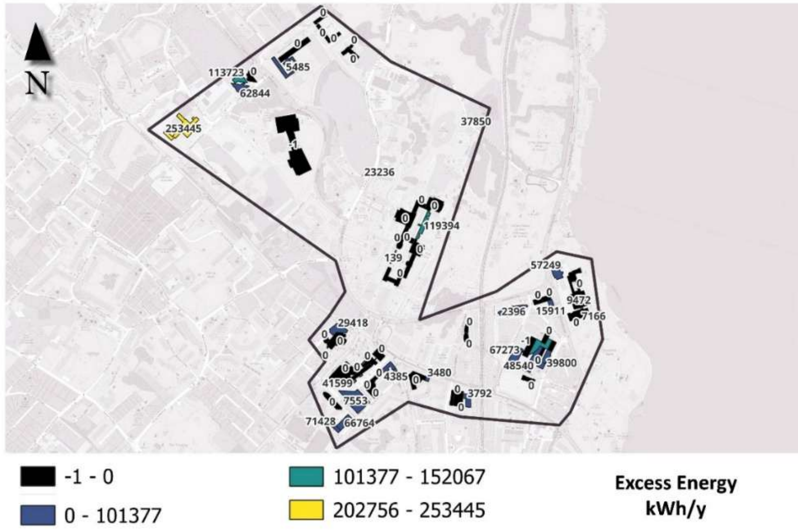

Figure 7.4: Map of the excess energy in the UN zone

This excess energy presents an opportunity for redistribution across the buildings within the "2050 Today" association. Figure 3 illustrates the specific buildings that contribute to this surplus.

And finally, self-sufficiency levels are calculated by applying Equations 1 and 2, which incorporate both the energy production and the self-consumption, adding 18.4% of self-sufficiency.

7.4.2 Parking

The outdoor parking areas are widespread in this zone, representing a potential surface area for solar deployment, and utilizing them for a SEC in the UN zone, adding a lot of value with a relatively low cost when solar sheds are installed.

Figure 7.5: Solar potential of parking sheds in the UN zone

However, the lower elevation of these areas could lead to shading issues. To address this, we used the irradiation map in raster format from the solar cadaster of Geneva. From this grid, we created a 1m x 1m point Grid, each representing an irradiation value on the roof of the parking area. Considering the removal of trees, instead of calculating the mean value of all points, the mean value of the major points was computed, as illustrated in Figure 7.6.

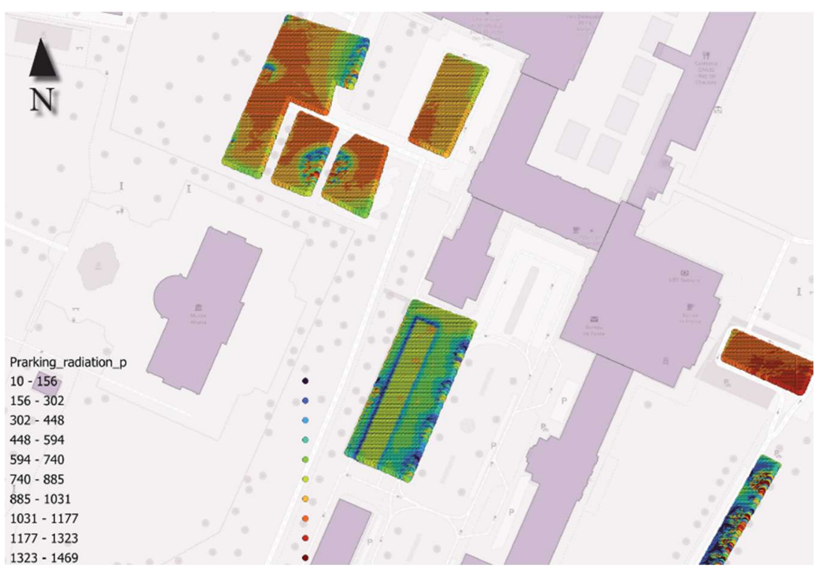

Figure 7.6: parking irradiance points

Using this information, the equation for energy production can be applied. The calculation of the solar production proceeds using the Šúri correlation formula, incorporating factors such as panel efficiency, surface irradiance, and available installation area (Šúri et al., 2007), as in Chapter 4:

$$\mathbf{E = PR\ Hs\ S\ \eta} \qquad (4)$$

By adding the parkings, the SF level reached with the use of parkings amounted to 25.9%

7.4.3 Green areas

Green areas are an alternative that could be possible but hard to approach when it comes to policies due to restrictions in what could be considered an option; nonetheless, that scenario is considered in the domain of possible implementation and respecting the protected areas of heritage, by the Geneva cadastral data available on the geoportal (SIG).

The heritage maps were downloaded from SIG and excluded the areas they contained to obtain the map shown in Figure 7.7. With the use of green areas, the SF amounted to 34.7%.

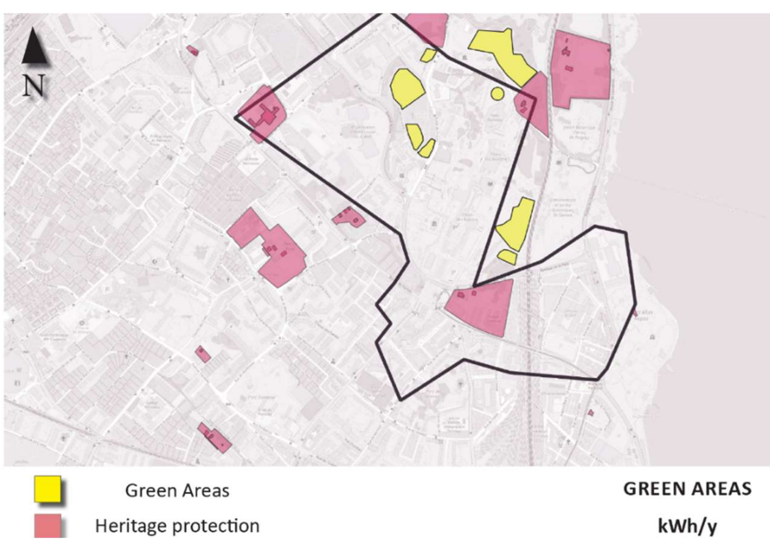

Figure 7.7: Green areas and protected heritage areas

7.4.4 Façade

The last two interventions were chosen according to the meetings with the main association (2050 Today), which suggested using these areas as potential developments, as the previous ones still weren't enough to satisfy their targets.

The solar energy production data were taken from the Swiss Federal Geoportal website, which provides the solar irradiance data both in summer and winter. In this study, both interventions were considered to maximize energy production. Figure 7.8 shows the S, SW, and SE facades and their solar potential, since the north face was not considered.

Figure 7.8: Façade production kWh/y

Using the Façade individually will make the SF 14.1%.

7.4.5 Railways

The railway areas are recently being used in Switzerland as a potential space for solar panels (Muth, 2025). The 2050 association was interested to see the potential in this case and added it as a scenario for their initiative. The area was pinpointed, and only 60% was considered, accounting for spaces where it wasn't possible to install any Solar PV (figure 7.9).

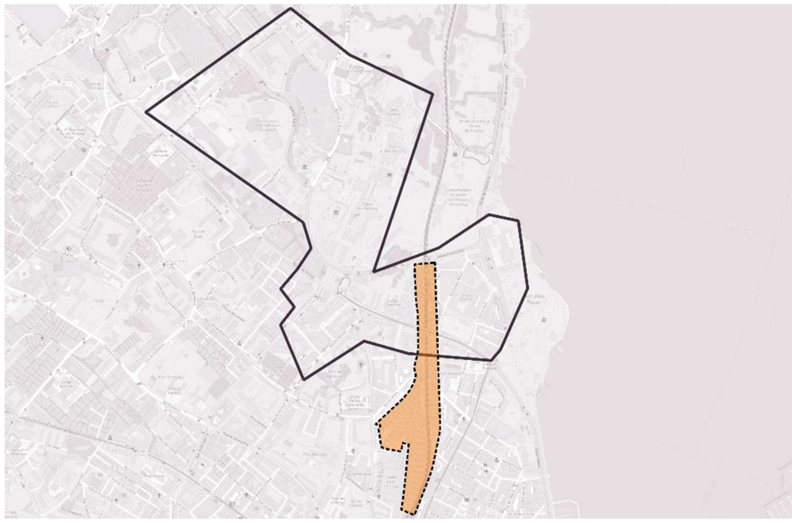

Figure 7.9: Railway intervention area

The railway alone adds 18.1% of SF. And finally, the global self-sufficiency for each type of intervention can be seen in the last figure 7.10, noting that the self-consumption for each type of intervention is technically 100% since everything on a yearly scale is consumed.

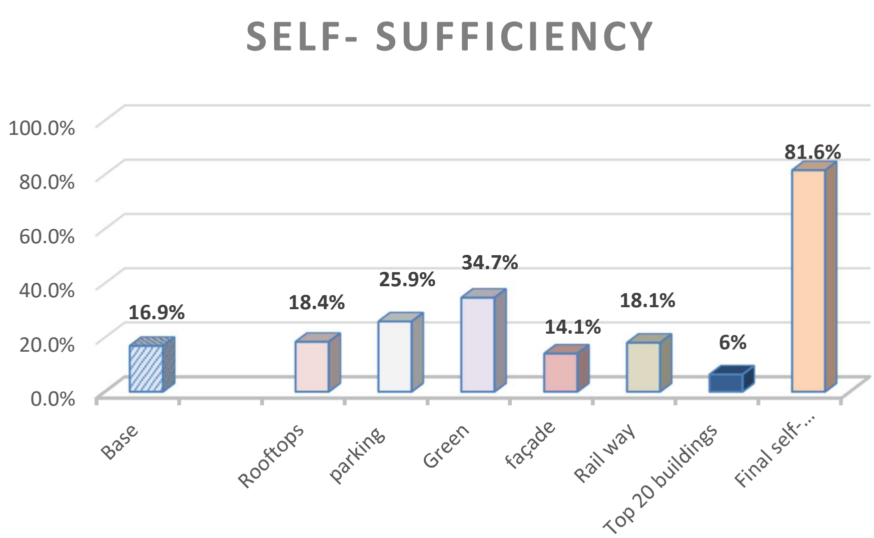

Figure 7.10: Self-sufficiency for each type of intervention within the United Nations area

7.5 Case Study: International Geneva District

7.5.1 Global Energy Balance Analysis

To understand how the global solar potential from all types of solar installations contributes to self-sufficiency, results will be analysed at three levels: yearly, monthly, and hourly. Stressing the fact of the global impact of solar energy production over time.

The analysis will first be shown yearly to understand the full scope of the United Nations zone. As mentioned previously, the data collected from the government provided the baseline for this study. Considering all the types of solar installations, the self-sufficiency of the area was calculated according to equation (1).

The previous results done only on a yearly basis showed that with all the additions (Rooftops, Façade, green areas, Parking, and railway), results show a global self-sufficiency level of 81.6%. But now, if we look at it at its hourly aggregates, we start to see differences in how the perspective is at a specific hour.

Knowing this, we will move and start the analysis on the two surfaces that are directly linked to the building itself, the rooftop and façade. Starting with scenarios 1 and 2, Figure 7.11 shows the self-sufficiency comparison between implementing the PV on the roofs and façade.

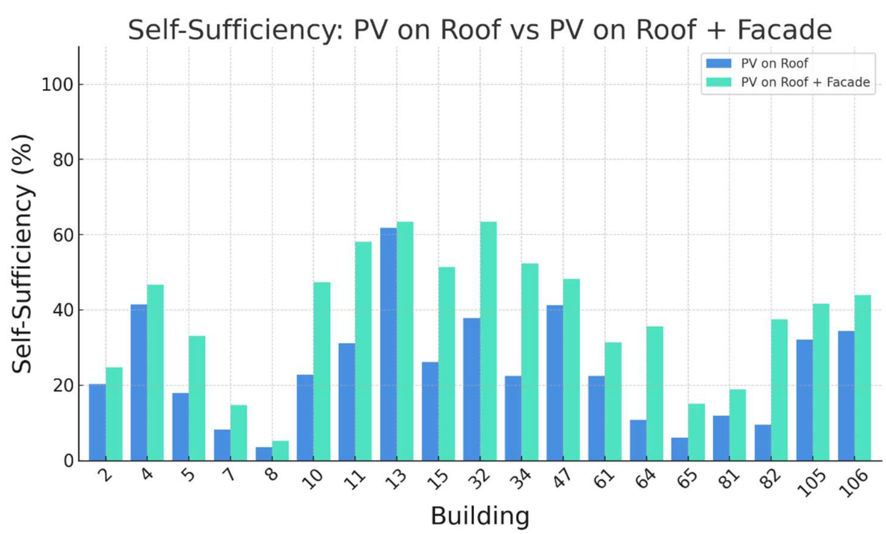

Figure 7.11: Yearly self-sufficiency by building block, comparing roof tops only and rooftops + façade

Adding façade PV lifts self-sufficiency across almost all buildings. With rooftop-only systems, most sit around 20–40%, and a few (such as 13 and 34) remain below 20%, indicating limited ability to cover demand from roofs alone. Once façade PV is added, self-sufficiency rises: many buildings exceed 50%, and some pass 60%. Facades, therefore, unlock additional generation for building blocks themselves with constrained roof area or high loads, reducing dependence on external electricity and relying on the addition attached to the building blocks themselves.

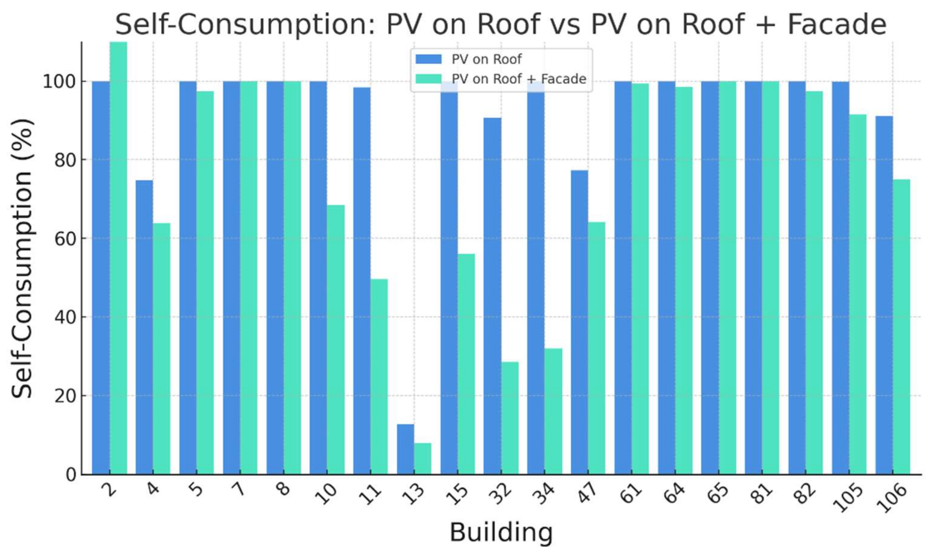

Figure 7.12: Yearly self-consumption by building block, comparing roof tops only and rooftops + façade

Self-consumption tells a different story, shown in Figure 7.12. With rooftop PV, most buildings use nearly all the generation, often 100% because output aligns with demand. After adding façade PV, self-consumption fell in several cases; Buildings 13 and 34 dropped sharply, indicating that extra generation exceeded real-time use and was exported.. In short, façade PV boosts output but doesn't always improve utilization without complementary measures (storage, flexible loads, or community sharing).

Overall all the addition of façade shows how effective it is, especially in winter when roof PV is less effective, making the addition of the façade useful for two main reasons, the first being the energy addition and the second being the integration with the building itself.

At this point, the monthly analysis comes as a collective result of the hourly analysis. However, the exact calculations and standardization on a monthly basis are available in Appendix I. So an hourly scale would also show a monthly perspective to better understand the Self-Sufficiency levels over time. The consumption data was standardized based on usage (as mentioned in the methodology section).

Figure 7.13: Self-sufficiency levels on average hourly per month

Figure 7.13 shows how much solar energy each building uses directly each hour of the representative day, using the rooftop only, as adding the facade will result in the same graph, so to ease understanding, only roof PV is represented here. The x-axis shows the hour of the year, while the y-axis shows the self-consumption ratio as a percentage. Each line represents one building.

The pattern of self-consumption peaks during the day, when solar panels have the most sun exposure. These peaks repeat every month and drop back down overnight. Some buildings, like Buildings 5, 10, 13, 32, 105, and 106, reach nearly 100% self-sufficiency during peak hours. That means they satisfy their energy demand at a specific hour using the solar energy they produce. Others, like

Buildings 8 and 64, have much lower peaks. Because they use less energy during the day or have loads that don't match their solar output.

The data is smoothed out to show the trends clearly, removing short-term spikes but making the overall pattern easier to read. Although the trend is the same, the main differences between them are the actual energy consumed at each hour and how well they manage to self-consume at a certain hour to meet their demand.

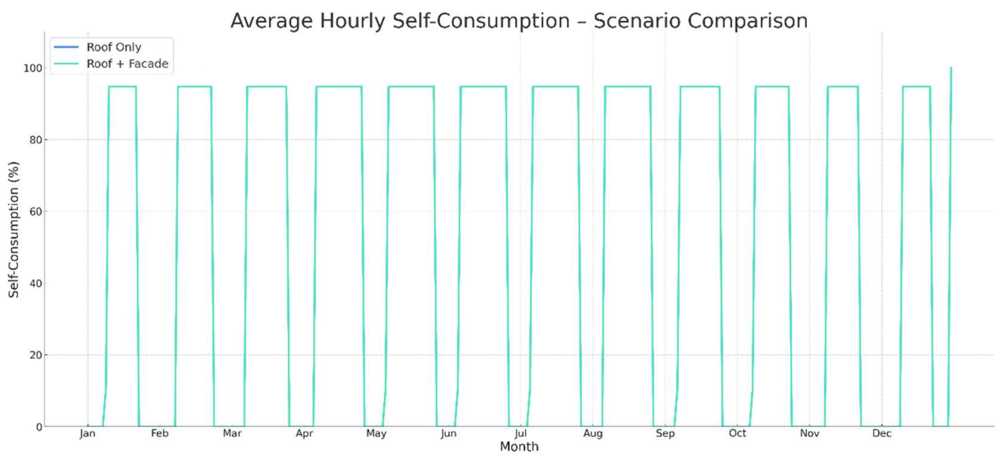

Figure 7.14: Self-consumption levels on average hourly per month

The self-consumption with rooftop PV only is nearly 100% throughout the day. When we add façade PV, that changes. During midday hours, self-consumption drops in Figure 7.14. We generate more, but we don't use more. The extra energy doesn't match the demand, so more of it goes unused or gets exported. We can see this clearly in the graph: the curve for roof + façade sits below the one for rooftop-only during daylight. That's the tradeoff. More panels increase generation, but unless we shift the demand, it uses a smaller share of it.

