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TITLE

“The strategic role of municipalities in the transition to clean energy: an energy and environmental analysis of the municipality of Tito using the ETSAP-TIMES model generator”

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Coordinatore del Dottorato: Ph.D. candidate:

Prof. Aurelia Sole Dr. Ikechukwu Ikwegbu Ibe

Supervisors:

Prof. Antonio D’Angola

Dr. Senatro Di Leo

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Table of Contents

Executive Summary

The global transition toward clean and sustainable energy systems is driven by the challenges of climate change mitigation, rising greenhouse gas (GHG) emissions, and increasing threats to energy security. Energy systems account for approximately three-quarters of global GHG emissions, rising from energy production, distribution, and end-use consumption. Therefore, the decarbonization of energy systems stands as a point for achieving climate neutrality while improving environmental quality, public health, and socio-economic resilience.

In Europe, these challenges have generated a legally binding policy framework through the European Green Deal, the European Climate Law, and the Fit for 55 package, which together establish a trajectory toward net-zero emissions by 2050 and a 55% reduction in GHG emissions by 2030 compared to 1990 levels. The Renewable Energy Directive (RED II and RED III), the Energy Efficiency Directive, and the REPowerEU frameworks explained the importance of renewable energy deployment, energy efficiency, electricity, and energy independence.

The new Italian National Energy Strategy – PNIEC 2024 established the updated national objectives on energy and climate and the provisions by sector to achieve them. It anticipates an expansion of renewable energy, building renovations, and the electrification of final consumption (heat pumps). However, achieving these targets requires effective implementation at the local level, where energy consumption patterns, infrastructure constraints, and socio-economic conditions ultimately determine the feasibility and impact of the transition.

Based on this context, municipalities translate national and European climate objectives into actions. Local governments are involved in promoting decentralized renewable energy production, enhancing energy efficiency, supporting citizen participation, and addressing social equity through place-based solutions. Renewable Energy Communities (RECs) represent an instrument to operationalize this local transition by integrating technical innovation, regulatory frameworks, and citizen engagement into a cohesive governance model.

Despite their recognized potential, the deployment of RECs and the design of effective local energy transition strategies remain constrained by the lack of quantitative planning tools capable of capturing long-term energy, technology interactions, and policy impacts at the municipal scale. This study addresses this gap by applying a well-established energy system modeling framework, ETSAP-TIMES, to analyse a local energy system, demonstrating its suitability and replicability for municipal-level energy and climate planning.

In this context, the study explores the following questions:

- To what extent can modeling energy systems at the municipal level contribute to achieving national and European climate neutrality goals?
- How will the integration of renewable energy communities influence energy transition pathways at the municipal level?
- Which policies effectively manage the deployment of renewable energy at the municipal level to reduce greenhouse gas emissions while maintaining cost efficiency?

The objective of this thesis is to apply the ETSAP-TIMES energy system model generator to conduct an energy and environmental analysis of the Municipality of Tito, Italy, examining the role of local governance in the transition toward a clean, secure, and sustainable energy system. The research investigates how small and medium municipalities can contribute to achieving national and European climate targets through integrated energy planning and the implementation of RECs.

The work builds upon a modeling framework traditionally used at national and regional scales and adapts it to a municipal context, demonstrating its methodological robustness and practical relevance for local energy planning. The analysis covers the period 2020–2050, aligning with the time horizons of the European Green Deal and Italy’s NECP.

The specific objectives of the thesis are to:

1. Represent and optimize the local energy system of the Municipality of Tito, including energy supply, local energy production, and end-use demand in the residential and tertiary sectors, and to define the data input for the frame model implementation.
2. Develop and analyze a Business-as-Usual (BaU) scenario to describe the long-term evolution of the local energy system in the absence of new policy interventions.
3. Assess alternative transition pathways in response to policy and market drivers, such as increasing natural gas prices.
4. Evaluate the role of electrification and renewable technologies, for example, photovoltaics and heat pumps, in decarbonising residential and tertiary sectors.
5. Implement a TIMES-Tito REC configuration to analyse the long-term impacts of Renewable Energy Communities on energy supply, electricity production, consumption patterns, and emissions.

6. Provide evidence-based insights to support local policymakers and stakeholders in designing energy transition strategies consistent with Italy's NECP and European climate objectives.

The methodological approach is rooted in the ETSAP-TIMES model generator developed under the International Energy Agency's Energy Technology Systems Analysis Programme, which has been utilized to represent a local-scale energy system, including a Renewable Energy Community submodel. TIMES allows the users to build bottom-up, technology-rich optimization models based on linear programming, designed to identify least-cost energy system configurations over medium- to long-term horizons under specified technical, economic, environmental, and policy constraints.

The objective function to be minimized is the total discounted system cost, including investment, operation, maintenance, and fuel costs, while satisfying energy service demands and policy constraints such as emission limits or renewable energy targets. It provides detailed outputs on technology capacity and investments, energy commodity prices, GHG emissions, and energy costs. TIMES has been widely applied at the supranational, national, and local scales thanks to its flexibility, allowing for adaptation to different contexts through careful definition of system boundaries, demand projections, technology, and scenarios characterization.

A prerequisite for model development is the definition of a Reference Energy System (RES), which represents the energy system under investigation from primary resources to final energy demand. Technology characterization includes technical efficiency, availability, average lifetime, investment and operating costs, emission factors, enabling comparison of competing technologies and assessment of future energy-technology pathways.

Final energy demand projections are usually derived using regression-based models based on historical factors and economic factors. The model is calibrated against a statistical base year to ensure consistency with observed energy balances. Following calibration, a set of scenarios is defined to explore alternative futures, including sensitivity analyses on energy prices and policy incentives, and scenarios for REC implementation.

Scenario analysis is the key element for energy system analysis, allowing comparison between the Business as Usual development (BaU scenario) and alternative possible futures (policy scenarios), enabling the identification of cost-optimal technology roadmaps that balance economic effectiveness, energy and technology availability with environmental performance.

The Business-as-Usual scenario serves as a benchmark for assessing the effectiveness of alternative transition pathways. BaU scenario evolves according to current trends in energy consumption, technologies adopted, and energy mix, without the introduction of additional measures. A Sensitivity analysis is then carried out to examine the system’s response to changes in external market conditions. It explores variations in natural gas prices combined with incentives for the deployment of heat pumps, allowing an assessment of the system's resilience to energy market volatility and analysing the effects of end-use electrification. The REC scenarios evaluate the impacts of implementing a REC through different configurations of photovoltaic systems, varying in installed capacity and the presence or absence of capital grants.

The modeling issues encountered in the case study are related to the limited availability of local data (end use energy demands and energy consumption), projection demand that involves efficiency improvements and technology substitution.

The main results show that under the BaU scenario, total final energy consumption in the Municipality of Tito decreases by 15% by 2050, driven by the replacement of biomass technologies with more efficient natural gas technologies. Biomass, LPG, and diesel are phased out, with biomass fully replaced by natural gas in the residential sector by 2040.

Electricity production from photovoltaics increases by 99% over the analysis period, illustrating a shift towards renewable energy. Solar thermal energy also exhibits strong relative growth by 187%, although its absolute contribution remains limited. Despite these developments, natural gas remains the dominant energy source throughout the time horizon, largely due to regional economic conditions that mitigate gas prices.

In the residential sector, overall energy consumption decreases by 30% by 2050, but this reduction does not translate into a proportional decrease in emissions due to continued reliance on natural gas for space heating and cooking. Electrification remains limited, and integration with renewable sources is insufficient to achieve deep decarbonization.

The tertiary sector exhibits a contrasting trend, with energy consumption increasing by 30%, driven by growth in healthcare and accommodation subsectors. In 2050, an increase in the Healthcare and Accommodation subsectors is expected (190% and 78% respectively), Food shows a 30% increase in the time horizon, while Schools and Public Buildings will reduce their consumption (37% and 12% respectively). Natural gas continues to dominate the energy mix, while electricity consumption grows moderately. As a result, CO_2 emissions increase by 28% by 2050, peaking around 2045, with the residential sector accounting for 61% of total emissions. These findings indicate that, under BaU conditions, the municipality cannot achieve a trajectory compatible with climate neutrality.

Sensitivity analysis demonstrates the impact of economic signals on technology adoption and emissions outcomes. A 30% increase in natural gas prices leads to a significant reduction in gas consumption and a corresponding 66% decrease in CO_2 emissions by 2050 compared to the BaU scenario. Substitution occurs through increased electrification and the use of biomass.

When higher gas prices are combined with non-repayable grants for heat pump deployment, the transition accelerates further. The GASCOST+20%_50_HP case, involving a 20% gas price increase combined with a 50% subsidy for electric heat pumps, achieves a 69% reduction in CO_2 emissions in 2050 compared to the case without capital grants (GASCOST+20% case), while also reducing total system costs relative to BaU. This result highlights the effectiveness of coordinated pricing and incentive policies in driving cost-efficient decarbonization.

REC scenarios assess the impact of shared renewable electricity generation on local energy systems. REC implementation leads to an increase in photovoltaic capacity, particularly in larger configurations (10 MW).

Electricity imports from the national grid decrease, with reductions of 31–32% by 2050 in the 10 MW REC scenarios, demonstrating enhanced local energy autonomy and resilience. Electricity consumption increases by 5.4%, while natural gas consumption decreases by 6%, reflecting fuel substitution driven by shared renewable generation.

CO_2 emissions decrease by approximately 10% relative to BaU, confirming the contribution of RECs to decarbonization objectives aligned with the EU Green Deal and Fit for 55 targets. From an economic perspective, REC scenarios generate higher revenues through a combination of energy sales and incentives, particularly in configurations without capital grants, where installed capacity is the main driver of economic performance. At the same time, energy sharing increases distributed energy consumption, reducing electricity grid losses and stabilizing the grid.

The novelty of this study consists in the adaptation of the ETSAP-TIMES framework to a small municipal energy system in Italy, integrating a REC to analyse configurations and financial incentives, highlighting its usefulness and value addition for local energy planning.

The thesis highlights the following original contributions:

1. Demonstration of the applicability of the ETSAP-TIMES modeling framework at the municipal scale, extending its traditional use.
2. Development of a replicable, data-consistent modeling methodology for local energy system analysis and scenario-based policy evaluation.
3. Modeling and assessing the role of REC in reducing emissions, enhancing energy security, and improving local system economics.
4. Evidence-based evaluation of combined policy instruments (energy pricing and investment incentives) in driving cost-effective decarbonization.
5. Provision of actionable insights to support municipal decision-making aligned with national and European climate strategies.

The results demonstrate the strategic importance of municipalities in achieving climate neutrality and highlight the need to adopt an integrated and systemic planning approach. REC emerges as an effective tool for combining decarbonization and energy security, particularly when supported by incentive policies and enabling regulatory frameworks.