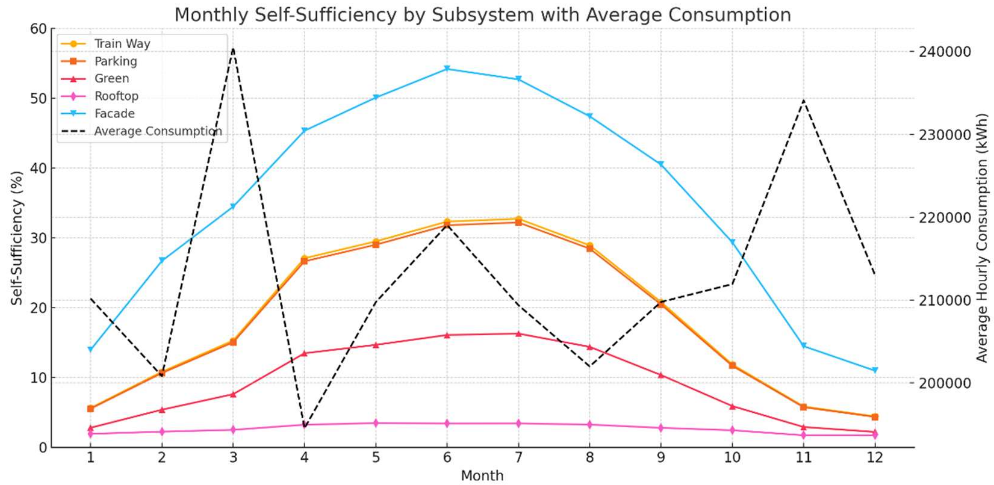

Figure 7.15: Global hourly self-consumption and self-sufficiency in the United Nations Zone

A global view of the possible individual contributions can help us see how the building blocks could interact and connect, using their consumption data average as a reference for their performance, as shown in Figure 7.15. By expanding PV deployment on surfaces like green areas, parking sheds, and railways, the overall energy pool is enhanced. Self-sufficiency rises, and more demand is met with local PV, which also means the total self-consumption would increase, since the newly added surfaces meet their energy demand.

Each contribution is highlighted in the graph and color-coded, on an hourly scale, trainways add 13.9%, parkings 27.5% green areas 34.4% and all of them combined make a 52% increase in self-sufficiency.

The energy analysis concludes with the fact that was also mentioned in chapter 4, using only the Rooftop with the addition of the façade as well, is unfortunately not enough to cover the overall consumption at any point of the year. However, adding only 1 extra source from any options, we start to see excess energy, where the self-sufficiency exceeds the consumption.

7.5.2 Financial balance analysis

In this section, we will carry out a financial balance analysis based on three scenarios representing different ways of implementing solar energy solutions in the UN district, as shown in Figure 7.16. The first two scenarios consider individual self-consumption of solar energy, installed either on rooftops only (scenario 1) or on rooftops and facades (scenario 2). Scenario 3 explores the implementation of a complex, city-wide SEC solution through the Swiss CEL model. This involves sharing solar energy from outdoor areas (i.e, green spaces, car parks, and railway lines) and buildings' excess production in order to increase the community's level of self-sufficiency. All scenarios compare current and future feed-in tariff schemes, highlighting how surplus energy can be monetised differently over time.

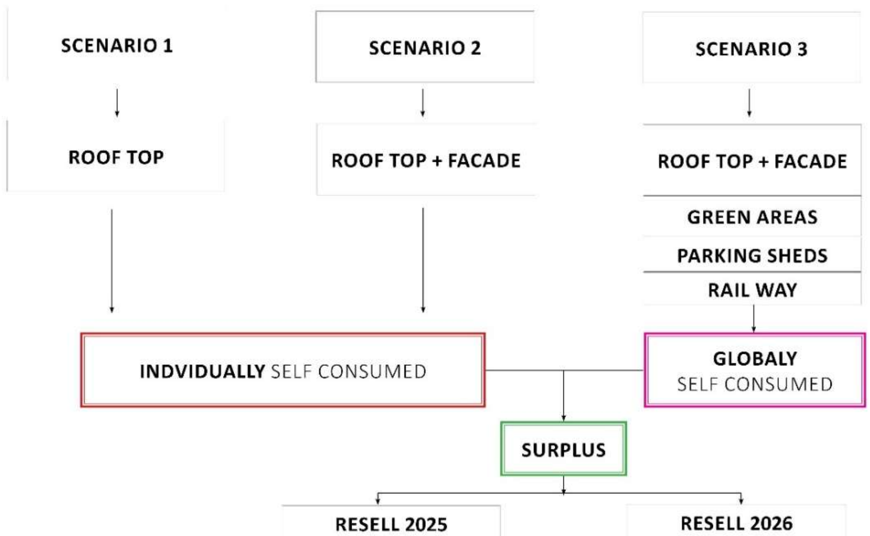

Figure 7.16: The road path of each scenario

Scenario 1: Rooftop Only

In this scenario, solar panels are installed only on the rooftops of buildings, making use of RTSPV technology. In this scenario, the electricity generated is individually self-consumed by each building, meaning that the energy is first used directly on-site. Any excess energy that is not consumed is considered a surplus, not will not be shared within the district but resold to the grid.

Scenario 2: Rooftop + Façade

This configuration includes both rooftop and building façade surfaces for PV installation. The increased surface area results in higher solar electricity generation. As in Scenario 1, the energy is consumed individually by each building, and any surplus is exported to the grid without being shared. Figure 7.14 shows two resale options:

- Resell 2025, according to the previous status where tariffs remained constant throughout the year in Switzerland with a fixed rate of 0.14 CHF/kWh (current tariff applied by SIG in Geneva in 2025)
- Resell 2026, according to the new federal regulation (Energy ordinance – OEne art. 12 al. 1bis), where the feed-in tariff is seasonal, as shown in the table:
- Fall: 0.12 CHF/kWh
- Winter: 0.14 CHF/kWh
- Spring: 0.08 CHF/kWh
- Summer: 0.06 CHF/kWh

Scenario 3: Use of the full solar potential + SEC

Scenario 3 expands PV deployment across additional urban surfaces: rooftops, façades, green areas, parking sheds, and railway infrastructure. Unlike the first two scenarios, here the electricity is not consumed individually but rather globally self-consumed, meaning that the energy is shared across the entire district or community, functioning as a solar energy community (SEC) or collective self-consumption model. Any remaining surplus is not absorbed by the shared load (unless batteries are installed, which are not considered in this study), is sold to the grid under the same resale schemes.

Each scenario will have all the financial calculations done according to the policies and incentives by the Swiss law in the years 2025 and 2026, since there were changes introduced as mentioned in the introduction of the chapter (Table 7.4). The model employs discounted cash flow (DCF) methods to compute net profitability, payback periods, and CO_2 savings.

Table 7.4: Financial metrics considered for the study

Category	Financial Metric	References
Capital Investment Metrics	Installation costs	(NREL, 2016)
	Maintenance costs	(Fraunhofer ISE, 2023)
	Net investment	(European Commission JRC, 2020; Lazard, 2023)
Financial Incentives & Environmental Impact	Incentives	(SIG, 2024; SFOE, 2023)
	Co2	(Itten et al., 2014; SFOE, 2022)
Tariff Rates	Calc_Tarif_Resell	(Pronovo AG, 2025)

	Calc_Tarif_Elec 2025	(SIG, 2025)
Seasonal Tariff Revenues	Tarif_SUMMER 2026	We made our own estimation based on the new federal law (SFOE, 2023c). tariffs can drop to minimum rate of **0.06 CHF/kWh in summer 2026**, and for the other seasons, we used the current 2025 rate as the maximum expected in **winter 2026**.(SFOE, 2023c)
	Tarif_WINTER 2026	
	Tarif_SPRING 2026	
	Tarif_FALL 2026	
	Tarif_SUM 2026	
Profitability Metrics	Calc_YEARLY_GAINS	(Desthieux & Thebault, 2024; Thebault et al., 2022)
	Calc_NET_GAINS	(European Commission JRC, 2020; Lazard, 2023)
	Calc_NET_GAINS 2026	(IEC, 2017; SFOE, 2023)

7.6 Results of the scenarios analysis

Each system was evaluated based on a consistent set of economic indicators, including installation and maintenance costs, net investment, tariff revenues, and projected net gains. For clarity and coherence, the results are organized into categories: capital expenditure (investments, maintenance costs, and incentives) and profitability, which are annual gains and net gains metrics (see Appendix). These categories show how different system sizes and configurations impact financial performance.

Assuming a typical installed cost range of 900 to 1,300 CHF·kWc^{-1} (1000 is applied) for decentralized systems (SFOE, 2023) and an average system size of 50 kWc per building**,** Under the current federal incentive scheme for added PV (section: Swiss legal context), each building installation expense is a one-time contribution, the maintaince is an annual fee of 1% of the insalltaion cost**.**

The installation cost of Solar (PV) systems is estimated according to the installed capacity (details provided in Appendix I). The equations express the pre-tax cost (in CHF) as a function of system power P (in kW), assigning a specific cost equation to each power range. Each equation combines a variable cost (the coefficient multiplied by the power, in CHF/kW) and a fixed cost. Smaller systems (<10 kW) show higher specific costs, while larger systems (>100 kW) benefit from more incentives since they scale on urban projects, so they lower the cost per kilowatt but add a higher fixed charge.

7.6.1 First and Second Scenarios (individual Entities)

In the first and second scenario we assume that all the energy generated from PV is self-consumed individually, meaning that the energy that each building produces is not shared, if there is a surplus, that energy is sold to the grid according to the tariffs mentiod previously, the tariff in 2025 is 0.14 and is a constant throughout all the year, where as the tariffs for 2026 differ according to the new policy framwork in Switzerland.

Provided that the main variable that determines the project's financial viability is the payback period, after using the formulas in the financial balance analysis, the following results were obtained in Table 7.5:

Table 7.5: Results of the first and second scenarios

building block	Sc 1 self-sufficiency	Sc1 self-consumption level	Sc 1 payback 2025	Sc 1 payback 2026	Sc 2 self-sufficiency	Sc2 self-consumption level	Sc 2 payback 2025	Sc2 payback 2026
2	20%	100%	4.2	4.2	40%	97%	3.2	3.3
4	41%	75%	3.9	4.2	47%	64%	1.8	2.0
5	18%	100%	2.1	2.1	33%	97%	1.4	1.5
7	8%	100%	1.7	1.7	15%	100%	1.4	1.4
8	4%	100%	3.1	3.1	5%	100%	1.4	1.4
10	23%	100%	3.4	3.4	47%	69%	1.7	1.9
11	31%	98%	3.7	3.7	58%	50%	1.9	2.2
13	62%	13%	6.0	9.9	63%	8%	2.7	4.2
15	26%	100%	4.1	4.1	51%	56%	1.8	2.1
32	38%	91%	15.8	16.4	63%	28%	2.3	2.9
34	22%	100%	5.1	5.1	52%	32%	3.5	4.4
47	41%	77%	5.7	6.2	48%	64%	4.9	5.6

61	22%	100%	1.8	1.8	31%	99%	1.7	1.7
64	11%	100%	4.0	4.0	36%	98%	2.3	2.3
65	6%	100%	3.7	3.7	15%	100%	2.4	2.4
81	12%	100%	1.8	1.8	19%	100%	1.7	1.7
82	10%	100%	5.0	5.0	37%	97%	2.4	2.4
105	32%	100%	2.0	2.0	42%	92%	2.0	2.0
106	34%	91%	2.0	2.1	44%	75%	2.1	2.2

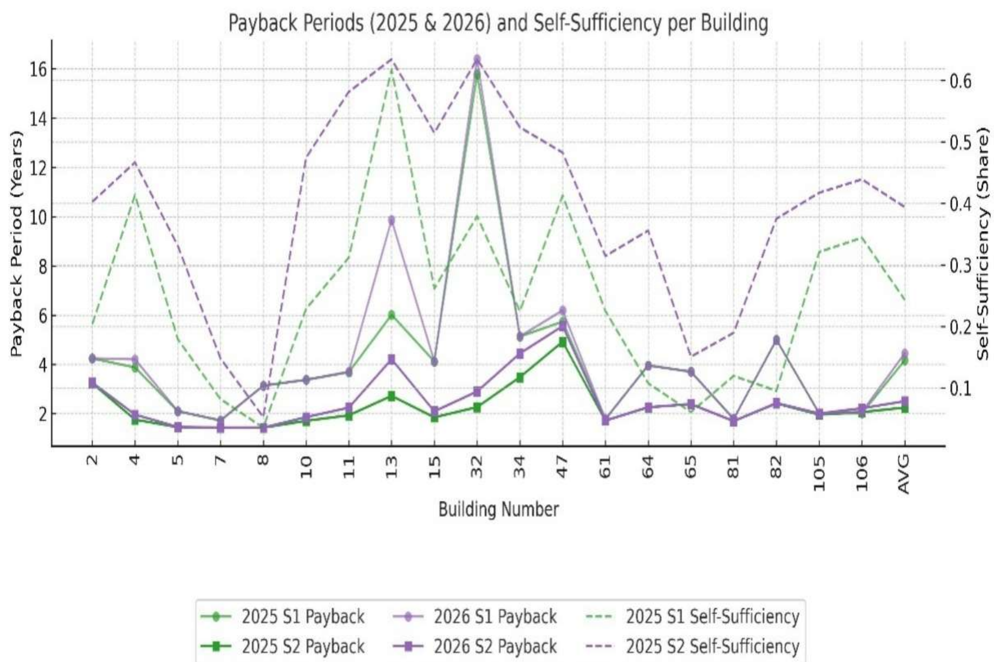

Figure 7.17: payback period for the first and second scenarios

Figure 7.17 compares the payback period with incentives from 2025 and 2026 and while showing energy self-sufficiency for both of them under two scenarios (S1 and S2)**.** Payback periods are plotted as solid lines, while self-sufficiency metrics appear as dashed lines. The color scheme distinguishes 2025 (green) from 2026 (purple), with variation in shading and markers used to differentiate between Scenario 1 and Scenario 2.

For all buildings, payback periods range from approximately 1.4 years to over 6 years, while self-sufficiency levels span from below 10% to over 60%**.** Scenario 2 consistently exhibits lower payback periods and higher self-sufficiency compared to Scenario 1 in both years. The shortest observed payback is 1.4 years (2026, Scenario 2), and the longest exceeds 6 years (2025, Scenario 1).

Scenario 2 results are overall better than Scenario 1 on both parameters (energy and finance). Payback periods are shorter in Scenario 2 (often by 1–2 years), which is 30–40% faster capital recovery. Energy self-sufficiency also rises: in several buildings, the 2025 Scenario 2 line exceeds 60%, while Scenario 1 stays below 30% for the same assets.

Overall sc 2 is the better choice, which has higher energy self-sufficiency and better payback periods, but not all buildings have this perk; some didn't benefit as much, but the general trend SC2 improves the overall projections both financially and technically.

7.6.2 The Third Scenario (SEC)

To assess the financial viability of a large-scale photovoltaic (PV) installation producing 53,514,702.54 $kWh·yr^{-1}$, the installed capacity was derived assuming 1,000 full-load hours per year (typical for the Geneva region) (SIG, 2025b), yielding ≈ 53.5 MWp. For utility-scale systems in Switzerland, installed costs commonly fall between 900 and 1,300 $CHF·kWc^{-1}$ (SFOE, 2023). This implies a total investment of 43.93 million CHF. Under the current one-time investment contribution scheme for added PV, the project would qualify for ≈ 21.4 million CHF in incentives (section: Swiss legal context), leading to a net investment of 22.5 million CHF.

The total amount of energy that can be resold to the grid is 21,516 MWh. Using a 3% real discount rate, discounted payback periods were computed for two revenue cases:

- 2025 net gains of 11,934,274.94 $CHF·yr^{-1}$ and
- 2026 net gains of 10,487,608.41$CHF·yr^{-1}$.

Results indicate robust economics across both cost scenarios (Table 6). In the low-cost case (900 $CHF·kWc^{-1}$), the discounted payback is 3.62 years (2025 gains) and 4.25 years (2026 gains). In the high-cost case (1,300 $CHF·kWc^{-1}$), the discounted payback is 6.06 years (2025 gains) and 7.16 years (2026 gains). These values confirm that even with a reduction in annual net gains between 2025 and 2026 (14%), the project remains economically attractive, as shown in Table 7.6.

Table 7.6: SEC R-RF-U COMPARISON

Scenario	Self-Sufficiency	Self-Consumption	Payback 2025 (yrs)	Payback 2026 (yrs)
SEC-R	14%	100%	1.63	1.58
SEC-RF	26%	100%	1.61	1.57
SEC-U	87%	60%	2.0	2.3

When creating a SEC, we start to see exactly how big the demand is collectively. In SEC (R AND RF), there is no excess energy, which means everything was consumed between the buildings within the SEC, which made us turn to other surfaces to utilize. The parking sheds, green areas, and railways, when adding them, we start to see the excess energy from approximately June to August, which is the peak for solar production, but in other parts of the year, we have no excess to sell, as explained in section 7.5.1. Looking through the financial returns of these cases amounts to the following:

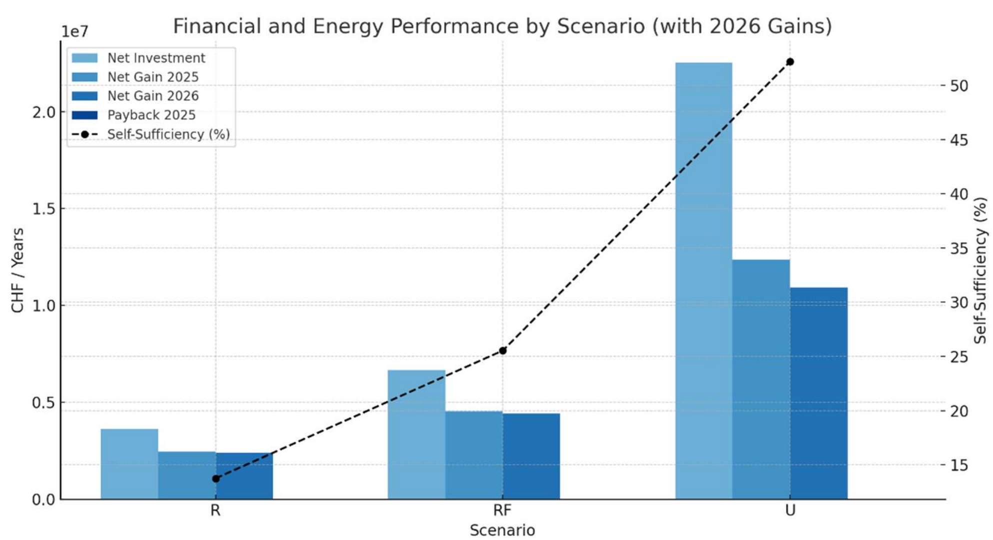

Figure 7.18: Scenarios R- RF-U comparison with net investment, net gains, and payback

Scenario R, RF, and U were compared on net investment, annual net gains (2025–2026), payback, and self-sufficiency. Scenario U is the largest system (Figure 7.18). It costs 22.53 M CHF. It delivers 12.37 M CHF in 2025 and 10.93 M CHF in 2026. Payback is 1.82 years. Self-sufficiency is 52.2%.

Generation aligns well with demand. Scenario R costs 3.62 M CHF. Scenario RF costs 6.65 M CHF. Both keep payback under two years, but self-sufficiency stays low: 13.8% (R) and 25.5% (RF). Smaller systems recover capital fast but add little autonomy; the larger system raises energy independence at a higher upfront cost.

Overall all the project shows how individually it's an energy profitable project in the long run, whether applied individually or as a SEC However, energy-wise, the Rooftops and the façade are not nearly enough to cover the needs of the community. Once the SEC was introduced, the perspective and future outcome changed into a viable path, the energy demand had durations of time when the productions met its needs, and that alone sets Geneva on the path of a sustainable post-carbon city.

The dataset provides a projection of the role photovoltaic integration can play within the second most populous urban cities in Switezelrand, combining economic returns with environmental benefits. Nonetheless, implementing these projections is needed. This method and study guide urban policy development and to realize the full potential of sustainable urban solar initiatives.

7.7 Implementation of SEC

As discussed previously, the UN zone has multiple owners, but many of them are owned by the same institution, and the other parcels are owned by a limited number of institutional actors, primarily United Nations agencies and affiliated organizations. With the help of 2050today, the urban precinct can have a consolidated ownership structure across large sections of the zone. Such a characteristic makes the United Nations district particularly well-suited for a SEC, as it simplifies governance, investment coordination, and infrastructure planning.

In this instance the one of the major owners of the areas is Foundation for Buildings for International Organizations (FIPOI), which is also a member of the 2050Today organization, Table 7.7 below, shows some of the buildings owned by them, all the buildings highlighted in gray are out of the 2050 Today one, hence they will not be considered in this pilot project (Figure 14).

Table 7.7: Ownership of FIPOI

Member	Address	City	NPA	Statut	Propriétaire bâtiment
Permanent Mission of Costa Rica - Office	Avenue de France, 23	Genève	1202	Locataire partie	FIPOI
Permanent Mission of Costa Rica - Residence	Chemin des Marais, 152			Locataire	FIPOI
Permanent Mission of Fiji - Office	Avenue de France, 23	Genève	1202	Locataire partie	FIPOI
Permanent Mission of Finland - Office	Avenue de France, 23	Genève	1202	Locataire partie	FIPOI
Permanent Mission of Switzerland - Office	Rue de Varembé, 11	Genève	1202	Locataire partie	FIPOI
ITU - International Telecommunication Union	Rue de Varembé, 2	Genève	1202	Propriétaire	FIPOI / UNION INTERNATIONALE DES TELECOMMUNICATIONS UIT
ITU - International Telecommunication Union	Rue de Varembé, 4	Genève	1202	Propriétaire	FIPOI
UNDP Office in Geneva	Chemin des Anemones, 9	Châtelaine	1219	Locataire partie	FIPOI
UNDP Office in Geneva	Chemin des Anemones, 11	Châtelaine	1219	Locataire partie	FIPOI
UNDP Office in Geneva	Chemin des Anemones, 13	Châtelaine	1219	Locataire partie	FIPOI
UNDP Office in Geneva	Chemin des Anemones, 15	Châtelaine	1219	Locataire partie	FIPOI

UNEP Europe	Chemin des Anemones, 11	Châtelain e	121 9	Locataire partie	FIPOI
UNHCHR - Office of the High Commissioner for Human Rights	Rue des Pâquis, 52	Genève	120 2	Locataire tout	FIPOI
UNHCR - The UN Refugee Agency	Rue de Montbrillan t, 94	Genève	120 2	Locataire tout	FIPOI
CAGI - International Geneva Welcome Center	Route de Ferney, 106	Genève	120 2	Locataire tout	FIPOI
Diplomatic Club of Geneva	Route de Ferney, 106	Genève	120 2	Locataire partie	FIPOI
FIPOI	Rue de Varembé, 9	Genève	120 2	Propriétair e	FIPOI
Fondation pour Genève	Route de Ferney, 106	Genève	120 2	Locataire partie	FIPOI
Geneva Call	Rue de Varembé, 11	Genève	120 2	Locataire partie	FIPOI
ISHR - International Service for Human Rights	Rue de Varembé, 1	Genève	120 2	Locataire partie	FIPOI
Kofi Annan Foundation	Rue de Varembé, 11	Genève	120 2	Locataire partie	FIPOI
PATH - Foundation for Appropriate Technologies in Health	Rue de Varembé, 7	Genève	120 2	Locataire partie	FIPOI

Given the ownership dynamics within the United Nations Zone, particularly in the United Nations district of Geneva, this project will adopt the single-ownership approach to implementing the energy community model and the third scenario (SEC). This effectively creates a consolidated ownership environment, which aligns well with the regulatory and technical requirements for establishing a collective self-consumption system (ZEV) (Provided buildings are connected to the same connection point, if not, it will be through CEL) under Swiss law. By leveraging this structure, the project can streamline decision-making, facilitate internal energy sharing through a microgrid setup, and reduce the legal and administrative complexity typically associated with multi-owner energy communities (section: Grid connections).

Figure 7.19: Buildings owned by FIPOI in the United Nations Zone

Based on the hourly energy analysis (section: Energy balance analysis), buildings owned by FIPOI (Figure 7.19) were selected. By combining their performance, we can assess how a small pilot project within the UN zone operates and see their coordination under scenario 3 conditions. Table 7.8 below presents a summary of the energy and financial assessment of the proposed energy community, showing the key metrics.

Table 7.8: energy and financial summary for FIPOI buildings

Metric	Value MWh
SEC Consumption	4,923
Solar Production rooftop	1,353
Solar Production roof top and façade	2,862
Solar Production on the rooftop, façade, and parking around the buildings	3,242

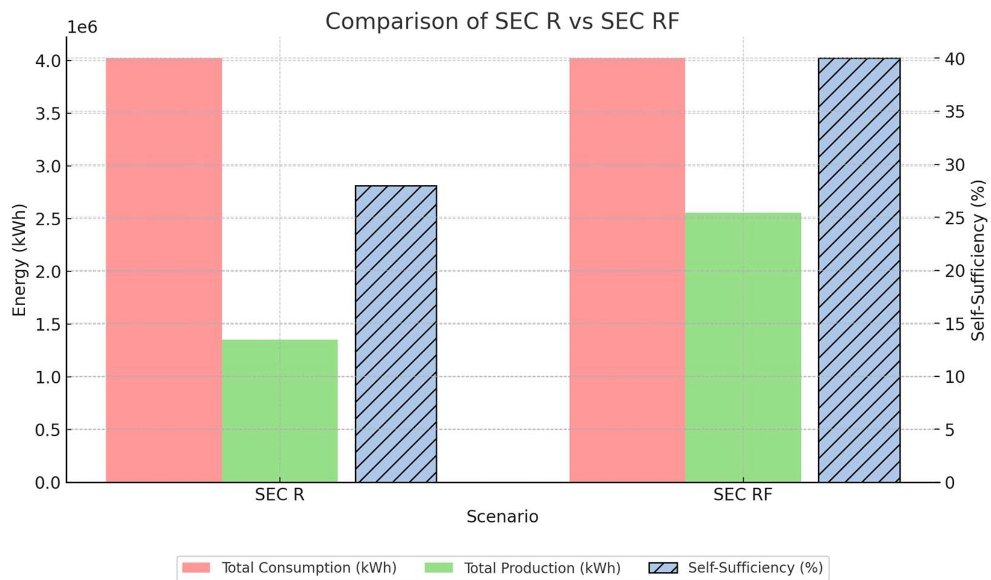

Figure 7.20: SEC-R and SEC-RF comparison

The façade is usually overlooked in solar analysis, but in turn, it generates a lot of power, especially in winter. The self-sufficiency, for example, increases from25% to 40% by only adding the solar PV on the façade.

The comparative analysis between SEC-R (rooftop-only solar integration) and SEC-RF (combined rooftop and façade integration)(Figure 7.20) shows performance and policy relevance of expanded photovoltaic deployment within the Geneva United Nations campus framework. While both scenarios serve the same annual electricity demand (4,021,636 kWh), SEC RF achieves a higher self-sufficiency rate of 40%, compared to 28% for SEC R, and nearly doubles the annual production (2.56 GWh vs. 1.35 GWh).

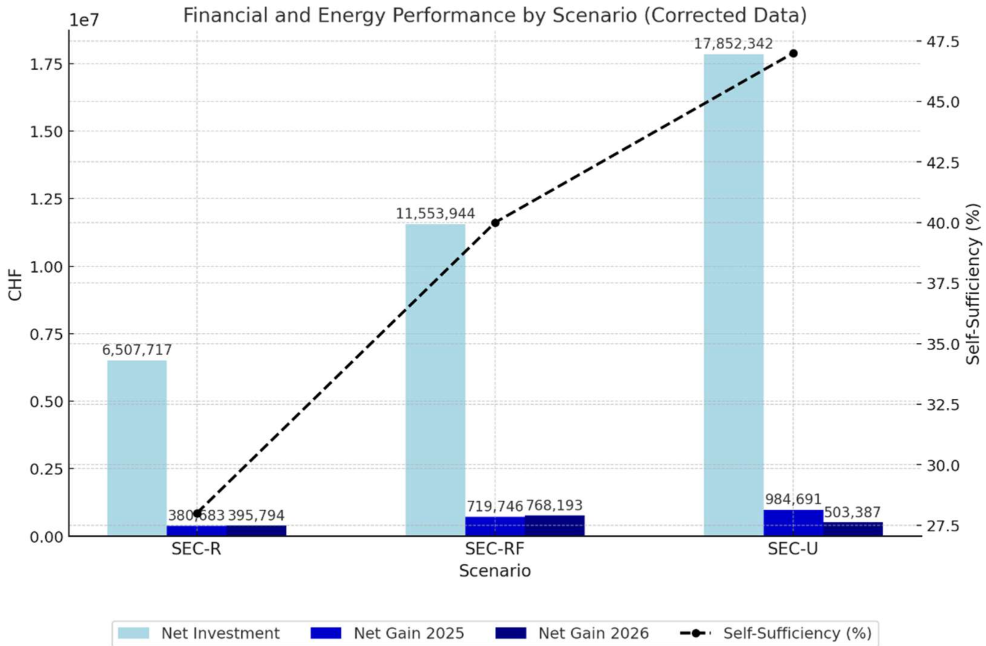

Figure 7.21: SEC-R, SEC-RF, and SEC-U

This improvement alone aligns with the energy autonomy objectives outlined in SDG 7 and supports the broader UN sustainability agenda by reducing dependency on grid-supplied electricity and enhancing local resilience. Economically, SEC RF yields greater financial returns, with net gains of CHF 634,153 in 2025 and CHF 598,434 in 2026, compared to CHF 380,683 and CHF 395,794 for SEC R, respectively. Despite a slightly longer payback period (1.95 vs. 1.8 years), the return on investment for SEC RF is more favorable in the medium term (Figure 7.21).

These findings support the inclusion of surfaces like the façade, particularly in dense urban contexts where roof space is limited. Moreover, the project reinforces creating energy communities within areas of multiple owners (an approach explored in this research through the Geneva case study and its alignment with the "anchor institution" governance model.

The third scenario, SEC-U, introduces parking shed surfaces near the FIPOI buildings, in addition to rooftops and façades. This addition results in a total solar production exceeding 4 million kWh annually, with a self-consumption rate of 100**%** and a self-sufficiency level reaching 52.2% (the highest among all the SECs evaluated). While it requires a net investment of 22.53 million CHF, it generates economic returns, with net gains of 984,691 CHF in 2025 and 503,387 CHF in 2026, and maintains a payback period of 1.82 years. This scenario remains within realistic planning constraints by excluding green areas and the railway in the UN zone.

SEC-U confirms the value of using structurally viable and underutilized surfaces like parking sheds. While the upfront investment is substantially higher, the rapid payback and energy self-sufficiency make SEC-U a highly viable and scalable model for institutional energy communities such as the UN/FIPOI zone. These findings reinforce the conclusions drawn in previous analyses: that a well-designed spatial deployment of PV, respecting urban constraints and usage rights, can pave the way for Energy communities in dense urban districts.

Ownership in this context gave a lot of room for the technical aspect to grow since decisions would be fast in this model and not slowed down by the different layers of governance. A single institutional owner, such as FIPOI, speeds decisions, keeps compliance clear, and makes building the infrastructure easier. This setup fits the Swiss rules for collective self-consumption (ZEV and CEL) and allows a clean rollout of a microgrid for energy sharing.

A coordinated single-owner approach delivers a net positive return after public incentives. A lot of the energy demand is met by production throughout the year, especially in the SEC-U model. A clear, consolidated ownership makes energy communities easier to implement. However, the use of the FIPOI pilot is a practical template for a broader vision of implementing this work on buildings with different owners, which, in this case, is the anchor institution of 2050Today. All done under the incentives and regulations of Switzerland

7.8 Discussion and Conclusion

This analysis evaluated the feasibility of establishing a Renewable Energy Community (REC) within the United Nations district in Geneva, under the administrative and technical framework coordinated by 2050Today. The methodological framework followed the same multi-scale structure applied in Turin, combining spatial, energetic, and financial layers to assess the collective self-consumption potential of the campus; however, it drove the collective creation of n SEC and expanded into the urban fabric among the buildings.

The analysis began with a GIS-based mapping of all photovoltaic-eligible surfaces (rooftops, façades, parking sheds, and adjacent areas) across the main UN buildings. Each surface type was simulated as a potential surface to derive hourly production profiles, later matched against real hourly electricity consumption data. The resulting energy balance determined the self-consumption ratio and self-sufficiency ratio for each building and for the aggregated system.

Scenario 1, which is considered the model, only RTSPv technology was used, which requires the lowest investment, but at the same time, resulted in relatively low self-sufficiency rates, averaging 15 %. The payback period ranged between 2 and 6 years for most buildings, which is very applicable financially, due to lower installation costs and steady local consumption. However, since rooftop areas are limited in the UN zone, this scenario was not enough to satisfy the energy demand of the urban precinct.

The second scenario used the façades of the buildings and supplied the demand directly for the buildings since it's attached to them, focusing on the south-oriented envelopes of the UN zone. With this addition, energy production raised self-sufficiency to approximately 27 % and reduced the payback period from 4.7 to 3.1 years on average. Financially, the investment nearly doubled compared with SEC-R, but the higher annual net gains in both 2025 and 2026 compensated for this difference, with the final scenario (SEC) analysis structured around three different SECs in scenario 3 (chapter 3):

- **SEC-R**: including only rooftop installations;
- **SEC-RF**: combining rooftops and façades;
- **SEC-U**: extending the system to parking sheds adjacent to the buildings.

Forming the SEC-U. This scenario achieved the highest self-sufficiency level (52 %)**,** as illustrated by the upward trajectory, and produced annual net gains exceeding 10 million CHF in 2025 and 11 million CHF in 2026. Although the capital investment was three times higher than in SEC-R, the payback period was at 1.8 years, confirming that large-scale integration brings strong economies of scale when spatially coordinated under a single governance entity, yet the possibility of this scnarion uder the current governance conditions is still unlikely, due to the fragmantaion and complications of connecting them and lack of coordination between the governing institutions and the owners

Methodologically, the work in the Geneva case study validated the transferability of the three-stage analytical framework (GIS mapping, Technical assessment, and economic assessment). This approach helps in tackling issues happening on each layer before moving on to the next stage, since any error that would occur on any stage would be detected immediately.

The Geneva case study had many results that enforce the creation of the SEC, but at the same time show some weaknesses. The FIPOI-led project shows how important ownership is and what its effects are on such initiatives. Split ownership usually slows things down. But with Strong incentives consolidated SEC can turn a high-cost project into financially viable pilots that expand into different owners.

Inside one building, energy flows stay simple. But as soon as we involve more buildings, we run into limits. We need new rules (rules for how to share energy, manage excess, and cover shortfalls throughout the year. That means aligning city codes with national and even global directives. These limitations should be acknowledged:

- First, the modelling relied on representative hourly load profiles derived from available consumption data. Although the profiles accurately reflect typical demand patterns, they do not capture short-term variability, peak-load anomalies, or future behavioural shifts (e.g., EV charging or flexible working patterns).
- Second, the financial assumptions: tariffs, incentives, and resale prices, were based on 2025–2026 projections, which may change under regulatory updates from OCEN or the Swiss Federal Energy Strategy.
- Third, the study assumed more or less idealized governance coordination under a single operator (FIPOI) and made 2050today the anchor institution for the bigger project of the urban precinct. In practice, cooperation and data-sharing between independent UN agencies could introduce administrative delays or require contractual adjustments.

The Geneva case doesn't just test a technology. It tests a system. It shows what happens when we take climate goals seriously, not in speeches, but in infrastructure. It gives a working model. One that other cities, not just other UN campuses, can use.

This study proves four things:

- **Governance is a priority.** One strong owner helps. Many owners slow things down.
- **Incentives shape outcomes.** Without them, projects don't happen.

- **Cities have space.** Rooftops and façades might not be enough, especially in dense urban areas, so the job of urban planners is to find spaces to use under the heritage regulations and public properties (parking sheds, railways can generate a lot)
- **Scaling needs rules.** One building is easy. Many buildings need clear contracts and fair tariffs, and urban areas need a system.

Geneva UN zone tuned its own buildings into a collective network that turned policy into practice and made lower emissions, better coordination, and measurable progress possible toward climate goals. Emphasizing that this is not a side experiment, it’s a test of how we govern the energy future, and for cities that take climate commitments seriously, it won’t be optional to do.

Chapter 8

8. Discussion: Synthesizing Pathways for Post-Carbon Cities

8.1 Integration mandate: from mapped potential to urban Energy Precincts

Our pathway builds on four results established earlier and connects them into one sequence. Chapter 4 sets a GIS-first workflow that translates the solar cadastre into PV output and tests hourly overlap with demand in QGIS, using explicit assumptions on usable roof area, and implements RTSPV. Chapter 5 showed that REC membership depends on the same primary cabin and mapped UniTo buildings across 7 of Turin's 11 primary cabins; then, a horly analysis was done for the consumption, production, and surface filters used to make UniTo a Solar Energy Community SEC. Chapter 6 justified a digital operating layer (an AMS/BIM/GIS stack integrated with BI tools) as a tool to manage meters, assets, and settlement at the precinct scale. Chapter 7, focusing on Geneva's UN Zone, demonstrated how ownership consolidation (e.g., 2050today) enables internal sharing favored by Swiss rules on collective self-consumption at a common connection point, supported by the 2050Today partnership. Together, these findings define the integration mandate we pursue here to create an Urban Energy Precinct: map potential, zones, mandate an anchor community manager, and digitize operations so spatial potential becomes a governable, bankable energy precinct.

Map first**.** Chapter 4 established the geospatial basis for PV planning using RTSPV technology and showed that, while Turin could theoretically cover 25% of annual electricity with 40% roof utilization, this is only theoretical since policies and financial analysis were not considered; however, the technical aspect is an important pillar for creating SEC. Chapter 5 then expands the technical inventory to the electrical consumption of buildings according to buildng topology and the and then ties it with the existing policies of REC in the specific city, for example the eligibility requires members to be under the same primary cabin, then identify candidate prosumers and consumers for cabin-aligned communities, and then applying the financial calculation to test the fesability of:

- Scenario 1: Applying RTSPV technology only on the campuses and selling any excess energy to the CEL without sharing energy
- Scenario 3: Making a Solar Energy Community SEC-R under the same primary cabin, and sharing the excess energy between the members

Anchor-led coordination. Chapter 5 demonstrates that SEC feasibility in Turin hinges on grouping buildings under the same primary cabin. Building on that, Chapter 6 argues UniTo has the scale and institutional credibility to move from participant to territorial energy orchestrator, coordinating municipalities, schools, hospitals, and utilities to run settlement and governance transparently under Italy's updated framework (Ld. 199/2021). In Geneva, Chapter 7 shows how consolidated ownership (notably FIPOI in the UN zone) enables single-ownership style internal sharing or CEL-based linkage where needed, streamlining decisions and internalizing energy sharing despite multi-owner REC constraints in Swiss law (Chapter 2), and then expanding on the unito case study, Geneva UN Zone expanded the potential by:

- Scenario 1: Applying RTSPV technology only on the building of the 2050Today mandate and sell any excess energy to the CEL without sharing energy
- Scenario: Applying PV on the Rooftop and façade and self-consuming the energy, and selling any excess energy to CEL without sharing the energy
- Scenario 3: Making a Solar Energy Community within the same sector (Swiss laws) and making three types of SEC, in each one, the energy is shared, and self-consumption comes in this case as a collective part of sharing:
    - SEC-R: PV on the rooftop only
    - SEC-RF: PV on the rooftop and façade
    - SEC-U: integrating the surrounding urban areas like Green areas, parking sheds, and railways

Furthermore more comparing the two scenarios wouldn't be the only way, so we should pause on the word "comparison". This isn't a "which is better?" debate; it's a complementary perspective analysis. Both Geneva and Turin reveal different pathways, conditions, and system behaviors for energy communities, Creating Using Anchor institutions (ANI).

Together, the two cases do not compete; they complete the conceptual spectrum of what energy communities can mean at the institutional, Urban precinct scale.