To conclude, energy system modeling provides a critical scientific basis for evaluating alternative transition pathways, identifying least-cost solutions, and aligning local actions with higher-level policy objectives. The TIMES-Tito model demonstrates how quantitative tools can support evidence-based policymaking and reduce uncertainty in long-term planning, also at the local scale.

Due to the specific topic and the aim of the study, the analysis focused on residential and tertiary sectors and does not explicitly model transport or industrial activities. Future research will extend the model to include transport electrification, industrial activities, energy storage technologies, grid flexibility options, and behavioral dynamics. Further work will also explore reductions in local air pollutants and the integration of consumer behavior into energy system modeling.

INTRODUCTION

1.1 Background

The global commitment to transition to “clean energy” is now being driven by the growing risks related to climate change, rising greenhouse gas (GHGs) emissions, and increasingly pressing threats to energy security. These factors have brought decarbonisation and sustainability to the forefront of international political and strategic agendas. Energy systems account for approximately three-quarters of the global GHG emissions resulting from energy production, distribution, and consumption. The transition to renewable energy and improved energy efficiency represents a profound transformation in the way energy is consumed and produced. It is environmentally important to reduce greenhouse gas emissions and to improve public health.

In line with this transformation, it is essential to minimize the adverse impacts of anthropogenic climate change. Global warming will continue to intensify due to the combustion of fossil fuels and unsustainable production models. Emissions targets, energy efficiency, and renewable energy are set in the Paris Agreement (2015) and regional plan frameworks, including the European Green Deal. The European Union (EU) has set the goal of achieving climate neutrality by 2050, with an intermediate target of reducing emissions by at least 55% by 2030, as set out in the Fit for 55 legislative packages.

Since the Industrial Revolution, the global energy system has experienced an intense transformation. Initially dominated by coal, it has progressively diversified with the introduction of oil and natural gas, which enabled industrialization and economic growth, but at the cost of increasing environmental degradation. According to the International Energy Agency (IEA, 2023), the increase of over 50% in global energy demand was recorded between 2000 and 2022, and CO_2 emissions from the energy sector reached 37 billion tonnes in 2022, caused by a combination of population growth, urbanization, and rising living standards (IEA, 2023). There is an increase in air emissions because of fossil fuel dependency, with the Global Carbon Project (2022) specifying that fossil fuel combustion and industrial processes accounted for 89% of total CO_2 emissions in 2021. Continued dependence on fossil fuels has not only boosted carbon emissions but has also caused environmental degradation, disrupted ecological balances, and increased the effects of climate change.

Energy security has emerged as a crucial aspect of the global energy transition. Fossil fuels' reliance exposes a country to geopolitical risks, supply disruption, and market volatility. The Russia–Ukraine energy crisis (2022) demonstrated the fragility of energy supply chains and the strategic vulnerability of countries dependent on external sources for natural gas and oil. In this context, the expansion of renewable energy sources and diversification of the energy mix have become fundamental components of national security and energy resilience policies.

Notwithstanding, in the progress of renewable energy deployment, Italy remains heavily dependent on fossil fuels for electricity production, industrial processes, and residential heating. Natural gas is the main source of energy in the national energy system, covering approximately 40% of total energy consumption. This reliance increases the vulnerability of the Italian energy system to external shocks, leading to price fluctuations and supply risks during international crises.

In Italy, the challenge is not only to increase the share of renewable energy but also to ensure a secure, cheap, and just transition. The expansion of renewable energy production from solar, wind, and biomass installations is the key. Infrastructure and administrative barriers, and grid integration challenges persist. The southern regions of Italy (Basilicata, Puglia, and Sicily) have abundant renewable energy potential, but they are faced with infrastructure and administrative barriers that hinder large-scale deployment. Also, the insufficient storage infrastructure and interregional transmission capacities hinder the integration of renewable energy sources. These explain the importance of planning between the national and local authorities to balance renewable energy integration with grid stability and reliability. To do so, Italy's PNRR (Piano Nazionale di Ripresa e Resilienza) allocates funding for renewable projects and digital transformation.

The energy consumed in buildings remains a hindrance to decarbonization, accounting for nearly 40% of final energy consumption and 36% of GHG emissions nationally (European Commission, 2020). Most residential buildings were built before the modern energy efficiency standards were introduced, resulting in improper insulation, inefficient appliances, and aged heating systems. They are mainly supplied by heating systems fueled by natural gas or biomass. There is a need to incorporate heat pumps and solar thermal systems to improve the energy systems in buildings, but high cost and limited public awareness are hindrances to achieving energy comfort. Superbonus 110% and Conto Termico have incentivized energy efficiency renovations at the national level.

Italy has aligned its energy and climate strategy with the European framework through its National Energy and Climate Plan (NECP) and the National Recovery and Resilience Plan (PNRR), fundamental tools for addressing the challenges of the ecological transition. The PNRR includes a strong commitment to expanding renewable energy, improving energy efficiency, and digitalizing the electricity grid, key elements for modernizing the national energy system. An innovative aspect of the plan concerns support for Renewable Energy Communities (RECs) and collective self-consumption systems, which promote local participation and democratize energy production. RECs allow municipalities, citizens, and local businesses to jointly produce, share, and consume renewable electricity, reducing costs and emissions.

Addressing Italy's energy and environmental challenges requires the integrated management of four interconnected pillars of the climate and energy transition.

- Climate Change Mitigation: to promote the Reduction of GHG emissions through renewable deployment, improved energy efficiency, and adoption of sustainable behaviors by citizens, businesses, and institutions.

- Energy Security: to reduce the dependence on imported fossil fuels and enhance energy system resilience through decentralized production and local renewable sources.

- Infrastructure Modernization: to develop sustainable and smart energy infrastructure, through grid upgrades, the implementation of storage systems, and the use of digital technologies to manage and optimize energy flows.

- Social Inclusion and Energy Justice: to ensure equitable and sustainable energy access, to promote citizens' active participation in energy governance, and to support vulnerable groups in transition to a low-carbon economy.

By integrating technical planning, regulatory innovation, and citizen engagement, they can bridge the gap between global commitments and local implementation. The concept of Renewable Energy Communities (RECs) embodies this integration by promoting local ownership, shared economic benefits, and decentralized renewable generation.

Contributing to achieving climate neutrality at the municipal level is of fundamental importance. Municipalities play a central role in implementing and localizing climate and energy policies, as the governance bodies closest to citizens. By participating in the Covenant of Mayors for Climate and Energy, municipalities commit to developing Sustainable Energy and Climate Action Plans (SECAPs), which highlight concrete pathways to reduce emissions, enhance efficiency, and adapt to climate impacts. The plans at the municipal level translate national objectives by tailoring strategies to the geographic, socio-economic, and infrastructural specificity of each territory.

The Municipality of Tito represents a case study for analyzing local energy transition strategies. The area is heavily dependent on fossil fuels like natural gas, which is used primarily for home heating and tertiary sector activities. At the same time, the area is exposed to increased climate impacts such as seasonal drought, land degradation, and temperature fluctuations. Basilicata has a significant potential for solar energy development, making Tito a promising location for deploying decentralized renewable systems. Analyzing Tito's energy system offers valuable insights into how municipalities can contribute to both national decarbonization goals and local energy resilience. RECs represent an effective mechanism for achieving both social and environmental objectives while simultaneously promoting the empowerment and active participation of local communities in energy transition processes.

Energy modeling can play a crucial role in guiding transition processes at the local level, providing analytical tools for defining sustainable strategies. The ETSAP-TIMES (The Integrated MARKAL-EFOM System) model, developed under the International Energy Agency's Energy Technology Systems Analysis Programme, represents a technologically detailed, bottom-up approach for the analysis and optimization of energy systems. It enables the optimization of resource use and technology penetration over long-term horizons, taking into account economic, environmental, and policy constraints. Although it has traditionally been applied at national or regional levels, its flexibility can allow for adaptation to local contexts. Through scenario analysis, it identifies least-cost pathways, evaluates renewable integration potential, and assesses policy impacts such as energy pricing, technology incentives, and REC integration.

For these reasons, the implementation of the TIMES-Tito model can be an effective tool for analyzing the local energy system, capable of providing solid scientific support for municipal energy planning. This approach can ensure consistency with the national objectives of the NECP and with the vision of the European Green Deal, which is geared towards climate neutrality and resource efficiency.

1.2 Objectives

The primary objective of this thesis is to apply the ETSAP-TIMES model generator to conduct an energy and environmental analysis of the municipality of Tito, examining the strategic role of local governments in the transition to a clean and sustainable energy system. The analysis aims to understand how small and medium municipalities, like Tito, can contribute to achieving national climate mitigation targets, supporting decision-making for regional energy and environmental policies. The work builds on a modeling framework originally conceived for global and national-scale applications, adapted here to a municipal scale to demonstrate its replicability and effectiveness for local energy planning. The specific objectives are:

1. To represent and optimise the local energy system of the Municipality of Tito (energy supply, local energy production, end-use demand for residential and tertiary sectors), and to define the data input for the implementation of the model.

2. To develop and analyze the Business-as-Usual (BaU) scenario for the period 2020–2050, to outline the trend evolution of the system in the absence of new policies.

3. Assessment of alternative transition pathways in response to policy and market drivers, such as increasing natural gas prices

4. Evaluation of the potential role of electricity and renewable technologies (e.g., photovoltaics, heat pumps) in decarbonising the residential and tertiary sectors.

5. Implementation of TIMES-Tito REC to analyse the effects of a Renewable Energy Community over a 30-year time horizon, with a particular focus on energy supply, local electricity production, and final consumption in the residential and tertiary sectors.

6. To provide insights for local policymakers and stakeholders to design effective energy transition strategies consistent with Italy’s NECP and EU climate targets.

1.3 Thesis Structure

The thesis is organized into five chapters. The following paragraphs describe the content of each chapter in more detail.

Chapter 1 illustrates the policy and regulatory framework in which the research is conducted. It provides an overview of the European and national legislative context governing energy and climate action. The main policy instruments are analyzed, including the European Green Deal, the *Fit for 55* policy packages, the Renewable Energy Directive (RED II and III), and the REPowerEU Plan. It also describes Italy's National Energy and Climate Plan (NECP) and highlights the governance dimension of energy transition, highlighting the crucial role of local authorities and Renewable Energy Communities (RECs) in achieving decarbonization objectives.

Chapter 2 describes the methodological framework and the modelling approach adopted in this thesis. It presents a review of energy models and decision-support tools used for energy planning, with a particular focus on the ETSAP-TIMES model generator and its suitability for local-scale analysis. The chapter also describes in detail the methodological steps for model development, data collection, energy system characterization, scenario formulation, and calibration of the TIMES-Tito model, as well as the integration of Renewable Energy Communities into the modelling framework.

Chapter 3 presents the case study of the Municipality of Tito, with a detailed description of its geographical, demographic, and socio-economic context. The chapter describes the municipal energy system, focusing on energy supply, energy consumption in residential and tertiary sectors, and renewable energy potential. Finally, the construction of the TIMES-Tito reference energy system (RES) is presented, along with modeling of photovoltaic generation and a representation of the energy-sharing system typical of Renewable Energy Community (REC).

Chapter 4 discusses the energy system evolution under different scenarios developed using the TIMES-Tito model. It presents the assumptions underlying the Business-as-Usual (BaU) and REC-based scenarios, with particular attention to expected energy prices, investment incentives, and technology costs. The results are analyzed to evaluate the impacts on energy production, imports, and consumption, along with the economic and environmental performance of different scenarios. The comparison between the scenarios highlights the contribution of renewable energy support policies and renewable energy communities to achieving decarbonization objectives and enhancing energy resilience.

Chapter 5 concludes the thesis by summarizing the main findings and contributions of the research. The implications of the findings for local energy planning are discussed, with reference to the formulation of sustainable policies and the development of strategies based on Renewable Energy Communities. The chapter also outlines recommendations for municipal authorities and proposes directions for future research to extend the analysis to other localities or integrate additional sectors such as transport and industry.

CHAPTER 1 THE FRAMEWORK

1.1 The Climate Change and the Green Energy Transition Challenge.

Climate change mitigation and adaptation are urgent challenges that scientists and policymakers must address. The rise in the frequency and severity of extreme weather events has devastating impacts on people's lives. However, human activities are primarily responsible for the increase in global average temperatures that are affecting climate patterns and the economy, and our current economic and consumption models are damaging to the environment and nature. (Shufian et al.,2025).

The environmental and social dangers posed by climate change represent one of the most complex issues of the 21st century that must be addressed in a multidisciplinary context, requiring coordinated efforts to counteract the negative effects and increase the resilience of territories.

All countries are becoming aware of the urgent necessity to mitigate climate change by consistently decreasing greenhouse gas emissions and adopting sustainable behaviors, and at the same time increasing the resilience of infrastructures to extreme weather events.

Their commitment is acknowledged by the Paris Agreement, which represents the first legally binding international treaty on climate change and was adopted by 195 Parties at the UN Climate Change Conference (COP21) in Paris, France, on 12 December 2015, entering into force on 4 November 2016. The Paris Agreement aims at limiting “the increase in the global average temperature to well below 2°C above pre-industrial levels” and pursuing efforts “to limit the temperature increase to 1.5°C above pre-industrial levels,” as established by the United Nations Framework Convention on Climate Change (UNFCCC, 2015).

This calls for a remarkable change in energy production and consumption of energy systems at a global level to be deployed with coordinated actions at different spatial scales aimed at supporting a radical change in energy supply and consumption models, with a wider diffusion of renewable resources to replace fossil fuels, the increase of technology efficiency and smart energy services to promote energy saving and virtuous consumers’ behavior.

In this context, it is necessary to consider the operational and structural barriers that may impede the transition to clean energy, which is essential for achieving such ambitious greenhouse gas reduction targets. These barriers mainly concern resistance to the infrastructural and behavioral changes needed to ensure the effective integration of renewable energy sources and more efficient technologies and management systems. From a socio-economic perspective, the acceptance of new infrastructure and services must be supported by ensuring a fair transition for citizens. Synergistic and systemic policies are therefore needed to ensure that energy and environmental objectives are achieved, while ensuring a fair and socially equitable transition and strengthening innovation and competitiveness in the economic system.

The European Union is at the forefront of the fight against climate change. The European Green Deal, launched in 2019 and officially ratified by the EU and all its Member States, takes up the Paris Agreement's goal of keeping global warming below 1.5 °C above pre-industrial levels and making the EU climate neutral by 2050, strengthening the Union's position as a leader in the global fight against climate change (UNFCCC, 2015) (European commission, 2019)

The European Green Deal is being implemented in practice through the Fit for 55 packages, which will be discussed in detail below. This package sets an interim goal of reducing greenhouse gas emissions from EU industry by at least 55% by 2030 compared to 1990 levels. Due to the complexity of the regulatory framework, multiple targets have been established to support the decarbonization of the EU energy system, focusing on key sectors such as buildings, biodiversity, energy, transport, and food.

This premise highlights that climate change mitigation must be implemented by defining inclusive and adaptive energy strategies that support the transition to clean energy, maximising the ability to combine technical, environmental, economic, and social dimensions. Rigorous policy coordination, advanced strategic planning methods, and system-level models can therefore significantly support this change, allowing for emerging uncertainties and risks to be considered and strengthening scientific cooperation for the exploitation of results and the implementation of technology roadmaps.

1.2 The European legislative framework on climate and energy

The European Green Deal, launched in 2019, ratifies the Paris Agreement, signed by the EU and all its member countries, which aims to keep global warming to a maximum of 1.5 °C above pre-industrial levels. With the European Green Deal, for the first time in history, the European Commission has presented a detailed vision that includes a set of coherent measures and an ambitious, legally binding target of net-zero emissions by 2050, recognising the imminent threat posed by climate change.

The implementation of the European Green Deal at both the EU and Member State levels requires a profound transformation of the entire economy, emphasising the need for a synergistic contribution from all policy sectors by identifying seven key areas: energy, climate, environment, industry, agriculture and food, transport, and finance

The strategic vision of the EU Green Deal was enshrined in the European Climate Law, adopted on 9 July 2021, which sets out the long-term trajectory for achieving climate neutrality by 2050 in a socially fair and cost-effective manner, ensuring that the transition is irreversible by setting an interim target of reducing greenhouse gas (GHG) emissions by at least 55% by 2030. This Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 (European Climate Law) (European Commission, 2021). Figure 1.1 shows the key aspect of the green deal.

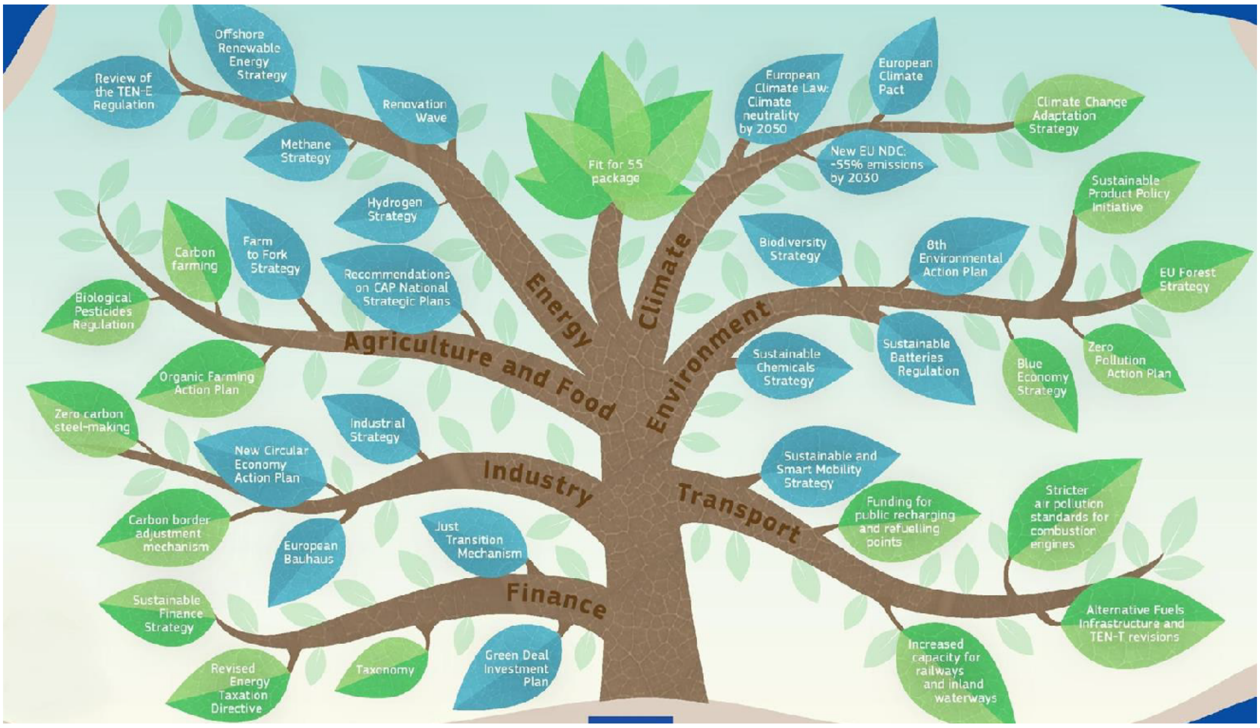

Figure 1.1: Key components of the Green Deal (ISL, 2023)

In this context, the ‘Investment Plan for the European Green Deal’ (Investment Plan for a Sustainable Europe) (D’Alfonso, 2020) presented by the European Commission aims to contribute to the financing of a sustainable transition, to attract at least Euro1 trillion over 10 years, and has allocated 30% of the EU's multiannual budget (2021-2027) and the National Recovery and Resilience Plan (PNRR) to green investments.

A comprehensive package of policy initiatives, Figure 1.2, has been defined to implement the EU Green Deal strategy and support the green transition in the Union, while ensuring the competitiveness of the economy.

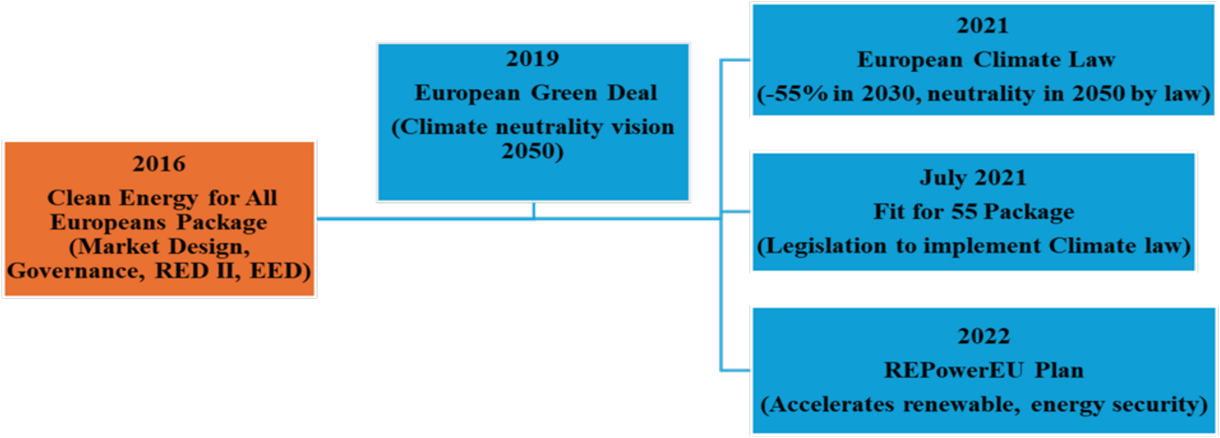

Figure 1.2: Chronological relationships of different packages in the actuation of the EU Green Deal (European Commission, 2019)

1.2.1 The Fit for 55 Policy Package

The Fit for 55 packages launched in July 2021 are the main tool designed to operationalize the legislative commitment of the 2030 Climate Action Plan, which aims to reduce greenhouse gas emissions by 55% by 2030 and put the EU on the path to achieving climate neutrality by 2050, addressing several key dimensions and sectors to achieve this goal. (European Commission, 2021). The Fit for 55 package objectives and pillars are illustrated in Figure 1.3.