We now design graphs not to show one case prevailing over the other but to highlight different strengths and conditions. Here are the indicators that would satisfy this purpose: Self-Sufficiency, Self-Consumption Payback Period, Installed Capacity, Grid Autonomy, Incentive Dependence, Investment Volume

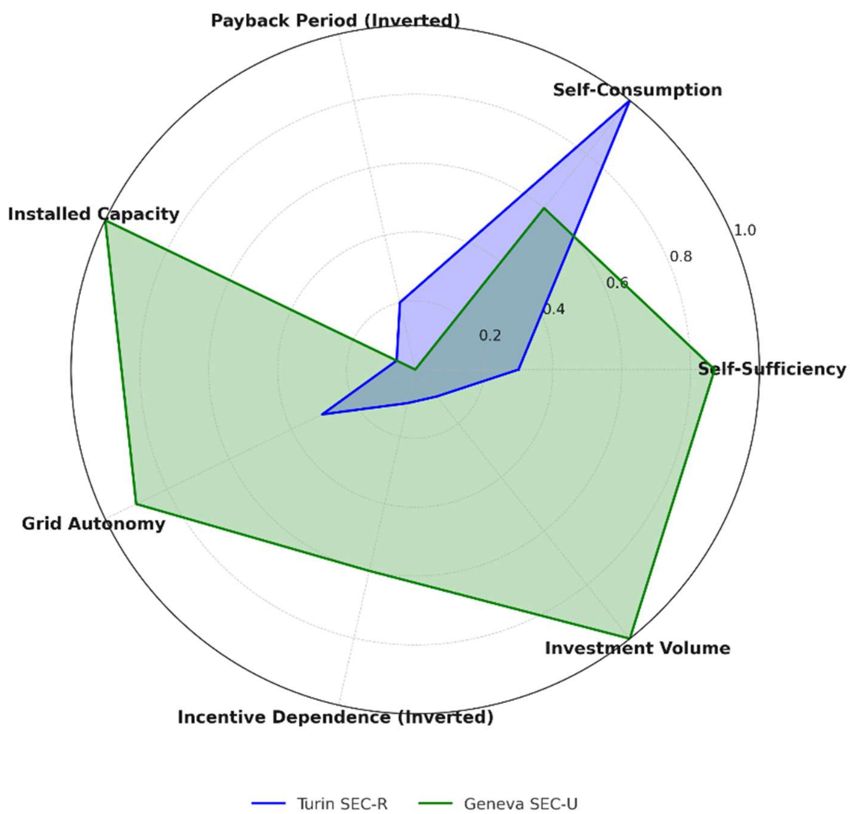

Figure 8.1: This radar chart compares key indicators across the two case studies. Turin's SEC-R is compact and financially efficient, relying heavily on national incentives and centralized coordination.

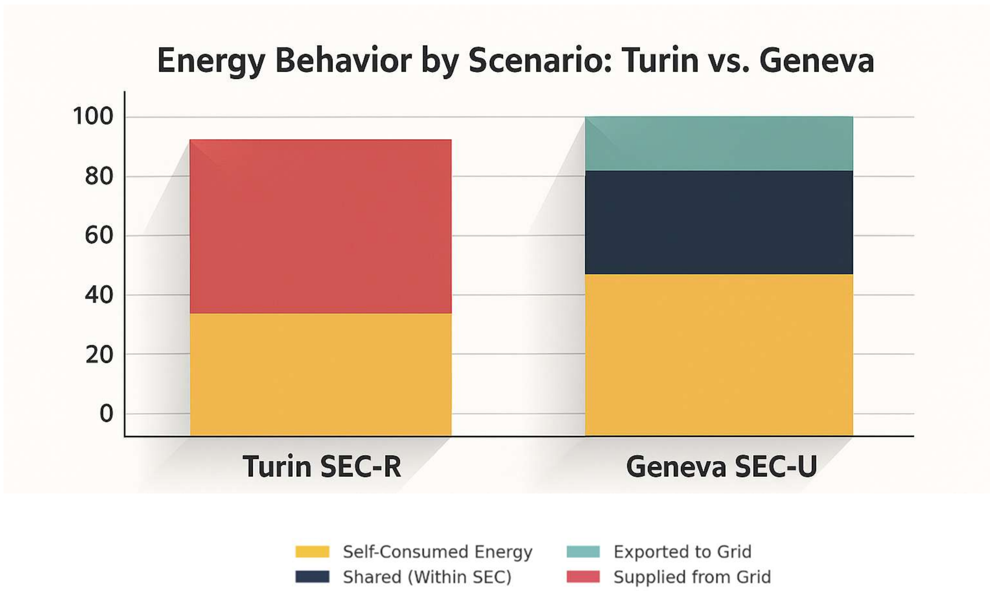

Figure 8.2: Energy Behavior by Scenario, Turin SEC-R and Geneva SEC-U.

Something worth noting is the energy dynamics between the two institutional Anchored SEC models. The Turin SEC-R has high levels of on-site self-consumption, yet remains reliant on the public grid for approximately 70% of its total demand. Notably, the absence of energy sharing or storage mechanisms shows its centralized, incentive-driven structure, where gains are primarily financial rather than infrastructural.

The Geneva SEC-U exhibits a more integrated and spatially distributed model. Here, over half of the total demand is met through Solar Energy, with energy sharing (35%) and controlled export to the grid. The focus in the UN Zone was also on the SF, which has reached a good level of **87%**, using the design logic in the conceptual framework (Chapter 3) that emphasizes autonomy, coordination, and infrastructural synergy.

This thesis tries to tie quantitative modeling with qualitative governance, to contrast two viable (yet philosophically divergent) approaches to institutional energy transitions.

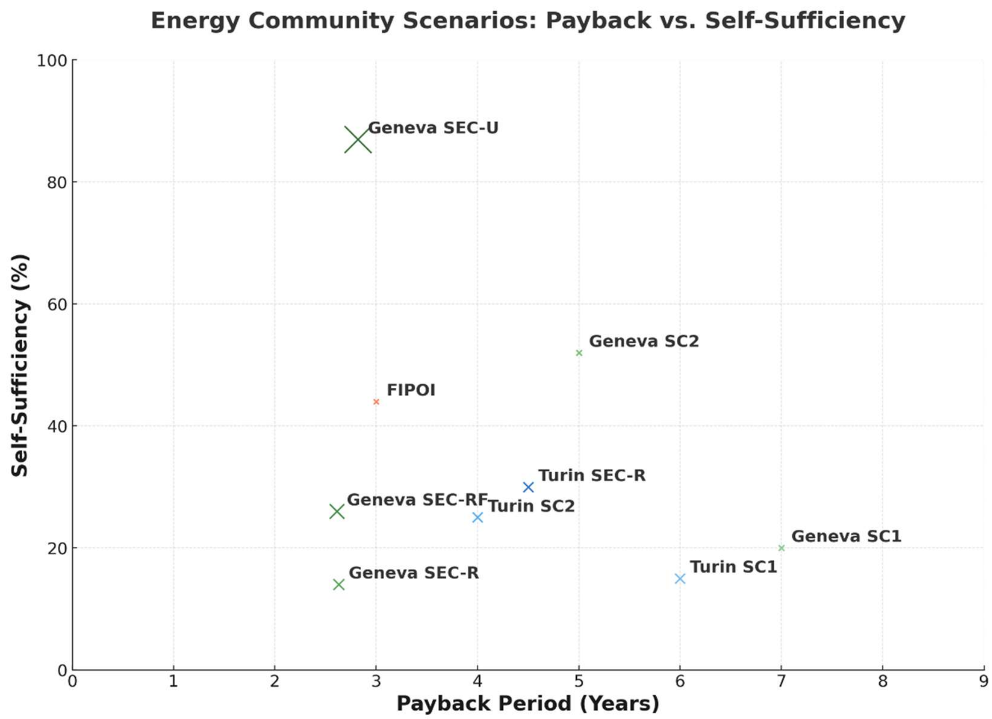

Figure 8.3: The overall results when plotted by SF vs PBP.

This figure maps the financial and energy performance of all the scenarios depicted in this thesis, which are in Italy and Switzerland. By plotting payback period with self-sufficiency, the figure captures the relation between the economic return of each scenario with its energy self-sufficiency, two pillars of the conceptual framework for a post-carbon city.

The Turin scenarios (SEC-R, SC1, SC2) cluster on the right side of the chart, reflecting moderate to medium payback periods and relatively low levels of self-sufficiency. Notably, even under the SEC-R configuration (which leverages energy sharing and centralized incentives), the system reaches only 30% self-sufficiency. This highlights the limitations of only using the rooftops configurationHowever when comparing it with Geneva SEC-R, we can see that it performs better in the self-sufficiency aspect. Moreover, these scenarios maintain low investment thresholds, making them easily replicable in mid-scale urban campuses.

Geneva's case study has a broader range on the graph and shows higher investment requirements. Geneva SEC-U scenario exhibits exceptional self-sufficiency (87%) with a relatively short payback period of 2.8 years.

Again, this figure stresses the fact that the chart is not a simplistic comparison. Instead, it reveals a spectrum of operational logics:

- **Compact & efficient models** (Turin SEC-R) optimize for fast deployment and low upfront cost
- **Autonomous, spatially integrated models** (Geneva SEC-U) prioritize long-term energy independence
- **Hybrid cases** (FIPOI) emerge as strategic middle grounds that balance autonomy and affordability

This figure serves as a synthesis of technical performance and a map for energy planning for decision making, emphasizing that no single configuration is universally optimal or the best. Each reflects a different trade-off envelope, shaped by local governance, spatial constraints, and existing infrastructure. From a policy standpoint, it reinforces the need for context-sensitive support schemes rather than one-size-fits-all incentives, which brings us to what all this forms and tells us.

Together, these results justify assigning an anchor Community Manager per precinct as a design rule, because it.

- Reduces energy sharing costs
- Converts spatial PV potential into an operable community,
- Prioritize shared energy over isolated self-consumption
- Coordinates energy sharing physically and the time of energy sharing
- Reduces the complexity and constraints regarding ownership to implement the SEC

In Turin, we progressed from building-only self-consumption to community sharing with anchor-led operation (SEC), demonstrating that sizing PV to the precinct's net load increases hourly shared energy, cuts curtailment, and outperforms the building-by-building approach introduced in Chapter 4 and implemented through cabin-aligned zoning in Chapter 5 (REC feasibility at UniTo). Chapter 7 applies the same operating logic in Geneva's International District, where ownership is consolidated to 2050today as an institution that brings multiple ownership into a single entity. Across both contexts: plan, size, and dispatch to maximize hourly E-shared at the precinct level, and let self-consumption follow as a by-product, not the goal.

Chapter 6 demonstrates that UniTo's Asset Management System (AMS) is the operational backbone that turns a pilot into a reliable service: it centralizes building geodata, energy use, occupancy flows, and PV siting into one environment to support metering, dispatch, settlement, and O&M at the precinct scale. The methodology formalizes how GIS (Chapter 4 outputs) and BIM (roof-by-roof constraints, fire-code buffers, shading) feed the AMS for decision-grade analytics and visualization, enabling a replicable, auditable operating layer for community energy management. Conceptually, this aligns with the "smart/sustainable campus" model, where data availability and interoperability are preconditions for effective governance and faster response cycles, which are exactly the capabilities needed for anchor-led RECs to function beyond pilots.

So the thesis formalizes a city-ready integration sequence:

map → cluster → govern → digitize → operate

Grounded in the chapters. First, map with the GIS solar cadastre to convert rooftop area into PV output using explicit parameters. Next, cluster by electrical topology: elects prosumers and consumers at the cabin scale. Then govern through an anchor, streamlining internal exchange and decisions under the EU law. Digitize with AMS (BIM + GIS as an example here) so metering, settlement, investment, and maintenance are auditable and repeatable, as demonstrated in Chapter 6. Finally, operate on context-specific instruments: Italy's CER pays for hourly shared energy, while Switzerland's RCP/ZEV (and forthcoming CEL) provides the legal connection for internal and local exchange.

8.2 Anchor-led governance ANI

The feasibility tests run make this explicit: SEC membership in Turin is determined by primary-cabin boundaries and by a workable mix of prosumers and consumers (Chapter 5). Those conditions alone don't deliver a functioning community unless a single, trusted actor can coordinate dozens of meters, sign participation agreements, size and procure DERs, and run monthly settlements. In the Italian case, UniTo is that actor because it already aggregates a large share of the building stock that is spread out in the cabin maps, energy procurement, and facilities management. In Geneva, the same logic holds through ownership consolidation: the UN zone shows how "2050toda" (with UN agencies and public partners) can achieve internal sharing style or CEL-mediated exchange where law permits (Chapter 2, ownership and grid-connection sections).

In that case, Unito was the Anchor Institution (ANI). The Anchor Institution first job is to form electrically valid precints and keep them compliant: in Italy, REC members must share the same primary cabin and each generating plant must be <1 MW, so the ANI must group candidates on primery cabin boundaries and check plant sizing before any contracting (Chapter 2) for Geneva the buildings must me in the same neighberhood defined by the district borders. The ANI also owns settlement and reporting under the Italian incentive stack (applying the tariff incentive on shared energy and, where eligible, layering the grant), so financial control sits centrally (Chapter 2). In parallel, the Turin case provides the operational map that the ANI will actually use: UniTo buildings already mapped by primary cabins and filtered by consumption/production/surface create ready-made candidate groups for SEC formation (Chapter 5).

For the ANI in Geneva, leverage comes from its consolidated ownership model: the UN zone shows how single-owner style arrangements simplify decisions and internalize sharing within its members, which is exactly why an anchor like 2050TODAY is effective.

To employ ANI as a regulatory process, the city must make three core instruments and processes that support them as a standard.

- First, a Participation Agreement that locks REC eligibility to the electrical boundary under the same primary cabin, and for Geneva, under the same district.
- Second, a Data-Sharing MoU, *Memorandum of Understanding,* that outlines how two or more parties agree to share data, defining the purpose, scope, responsibilities, data protection, and governance framework, without necessarily being a legally binding contract. That guarantees interval metering and data access for hourly settlement of shared energy, specifically in Italy, since Italian incentives are paid on the hourly minimum between member injections and consumptions (Chapter 2).
- Third, a Rulebook that creates a system by codes according to the tariff incentive computed according to shared MWh (fixed/variable TIP by size band, geographic bonus for the North, 20-year duration, grant–TIP trade-off).

Operationally, Chapter 5 already equips the ANI with the working zone map. For a Geneva-type portfolio, the instrument changes, but the logic holds: use consolidated ownership (e.g., 2050TODAY) to enable internal sharing at common connection points, streamlining decisions and internalizing exchange within one manager's perimeter. This layout makes a single operational foundation, with ANIs accountable for the technical, financial, and governance attributes of the SEC.

8.2.1 Policies to support ANI

The results of the study in Geneva specifically highlight the structural challenges of energy communities in urban contexts. SC1 and SC2 show that subsidies for single-building, self-consumption installations lead to medium net positive investment profiles. Although financially successful, they depend entirely on state support and do little to scale into the precincts they are within. SC3, however, unlocks collective cooperation and improves both energy balance and carbon reduction. Still, they face real-world obstacles: legal fragmentation, low tariff incentives, and higher costs.

The following four policy areas are derived from these findings. Each one includes insights for policy design (what the regulation should include) and insights for policy implementation (what processes and tools must accompany those rules).

Stressing the fact that these policies are drawn from the results accumulated in this thesis, they are not seen as an impeccable design of policies, but more of an initial trial for how policies can improve and then later on compound to create even more articulated policies

8.3.1 Subsidy Reform

Subsidies in Geneva currently favor an individual building level; in this case, financial returns in SC1 and SC2 led to a net positive. However, Such outcomes are sometimes misleading; future subsidy schemes should limit support for single-building PV to a percentage share of the total cost, setting a cap of 60% for example. At the same time, collective energy communities like SC3 require larger upfront investment and face higher legal and coordination costs. These systems should qualify for more support to promote them, or even turn the individual scenarios into them, potentially up to 80% of total eligible costs, including non-technical expenditures such as governance and legal advice.

To discourage misuse, subsidy programs should include a mandatory disclosure of the net private contribution (the portion not covered by public funds) and the resulting CO_2 savings. These disclosures should be standard across all applications, forming the basis for evaluation and comparison.

To avoid misuse of funds and make the process transparent, all energy communities should submit a yearly Energy Balance Sheet. This document would record the total capital cost, the share funded through public subsidies, the private contribution, and estimated annual CO_2 reductions. Moreover, a fast-track review system could prioritize applications from collective projects that combine multiple owners, reducing bureaucratic delay for SECs and inducing their operation.

8.3.2 Governance and Ownership

Scenario SC3 showed that Solar energy communities offer greater benefits but face higher organizational complexities due to fragmented ownership. Policy design must recognize that cities rarely consist of a single ownership. But with the use of an Anchor Institution model, we can simplify things: for example, an entity (2050Today or university, hospitals, governmental institutions, etc.) can assume legal and financial responsibility for managing the new infrastructure (SEC), while other members could participate through a pre-defined contract.

The Cantonal Energy Office would publish and legally validate standard agreements for energy communities; although they would be optional, they would be legally enforceable if adopted.

To make negotiations easier between property owners, the canton should also employ a neutral mediation service specifically for energy community formation. Finally, a subsidy system can reward communities that bring together a greater number of owners, encouraging collaboration across zones.

8.3.3 Tariffs and Grid Integration

Under the current Swiss energy laws, energy that is sold to the grid is compensated at a different seasonal rate. This discourages communities from sharing energy externally, particularly in summer when surplus is highest. The financial logic of energy communities must shift, and tariffs should reward communities that avoid grid demand and CO_2 displacement, and not penalize surplus resale.

Policy design should calculate tariffs flat or dynamic, depending on grid cost avoidance, and not price differently depending on seasons. Virtual net metering should also be allowed, making energy sharable across separate plots within the same zone, which is important for urban energy communities.

SIG should also develop a digital platform like an AMS that tracks internal energy sharing and distributes it fairly. To ensure transparent interactions between members. Grid operators must also be required to connect new community networks within a fixed time window (i.e., 6 months), avoiding indefinite delays.

8.3.4 Demand Reduction

The current subsidy focus on PV overlooks that reducing demand should come before new production is added. Energy communities in a best-case scenario should be required to conduct building inspections and renovations before applying for subsidies and implement basic efficiency measures, such as insulation, heating, or smart load management.

So, for example, communities that achieve demand reduction (over 20%) prior to PV installation would qualify for higher subsidies or receive additional incentives tied to long-term performance.

A public registry of certified energy auditors should also be established, and require an official certificate with every PV subsidy application, certifying efficiency. Table 8.1 summarizes all the suggested policy reforms and designs.

Table 8.1: Summary of policy design

Reform Area	Insights for Policy Design	Insights for Policy Implementation
Subsidy Reform	Limit subsidies for individual PV to 60% of costs, conditional on efficiency upgrades. - Allow up to 80% support for collective networks, including legal/coordination costs.	Require communities to submit annual Net Energy Balance Sheets. - Conduct periodic audits. Fast-track applications that combine efficiency + PV deployment.
Governance & Ownership	Require a lead operator to take legal and financial responsibility. Approve and enforce standard contracts for metering, billing, and dispute resolution. - Guarantee minimum governance rights (30%) for smaller owners.	Publish legally valid contract templates. - Offer public mediation services to resolve owner disputes. - Provide bonus subsidies for projects involving 3+ owners.
Tariffs & Grid Integration	Replace seasonal resale tariffs with flat or dynamic credits reflecting avoided grid costs. - Enable virtual net metering across	Develop a digital platform via SIG for real-time tracking of energy flows and credit distribution. -

	non-contiguous plots. - Mandate priority dispatch for community-generated energy.	Require grid integration within 6 months of community approval.
Demand Reduction	Make energy audits and basic upgrades a prerequisite for PV subsidies. - Offer additional incentives for >20% demand reduction before generation.	Require official efficiency certificates with each application. Fast-track processing for combined efficiency + PV projects. - Monitor long-term performance.

If cities like Geneva and Torino want a real energy transition, they must consider collective participation that constitutes cooperation between different ownerships and ties them together. Individual models hide this inefficiency. Collective networks, though harder to build, unlock the real potential of urban decarbonization, but only if policy tears down today's barriers of ownership, tariffs, and bureaucracy.