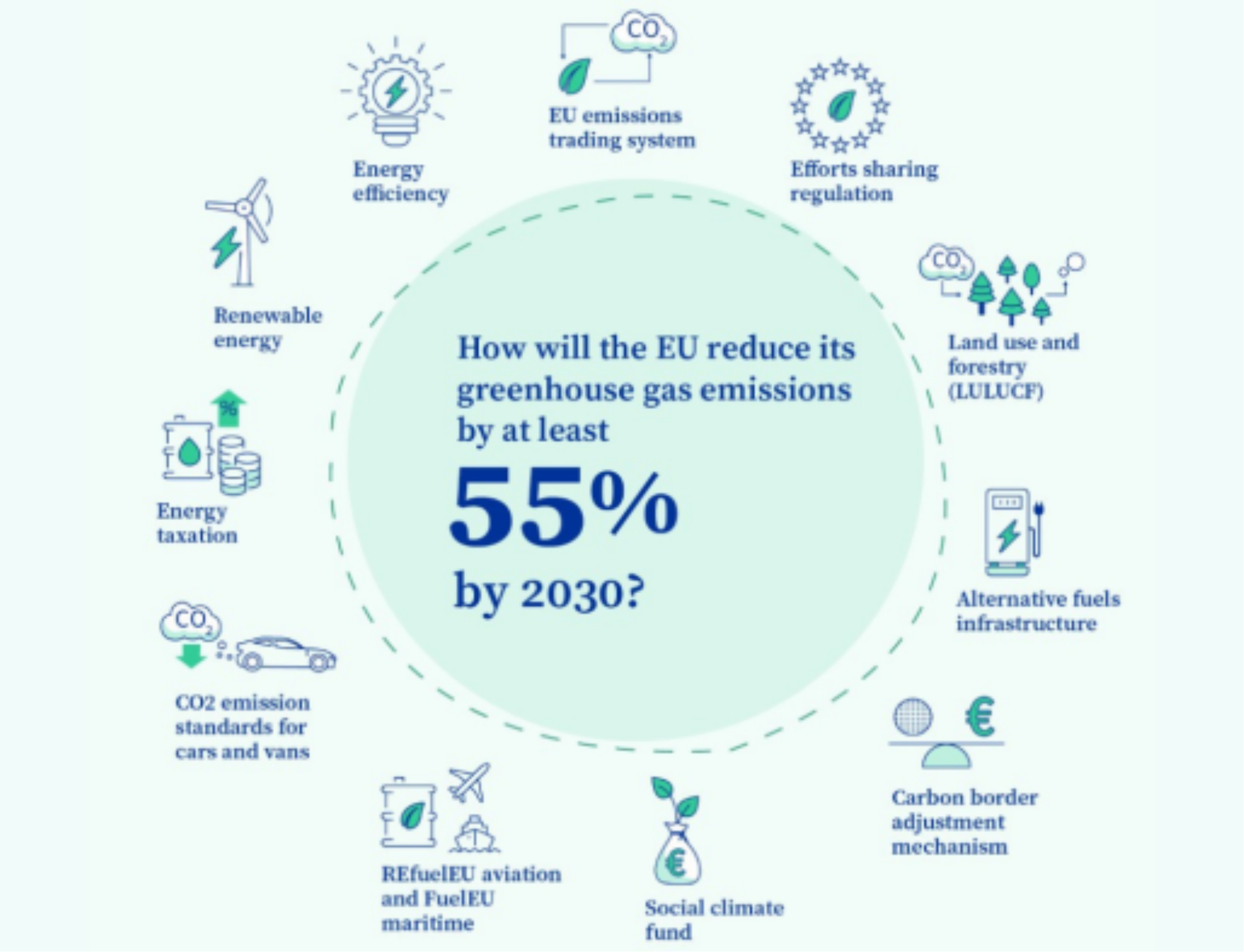

Figure 1.3: Fit for 55 Package objectives and pillars (RepowerEU, 2022)

The mechanisms included in the "Fit for 55" package address different sectors and issues as reported in the following:

1. Reform of the EU trading system (EU ETS):

- Extends coverage to new sectors beyond electricity and heat generation, energy-intensive industrial sectors, and commercial aviation (flights within the European Economic Area), which currently account for approximately 40% of total EU emissions.
- Sets a 62% reduction target by 2030, requiring a more rapid reduction in the cap and a smaller number of allowances available on the market, as well as the phasing out of free allowances for certain sectors.
- Introducing a new emissions trading system for buildings, road transport, and fuels.

2. Carbon Border Adjustment Mechanism (CBAM):

- ❖ Introduces a carbon pricing system applicable to energy-intensive products imported into the EU.

3. Revision of the Effort Sharing Regulation (ESR):

- ❖ Includes sectors not covered by the EU ETS to further reduce carbon emissions from key economic sectors (increase the target from the current 29% for 2030 to a new 40% reduction for 2030).
- ❖ Distributes the burden among Member States fairly and cost-effectively.

4. Revision of the Regulation on Land Use, Land-Use Change and Forestry (LULUCF):

- ❖ Aims to achieve climate objectives in the land use and forestry sectors.

5. Hydrogen and decarbonized gas market:

- ❖ Promotes the shift from fossil gas to renewable and low-carbon gases and stimulates their adoption in the EU by 2030 and beyond to create a hydrogen market, reduce the carbon footprint of fuels, increase security of energy supply, and reduce dependence on imports, while engaging and protecting consumers.

6. Transport:

- ❖ Reduction of fossil fuel use in transport through the revision of the Regulation on Alternative Fuels Infrastructure, setting concrete targets for the deployment of such infrastructure in the EU to promote the use of alternative fuels.
- ❖ Increasing the use of sustainable fuels by aircraft and ships (ReFuelEU Aviation and FuelEU Maritime).
- ❖ Tightening CO_2 emission standards for cars and vans to reduce EU greenhouse gas emissions by at least 55% by 2030.

7. Regulation on the reduction of methane emissions aims to establish new rules to reduce methane emissions in the energy sector
8. Revision of the Energy Taxation Directive: to ensure that the taxation of different energy products reflects their environmental impact, encouraging businesses to make greener choices
9. Revision of the Renewable Energy Directive (RED III – EU/2023/2413): to increase the 2030 renewable energy target to 42.5% plus an additional 2.5%.
10. Revision of the EU Energy Efficiency Directive: This directive establishes an 11.7% reduction in EU-wide energy consumption by 2030 compared to the forecast, with a

gradual increase in energy savings from 2024 to 2030 (from 1.49% to 1.9% of total consumption per year) in buildings, transport, industry, and the public sector.

11. Revision of the Energy Performance of Buildings Directive: The new directive (EU/2024/1275, EPBD) published in May 2024 sets more ambitious energy efficiency standards for new and renovated buildings in the EU, to achieve a zero-emission and fully decarbonized building stock by 2050, stimulating the deployment of renewable energy in buildings, reducing energy bills, and promoting healthier living conditions through smart building management services.

These "packages" are closely interconnected to cooperate towards achieving EU climate neutrality by 2050. To ensure a fair and socially just transition, the package also includes a Social Climate Fund, which draws its revenue from the sale of allowances and is intended to support vulnerable households, vulnerable micro-enterprises, and vulnerable transport users.

1.2.2 The Renewable Energy Directive

A key role is covered by the Renewable Energy Directive and its amendment (RED II and RED III), which recognizes the key role of renewable energy in the transition to clean energy promoted by the EU Green Deal. In fact, the Renewable Energy Directive sets targets for renewable energy in the EU's energy mix and includes a series of policy measures aimed at facilitating the energy transition and supporting cooperation between EU countries. Given the need to accelerate the EU's transition to clean energy, these targets and the measures needed to achieve them are regularly reviewed and, as a result, the Renewable Energy Directive is updated and amended. The former Renewable Energy Directive RED II (2018/2001/EU), amending Directives 2009/125/EC and 2010/30/EU, came into force in December 2018 as part of the “Clean Energy for All Europeans” package setting a binding EU target for 2030 of at least 32% renewable energy in the energy mix, with a clause allowing for a possible upward revision by 2023 in line with the 20% target set for 2020 (European Commission, 2019).

In particular, RED II established specific binding targets for the share of renewable energy in the transport sector, while providing support mechanisms and incentives for the production and consumption of advanced biofuels, encouraged the sustainable production of biomass, and established improved criteria to ensure the sustainability of bioenergy.

Furthermore, a wider adoption of renewable technologies was promoted, with a focus on decentralising the energy system and actively involving citizens by establishing conditions for local renewable energy production and promoting self-consumption at the community level. The concept of Renewable Energy Communities was thus introduced, including new provisions to enable citizens to play an active role in the development of renewable energy.

In this context, Renewable Energy Communities therefore play a key role, as they can provide energy services to national electricity grids, thus contributing to a more efficient and flexible energy system. Other aspects of RED II include simplifying procedures for installing renewable energy production facilities and increasing national renewable energy production targets by 2030.

The strategic framework set up by REDII was further strengthened in amending Directive EU/2023/2413, RED III, which entered into force in November 2023, based on the revision of Directive EU/2018/2001, which aligns the binding renewable energy targets to 42.5% by 2030 (intending to reach 45%).

Further provisions enabling new forms of consumer participation are contained in Directive (EU) 2019/944 (EU, 2019), included in the Clean energy package and amended in 2024 by Directive (EU) 2024/1711 (EU, 2024), which lays down rules for the generation, transmission, distribution and storage of electricity, as well as for consumer protection, with a view to creating integrated, competitive, consumer-focused, flexible and fair electricity markets in the European Union. Among other things, it contains rules on retail electricity markets, while Regulation (EU) 2019/943 mainly contains rules on the wholesale market and network management.

Noteworthy is also the revised EU Directive 2023/1791 (EED) on energy efficiency, which came into force on 10 October 2023, marking an important step forward in the fight against climate change, to reduce energy consumption by 11.7% by 2030 compared to the projections of the EU 2020 reference scenario. Member States, including Italy, must transpose the new Directive by 11 October 2025. Companies with an average annual energy consumption exceeding 85 TJ in the previous three years, considering all energy carriers, will be required to implement an energy management system compliant with EN ISO 50001 by 11 October 2027.

1.2.3 The REPowerEU Plan

The REPowerEU plan, a comprehensive European initiative designed to enhance energy independence and accelerate the green transition, is the strategic response of the EU to the Russian military aggression in Ukraine that highlighted the European Union's vulnerability and dependency on Russia's fossil fuels (RepowerEU, 2022).

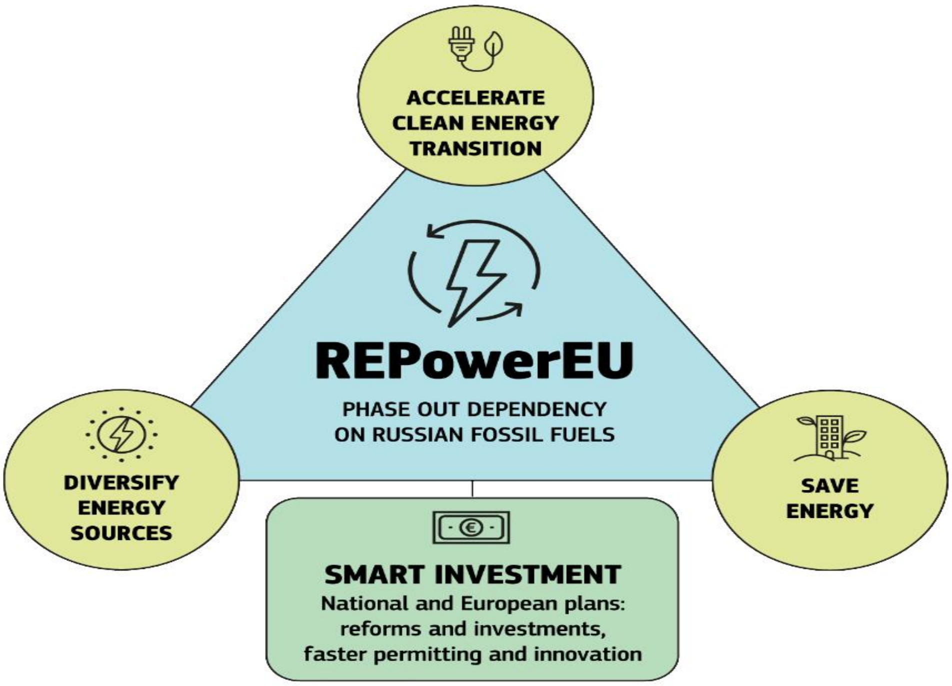

Figure 1.4: REPowerEU Plan (RepowerEU, 2022)

The REPowerEU plan is built on fully implementing the "Fit for 55" package, focusing on measures to reduce energy demand, increase efficiency, and promote renewable energy and hydrogen value chains. The fundamental purpose is to phase out the European Union's dependency on fossil fuels from Russia well before 2030.

Several core strategic pillars are designed to enhance European energy independence and accelerate the green transition. These strategies are supported by ambitious, quantified targets across the renewable energy, efficiency, and infrastructure sectors.

The key strategic pillars proposed include:

1. Reducing Energy Demand and Increasing Efficiency: The plan aims to reduce energy demand and increase energy and digital efficiency. This is achieved by increasing the binding EU energy saving target.
2. Accelerating Renewable Energy Deployment: A primary focus is the rapid expansion of renewable energy sources and the simplification of the deployment process. Measures include:
    - Renewable Energy Targets: Significantly increasing the share of renewable energy in the EU's energy mix.
    - Photovoltaics (PV): Accelerating the deployment of solar energy via a dedicated European Solar Energy Strategy and implementing the European Solar Roof Initiative, which requires the installation of solar panels on the roofs of certain categories of buildings through an EU legal requirement.
    - Permit Acceleration: Simplifying and minimizing the timeframe for implementing renewable energy projects. This is supported by a revision of the proposed Renewable Energy Directive, which would designate renewable energy as an overriding public interest and introduce the designation of "go-to areas".
3. Decarbonizing Heating and Industry: The plan promotes the decarbonization of heating and industry through electrification and hydrogen:
    - Heat Pumps: Doubling the current deployment rate of individual heat pumps.
    - Industrial Shift: Accelerating the shift to electrification and renewable hydrogen in industry, alongside expanding low-carbon production capacity.
4. Infrastructure and Value Chain Support: The strategy involves building skills for the green transition in both the public and private sectors. It also includes measures to promote renewable energy and hydrogen value chains by facilitating access to credit and tax credits.
5. Cross-border Projects: Supporting key cross-border EU energy infrastructure projects to phase out EU dependency on fossil fuels from Russia well before 2030.

To cope with these issues, the REPowerEU plan sets forth specific, ambitious quantified targets, often increasing existing goals from the Energy Efficiency Directive or the Fit for 55 packages, as reported in Table 1.1.

Table 1.1: Quantitative targets of the REPowerEU plan

Area of Focus	**Target**	**Details/Deadline**
Renewable Energy Share	45% of the EU's energy mix	By 2030. This adds 169 GW to the 1067 GW target of the Fit for 55 packages for 2030.
Energy Savings/Efficiency	13% binding EU energy saving target	By 2030. This is an increase from the 9% target under the Energy Efficiency Directive.
Photovoltaics (PV)	Deploy over 320 GW of new PV	By 2025.
Photovoltaics (PV)	Deploy nearly 600 GW of new PV	By 2030.
Heat Pumps	Reach 10 million cumulative units	By 2023-2027 (reflecting a doubling of the current deployment rate).
Infrastructure Funding	Up to Euro 800 million estimated budget	Call for project proposals launched in May 2022 under the Connecting Europe Facility (CEF) for Energy to support key cross-border projects.

1.3 The National Energy and Climate Plans (NECPs)

The National Energy and Climate Plans (NECPs) are ten-year strategies covering the period 2021-2030 that are submitted by European Union Member States to detail their national contributions to the EU’s binding energy and climate targets. Provided for in Regulation (EU) 2018/1999, their main objective is to ensure the collective achievement of the EU's 2030 targets concerning the reduction in greenhouse gas emissions, the minimum share of renewable energy in consumption, improved energy efficiency, and better development of electricity interconnections. NECP’s strategic planning tool is to deliver a fair, resilient, and climate-neutral Europe, steering investments for climate and energy transition and helping to mobilise spending (NECP, 2021).

They describe the Member State's strategy for aligning with the EU's collective target for 2030, as well as for achieving net-zero emissions by 2050, with an overview of the procedure followed to develop the NECP itself and a detailed description of the objectives, targets, and national contributions to the Energy Union and decarbonization, together with the measures and interventions to achieve them.

The governance mechanism governing the NECPs is based on a transparent iterative process of monitoring, evaluation, and updates required for plans to realign policies and targets to achieve the long-term goal of climate neutrality by 2050.

The NECPs must be updated once during the decade. For the first cycle of NECPs, the revision was aimed at reflecting the increased overall ambition of the EU Green Deal, the updated EU's 2030 climate target, as well as the amendment of climate and energy legislation, and Member States submitted their updated plans by June 2024.

1.3.1 The Italian National Energy and Climate Plan

The Italy NECP, prepared with the Ministry of the Environment, Land and Sea Protection and the Ministry of Infrastructure and Transport and issued in 2020, contains Italy's strategic development guidelines for energy and climate incorporating the new provisions contained in the Climate Decree Law as well as those on investments for the Green New Deal envisaged in the 2020 Budget Law establishing the national objectives for 2030 for each of the five dimensions of the Energy Union: decarbonization; energy efficiency; energy security; internal energy market; research, innovation, and competitiveness. (NECP, 2021)

The revised version (new Italian National Energy Strategy - PNIEC 2024) was delivered in July 2024 and establishes the updated national objectives on energy and climate and the provisions by sector to achieve them. In line with the already planned and pursued path of decarbonization for climate change, energy independence, and the development of renewables, envisages a significant acceleration in the deployment of renewable electricity sources, the production of renewable fuels (biomethane and hydrogen), building renovations and the electrification of final consumption (heat pumps), the deployment of electric vehicles, and policies to reduce private mobility and CCS (carbon dioxide capture, storage, and transportation) (European Commission, 2024).

Regarding renewable energy, the 2024 Energy and Climate Plan set a target of 39.4% of gross final energy consumption by 2030, differentiating between the different electricity, thermal, and transport segments, with a projected increase of 9.4% compared to the 2019 NECP. This implies a contribution from RES of 43 Mtoe out of the total 110 Mtoe consumed. This is a huge and ambitious target considering that in 2023, renewables covered about 19.9% of final energy consumption.

In the electricity sector, the share of consumption covered by renewable sources is expected to reach 63.4% by 2030, driving the entire RES sector. This would mean renewable electricity production of approximately 237 TWh by 2030, including approximately 10 TWh for green hydrogen production.

In terms of installed power, this implies an operating renewable capacity of 131 GW, considering the overall contribution of wind, photovoltaic, hydroelectric, geothermal, and bioenergy, of which only 74 GW would be new built capacity. In particular, for solar energy, the Government has set a total installed capacity of 79.2 GW, of which 80 MW will be concentrated solar power. Excluding the contribution of thermodynamic solar power, which appears to be significantly lower than the text of the old PNIEC photovoltaic capacity, would grow by 57 GW.

Looking at the details of final consumption, bioenergy dominates, covering 7.4 Mtoe, followed by ambient energy (5.2 Mtoe), biomethane (3.1 Mtoe), solar thermal (699 ktoe), geothermal (208 ktoe), and hydrogen (315 ktoe). Heat pumps account for 5,225 ktoe, and a possible contribution of waste heat recovery (450 ktoe) to achieve the new target.

Regarding greenhouse gas emissions, Italy will not be able to meet the greenhouse gas emissions reduction and gas removal targets required by European commitments.

A main contribution to the achievement of the 40% reduction targeted for 2030 is foreseen by the construction industry, to accelerate the pace of efficiency improvements in existing buildings, through extensive retrofitting, the deployment of heat pumps, and BACS systems in residential and commercial buildings. Furthermore, among the measures to be adopted in the coming years, new tools for engaging the private and public sectors in the redevelopment of the country's existing

1.4 The Local Governance

1.4.1 Renewable Energy Communities (RECs): citizen governance for a sustainable transition

Renewable Energy Communities (RECs) were created with a clear goal: to produce, share, and optimise clean energy, creating more sustainable and accessible energy systems at a local level. In fact, their overarching goal is to foster socio-economic and environmental benefits through a sustainable energy transition, with a focus on local production and use, contributing to support energy independence and security.