This study shows a path to do that, while also pushing the boundaries in scenarios like SEC-U, it still recognizes the scalability under realistic boundaries. By reforming subsidies, simplifying governance, fixing tariffs, and prioritizing demand reduction, Geneva and Turin can set a global path: energy communities not as exceptions, but as the new normal. What emerges from this is more than a technical fix; it is a blueprint for transforming fragmented cities into collective powerhouses, proving that cooperation, not isolation, is the engine of the postcarbon cities.

8.3 Urban Energy Precincts (UEP)

The empirical analysis of the UniTo campus in Turin and the United Nations Zone in Geneva shows complementary approaches to their localized energy transition. They reflect broader patterns in how urban precincts organize energy systems around anchor institutions, boundaries, and ownership logics. This section shows the typologies that make Urban Energy Precincts (UEPs), which would offer a scalable classification framework.

The three typologies depicted in this thesis are Institutional**,** Hybrid, and Collective, based on the scenarios, and provide a preliminary overview of what an urban precinct can accommodate.

From this thesis, we can define the following: Urban Energy Precincts are localized, spatially bounded zones inside the boundary of cities where energy production, consumption, and management are coordinated and governed at the district level, and typically anchored by a dominant institution.

They go beyond just forming a "community"; they form a precinct-level energy ecosystem, and it's an ecosystem since it introduces a new type of environment that encourages other buildings to belong to it, shaped by urban morphology, governance boundaries, and infrastructure access.

Each typology is defined by its governance structure, ownership complexity, and spatial integration logic, and scored (1 to 5 scale) across the five dimensions, from the thesis. The estimations are based on comparative interpretation of: Energy metrics, Economic, and Governance.

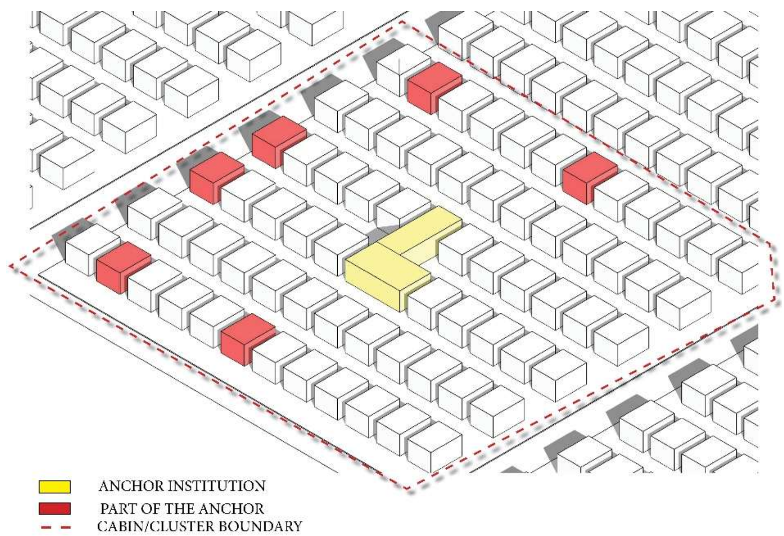

Figure 8.4: Institutional Urban Energy Precinct

The **Institutional UEP** is the most consolidated model, where all participating buildings fall under the same institutional entity, typically a university, hospital, or governmental institution. Energy production and consumption are managed internally, ideally through a private microgrid or a virtual one, but these things are future projections, to optimize on-site self-sufficiency.

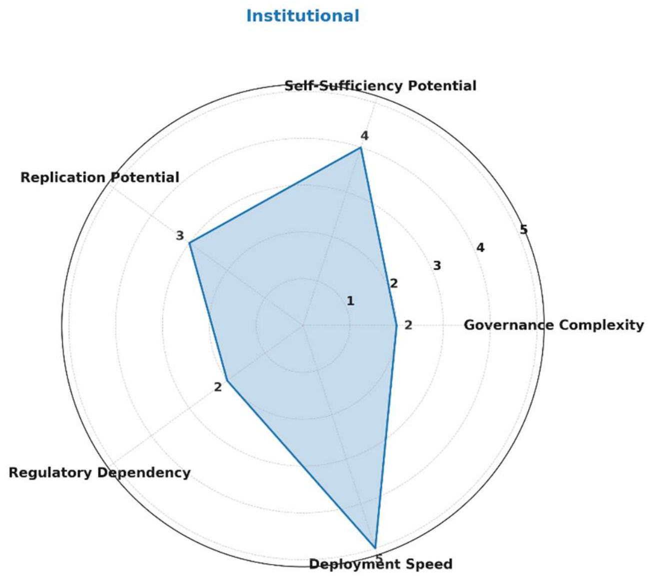

Figure 8.5: Institutional Urban Energy Precinct dual radar chart

Figure 8.6: Hybrid Urban Energy Precinct.

Hybrid UEP builds on a central anchor institution but includes additional actors, such as municipal offices, public schools, or libraries, each with distinct ownership and administrative structures. These precincts require moderate coordination effort and rely on shared grid access, which attributes energy balancing and maintains coordination between members.

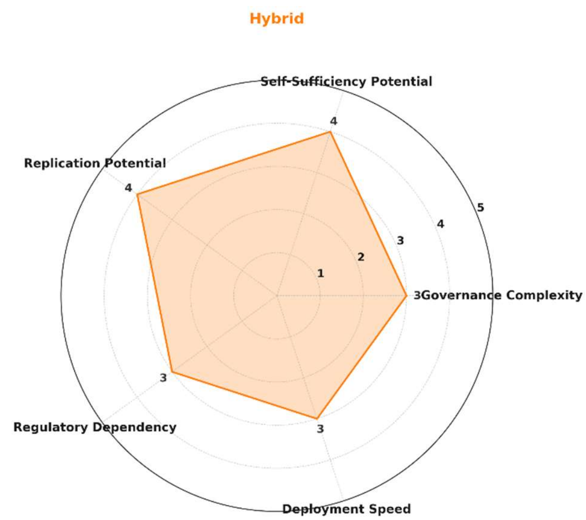

Figure 8.7: Hybrid Urban Energy Precinct dual radar chart

Figure 8.8: Collective Urban Energy Precinct.

Finally, the **Collective UEP** represents the most decentralized form. Here, residential, commercial, and institutional buildings voluntarily participate in an energy community with or without a dominant anchor. Governance is typically cooperative or platform-based, and grid dependency is high. While collective models offer flexibility and scalability, they have significant challenges in terms of synchronization, data exchange, and legal alignment, especially in dense, mixed-use urban areas, so the best-case scenario a collective model can join is when there is an institutional UEP formed first, and the voluntary participants join.

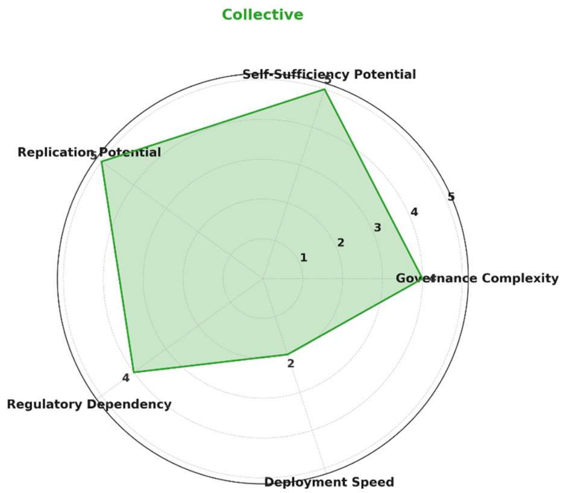

Figure 8.9: Collective Urban Energy Precinct dual radar chart

Each typology is a different yet complementary pathway for the institutional UEP to implement and transition energy sources into a sustainable one, starting at the precinct scale.

This classification serves as a preliminary index and a constructive tool that builds on itself, relying on feasibility, governance requirements, and energy potential in diverse city contexts. Table 8.2 summarizes the three typologies.

Table 8.2: UEP typologies

Typology	Description	Ownership & Governance	Urban Form	Key Examples
Institutional UEP	Precincts are organized within a single institutional boundary. Energy is managed internally with minimal legal fragmentation.	Single-owner or umbrella governance. Centralized decision-making.	Enclosed blocks or campus-style sites with clear boundaries.	UniTo SEC-R
Hybrid UEP	A shared energy precinct anchored by an institution but involving other public or semi-public buildings.	Multi-owner with a lead coordinator Community manager is often needed.	Clustered civic blocks or districts.	FIPOI and 2050Today

	Intermediate coordination complexity.			
Collective UEP	Open precincts built around a voluntary association of diverse stakeholders (residential, commercial, small offices) with no central anchor. High governance needs.	Fully decentralized or cooperative governance. Requires an energy community platform or aggregator.	Mixed-use urban fabric. Often retrofit.	Geneva SEC U

Table 8.3 below summarizes the system that was used to score each typology relying on governance, energy metrics.

Table 8.3: UEP scores and justifications

Dimension	Institutional UEP	Hybrid UEP	Collective UEP
Governance Complexity	**1.5** Single-entity ownership simplifies governance.	**3** Requires coordination between 2–3 anchor institutions or mixed-use ownership.	**4.5** High: many stakeholders, meter points, legal interfaces.
Self-Sufficiency Potential	**4.5** High alignment between demand and production; optimized sizing/sharing.	**4** Good surface coverage and diversified loads.	**3.5** High potential, but demand coordination is harder.
Replication Potential	**4** Easily replicable on similar campuses or clusters.	**3** Somewhat replicable, depends on case-specific mix.	**4.5** High potential across cities if tech/legal conditions are met.
Regulatory Dependency	**2** Moderate: requires grid interaction, but internalized operations are simple.	**3** Must engage grid and regulatory tools.	**4.5** Very high: reliant on formal energy-sharing laws
Deployment Speed	**4** Fast deployment due to centralized decision-making.	**3** Slower due to MoUs, data-sharing, and technical coordination.	**2.5** Slowest: many stakeholders and infra constraints.

Conclusion

The main goal of the thesis has been to contribute to expanding the knowledge about Urban planning, policies, and energy transition, to create a path that cities can take to reduce their carbon emission when it comes to the energy sector. The thesis has been arranged in two main parts: the framework of reference, in which the background analysis has been developed, and a second part named "applied research", in which the main issues to be faced are explored on a case study basis for the development of SECs and the establishment of UEP.

This thesis has tackled the difficult task of generating meaningful insights in the complex and thoroughly discussed subject of post-carbon cities. Other approaches could have been less controversial and challenging.

The pertinence of the research approach could be appraised by applying the four rules of scientific research as formulated by Umberto Eco[1] in his guidelines for the elaboration of a thesis:

a) The research addresses a well-defined subject, which is known and acknowledged by others.

b) It provides original insights or presents previous research under a different perspective.

c) It is useful to others.

d) It incorporates elements to verify or refute the research hypothesis. Other specialists, with enough knowledge in the field, could reach the same results.

a) The significance of the subject

The origin and idea of focusing on cities and the influence of the built environment on urban energy performance can be easily justified. Cities are concentrations of human development, which makes them, in some sense, energy black holes. They consume resources on a global scale to sustain all the processes that take place inside their boundaries, and then, they spread wasteful residues to the surrounding environment. Since going back in time to a preindustrial era is not possible, we are forced to solve all the problems caused by our current cities. From the literature we always read and repeat, we know that nearly 80% of people living in cities, prospering, developing, and neglecting. This research explores how energy can be taken control of to find ways in which cities may evolve and fix the damage done in the past.

b) The new perspective and original findings

This thesis reframes energy communities as Urban Energy Precincts (UEPs), which are energy-coordinated building blocks managed by an anchor institution and operated through a digital layer that maximizes hourly shared energy. Instead of treating policy, mapping, governance, finance, and operations as separate topics, the work integrates them into a single, executable path by mapping the buildings and then pinpointing potential communities and establishing a governing body to finally operate, and demonstrates it across two contrasting contexts (Italy and Switzerland).

This thesis has contributed to clarifying some controversial aspects about carbon, climate change, and energy. It did not investigate every single cause of climate change, but instead it focused on energy demand on an urban scale. This was identified as a field that urgently requires study modification and innovation to bridge the gap between urban planners and energy providers. This makes a balance between quantitative analysis and the contextualization of the data for each case.

The contributions are distributed across chapters, with novelty ranging from reinterpretation of known constraints to the development of pragmatic tools, rules, and templates that others can directly reuse:

- Chapter 2 is a Reading and positioning of of the research theoretical references drawn form studies and freaworks, from the top studies in this field and international associations reports with an oriented reading of REC/ZEV/CEL rules, not as passive background but as design constraints and rules that shape zoning and what can be done in the restricted environment of a city from DSO, governance and technicality.
- Chapter 3 draws from Chapter 2, a framework that was adopted and a methodology developed and built upon using a scenario-based approach to reach the UEP concept that binds coordination, governance roles, and financial pillars. Originality lies in sequencing these steps so that each produces a concrete artifact (solar atlas, sequence, digital data model) that makes the following steps less risky and more reliant.

- Chapter 4 Translates rooftop mapping into an hourly, dispatch-relevant inventory by keeping conversion assumptions explicit (usable area, PR, orientation) and coupling them with cabin boundaries. New findings include the estimation of variations in solar potential due to SVF and weather data. The correspondence between density and land cover. The last part of the chapter shows what potential the city of Turin has to satisfy its energy demand of urban energy consumption using only RTSPV technology.
- Chapter 5 proposes a feasibility filter (consumption, production, surface) to balance prosumers/consumers inside each primary cabin, and elevates the university from a participant to an Anchor Institution (ANI) with defined decision rights.
- Chapter 6 draws on Chapter 5 to create an introductory asset management system (AMS).
- Chapter 7 draws upon all the empirical chapters as the cumulative case study that combines all three pillars (technical, governance, and financial), showing all the scenarios that were described in Chapter 3 in application, and considers both individual creation and global ones (e.g., FIPOI/UN district) can reproduce UEP logic without EU-style REC incentives, but the local ones. This cross-context result isolates what is universal (anchor + digital + hourly sharing) from what is context-specific (legal/incentive rails).
- Chapter 8 synthesizes and puts into evidence the two parts of the thesis, theoretical and applied, and add the results of all the scenarios, not to compare but to conceptualize the results that build upon each other, to establish and suggest the outcomes of the thesis in a encapsulated path of the UEP, describing what they are and what are there typologies and the policies that can help establish and support there formation.

Together, these elements position and solidify energy communities from an abstract policy that is applied in complex ways to a governable urban Energy Precinct, that cities can replicate precinct by precinct, with anchors and SECs as the operational core.

c) Research applicability

The research undertaken for this thesis has looked into the past but focused on the current and writes for the future. It went to the past to gain critical understanding, focused on the current to solve the current issues from the past, and wrote for the future to make the current a better past. In addition, it has proposed new instruments to pave the way for the post-carbon city. It is expected that the UEP can develop even further by incorporating it as an international model accessible as a tool by a web browser or app to identify and see different possibilities for each context or city. In this way, it could be accessible to planners, designers, and energy providers who seek to transition to sustainable energy aspects from the preliminary stages of decision-making. Its current configuration is highly variable for different cities, and like any project, development would have gaps to be filled. It could then become a common aid to manage energy strategies at the urban scale. Potential applications include:

- **Targeting the right precincts**

  by identifying ares where PV, storage, and diverse loads under the same cabin yield high hourly shared energy and publish a ranked precinct atlas for policy and funding.

- **Policy and tariff testing**

  to simulate incentive or tariff changes (e.g., TIP levels, export prices) on shared-energy cashflows to prioritize public spending where € per shared-kWh is highest.

- **Anchor governance design**

  to elevate energy Communities with the ANI.

- **Equity & participation**

  by applying and illustrating final metrics of SECs to the community and keeping them engaged in a transparent relationship.

- **Different replication.**

  Applying the same methodology and framework to other cities (different DSOs, tariffs, legal rails) to confirm transferability.

d) Replicability

All procedures and methods used in this thesis are documented step by step. Supplementary data accompany each stage to provide objective evidence. Results that were weak or inconclusive are reported openly to clarify the study's limits and scope. With the same inputs and tools, a qualified reader can replicate the analyses and reach similar results. The full workflow, datasets, and parameter choices are detailed in the methods and synthesis chapter.

Research hypothesis

1. What physical and spatial parameters limit the adoption of Solar Energy Communities (SEC) in urban areas and districts? (Technical)

All energy commuties can be adapted from different sources or a combination of them, between them solar presents the most mobile and well placed one in the context of the boudreis inside the city, if we use air as a source, we would require a vast amount of area out side the city, water, would require a strong current in a river, nuclear would require a rural space far from the city and political agreement, solar however is the only source were restrictions are lower and very adaptibile to context specific cases. Nonetheless, nothing is perfect; solar energy requires PV system implementation and a clear surface to place it on, in cities, which is hard to do, but only when using it with no plan in mind. Area, sun exposure, and density are not limits, but incentives, that governance, policies, and coordination either stand in its way or transcend it to replace one of the major sources of unsustainable energy. The more we advance in our path for solar development, the less the technology becomes less of a problem, and our coordination becomes the issue.

Open source data was available to some extent, there was a limitation in both turin and Geneva, one worth notting is the energy consumption for some buildings that lacked a meter and the height of the builings of the city, yet open source data integrated with gis, made the research adapt a model to process it in the back-end and present the encapsulated results easier to read and acceabile to the public, to show how self sufficiency can be achived and make an autonomous precint

In this spirit, the methodology that examined the technical aspects, like the simulation in the city of Turin and Geneva, the scenario-based approach showed how it can make a complete self-sufficient urban precinct possible, but paved the way to explore the dynamics of application making governance the next dynamic.

What are and how can we establish anchor institutions that glue the SEC together? (Governance)

Governance and policies are the engines og a city, making them well oiled meanes taking time and the right amount if adaptation as main factors, Geneva in this case prsents how polices weren't always clear when it comes to applying them they were transparent in sense, as if it was written to be politically correct and not operationall correct, the cabins on Geneva are fragmanetd and not presented as an opensource data, and there law required that energy communities must be eseatblished in the same neighberhood/cluster with different parcel, yet if we look at it from another prespective it presented an opportunity to create an anchore institution capable of handling the governance part to ease the path of SEC, with the help of the scenario based approach, and after many meeting with the stake holder (SIG, 2050Today, UN) , we were able to present and apply the framework of the anchor institution, with the main gold of increasing self-sufficency, reducing energy demand and making the scenario financially viable.

Achieving these results wasn't easy, even when presenting very tangible scenarios and an extremely feasible one (SEC-U), the research proceeded successfully, but incorporating incentives and main capital costs imposed by the Swiss law. Paving the way to the concept of ANI with the help of AMS and policy suggestions to help implement them, and achieving a framework to reach Urban Energy Precincts UEP.

What concrete strategies, drawn from the Turin and Geneva experiences, establish Urban Energy Precincts (UEP)?

The Theoretical work was grounded in two applied case studies, Turin and Geneva, to make the research as operational and applied as possible. Studying real decision chains, data constraints, and institutional frictions served as a filter that separated what is merely plausible from what is actually feasible. This empirical part refined the scope of the hypotheses and sharpened the relevance of the findings.

The cases were chosen to reflect a complex present shaped by distinct governance regimes under a shared international framework. Turin operates within EU REC rules; Geneva advances through ZEV/CEL logics outside the EU. They are not "comparable" in a narrow sense; they are complementary, each illuminates different limits and levers of the same urban-energy problem. Methodologically, we privileged processes that had not yet been read through an energy-community/precinct lens, so the analysis could add value rather than repeat existing environmental appraisals. The result is a set of conclusions that travel across contexts while remaining anchored to how cities, institutions, and grids actually work.

Urban energy precints emerges as the synthesis of the the thesis, in ordet to make it easier for the public and impment it as a tool, the final chapter presented and separated it as typologies, accorind to the evaluation metrics adpted in the begging, UEP most admring advantage is its adabtbility to the contexted if different city, its not a static set of rules, because genrilcally cities are complex sytyems that differ in many ways, but there gols align, and with any issue we face an adbtable solution is always the beging to set a path for a post carbon city.