A REC is an autonomous legal entity, characterised by a constitutive act and a statute, that brings together citizens, businesses, public and private entities (including non-profit organizations, cooperatives and associations, small and medium-sized enterprises, but excluding central administrations and large enterprises) with a common goal: to produce, consume, and share renewable energy at a local level. In practice, it is a group of people and/or organisations that join forces to generate clean energy – such as solar energy – and distribute it among the members of the community itself, promoting a model of energy self-consumption. RECs were created to respond to a growing need for energy independence and environmental sustainability, offering their members the opportunity to reduce their environmental impact and, at the same time, cut their energy costs. This system makes it possible to make the most of the natural resources available in the area, ensuring both economic and social benefits for the community. Anyone can join a REC, regardless of whether they own a renewable energy production facility

The RECs offer a new perspective on energy production and distribution, highlighting the importance of citizen and policy governance in their establishment.

RECs play a crucial role in the energy transition, integrating energy production from renewable sources such as photovoltaics or wind with the consumption patterns of local communities and represent an important social innovation, empowering communities, supporting a participatory way of managing energy, and promoting local economic development, creating a more sustainable and accessible model for everyone (European Commission, 2018). Table 1.2 highlights the contribution of REC to the energy transition.

Table 1.2: RECs’ contribution to energy transition

Challenges	**Main advantages**
Renewable energy and lower emissions:	RECs use clean sources such as the sun, wind and biomass to generate electricity, helping to reduce CO_2 emissions and combat climate change.
Self-consumption and smart sharing	Each member of a REC can consume the energy they produce and share it with others. Excess energy can be fed into the grid, generating a financial return and creating a more efficient and sustainable energy system
Independence from large energy companies	RECs reduce dependence on multinational energy companies and fossil fuels, giving citizens greater control over their energy production and consumption
Greater awareness and sustainability	Participating in a REC means learning to manage energy better, promoting a more sustainable lifestyle and conscious growth within the community

Energy communities first emerged at the beginning of the 20th century, but it was in the 1970s, following the oil crisis, that the first significant ones were established in Europe, in the form of citizen cooperatives. Denmark was the first to exploit wind power (Mohammadi, 2023), followed by Germany and Belgium. (Wierling et al., 2018)

In Italy, an early example of community energy management was established Morbegno in 1897, with the founding of the Morbegno Electricity Company (SEM) using sources such as hydroelectric and thermoelectric power to meet local needs, while the first renewable energy community was established in Funes, South Tyrol, in 1921, still active today and produces energy from hydroelectric, photovoltaic and biomass plants.

In the 2000s, thanks to the liberalisation of the energy market and technological innovation, energy communities gained greater acceptance and momentum.

From a legislative point of view, RECs have been under consideration in Europe since 2018. The EU has played a key role in institutionalizing and promoting RECs as a key tool for the clean energy transition. The EU Clean Energy for All Europeans Package, adopted in 2019, which includes the Renewable Energy Directive (RED II) (Directive (EU) 2018/2001), explicitly recognizes RECs introducing the concept of energy communities in its legislation, notably as citizen energy communities and renewable energy communities (European Commission, 2018), and enshrines in law citizens' rights to generate, consume, store, and sell renewable energy. Since then, legislation on energy communities has been further strengthened by new or revised EU rules.

Italy has definitively and fully transposed the REC definition with Legislative Decree 199/2021 (REScoop.eu, 2025), which defined the new procedures for granting incentives aimed at promoting the construction of plants powered by renewable sources included in energy community configurations, self-consumption groups, and remote self-consumers.

The REC Decree aims to support the construction of renewable energy production systems (photovoltaic) and RECs with a composite series of economic incentives aimed at supporting the installation of plants and reward self-consumption and energy sharing among community members, including feed-in tariffs, Self-consumed energy fee, and valorisation of excess energy.

A capital grant of up to 40% of the total investment cost, financed with resources from the PNRR (National Recovery and Resilience Plan), was initially attributed to municipalities with less than 5000 inhabitants, and subsequently, the Ministerial Decree no. 127 of 16 May 2025 raised the threshold for the contribution to 50,000 inhabitants, making incentives more accessible even to larger territories. This grant can cover a significant portion of the initial costs, making the installation of systems such as photovoltaic systems more accessible. In addition to government incentives, many Italian regions and municipalities have launched calls for proposals and funding dedicated to Renewable Energy Communities, with the aim of further supporting the energy transition. Furthermore, it is possible to combine the incentive tariff with the PNRR contribution or other regional/provincial capital contributions up to a maximum of 40%, with a reduction of the incentive tariff of 50%.

In addition to grants on purchasing, fee and tariffs incentives on renewable energy produced and consumed are provided, which are in detail in Table 1.3.

Table 1.3: Tariffs and fee incentives on renewable energy and its financial mechanisms

Tariffs and Fees	**Financial Mechanism**
Feed-in tariff	REC members receive a feed-in tariff for energy produced from renewable sources and virtually self-consumed. This tariff, recognized by the Energy Services Manager (GSE), is valid for 20 years from the date each plant enters into operation, and it is calculated based on the following formula: $TIP_a = (TP_{base} + Z + FC_{ZONALE}) * (1 - f)$ where TP_{base} is the fixed component based on the size (P_i) of the REC TP_{base}= 80Euro/MWh with P_i<=200 kW TP_{base}= 70Euro/MWh with 200 kW< P_i<=600 kW TP_{base}= 60Euro/MWh with P_i>600 kW Z is the average value of the variable part defined by the REC decree and can vary between 0 and 40 Euro/MWh FC_{zonale} is a correction factor that considers the location of the plant FC_{zonale} =+10 Euro/MWh in North Italy FC_{zonale} =+4 Euro/MWh in Central Italy FC_{zonale} =0 Euro/MWh in Southern Italy

	f is a parameter that considers any contributions. In the case of benefiting from the PNRR contribution, f = 0.5 The tariff ranges from 0.06 Euro/kWh to 0.12 Euro/kWh depending on the size of the plant and the market value of the energy. Additionally, for photovoltaic systems, a surcharge of up to 0.01 Euro/kWh is applicable depending on the geographic location.
Self-consumed energy fee	The Italian Regulatory Authority for Energy, Networks and the Environment (ARERA) has established a financial contribution for self-consumed energy, which for 2024 amounts to 0.0104 Euro/kWh. This contribution represents an additional incentive for those who decide to consume energy produced by their community.
Excess energy valorization	Excess energy produced, i.e., energy not self-consumed by the community, can be sold on the market. Producers can apply to the GSE for "dedicated withdrawal," a mechanism that guarantees favorable economic conditions for the sale of renewable energy or hourly zonal price.

Currently, in Italy, there are 212 active RECs (as of March 6, 2025) with 326 plants, a total installed power of 18MW, and 1,956 users involved. Energy Service Manager makes available a portal to monitor the status of RECs in Italy (TensorLoops, 2025). The current installed capacity represents a very modest figure considering that the National Recovery and Resilience Plan (PNRR) targets 1,730 MW of installed capacity through collective self-consumption or energy communities by 30 June 2026 (Italian Government, 2021). However, as of 31 March 2025, the GSE had received nearly 4,000 applications for new RECs, corresponding to a total capacity of approximately 390 MW (approximately 23% of the PNRR target). Southern Italy holds considerable potential for RECs' expansion. The region is endowed with abundant solar and biomass resources. Southern Italy currently hosts 30% of the active RECs: 62 communities, with 84 plants for 5.9 MW of installed capacity and 494 users. In the Campania region, in particular, there are 15 operating communities, with 17 plants for 1.4 MW and 63 users.

The environmentalist association Legambiente has promoted the creation of the first renewable and supportive energy community – C.E.R.S. – in the San Giovanni a Teduccio neighborhood of Naples, with the financial support of the Fondazione con il Sud, which is providing Euro100,000 for the construction of the solar plant. This energy community is unique in its ability to bring together families in difficult circumstances, raise awareness, and encourage lifestyle changes regarding consumption and savings.

More recent studies (Ahmed et al., 2024) discussed the role of RECs in integrating energy storage, peer-to-peer trading, and demand-side flexibility, placing them as bedrocks of future smart, regional, and local energy systems.

The development of RECs will involve the predominant use of local smart-grid systems, which will allow for the management of bidirectional flows, modulation of loads, and participation in ancillary services such as balancing or reserve capacity. Digital technologies such as the Internet of Things, blockchain for energy sharing, and shared management platforms will become an integral part of RECs and will enable more transparent governance, detailed monitoring, and member engagement. Energy communities will contribute not only to renewable energy production but also to microgrid models, which can function partially autonomously in the event of main grid outages.

1.4.2 Multiscale influence on climate and energy strategies: the Role of Municipalities

The EU is recognized as having a significant influence on Member States' policies, particularly through establishing ambitious energy, environmental, and climate policies and directives. The relationship between higher-level policies (national and European) and local strategies is complex, and definitive causal relationships cannot always be established. The European Climate Law, the legal elaboration of the goals set in the European Green Deal, explicitly mentions the importance of climate action at a local level [art. 38 Regulation (EU) 2021/1119] supporting a multi-scale approach with a key role of local governments to address climate change, acknowledging a shared responsibility in defining and implementing local climate strategies. (Kastelein, 2024)

Governments can provide an overarching framework for climate policies and/or guidance documents that direct regional and local actions with a shared responsibility between different policy levels. (Armstrong, 2023)

Vertical coordination with the national level can be seen in many countries where national laws require municipalities to prepare urban climate strategies, often resulting in a large number of cities developing climate and energy strategies.

Relevant examples are briefly reported in the following. In the United Kingdom (UK) the Climate Change Act (2008) drove the adoption of a substantial number of local climate strategies, resulting in about 93% of the cities having a mitigation strategy (Burnett, 2025). The same happened in France, where the Grenelle II Law (2010) made it legally binding for regions, departments, and groups of cities over 50,000 inhabitants to release Climate-Energy Plans (PCETs) (Armstrong, 2023). In Spain, the National Climate Change Adaptation Plan 2021-2030 specifies detailed tasks for local governments, often requiring collaboration with the national government and Autonomous Communities for achieving objectives, including measures in mobility, energy efficiency, and building quality with new digital tools enabling tailored support for regional implementation (Climate high-level Champions, 2025).

In Germany, the national climate plan (NCP) [Climate Action Program 2050] sets goals and principles but does not specify tasks and/or responsibilities for local governments, although their involvement is mentioned. However, climate action carried out by municipalities must be implemented within the legal framework established by the federal government, which provides local authorities with little financial support.

In Ireland, the Climate Action and Low Carbon Development Act 2021 assign specific roles and responsibilities to local authorities that are legally obligated to achieve climate objectives. Local authorities are therefore mandated to take the lead in local climate action, and the actions undertaken must align with the national plan.

In Finland, national policy has been successfully translated into regional and urban policies, resulting in coherent local actions (Armstrong, 2023).

The Netherlands utilizes a model of decentralized governance where local governments are explicitly assigned and legally bound to carry out specific climate tasks, with a strong operational focus on cooperation across various governmental and non-governmental actors. The national government plays a coordinating role in decentralization, outlining tasks related to energy and climate.

In Italy, there is no specific coordination mechanism dedicated solely to climate change that has been adopted. Italy operates within a decentralized framework where subnational entities, especially the Autonomous Provinces, have significant constitutional powers to legislate and implement climate and energy policies. However, the lack of a specific national coordination mechanism and difficulties in achieving effective horizontal (interdepartmental) coordination represent ongoing challenges for policy integration (Bertuzzi et al., 2022).

The existence of global policies or national legislation does not guarantee the development of effective local strategies. A national framework alone is not always sufficient to trigger climate change action locally

The influence of EU initiatives and networks is particularly important in supporting city engagement and promoting action, capacity building, cooperation, and resource sharing. Their actions have a substantial impact in bridging the national policy divide in countries where national policies are weaker or absent.

In fact, key initiatives like the Covenant of Mayors (CoM) and Mayors Adapt and networks (including Eurocities, Energy Cities, and ICLEI) support, coordinate, and bundle city actions, offering financial support and transferring knowledge and expertise (IEA, 2023; Eurofound, 1999). International networks and alliances act as motivators for developing and approving local strategies. Participating in these transnational networks supports the development of an explicit urban approach to climate change, offering access to best practices and

The Covenant of Mayors initiative, launched in 2008 (EU Covenant of Mayors, 2022), introduced a bottom-up approach to energy and climate action. It was highly popular in Southern European countries where national mitigation strategies were lacking or implemented relatively late, and its success quickly went beyond expectations, supporting the voluntary implementation of thousands of mitigation strategies (Sustainable Energy Action Plans or SEAPs) even without a legal obligation at the national level. The Global Covenant of Mayors for Climate and Energy, launched in 2015, has been capitalising on this experience and its key success factors: the bottom-up, multi-level approach and a context-driven framework for action

(Global Covenant of Mayors, 2022). Membership in organizations like ICLEI, which link local governments to sustainable practices, boosts action on climate and energy at the local level, strengthening city engagement and motivation.

In this context, the application of systems analysis-based methodologies to local energy and climate planning is a prerequisite for defining coherent long-term strategies that ensure the achievement of sustainability objectives through the most effective combination of technological, energy, and economic measures. The development of energy system models and integrated planning tools to support local energy planning was fostered by the International Energy Agency (IEA) since the 90’s through Annexes 22 and 33 focusing on Energy Efficient Communities & Advanced Local Energy Planning (ALEP) (IEA-EBC, 2005), which ran from 1991 to 1998 representing the first example of application of a systems analysis approach to local energy planning in five European countries. This collaborative effort allowed us to explore the various aspects of local energy planning, including software tools, environmental impact assessment models, and strategies for integrated planning, proving the effectiveness of the IEA energy system models to derive multi-objective long-term planning strategies for the urban energy systems.

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CHAPTER 2 METHODOLOGY

2.1 Review of energy models and tools to support energy planning

Over the last few decades, the role of energy system analysis in policy has expanded noticeably, as documented by DeCarolis (2012). Various international organizations and research institutions have developed energy models to support decision-makers in shaping short-term energy and climate strategies in the context of long-term sustainable development. Model-based scenario analysis has enabled the definition of a baseline and the investigation of possible future energy-technology trajectories aimed at achieving policy objectives that enhance technological development (IEA, 2025; Mundu et al, 2024). Energy system models strive to find a balance between accuracy and manageability across a spectrum of model complexity, ranging from simpler simulation-based spreadsheets to more complex energy system optimization models (DeCarolis, 2012). Although energy models are rapidly advancing in addressing the most pressing energy and environmental challenges, most cities are still unable to use them to define their energy and climate policies. To facilitate the adoption of analytical decision-support tools, it is useful to conduct an in-depth characterization of the most widely used models, focusing on their most important features. This can help decision-makers in choosing the most suitable models for different purposes and, particularly, to support policy assessment and energy-environmental planning (Molina-Perez, 2023; Van Beeck, 1999).

In fact, energy and environmental planning are fundamental tools for ensuring the implementation of global policies within the national, regional, and local framework, and for ensuring that the demand for energy and services is met through strategies that guarantee a secure, accessible, and environmentally friendly supply, while supporting economic development and social well-being. Quantitative models and decision support tools are therefore essential for adequately managing the complexity of energy planning in the context of current policy challenges. Quantitative energy models can acquire and manage large amounts of heterogeneous data, analysing a variety of scenarios and providing useful information on the configuration of the energy system and the feasibility of technological options, designing robust pathways to achieve different policy objectives.

Energy models are widely used for policy analysis and to support decision-making at all geographical levels. Large-scale models support global scenario analysis of future energy trends. For example, the Global Energy and Climate Model (GEC Model) was developed under the auspices of the International Energy Agency and used to conduct the world's first comprehensive study on the transition to a net-zero CO_2 energy system by 2050 (IEA, 2024). Many examples of application of energy models for policy assessment at different spatial scales can be found in the literature (Huppmann et al., 2019; Calvin, 2019; Di Leo et al., 2024; Barnes, 2022; Comodi, 2012). In-depth global, multi-country, national, and local energy and environmental analyses are performed within the Energy Technology Systems Analysis Program (ETSAP), a long-running Technology Collaboration Program of the International Energy Agency (IEA).

At the local level, energy models mainly support energy planning for the assessment of EU and national energy and climate targets, the definition of sustainable energy and climate action plans, and the roll-out of community-based actions aimed at supporting the green energy transition.

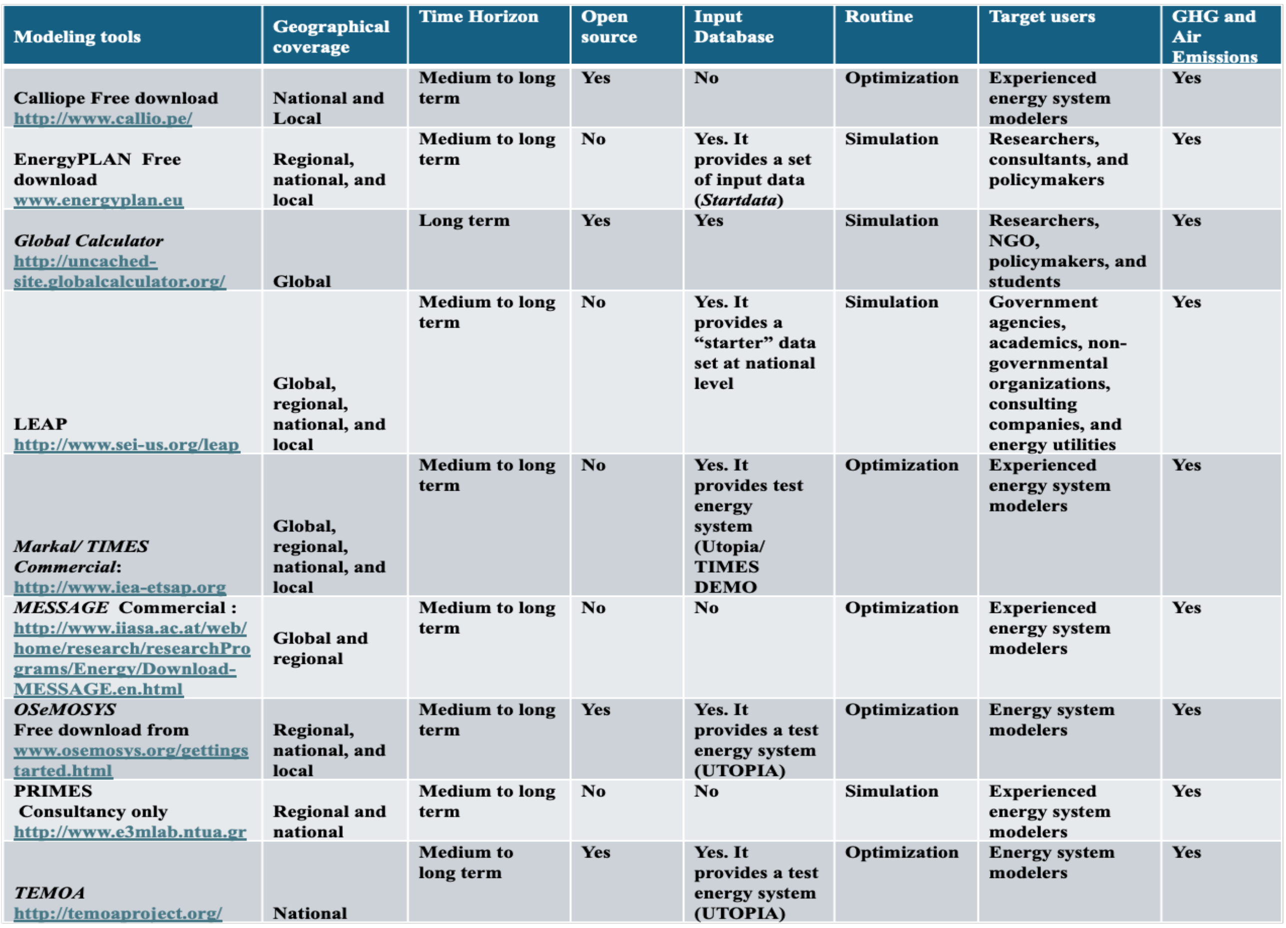
Recently, energy models should encompass sole techno-economic aspects, including drivers and parameters to consider social issues as behavioral changes and public acceptance, enabling a fair and just energy transition (Huckebrink et al.,2021).

The selection of appropriate energy models is a key issue for modelers and decision-makers, who need dynamic, sector-specific, policy-focused economic models with detailed representations of technological progress to understand the impact of different policies on achieving the energy transition (Barbrook-Johnson et al., 2024).

Table 2.1 presents a selection of well-known comprehensive models used for policy assessment at both the supra-national and national levels. These models demand a significant level of expertise in energy system modeling or scenario analysis. The MARKAL/TIMES model generator has been used to represent and analyze energy systems on a local scale, showcasing its effectiveness and scalability (Di Leo et al., 2015; IEA-ETSAP, 2016; Salvia et al., 2014; Jank et al.,2005).

Table 2.2 presents a list of sectoral models, but not limited to these. Recently, there has been a shift towards the use of open-source tools, including open models and open data, which are accessible without the need for a commercial license or a research agreement. This shift has afforded greater autonomy for both model developers and users, thereby enhancing the quality, transparency, and credibility of the models. Additionally, it has promoted their use in providing policy advice across various public authorities at local, regional, and national levels. Furthermore, the proliferation of open data and cloud computing has facilitated the sharing of tools and data, resulting in reduced costs, invigorated research activities, and the generation of value-added products derived from the associated data streams (MELODIES, 2016).