Future research

This thesis aims to be a seminal work to be continued by the author and others in some of the research lines that it puts forward. Possible lines of investigation include further analysis on SEC reconfigurations with time-based applications, urban energy efficiency, or the impact of new economic models on UEP. The advance of new theories on Energy communities and the exploration of their influence on the global performance still require further attention. This exploration of urban energy dynamics that combine quantitative values with qualitative governance is an interesting design exercise that involved the use of new instruments and the revision of built examples. However, the main priorities to keep up with the investigation in the short term would focus on:

- Development of the Urban Energy Precinct Index
- The full integration of the UEP as a tool in GIS or a dedicated application
- The extrapolation of the analytic methodology to other locations

Europe’s main planning challenge now lies within existing cities. The 20th-century growth model has run its course. Most urban areas are already large enough to host projected populations, but much of the fabric was built for different times and needs. It must be adapted, not expanded.

Urban areas vary in how easily they can change. Ownership patterns, density, and current uses set the transformation potential. Dense residential districts with fragmented, strata ownership change and transform with UEP over long horizons.

Retrofit can improve conditions within dense neighborhoods, but achieving true energy descent will demand a real dedication to the application of Urban Energy Precincts. Cities need instruments that promote community development and avoid nonsensical interventions.

Asset digital management and open information can accelerate this shift. Integrating new technologies into urban operations improves resource optimization. Open data and shared metrics expand collective understanding of how each city performs. With reliable, public evidence, we can design urban models that deliver efficient, equitable, and fulfilling post-carbon city life.

Appendix I: Calculations and equations

To evaluate the financial feasibility and environmental impact of solar photovoltaic (PV) systems, a series of analytical equations is applied. These formulas integrate investment costs, operational returns, carbon emissions savings, and various financial incentives, offering a holistic model of PV system performance over its lifecycle.
The total installation cost of a PV system, C_invest, is modeled as a function of the installed capacity in kilowatts-peak (kWp), denoted P_kwp. The formulation accounts for nonlinear cost reductions with scale and specific correction factors:

Table A1: Equation symbols definition

Symbol	Description
PKWC	System capacity (kWc)
SELFCONSOS	Self-consumed energy (kWh/year)
EXCESS	Energy fed to grid (kWh/year)
CAT_SIA	Building type (1–2: residential, ≥3: commercial

$$C_{\text{invest}} = \left(\frac{8120}{P_{\text{kwp}}^{0.766}} + 1140 \cdot e^{-2.99\times10^{-4}\cdot P_{\text{kwp}}} \right) \cdot P_{\text{kwp}} \cdot 1.077 \quad (6)$$

Costs decrease nonlinearly with scale due to economies of scale () and exponential decay in marginal costs. The factor 1.0771.077 accounts for taxes/overheads.

Smaller systems (e.g., PKWC<30 kWcPKWC<30 kWc) show higher per-kWc costs, while larger systems (e.g., PKWC>100 kWcPKWC>100 kWc) benefit from lower costs .

Annual maintenance costs, C_maint, are approximated as 1% of the initial investment:

$$C_{\text{maint}} = 0.01 \cdot C_{\text{invest}} \tag{7}$$

Government and local incentives, I, are tiered based on installed capacity and include Geneva-specific bonuses for small-scale systems In accordance with the SIG 2025 Solar Bonus program, eligible photovoltaic installations in Geneva with certified capacities between 2 kWp and 30 kWp may receive an additional local subsidy equivalent to **20% of the federal subsidy** (SIG, 2025a). The bonus is available only for installations enabling self-consumption and is awarded on a first-come, first-served basis, subject to available funding.:

$$\text{Incentive}(P) = \begin{cases} (360 \cdot P) \cdot 1.2 & \text{if } P \leq 30 \\ (360 \cdot 30 + 300 \cdot (P - 30)) \cdot \frac{4}{3} & \text{if } 30 < P < 100 \\ 360 \cdot 30 + 300 \cdot 70 + 250 \cdot (P - 100) & \text{if } P \geq 100 \end{cases} \tag{8}$$

Progressive incentives favor smaller systems (e.g., +33%+33% bonus for PKWC ≤100 kWc *P*KWC≤ 100 kWc). The net investment, C_net, is then:

$$C_{\text{net}} = C_{\text{invest}} - I \tag{9}$$

The CO_2 emissions saved annually through solar production, ΔCO_2, is a product of the yearly solar generation, E_PV, and the carbon differential between Swiss grid emissions (0.125 kg/kWh0.125 kg/kWh) and PV emissions (0.043 kg/kWh). δ_CO_2 = 0.082 kg CO_2/kWh (Climate Forward, 2022):

$$\Delta CO_2 = E_{PV} \cdot \delta_{CO_2} \tag{10}$$

Total savings = 5.42M tons

Electricity resale tariffs, T_resell, vary based on installed capacity, according to the local energy utility which is SIG (Geneva industrial service) in Geneva (SIG, 2025b):

$$T_{\text{resell}} = \begin{cases} 0.1546\,\text{CHF/kWh}, & \text{if } P_{\text{kwp}} < 30 \\ 0.1524\,\text{CHF/kWh}, & \text{if } 30 \leq P_{\text{kwp}} < 100 \\ 0.1438\,\text{CHF/kWh}, & \text{if } P_{\text{kwp}} \geq 100 \end{cases} \tag{11}$$

The electricity resale tariff, T_elec, also fixed by the local energy utility (SIG) based on annual consumption C_el and building use category CAT_SIA, is:

$$T_{\text{elec}} = \begin{cases} 0.298\,\text{CHF/kWh}, & \text{if } C_{\text{el}} < 30000 \text{ or } \text{CAT}_{\text{SIA}} < 3 \\ 0.228\,\text{CHF/kWh}, & \text{if } C_{\text{el}} \geq 30000 \text{ and } \text{CAT}_{\text{SIA}} \geq 3 \end{cases} \tag{12}$$

Annual gross revenue, R_gross, combines the savings from self-consumed energy and income from excess energy resold to the grid :

$$R_{\text{gross}} = E_{\text{self}} \cdot T_{\text{elec}} + E_{\text{excess}} \cdot T_{\text{resell}} \tag{13}$$

Therefore, for the net annual gains, R_net, are then:

$$R_{\text{net}} = R_{\text{gross}} - C_{\text{maint}} \quad (14)$$

The payback period, t_payback, is the time required to recover the net investment, discounted at a rate r = 0.03(LAM, 2009):

$$t_{\text{payback}} = \frac{\ln\left(\frac{1}{1-\frac{r \cdot C_{\text{net}}}{R_{\text{tot}}}}\right)}{\ln(1+r)} \quad (15)$$

Where R_tot is the cumulative undiscounted net gain. If the denominator becomes non-positive due to infeasibility, t_payback → ∞.

The annuity value, A, distributes the net investment over N = 25 years using the discount rate:

$$A = \frac{(C_{\text{invest}} - I) \cdot r}{1 - (1+r)^{-N}} \quad (16)$$

Finally, the surplus, S, defines the annual profit above the annuitized investment:

$$S = R_{\text{gross}} - A \quad (17)$$

Negative net gains reflect high initial costs; positive net gains result from incentives and economies of scale.

For the monthly standardization, the following data suifn chnider as a reference were used. By comparing the standardization of consumption and production, we can observe the trend within the 2 case studies, as shown in Figure. A2.

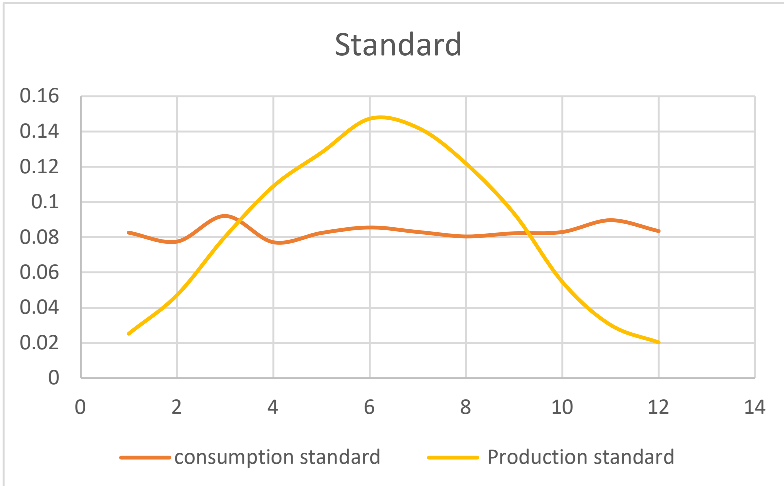

Figure A2: Consumption and Production patterns on a monthly scale

The standardized consumption and production levels over time reveal distinct patterns. Consumption remains relatively stable around 0.08, while production shows a sharp rise, peaking at approximately 0.15 around month 6, before declining to about 0.02. This indicates a mismatch between production and consumption, with production varying significantly while consumption stays consistent. The peak may reflect seasonal factors or operational changes, while the decline suggests reduced production capacity. Optimizing production to better align with consumption could help minimize surpluses and improve efficiency.

Appendix II

DIRECTIVE (EU) 2018/2001 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 11 December 2018 on the promotion of the use of energy from renewable sources (recast) Article 22 1.

1. Member States shall ensure that final customers, in particular household customers, are entitled to participate in a renewable energy community while maintaining their rights or obligations as final customers, and without being subject to unjustified or discriminatory conditions or procedures that would prevent their

participation in a renewable energy community, provided that for private undertakings, their participation does not constitute their primary commercial or professional activity.

2. Member States shall ensure that renewable energy communities are entitled to:

(a) produce, consume, store and sell renewable energy, including through renewables power purchase agreements;

(b) share, within the renewable energy community, renewable energy that is produced by the production units owned by that renewable energy community, subject to the other requirements laid down in this Article and to maintaining the rights and obligations of the renewable energy community members as cutomers

(c) access all suitable energy markets both directly or through aggregation in a non-discriminatory manner.

3. Member States shall carry out an assessment of the existing barriers and potential of development of renewable energy communities in their territories. 4. Member States shall provide an enabling framework to promote and facilitate the development of renewable energy communities. That framework shall ensure, inter alia, that:

(a) unjustified regulatory and administrative barriers to renewable energy communities are removed;

(b) renewable energy communities that supply energy or provide aggregation or other commercial energy services are subject to the provisions relevant for such activities;

(c) the relevant distribution system operator cooperates with renewable energy communities to facilitate energy transfers within renewable energy communities; (d) renewable energy communities are subject to fair, proportionate and transparent procedures, including registration and licensing procedures, and costreflective network charges, as well as relevant charges, levies and taxes, ensuring that they contribute, in an adequate, fair and balanced way, to the overall cost sharing of the system in line with a transparent cost-benefit analysis of distributed energy sources developed by the national competent authorities;

(d) renewable energy communities are not subject to discriminatory treatment with regard to their activities, rights and obligations as final customers, producers, suppliers, distribution system operators, or as other market participants;

(e) the participation in the renewable energy communities is accessible to all consumers, including those in low-income or vulnerable households;

(f) tools to facilitate access to finance and information are available;

(g) regulatory and capacity-building support is provided to public authorities in enabling and setting up renewable energy communities, and in helping authorities to participate directly; 138

(h) rules to secure the equal and non-discriminatory treatment of consumers that participate in the renewable energy community are in place.

5. The main elements of the enabling framework referred to in paragraph 4, and of its implementation, shall be part of the updates of the Member States' integrated national energy and climate plans and progress reports pursuant to Regulation (EU) 2018/1999.

6. Member States may provide for renewable energy communities to be open to cross-border participation.

7. Without prejudice to Articles 107 and 108 TFEU, Member States shall take into account specificities of renewable energy communities when designing support schemes in order to allow them to compete for support on an equal footing with other market participants.

References

Ableitner, L., Tiefenbeck, V., Meeuw, A., Wörner, A., Fleisch, E., & Wortmann, F. (2020). User behavior in a real-world peer-to-peer electricity market. *Applied Energy*, *270*, 115061. https://doi.org/10.1016/j.apenergy.2020.115061

Ahmed, S., Ali, A., & D'Angola, A. (2024a). A Review of Renewable Energy Communities: Concepts, Scope, Progress, Challenges, and Recommendations. *Sustainability*, *16*(5), 1749. https://doi.org/10.3390/su16051749

Ahmed, S., Ali, A., & D'Angola, A. (2024b). A Review of Renewable Energy Communities: Concepts, Scope, Progress, Challenges, and Recommendations. *Sustainability*, *16*(5), Article 5. https://doi.org/10.3390/su16051749

Allegrini, J., Orehounig, K., Mavromatidis, G., Ruesch, F., Dorer, V., & Evins, R. (2015). A review of modelling approaches and tools for the simulation of district-scale energy systems. *Renewable and Sustainable Energy Reviews*, *52*, 1391–1404. https://doi.org/10.1016/j.rser.2015.07.123

Alsibai, H., Gasbarri, P., Boscariol, M., Meschini, S., Tagliabue, L. C., Dansero, E., & Tartaglino, A. (2024). *Solar Potential and RES Evaluation into*

UniTO's Digital Asset Management System for Sustainable Campus Development. University of Vigo. https://iris.polito.it/handle/11583/2995440

Anselmo, S., Safaeianpour, A., Moghadam, S. T., & Ferrara, M. (2024). GIS-based solar radiation modelling for photovoltaic potential in cities: A sensitivity analysis for the evaluation of output variability range. *Energy Reports*, *12*, 4656–4669. https://doi.org/10.1016/j.egyr.2024.10.031

ARERA, A. di R. per E. R. e A. (2020). *REGOLAZIONE DELLE PARTITE ECONOMICHE RELATIVE ALL'ENERGIA ELETTRICA CONDIVISA DA UN GRUPPO DI AUTOCONSUMATORI DI ENERGIA RINNOVABILE CHE AGISCONO COLLETTIVAMENTE IN EDIFICI E CONDOMINI OPPURE CONDIVISA IN UNA COMUNITÀ DI ENERGIA RINNOVABILE*. Autorità di Regolazione per Energia Reti e Ambiente. https://www.assistal.it/comunita-di-energia-rinnovabile-dallarera-la-regolazione-delle-partite-economiche/

ARERA, A. di R. per E. R. e A. (2022). *Testo Integrato Autoconsumo Diffuso (TIAD) (Delibera 727/2022/R/eel)*. DMEA Direzione Mercati Energia all'Ingrosso e Sostenibilità Ambientale. https://www.arera.it/atti-e-provvedimenti/dettaglio/22/727-22

Aruta, G., Ascione, F., Fistola, R., & Iovane, T. (2024). The City as a Power Hub for Boosting Renewable Energy Communities: A Case Study in Naples. *Sustainability*, *16*(18), 7988. https://doi.org/10.3390/su16187988

Bai, X., Dawson, R. J., Ürge-Vorsatz, D., Delgado, G. C., Salisu Barau, A., Dhakal, S., Dodman, D., Leonardsen, L., Masson-Delmotte, V., Roberts, D. C., & Schultz, S. (2018). Six research priorities for cities and climate change. *Nature*, *555*(7694), 23–25. https://doi.org/10.1038/d41586-018-02409-z

Bao, Z., Hashim, K. F., Almagrabi, A. O., & Hashim, H. binti. (2023). Business intelligence impact on management accounting development given the role of mediation decision type and environment. *Information Processing & Management*, *60*(4), 103380. https://doi.org/10.1016/j.ipm.2023.103380

Bauwens, T. (2016). Explaining the diversity of motivations behind community renewable energy. *Energy Policy*, *93*, 278–290. https://doi.org/10.1016/j.enpol.2016.03.017

Bergamasco, L., & Asinari, P. (2011). Scalable methodology for the photovoltaic solar energy potential assessment based on available roof surface area: Application to Piedmont Region (Italy). *Solar Energy*, *85*(5), 1041–1055. https://doi.org/10.1016/j.solener.2011.02.022

Bertoldi, P., Kona, A., Rivas, S., & Dallemand, J. F. (2018). Towards a global comprehensive and transparent framework for cities and local governments enabling an effective contribution to the Paris climate agreement. *Current*

Opinion in Environmental Sustainability, *30*, 67–74. https://doi.org/10.1016/j.cosust.2018.03.009

Bollino, C. A. (2009). *Incentives for wind energy: The role of GSE*. *55*(2), 50–57.

Brummer, V. (2018). Community energy – benefits and barriers: A comparative literature review of Community Energy in the UK, Germany and the USA, the benefits it provides for society and the barriers it faces. *Renewable and Sustainable Energy Reviews*, *94*, 187–196. https://doi.org/10.1016/j.rser.2018.06.013

Brunoro, S., Bizzarri, G., & Boldrin, E. (2024). Exploring the potential of energy communities in the Italian territory. *Frontiers in Built Environment*, *10*. https://doi.org/10.3389/fbuil.2024.1365115

Bulkeley, H., & Betsill, M. M. (2013). Revisiting the urban politics of climate change. *Environmental Politics*, *22*(1), 136–154. https://doi.org/10.1080/09644016.2013.755797

Bulkeley, H., Castan Broto, V., & Edwards, G. (2014). *An Urban Politics of Climate Change: Experimentation and the Governing of Socio-Technical Transitions*. https://doi.org/10.4324/9781315763040

Candelise, C., & Ruggieri, G. (2020). Status and Evolution of the Community Energy Sector in Italy. *Energies*, *13*(8), 1888. https://doi.org/10.3390/en13081888

Canton of Geneva, & OCEN. (2025b, March 26). *Catalogue des subventions 2025 (PDF)*.

Canton of Geneva, & OCEN. (2025a). *Installation solaire photovoltaïque (GEnergie portal)*. https://www.ge-energie.ch/installation-solaire-photovoltaique

Cantonal Energy Office (OCEN). (2020). *Plan directeur de l'énergie 2020-2030* [Cantonal master plans]. https://www.ge.ch/node/22488

Caramizaru, E., & Uihlein, A. (2020). *Energy communities: An overview of energy and social innovation*. JRC Publications Repository. https://doi.org/10.2760/180576

Carley, S., & Konisky, D. M. (2020). The justice and equity implications of the clean energy transition. *Nature Energy*, *5*(8), 569–577. https://doi.org/10.1038/s41560-020-0641-6

Chang, K., & Tsai, B. (1991). The Effect of DEM Resolution on Slope and Aspect Mapping. *Cartography and Geographic Information Systems*. https://doi.org/10.1559/152304091783805626

Climate Forward. (2022). *Solar Photovoltaic Forecast Methodology Version 2.0*. https://climateforward.org/program/methodologies/solar-photovoltaic/

Corasaniti, S., Coppa, P., Atzori, D., & Rehman, A. U. (2025). Renewable Energy Communities (RECs): European and Worldwide Distribution, Different

Technologies, Management, and Modeling. *Energies*, *18*(15), 3961. https://doi.org/10.3390/en18153961

Creutzig, F., Agoston, P., Goldschmidt, J. C., Luderer, G., Nemet, G., & Pietzcker, R. C. (2017). The underestimated potential of solar energy to mitigate climate change. *Nature Energy*, *2*(9), 17140. https://doi.org/10.1038/nenergy.2017.140

Creutzig, F., Agoston, P., Minx, J. C., Canadell, J. G., Andrew, R. M., Quéré, C. L., Peters, G. P., Sharifi, A., Yamagata, Y., & Dhakal, S. (2016). Urban infrastructure choices structure climate solutions. *Nature Climate Change*, *6*(12), 1054–1056. https://doi.org/10.1038/nclimate3169

Creutzig, F., Roy, J., Lamb, W. F., Azevedo, I. M. L., Bruine de Bruin, W., Dalkmann, H., Edelenbosch, O. Y., Geels, F. W., Grubler, A., Hepburn, C., Hertwich, E. G., Khosla, R., Mattauch, L., Minx, J. C., Ramakrishnan, A., Rao, N. D., Steinberger, J. K., Tavoni, M., Ürge-Vorsatz, D., & Weber, E. U. (2018). Towards demand-side solutions for mitigating climate change. *Nature Climate Change*, *8*(4), 260–263. https://doi.org/10.1038/s41558-018-0121-1

Davis, S. J., Lewis, N. S., Shaner, M., Aggarwal, S., Arent, D., Azevedo, I. L., Benson, S. M., Bradley, T., Brouwer, J., Chiang, Y.-M., Clack, C. T. M., Cohen, A., Doig, S., Edmonds, J., Fennell, P., Field, C. B., Hannegan, B., Hodge, B.-M., Hoffert, M. I., … Caldeira, K. (2018). Net-zero emissions energy systems. *Science*, *360*(6396), eaas9793. https://doi.org/10.1126/science.aas9793

Davis, S., & Socolow, R. (2014). Commitment accounting of CO2 emissions. *Environmental Research Letters*, *9*, 084018. https://doi.org/10.1088/1748-9326/9/8/084018

De Franco, A., Venco, E., De Lotto, R., Pietra, C., Kutzner, F., Bielig, M., & Vogel, M. (2023). Drivers, Motivations, and Barriers in the Creation of Energy Communities: Insights from the City of Segrate, Italy. *Energies*, *16*(16), 5872. https://doi.org/10.3390/en16165872

De Santi, F., Moncecchi, M., Prettico, G., Fulli, G., Olivero, S., & Merlo, M. (2022). To Join or Not to Join? The Energy Community Dilemma: An Italian Case Study. *Energies*, *15*(19), 7072. https://doi.org/10.3390/en15197072

Desthieux, G., & Thebault, M. (2024). Solar governance for the transborder agglomeration of the Greater Geneva based on the solar cadaster development. *Frontiers in Built Environment*, *10*. https://doi.org/10.3389/fbuil.2024.1347056

Di Giuda, G. M., Accardo, D., Gasbarri, P., Meschini, S., Tagliabue, L. C., & Scomparin, L. (2023). *BIM-GIS and BI Integration for Facility and Occupancy Management of University Assets: The UNITO Pilot Case*. ITA. https://iris.unito.it/handle/2318/1958831

Dong, Z. Y., Zhang, Y., Yip, C., Swift, S., & Beswick, K. (2020). Smart campus: Definition, framework, technologies, and services. *IET Smart Cities*, *2*(1), 43–54. https://doi.org/10.1049/iet-smc.2019.0072

Duffie, J., & Beckman, W. (2013). *Solar Engineering of Thermal Processes* (4th edn). John Wiley & Sons, Ltd. https://doi.org/10.1002/9781118671603.fmatter

ENEA., A. nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile. (2022). *Rapporto Annuale sull'efficienza energetica 2022*. https://www.efficienzaenergetica.enea.it/pubblicazioni/raee-rapporto-annuale-sull-efficienza-energetica/https%3A%2F%2Fwww.efficienzaenergetica.enea.it%2Fpubblicazioni%2Fraee-rapporto-annuale-sull-efficienza-energetica%2Frapporto-annuale-sull-efficienza-energetica-2022.html

ENEA Renewables. (2006). *ENEA - Solaritaly | Table values of Solar Radiation in Italy*. http://www.solaritaly.enea.it/TabelleRad/TabelleRadEn.php

EnergeiaPlus, & Swiss Federal Office of Energy (SFOE). (2024, November 20). *Abnahmevergütung und Minimaltarife für Photovoltaik-Anlagen ab 2026*. BFE-Magazin Energeiaplus | Energiemagazin Des Bundesamtes Für Energie. https://energeiaplus.com/2024/11/20/abnahmeverguetung-und-minimaltarife-fuer-photovoltaik-anlagen-ab-2026/

European Commission. (2019a). *Clean energy for all Europeans*. Publications Office of the European Union. https://data.europa.eu/doi/10.2833/9937

European Commission. (2019b). *Communication on The European Green Deal*. https://commission.europa.eu/publications/communication-european-green-deal_en

European Parliament. (2018a). *Directive (EU) 2018/2001 of the European Parliament and of the Council on the promotion of the use of energy from renewable sources*. 82–209.

European Parliament. (2018b). *Directive—2018/2001—EN - EUR-Lex* (pp. 82–209). Official Journal of the European Union. https://eur-lex.europa.eu/eli/dir/2018/2001/oj/eng

European Parliament, & Council of the European Union. (2019). DIRECTIVE (EU) 2019/944 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 5 June 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EU (recast). *Official Journal of the European Union*, 125–199.

Federal Council. (2025, February 19). *Deuxième volet d'ordonnances – entrée en vigueur le 1er janvier 2026*. https://www.news.admin.ch/fr/nsb?id=104172&utm

Ferroni, S., Causone, F., Minchio, F., Sordi, G., Giuliani, I., Paci, C., & Cremascoli, E. (2024). Virtual energy sharing and energy communities for the

Municipality of Milan: The case of the Chiaravalle area. *E3S Web of Conferences*, *523*, 05006. https://doi.org/10.1051/e3sconf/202452305006

Filimonova, I. V., Komarova, A. V., Kuzenkova, V. M., Provornaya, I. V., & Kozhevin, V. D. (2022). Emissions of CO2 in Europe and the Asia–pacific region: Panel data model. *Energy Reports*, *8*, 894–901. https://doi.org/10.1016/j.egyr.2022.10.164

Fouquet, R. (2016). Path dependence in energy systems and economic development. *Nature Energy*, *1*(8), 16098. https://doi.org/10.1038/nenergy.2016.98

Fu, P., & Rich, P. (1999). Design and implementation of the Solar Analyst: An ArcView extension for modeling solar radiation at landscape scales. *Proceedings of the 19th Annual ESRI User Conference*.

Garde, F., & Donn, M. (2014). *Solution Sets and Net Zero Energy Buildings: A review of 30 Net ZEBs case studies worldwide*. IEA Solar Heating and Cooling Programme. https://doi.org/10.18777/ieashc-task40-2014-0002

Geels, F. W. (2011). The multi-level perspective on sustainability transitions: Responses to seven criticisms. *Environmental Innovation and Societal Transitions*, *1*(1), 24–40. https://doi.org/10.1016/j.eist.2011.02.002

Good, N., Karangelos, E., Navarro-Espinosa, A., & Mancarella, P. (2015). Optimization Under Uncertainty of Thermal Storage-Based Flexible Demand Response With Quantification of Residential Users' Discomfort.

IEEE Transactions on Smart Grid, *6*, 1–1. https://doi.org/10.1109/TSG.2015.2399974

Gouldson, A., Colenbrander, S., Sudmant, A., McAnulla, F., Kerr, N., Sakai, P., Hall, S., Papargyropoulou, E., & Kuylenstierna, J. (2015). Exploring the economic case for climate action in cities. *Global Environmental Change*, *35*, 93–105. https://doi.org/10.1016/j.gloenvcha.2015.07.009

Grohmann, C. H. (2015). Effects of spatial resolution on slope and aspect derivation for regional-scale analysis. *Computers & Geosciences*, *77*, 111–117. https://doi.org/10.1016/j.cageo.2015.02.003

Groupe E. (2025). *Buy-back prices for surplus photovoltaic production | Groupe E*. https://www.groupe-e.ch/de/solarstrom/ruecknahmetarife

Gruber, L., Bachhiesl, U., & Wogrin, S. (2021). The current state of research on energy communities. *E & i Elektrotechnik Und Informationstechnik*, *138*(8), 515–524. https://doi.org/10.1007/s00502-021-00943-9

Grubler, A., Wilson, C., Bento, N., Boza-Kiss, B., Krey, V., McCollum, D. L., Rao, N. D., Riahi, K., Rogelj, J., De Stercke, S., Cullen, J., Frank, S., Fricko, O., Guo, F., Gidden, M., Havlík, P., Huppmann, D., Kiesewetter, G., Rafaj, P., … Valin, H. (2018). A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. *Nature Energy*, *3*(6), 515–527. https://doi.org/10.1038/s41560-018-0172-6

GSE, G. S. E. (2022). *CONFIGURAZIONI PER L'AUTOCONSUMO DIFFUSO*. https://www.gse.it/servizi-per-te/autoconsumo/gruppi-di-autoconsumatori-e-comunita-di-energia-rinnovabile

GSE, G. S. E. (2023). *COMUNITÀ ENERGETICHE RINNOVABILI E GRUPPI DI AUTOCONSUMATORI*. https://www.gse.it/servizi-per-te/attuazione-misure-pnrr/comunit%C3%A0-energetiche-5000abitanti

GSE, G. S. E. (2025a). *DECRETO CACER e TIAD – Regole operative per l'accesso al servizio per l'autoconsumo diffuso e al contributo PNRR*.

GSE, G. S. E. (2025b). *Mappa interattiva delle cabine primarie*. https://www.gse.it/servizi-per-te/autoconsumo/mappa-interattiva-delle-cabine-primarie

GSE, G. S. E. (2024a). *Corrispettivi e tariffa*. https://www.gse.it/servizi-per-te/autoconsumo/gruppi-di-autoconsumatori-e-comunita-di-energia-rinnovabile/corrispettivi-e-tariffat.com

GSE, G. S. E. (2024b). *Regole operative per l'accesso al servizio per l'energia condivisa*.

Gui, E. M., & MacGill, I. (2018). Typology of future clean energy communities: An exploratory structure, opportunities, and challenges. *Energy Research & Social Science*, *35*, 94–107. https://doi.org/10.1016/j.erss.2017.10.019

Haberl, H., Wiedenhofer, D., Erb, K.-H., Görg, C., & Krausmann, F. (2017). The Material Stock–Flow–Service Nexus: A New Approach for Tackling the

Decoupling Conundrum. *Sustainability*, *9*(7), Article 7. https://doi.org/10.3390/su9071049

Heijer, A. den, Vries, J. de, & Jonge, H. de. (2012). Developing Knowledge Cities: Towards Aligning Urban and Campus Strategies. *Chapters*. https://ideas.repec.org//h/elg/eechap/14402_5.html

Hertwich, E., Lifset, R., Pauliuk, S., & Heeren, N. (2020). *Resource Efficiency and Climate Change: Material Efficiency Strategies for a Low-Carbon Future | UNEP - UN Environment Programme*. https://www.unep.org/resources/report/resource-efficiency-and-climate-change-material-efficiency-strategies-low-carbon

Hewitt, R., Bradley, N., Baggio Compagnucci, A., Barlagne, C., Ceglarz, A., Cremades, R., Mckeen, M., Otto, I., & Slee, R. (2019). Social Innovation in Community Energy in Europe: A Review of the Evidence. *Frontiers in Energy Research*, *7*, 31. https://doi.org/10.3389/fenrg.2019.00031

Hoeger, K., & Christiaanse, K. (2007). *Campus and the City: Urban Design for the Knowledge Society*. GTA Verlag.

Hoicka, C., Lowitzsch, J., Brisbois, M. C., Kumar, A., & Ramirez Camargo, L. (2020). *Implementing a Just Renewable Energy Transition: Policy Advice for Transposing the New European Rules for Renewable Energy Communities* (SSRN Scholarly Paper No. 3729512). Social Science Research Network. https://doi.org/10.2139/ssrn.3729512

House of Switzerland. (2021, October 6). *Water from Lake Geneva used to heat and cool buildings | House of Switzerland*. http://houseofswitzerland.org/swissstories/environment/water-lake-geneva-used-heat-and-cool-buildings

ICLEI, C40, & World Resources Institute. (2014). *GHG Protocol for Cities | GHG Protocol*. https://ghgprotocol.org/ghg-protocol-cities#supporting-documents

IEA. (2020). *Global Energy Review 2020*. OECD Publishing. https://www.oecd.org/en/publications/global-energy-review-2020_a60abbf2-en.html

IEA, I. E. A. (2017). *Digitalization and Energy – Analysis*. https://www.iea.org/reports/digitalisation-and-energy,

IEA, I. E. A. (2021). *Empowering Cities for a Net Zero Future – Analysis*. https://www.iea.org/reports/empowering-cities-for-a-net-zero-future

IEA, I. E. A. (2022). *World Energy Outlook 2022 – Analysis—IEA*. International Energy Agency. https://www.iea.org/reports/world-energy-outlook-2022

Ineichen, P., & Perez, R. (2002). A new airmass independent formulation for the Linke turbidity coefficient. *Solar Energy*, *73*(3), 151–157. https://doi.org/10.1016/S0038-092X(02)00045-2

Inês, C., Guilherme, P. L., Esther, M.-G., Swantje, G., Stephen, H., & Lars, H. (2020). Regulatory challenges and opportunities for collective renewable energy prosumers in the EU. *Energy Policy*, *138*, 111212. https://doi.org/10.1016/j.enpol.2019.111212

Intergovernmental Panel on Climate Change (IPCC) (Ed.). (2022). Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development. In *Global Warming of 1.5°C: IPCC Special Report on Impacts of Global Warming of 1.5°C above Pre-industrial Levels in Context of Strengthening Response to Climate Change, Sustainable Development, and Efforts to Eradicate Poverty* (pp. 93–174). Cambridge University Press. https://doi.org/10.1017/9781009157940.004

IPCC, I. P. on C. C. (2018). *Global Warming of 1.5 ºC —*. https://www.ipcc.ch/sr15/

IRENA. (2019a). *Future of Solar Photovoltaic: Deployment, investment, technology, grid integration and socio-economic aspects (A Global Energy Transformation: Paper)*. https://www.irena.org/publications/2019/Nov/Future-of-Solar-Photovoltaic

IRENA, I. R. E. A. (2019b). *IRENA Virtual Power Lines 2020 | PDF | Energy Storage | Electrical Grid*. IRENA. https://www.scribd.com/document/727684347/IRENA-Virtual-power-lines-2020

IRENA, I. R. E. A. (2022). *Renewable power generation costs in 2022*. IRENA.

Italian National Standardization Body. (2022). *Guida tecnica CEI 82-25 "Guida alla progettazione, realizzazione e gestione di sistemi di generazione fotovoltaica" – Parte 2 "I moduli fotovoltaici*. https://www.certifico.com/normazione/documenti-riservati-normazione/organismi-normazione/documenti-cei/cei-82-25-1-2022

Jakubiec, J. A., & Reinhart, C. F. (2013). A method for predicting city-wide electricity gains from photovoltaic panels based on LiDAR and GIS data combined with hourly Daysim simulations. *Solar Energy*, *93*, 127–143. https://doi.org/10.1016/j.solener.2013.03.022

Jarre, M., Macagno, S., & Noussan, M. (2017). Energy Consumption Data as a Decision-making Tool for Energy Efficient Interventions in PA: The Case-study of Turin. *Energy Procedia*, *111*, 1050–1059. https://doi.org/10.1016/j.egypro.2017.03.268

Jenčo, M. (1992). The Morphometric Analysis of Georelief in Terms of a Theoretical Conception of the Complex Digital Model of Georelief. *Acta Facultatis Rerum Naturalium Universitatis Comeniane, Geographica*, *33*, 133–153.

Jenkins, J. D., Luke, M., & Thernstrom, S. (2018). Getting to Zero Carbon Emissions in the Electric Power Sector. *Joule*, *2*(12), 2498–2510. https://doi.org/10.1016/j.joule.2018.11.013

Joshi, S., Mittal, S., Holloway, P., Shukla, P. R., Ó Gallachóir, B., & Glynn, J. (2021). High resolution global spatiotemporal assessment of rooftop solar photovoltaics potential for renewable electricity generation. *Nature Communications*, *12*(1), 5738. https://doi.org/10.1038/s41467-021-25720-2

Kalkbrenner, B. J., & Roosen, J. (2016). Citizens' willingness to participate in local renewable energy projects: The role of community and trust in Germany. *Energy Research & Social Science*, *13*, 60–70. https://doi.org/10.1016/j.erss.2015.12.006

Kasten, F. (1996). The linke turbidity factor based on improved values of the integral Rayleigh optical thickness. *Solar Energy*, *56*(3), 239–244. https://doi.org/10.1016/0038-092X(95)00114-7

Kennedy, C. A., Stewart, I., Facchini, A., Cersosimo, I., Mele, R., Chen, B., Uda, M., Kansal, A., Chiu, A., Kim, K., Dubeux, C., Lebre La Rovere, E., Cunha, B., Pincetl, S., Keirstead, J., Barles, S., Pusaka, S., Gunawan, J., Adegbile, M., … Sahin, A. D. (2015). Energy and material flows of megacities. *Proceedings of the National Academy of Sciences*, *112*(19), 5985–5990. https://doi.org/10.1073/pnas.1504315112

Keramidas, K., Fosse, F., Diaz, R. A., Dowling, P., Garaffa, R., Ordonez, J., Russ, P., Schade, B., Schmitz, A., Soria, R. A., Van, D. V. C., & Weitzel, M.

(2023). *Global Energy and Climate Outlook 2023*. JRC Publications Repository. https://doi.org/10.2760/836798

Kishore, T. S., Kumar, P. U., & Ippili, V. (2025). Review of global sustainable solar energy policies: Significance and impact. *Innovation and Green Development*, *4*(2), 100224. https://doi.org/10.1016/j.igd.2025.100224

Kittler, R., & Milker, jozef. (1986). *Basics of using solar radiation*. VEDA. https://www.chaluparium.sk/zaklady-vyuzivania-slnecneho-ziarenia

Klein, S. A. (1977). Calculation of monthly average insolation on tilted surfaces. *Solar Energy*, *19*(4), 325–329. https://doi.org/10.1016/0038-092X(77)90001-9

Koirala, B. P., van Oost, E., & van der Windt, H. (2018). Community energy storage: A responsible innovation towards a sustainable energy system? *Applied Energy*, *231*, 570–585. https://doi.org/10.1016/j.apenergy.2018.09.163

Köker, N. I., Manni, M., Giorio, M., Jelle, B. P., Di Sabatino, M., & Lobaccaro, G. (2025). Defining challenges of solar irradiance modeling on façades in urban environments: A systematic review. *Energy and Buildings*, *347*, 116137. https://doi.org/10.1016/j.enbuild.2025.116137

Kooij, H.-J., Oteman, M., Veenman, S., Sperling, K., Magnusson, D., Palm, J., & Hvelplund, F. (2018). Between grassroots and treetops: Community power and institutional dependence in the renewable energy sector in Denmark, Sweden and the Netherlands. *Energy Research & Social Science*, *37*, 52–64. https://doi.org/10.1016/j.erss.2017.09.019

Koukoufikis, G., Schockaert, H., Paci, D., Filippidou, F., Caramizaru, A., Della, V. N., Candelise, C., Murauskaite-Bull, I., & Uihlein, A. (2023). *Energy Communities and Energy Poverty*. JRC Publications Repository. https://doi.org/10.2760/389514

Krcho, J. (1990). *Morphometric analysis and digital georelief models*. Science, publishing house of the Slovak Academy of Sciences, Bratislava. https://www.antikvariatik.sk/

Kumar, L., Skidmore, A. K., & Knowles, E. (1997). Modelling topographic variation in solar radiation in a GIS environment. *International Journal of Geographical Information Science*, *11*(5), 475–497. Scopus. https://doi.org/10.1080/136588197242266

LAM, K. P. (2009). *Understanding the Discounted Payback technique and its uses for Small Business*. chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www1.se.cuhk.edu.hk/~seem2510/seg2510r6.pdf

Lasseter, R. H. (2002). MicroGrids. *2002 IEEE Power Engineering Society Winter Meeting. Conference Proceedings (Cat. No.02CH37309)*, *1*, 305–308 vol.1. https://doi.org/10.1109/PESW.2002.985003

Li, H. X., Zhang, Y., Edwards, D., & Hosseini, M. R. (2019). Improving the energy production of roof-top solar PV systems through roof design. *Building Simulation*, *13*. https://doi.org/10.1007/s12273-019-0585-6

Li, Y., He, J., Chen, F., Han, Z., Wang, W.-D., Chen, G., & Huang, J. (2021). Generation of Homogeneous Slope Units Using a Novel Object-Oriented Multi-Resolution Segmentation Method. *Water*, *13*, 3422. https://doi.org/10.3390/w13233422

Lowitzsch, J., Hoicka, C. E., & van Tulder, F. J. (2020). Renewable energy communities under the 2019 European Clean Energy Package – Governance model for the energy clusters of the future? *Renewable and Sustainable Energy Reviews*, *122*, 109489. https://doi.org/10.1016/j.rser.2019.109489

Luthander, R., Widén, J., Nilsson, D., & Palm, J. (2015). Photovoltaic self-consumption in buildings: A review. *Applied Energy*, *142*, 80–94. https://doi.org/10.1016/j.apenergy.2014.12.028

Lützkendorf, T., & Balouktsi, M. (2022). *Embodied carbon emissions in buildings: Explanations, interpretations, recommendations | Buildings & Cities*. https://doi.org/10.5334/bc.257

Marino, C., Nucara, A., Panzera, M. F., & Pietrafesa, M. (2024). Energetic and economic advantages of energy communities: A case study referred to a southern Italian town. *Energy Reports*, *12*, 6072–6081. https://doi.org/10.1016/j.egyr.2024.11.078

MASE, M. dell'Ambiente e della S. E. (2022). *Investimento 1.2—Promozione rinnovabili per le comunità energetiche e;auto-consumo*. https://www.mase.gov.it/portale/-/investimento-1.2-promozione-rinnovabili-per-le-comunita-energetiche-e-l-039-auto-consumo

Mercure, J.-F., Pollitt, H., Viñuales, J. E., Edwards, N. R., Holden, P. B., Chewpreecha, U., Salas, P., Sognnaes, I., Lam, A., & Knobloch, F. (2018). Macroeconomic impact of stranded fossil fuel assets. *Nature Climate Change*, *8*(7), 588–593. https://doi.org/10.1038/s41558-018-0182-1

MINES ParisTech, & Vaisala. (2014). *Linke turbidity factor*. SoDa. https://www.soda-pro.com

Ministero dell'Interno, D. dei V. del F., del Soccorso Pubblico e della Difesa Civile, &. Direzione Centrale per la Prevenzione e la Sicurezza Tecnica. (2022). *Testo coordinato della Nota 07 febbraio 2012—Guida per l'installazione degli impianti FV – Edizione anno 2012*. https://certifico.com/prevenzione-incendi/nota-vvf-07-febbraio-2012-testo-coordinato

Moran, D., Hasanbeigi, A., & Springer, C. (2018). *The Carbon Loophole in Climate Policy*. KGM & Associates, Global E ciency Intelligence. https://www.globalefficiencyintel.com/carbon-loophole-in-climate-policy

Moran, D., Kanemoto, K., Jiborn, M., Wood, R., Többen, J., & Seto, K. C. (2018). Carbon footprints of 13 000 cities. *Environmental Research Letters*, *13*(6), 064041. https://doi.org/10.1088/1748-9326/aac72a

Moretti, N., Ellul, C., Re Cecconi, F., Papapesios, N., & Dejaco, M. C. (2021). GeoBIM for built environment condition assessment supporting asset management decision making. *Automation in Construction*, *130*, 103859. https://doi.org/10.1016/j.autcon.2021.103859

Muneer, T., Younes, S., & Munawwar, S. (2007). Discourses on solar radiation modeling. *Renewable and Sustainable Energy Reviews*, *11*(4), 551–602. https://doi.org/10.1016/j.rser.2005.05.006

Muth, L. J., with input from Tomoko. (2025, April 29). Switzerland turns train tracks into solar power plants. *SWI Swissinfo.Ch*. https://www.swissinfo.ch/eng/climate-solutions/switzerland-turns-train-tracks-into-solar-power-plants/89227914

Neij, L., Palm, J., Busch, H., Bauwens, T., Becker, S., Bergek, A., Buzogány, A., Candelise, C., Coenen, F., Devine-Wright, P., Hoppe, T., Kortetmäki, A., Pantazis, K., Palaiogiannis, F., Margosi, M., Petrovics, D., Plöchl, J., Ruggieri, G., Ruggiero, S., … Soutar, I. (2025). Energy communities—Lessons learnt, challenges, and policy recommendations. *Oxford Open Energy*, *4*, oiaf002. https://doi.org/10.1093/ooenergy/oiaf002

Neteler, M., & Mitasova, H. (2002). *Open Source GIS: A GRASS GIS Approach*. Springer Science & Business Media.

Newman, P., & Kenworthy, J. (2015). The End of Automobile Dependence: How Cities Are Moving Beyond Car-Based Planning. In *The End of Automobile*

Dependence: How Cities Are Moving Beyond Car-Based Planning (p. 300). https://doi.org/10.5822/978-1-61091-613-4

Nik, V. M., & Sasic Kalagasidis, A. (2013). Impact study of the climate change on the energy performance of the building stock in Stockholm considering four climate uncertainties. *Building and Environment*, *60*, 291–304. https://doi.org/10.1016/j.buildenv.2012.11.005

Nilsson, M., Griggs, D., & Visbeck, M. (2016). Policy: Map the interactions between Sustainable Development Goals. *Nature*, *534*(7607), 320–322. https://doi.org/10.1038/534320a

Nouvel, R., Zirak, M., Coors, V., & Eicker, U. (2017). The influence of data quality on urban heating demand modeling using 3D city models. *Computers, Environment and Urban Systems*, *64*, 68–80. https://doi.org/10.1016/j.compenvurbsys.2016.12.005

OpenStreetMap contributors. (2015). *OpenStreetMap*. OpenStreetMap. https://www.openstreetmap.org/about

Organization (WMO), W. M. (n.d.). *Meteorological aspects of the utilization of solar radiation as an energy source: Annex - World maps of relative global radiation*. Retrieved 13 September 2024, from https://library.wmo.int/ru/records/item/54969-meteorological-aspects-of-the-utilization-of-solar-radiation-as-an-energy-source-annex-world-maps-of-relative-global-radiation?offset=8609

Parag, Y., & Sovacool, B. K. (2016). Electricity market design for the prosumer era. *Nature Energy*, *1*(4), 16032. https://doi.org/10.1038/nenergy.2016.32

Perera, A. T. D., Nik, V. M., Chen, D., Scartezzini, J.-L., & Hong, T. (2020). Quantifying the impacts of climate change and extreme climate events on energy systems. *Nature Energy*, *5*(2), 150–159. https://doi.org/10.1038/s41560-020-0558-0

Peters, G. P., Minx, J. C., Weber, C. L., & Edenhofer, O. (2011). Growth in emission transfers via international trade from 1990 to 2008. *Proceedings of the National Academy of Sciences*, *108*(21), 8903–8908. https://doi.org/10.1073/pnas.1006388108

Petrovics, D., Cobut, L., Huitema, D., Giezen, M., & Orsini, A. (2024). Diverse scaling strategies of energy communities: A comparative case study analysis of varied governance contexts. *Earth System Governance*, *19*, 100203. https://doi.org/10.1016/j.esg.2024.100203

pronovo. (2023). *Single Fee (RU) – Pronovo AG*. https://pronovo.ch/fr/subventions/photovoltaique/

Pryor, S. C., Schoof, J. T., & Barthelmie, R. J. (2006). Winds of change?: Projections of near-surface winds under climate change scenarios. *Geophysical Research Letters*, *33*(11), 2006GL026000. https://doi.org/10.1029/2006GL026000

Qian, X., & Papadonikolaki, E. (2020). Shifting trust in construction supply chains through blockchain technology. *Engineering, Construction and Architectural Management*, *ahead-of-print*. https://doi.org/10.1108/ECAM-12-2019-0676

Ramaswami, A., Russell, A. G., Culligan, P. J., Sharma, K. R., & Kumar, E. (2016). Meta-principles for developing smart, sustainable, and healthy cities. *Science*, *352*(6288), 940–943. https://doi.org/10.1126/science.aaf7160

Regione Piemonte. (2015). *Home—Geoportale Piemonte*. GEO PIEMONTE. https://geoportale.igr.piemonte.it/cms/

Regione Emilia-Romagna. (2024). *Comunità energetiche e autoconsumo collettivo*. https://energia.regione.emilia-romagna.it/leggi-atti-bandi/finanziamenti-e-agevolazioni/incentivi-nazionali/elenco-incentivi/comunita-energetiche-e-autoconsumo-collettivo

Revi, A., Satterthwaite, D., Aragón-Durand, F., Corfee-Morlot, J., Kiunsi, R. B. R., Pelling, M., Roberts, D., Solecki, W., Gajjar, S. P., & Sverdlik, A. (2014). Towards transformative adaptation in cities: The IPCC's Fifth Assessment. *Environment & Urbanization*, *26*(1), 11–28. https://doi.org/10.1177/0956247814523539

Roberts, J. (2019). *What energy communities need from regulation*. https://doi.org/10.4337/eecj.2019.03-04.01

Rogelj, J., den Elzen, M., Höhne, N., Fransen, T., Fekete, H., Winkler, H., Schaeffer, R., Sha, F., Riahi, K., & Meinshausen, M. (2016). Paris Agreement climate proposals need a boost to keep warming well below 2 °C. *Nature*, *534*(7609), 631–639. https://doi.org/10.1038/nature18307

Sailor, D. J., Smith, M., & Hart, M. (2008). Climate change implications for wind power resources in the Northwest United States. *Renewable Energy*, *33*(11), 2393–2406. https://doi.org/10.1016/j.renene.2008.01.007

Santamouris, M., Papanikolaou, N., Livada, I., Koronakis, I., Georgakis, C., Argiriou, A., & Assimakopoulos, D. N. (2001). On the impact of urban climate on the energy consumption of buildings. *Solar Energy*, *70*(3), 201–216. https://doi.org/10.1016/S0038-092X(00)00095-5

Scharmer, k, & Greif, J.-J. (2000). *The European Solar Radiation Atlas: Vol. 2 Database and exploitation software*. Les Presses de l'École des Mines. https://www.pressesdesmines.com/produit/the-european-solar-radiation-atlas-vol-2/

Schneider, S., Le Strat, P., & Patel, M. (2017). Electro What: A platform for territorial analysis of electricity consumption. *Energy Procedia*, *122*, 92–97. https://doi.org/10.1016/j.egypro.2017.07.376

Seto, K. C., Davis, S. J., Mitchell, R. B., Stokes, E. C., Unruh, G., & Ürge-Vorsatz, D. (2016). Carbon Lock-In: Types, Causes, and Policy Implications. *Annual*

Review of Environment and Resources, *41*(Volume 41, 2016), 425–452. https://doi.org/10.1146/annurev-environ-110615-085934

Seto, K. C., Güneralp, B., & Hutyra, L. R. (2012). Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. *Proceedings of the National Academy of Sciences*, *109*(40), 16083–16088. https://doi.org/10.1073/pnas.1211658109

Seyfang, G., Park, J. J., & Smith, A. (2013). A thousand flowers blooming? An examination of community energy in the UK. *Energy Policy*, *61*, 977–989. https://doi.org/10.1016/j.enpol.2013.06.030

SFOE, S. F. O. of E. (2023a). *Connection conditions for producers of electricity from renewable energy sources*. https://www.bfe.admin.ch/bfe/en/home/versorgung/erneuerbare-energien/anschlussbedingungen-fuer-produzenten-von-elektrizitaet-aus-erneuerbaren-energien.html

SFOE, S. F. O. of E. (2023b). *Energy Strategy 2050*. https://www.bfe.admin.ch/bfe/en/home/politik/energiestrategie-2050.html

SFOE, S. F. O. of E. (2023c). *Federal act on a secure electricity supply*. https://www.bfe.admin.ch/bfe/en/home/versorgung/stromversorgung/bundesgesetz-erneuerbare-stromversorgung.html

SFOE, S. F. O. of E., & DETEC, D. fédéral de l'environnement, des transports, de l'énergie et de la communication. (2024). *Loi fédérale relative à un* *approvisionnement en électricité sûr reposant sur des énergies renouvelables: Modification de l'ordonnance sur l'approvisionnement en électricité: Rapport explicatif sur le projet mis en consultation* (p. chapitre 2.6: Communautés électriques locales-CEL).

Shukla, P. R., Skea, J., Slade, R., Al Khourdajie, A., van Diemen, R., McCollum, D., Pathak, M., Some, S., Vyas, P., Fradera, R., Belkacemi, M., Hasija, A., Lisboa, G., Luz, S., & Malley, J. (Eds). (2022). *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. https://doi.org/10.1017/9781009157926

SIA. (2016). Sia 2039—Mobilit´e—Consommation ´energ´etique des bˆatiments enfonction de leur localisation,. *wiss Society of Engineeres and Architects*. https://shop.sia.ch/collection%20des%20normes/architecte/2039_2016_f/D/Product/

SIG. (2021a). *Genilac: A major, sustainable energy innovation for Geneva*. Genie.Ch. https://www.genie.ch/project/h/genilac-a-major-sustainable-energy-innovation-for-geneva.html

SIG. (2024). *Solariis Communauté ((DSO guidance & process in Geneva)*. https://ww2.sig-ge.ch/artisans_independants/offres/solaire/communaute-autoconsommation

SIG. (2025a). *Apply for the solar bonus | SIG*. https://ww2.sig-ge.ch/particuliers/offres/solaire/offres-solaires/maison-solaire/demande-la-prime-solaire

SIG. (2025b). *Offres solaires: Particuliers | SIG*. https://ww2.sig-ge.ch/particuliers/offres/solaire/offres-solaires

SIG. (2025c). *Regroupement dans le cadre de la Consommation Propre*. https://ww2.sig-ge.ch/artisans_independants/offres-energies/solaire/regroupement-consommation-propre

SIG, S. I. de G. (SIG). (2021b). *SIG deploys GeniLac, its ecological hydrothermal network | SIG*. https://ww2.sig-ge.ch/actualites/sig-deploie-genilac-son-reseau-hydrothermique-ecologique

Smil, V. (2018). *Energy and Civilization: A History*. MIT Press.

Sousa, T., Soares, T., Pinson, P., Moret, F., Baroche, T., & Sorin, E. (2019). Peer-to-peer and community-based markets: A comprehensive review. *Renewable and Sustainable Energy Reviews*, *104*, 367–378. https://doi.org/10.1016/j.rser.2019.01.036

Sovacool, B. K. (2016). How long will it take? Conceptualizing the temporal dynamics of energy transitions. *Energy Research & Social Science*, *13*, 202–215. https://doi.org/10.1016/j.erss.2015.12.020

State of Geneva. (1991). *Système d'information du territoire genevois (SITG)*. https://sitg.ge.ch/

Stern, P. C., Sovacool, B. K., & Dietz, T. (2016). Towards a science of climate and energy choices. *Nature Climate Change*, *6*(6), 547–555. https://doi.org/10.1038/nclimate3027

Šúri, M., & Hofierka, J. (2004). A New GIS-based Solar Radiation Model and Its Application to Photovoltaic Assessments. *Transactions in GIS*, *8*(2), 175–190. https://doi.org/10.1111/j.1467-9671.2004.00174.x

Suri, M., Huld, T., Dunlop, E., & Ossenbrink, H. (2008). Potential of Solar Electricity Generation in the European Union Member States and Candidate Countries. *SOLAR ENERGY*. https://doi.org/10.1016/j.solener.2006.12.007

swiss federal office of energy. (2024). *Energy Consumption in Switzerland 2023*. https://www.bfe.admin.ch/bfe/en/home/news-and-media/press-releases/mm-test.msg-id-101514.html

Swissolar. (2024). *New electricity law*. https://www.swissolar.ch/fr/marche-et-politique/nouvelle-loi-sur-l-electricite

Szinai, J., Sheppard, C., Abhyankar, N., & Gopal, A. (2020). Reduced grid operating costs and renewable energy curtailment with electric vehicle charge management. *Energy Policy*, *136*, 111051. https://doi.org/10.1016/j.enpol.2019.111051

Tatti, A., Ferroni, S., Ferrando, M., Motta, M., & Causone, F. (2023). The Emerging Trends of Renewable Energy Communities' Development in Italy. *Sustainability*, *15*(8), 6792. https://doi.org/10.3390/su15086792

Tehrani, A. A., Veisi, O., Fakhr, B. V., & Du, D. (2024). Predicting solar radiation in the urban area: A data-driven analysis for sustainable city planning using artificial neural networking. *Sustainable Cities and Society*, *100*, 105042. https://doi.org/10.1016/j.scs.2023.105042

Thebault, M., Desthieux, G., Castello, R., & Berrah, L. (2022). Large-scale evaluation of the suitability of buildings for photovoltaic integration: Case study in Greater Geneva. *Applied Energy*, *316*, 119127. https://doi.org/10.1016/j.apenergy.2022.119127

Tovar-Pescador, J., Pozo-Vázquez, D., Ruiz-Arias, J. A., Batlles, J., López, G., & Bosch, J. L. (2006). On the use of the digital elevation model to estimate the solar radiation in areas of complex topography. *Meteorological Applications*, *13*(3), 279–287. https://doi.org/10.1017/S1350482706002258

UN, U. N. (2015). *Transforming our world: The 2030 Agenda for Sustainable Development | Department of Economic and Social Affairs*. https://sdgs.un.org/2030agenda

UNFCCC, U. N. F. C. on C. C. (2015). *The Paris Agreement | UNFCCC*. https://unfccc.int/process-and-meetings/the-paris-agreement

United Nations. (2022). *World Population Prospects 2022: Summary of Results | Population Division*. https://www.un.org/development/desa/pd/content/World-Population-Prospects-2022

Unruh, G. C. (2000). Understanding carbon lock-in. *Energy Policy*, *28*(12), 817–830. https://doi.org/10.1016/S0301-4215(00)00070-7

Ürge-Vorsatz, D., Rosenzweig, C., Dawson, R. J., Sanchez Rodriguez, R., Bai, X., Barau, A. S., Seto, K. C., & Dhakal, S. (2018). Locking in positive climate responses in cities. *Nature Climate Change*, *8*(3), 174–177. https://doi.org/10.1038/s41558-018-0100-6

valfor. (2025, June 24). *Virtual self-consumption community (vZEV)*. English. https://www.valfor.ch/en/news-insights/energy-law-quarterly-virtueller-zusammenschluss-zum-eigenverbrauch-vzev

Vivi, Q. L., Parlikad, A. K., Woodall, P., Ranasinghe, G. D., & Heaton, J. (2019). *Developing a dynamic digital twin at a building level: Using Cambridge campus as case study*. ICE Publishing. https://doi.org/10.17863/CAM.38523

Walker, G., & Devine-Wright, P. (2008). Community renewable energy: What should it mean? *Energy Policy*, *36*(2), 497–500. https://doi.org/10.1016/j.enpol.2007.10.019

Wang, B., Ke, R.-Y., Yuan, X.-C., & Wei, Y.-M. (2014). China′s regional assessment of renewable energy vulnerability to climate change. *Renewable and Sustainable Energy Reviews*, *40*, 185–195. https://doi.org/10.1016/j.rser.2014.07.154

Wiedmann, T., & Minx, J. (2008). A Definition of Carbon Footprint. *CC Pertsova, Ecological Economics Research Trends*, *2*, 55–65.

Wierling, A., Schwanitz, V. J., Zeiß, J. P., Bout, C., Candelise, C., Gilcrease, W., & Gregg, J. S. (2018). Statistical Evidence on the Role of Energy Cooperatives for the Energy Transition in European Countries. *Sustainability*, *10*(9), 3339. https://doi.org/10.3390/su10093339

Wilmsen, F., & Gesing, F. (2016). *The Global Protocol for Community-Scale Greenhouse Gas Emission Inventories (GPC) – A New Passage Point on an Old Road?* (SSRN Scholarly Paper No. 2874704). Social Science Research Network. https://papers.ssrn.com/abstract=2874704

World Bank Group. (2019). *Global Solar Atlas*. https://globalsolaratlas.info/map?c=11.609193,8.4375,3