Table 2.1: Highlights of the main comprehensive Model (Cosmi et al.,2017)



Modeling tools	Geographical coverage	Time Horizon	Open source	Input Database	Routine	Target users	GHG and Air Emissions
Calliope Free download http://www.callio.pe/	**National and Local**	**Medium to long term**	**Yes**	**No**	**Optimization**	**Experienced energy system modelers**	**Yes**
EnergyPLAN Free download www.energyplan.eu	**Regional, national, and local**	**Medium to long term**	**No**	**Yes. It provides a set of input data (*Startdata*)**	**Simulation**	**Researchers, consultants, and policymakers**	**Yes**
Global Calculator http://uncached-site.globalcalculator.org/	**Global**	**Long term**	**Yes**	**Yes**	**Simulation**	**Researchers, NGO, policymakers, and students**	**Yes**
LEAP http://www.sei-us.org/leap	**Global, regional, national, and local**	**Medium to long term**	**No**	**Yes. It provides a "starter" data set at national level**	**Simulation**	**Government agencies, academics, non-governmental organizations, consulting companies, and energy utilities**	**Yes**
***Markal/ TIMES Commercial*:** http://www.iea-etsap.org	**Global, regional, national, and local**	**Medium to long term**	**No**	**Yes. It provides test energy system (Utopia/ TIMES DEMO**	**Optimization**	**Experienced energy system modelers**	**Yes**
***MESSAGE* Commercial :** http://www.iiasa.ac.at/web/home/research/researchPrograms/Energy/Download-MESSAGE.en.html	**Global and regional**	**Medium to long term**	**No**	**No**	**Optimization**	**Experienced energy system modelers**	**Yes**
OSeMOSYS **Free download from** www.osemosys.org/gettingstarted.html	**Regional, national, and local**	**Medium to long term**	**Yes**	**Yes. It provides a test energy system (UTOPIA)**	**Optimization**	**Energy system modelers**	**Yes**
PRIMES **Consultancy only** http://www.e3mlab.ntua.gr	**Regional and national**	**Medium to long term**	**No**	**No**	**Simulation**	**Experienced energy system modelers**	**Yes**
TEMOA http://temoaproject.org/	**National**	**Medium to long term**	**Yes**	**Yes. It provides a test energy system (UTOPIA)**	**Optimization**	**Energy system modelers**	**Yes**

Table 2.2: Highlights of the main Models for subsystems Analysis (Cosmi et al.,2017)

Modeling tools	**Analyzed sectors**	**Geographical coverage**	**Time Horizon**	**Open source**	**Input Database**	**Routine**	**Target users**	**GHG and Air Emissions**
Balmorel Free download from http://balmorel.com/	Power and CHP (Combined heat and power) sectors	National	Short to long term	Yes	Yes	Optimization	Experienced energy system modelers	Yes
DESSTINEE Free download from http://tinyurl.com/desstinee	Entire energy system with a focus on the electricity system	Regional (Europe)	Medium to long term	Yes	Yes.	Simulation	Experienced energy system modelers	Yes
DIETER Free download from www.diw.de/de/diw_01.c.508843.de/forschung_beratung/projekte/projekt_homepages/dieter/dieter.html	Power system	National	Annual, with a long-term perspective	Yes	Yes	Optimization	Experienced energy system modelers	No
EMPS Commercial : https://www.sintef.no/en/software/empsmulti-area-powermarket-simulator/	Power systems with a focus on hydro power	Regional (e.g., Nordic countries)	Short to long term	No	Yes	Simulation Optimization	Experienced energy system modelers	Yes
GTMax Commercial: http://www.adica.com/software.html (forAmerican market)	Electric market analysis, generation and transmission investment, regional interconnection and power exchange	National and local	Annual	No	No	Optimization	Electric utilities, transmission companies, regulatory bodies, research institutes, and consulting firms	No
URBS Free download from https://urbs.readthedocs.org/en/latest/	Multicommodity energy systems with a focus on optimal storage sizing and use	Regional, national, and local	Annual	Yes	Yes	Optimization	Research institutes, universities	Yes

2.2 Types of models

2.2.1 Optimisation Models

Mathematical optimisation models are used to find the best solution to a problem from a set of possible choices, considering specific constraints. With reference to energy modeling, the scope is to identify the optimal minimum-cost configuration of an energy system fulfilling physical, technical, and policy constraints, such as, for example, resources and technologies availability, emissions cap, etc. These models, in general, have a deterministic approach, assuming that the future can be precisely determined based on the current state. However, in some cases, their stochastic version allows for considering randomness and uncertainty in the modeling process. Outstanding examples include the IEA- ETSAP models (Loulou R et al.; 2005), the open-source modelling system (OSeMOSYS, 2008) widely used for energy planning, and HOMER, utilized for designing hybrid renewable micro grids.

2.2.2 Simulation Models

Simulation models use mathematical algorithms and computational techniques to simulate interactions and dynamics between various components and reproduce their behaviour over time. The main objective is to understand the behaviour of the system, evaluate alternative scenarios, and guide decision-making processes through a virtual representation of the system under study based on the transformation of the complex system into a simplified model. The integration of stochastic elements to account for uncertainty and iterative simulation of the system's behaviour allows its performance to be analysed under different conditions (Mundu, 2024). Examples of simulation models are EnergyPLAN, Renewable Energy and Energy Efficiency Technology Screen (RETScreen), which can be used for planning of power, heating, and cooling facilities, including district energy and cogeneration (or combined heat and power), and HOMER.

2.2.3 Econometric Models

Econometric models investigate the statistical relationships between the various economic quantities of a particular economic phenomenon, using statistical methods to extrapolate from measured parameters past market behavior into the future. They forecast the short- or medium-term future in terms of labor, capital, or other inputs using aggregated data that has been measured previously. In strategic planning, they are often used to analyse the energy-economic relations within a system.

Macro-Economic Models

Macroeconomic models are designed to describe the operation of the problems of the economy of a country or a region, focusing on the overall economy and the interactions between the various sectors. They can be used in energy demand analysis (i.e., the output is determined by demand), to describe transactions among economic sectors, and assist in the analysis of energy-economic interactions (e.g., Input-Output tables).

Economic Equilibrium Models

Economic equilibrium occurs when market forces are balanced, and supply meets demand without external influences. Economic equilibrium models examine Energy in the framework of the economic system as a part of a larger system, highlighting the relationships between the economic sectors.

Generally, two types of equilibrium models are distinguished: partial equilibrium models that investigate specific market segments while prices and quantities on other markets are taken as given, and general equilibrium models that analyse the whole economy with many interacting markets/sectors.

An outstanding example of a macroeconomic model most utilized in policy assessment is GEM-E3, a multi-regional, multi-sectoral, recursive dynamic computable general equilibrium (CGE) model that covers the interactions between the economy, the energy system, and the environment, providing details on the macroeconomy.

2.2.4 Analytical approach

In energy systems modelling, the analytical approach can be generalised into three main groups:

Top-down energy models, which are macroeconomic models that analyze the aggregated effects of energy policies and market changes on the economy as a whole, are measured in the form of GDP, employment, and national energy consumption. Rather than focusing on individual technologies or consumer behaviors, they take a broad, economy-wide view to simulate economic development, energy demand, and supply (Cosmi et al, 2017). They are often derived from Computable General Equilibrium (CGE) or macroeconomic models, such as, for example. GEM-E3 and the Global Trade Analysis Project (GTAP) are two well-known top-down models used to support decision-making. Top-down models are useful for understanding the general effects of policies and the resulting feedback effects on the economy, but they may be inadequate for the more specific details required for technology assessment or planning at the community level (Fattahi et al, 2023).

Bottom-up energy models forecast energy demand by aggregating detailed information on individual energy-using devices, goods, and service needs and consumer behavior. They build an understanding of future energy use by analyzing how specific sectors, such as buildings, industry, or transport, consume energy. This approach contrasts with top-down models, which use macroeconomic factors to predict energy consumption at a national or global level. Bottom-up models are particularly useful for municipal and regional planning, which requires analysis of technology configurations specific to a particular country or context (Prina et al, 2020). Well-known examples of scenario-based bottom-up models widely used for long-term strategic planning include IEA-ETSAP MARKAL and TIMES models, MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impact) (Zhou et al, 2019), MESSAGEix, a new generation of the MESSAGE integrated assessment model, OSeMOSYS

(Open-Source Energy Modelling System), and LEAP (Long-range Energy Alternatives Planning System).

Bottom-up models can be used within a hybrid modeling approach by linking them with other types of models. In particular, a "soft-link" to macroeconomic models, such as the MACRO model for the MESSAGE (Messner, 1995), combines the detailed technology data of a bottom-up model with the macroeconomic feedback loops of a top-down model, providing a more comprehensive integrated assessment. Another example of integrated modelling is the IEA's Global Energy and Climate Model (GEC), which integrates the World Energy Model (WEM), a large-scale simulation model designed to replicate the functioning of energy markets, and the Energy Technology Perspectives (ETP) model, a technology-rich bottom-up model developed to be used in parallel with the WEM. The GEC Model is currently the main tool used by the IEA studies to generate detailed sector-by-sector and region-by-region long-term scenarios.

2.2.5 Other models feature

Geographical coverage

Geographical coverage is a key factor in structuring models. Global models provide a macroeconomic view of the entire world economy. Regional models refer to large international divisions, such as Europe, Latin America, and Southeast Asia, although in some cases they can also denote multi-regional divisions at the national level (e.g., the MONET Multi-regional Energy model of the 20 Italian Regions) (Gelmini, 2012).

National models assume that the global market is exogenous, but also account for the principal macroeconomic sectors, addressing the complex dynamics and linkages between them and their subsectors. Typical national models include short-term econometric models or long-term general equilibrium models. Global, regional, or national models often require the use of very aggregated data, implying strong simplifications for the energy system.

Local-scale models focus on national regions and cities, addressing planning issues through a multidisciplinary energy-environment-economy approach. This supports a bottom-up perspective that requires disaggregated information for more in-depth analysis.

Sectoral coverage

Energy models can cover different sectors, including energy systems, transport, industry, buildings, and agriculture, often through "sector coupling" to capture interactions between them. Different energy models vary in their sectoral focus depending on their purpose. Multi-sector models focus on interactions between different sectors, while single-sector models provide specific information on a particular sector (Cosmi et al, 2017). A soft-link between multi-sector and single-sector models can be envisaged for an in-depth analysis of specific energy sectors (power system, industrial sector, transport, and buildings), while allowing for consideration of relationships with the entire energy system.

Time horizon

The choice of time horizon is fundamental in energy modelling and is made based on the scope of the analysis and the characteristics of the energy models. The choice of the appropriate model depends heavily on the time horizon of the analysis, which is therefore a key parameter.

Short-term, mid-term, or long-term time horizons are usually defined as follows:

- Short term: up to 5 years or less.
- Medium term: 5 to 15 years.
- Long term, over 15 years.

Short-term models focus on operational dynamics and market decisions in the immediate future. They are used by energy network operators and power plant managers for real-time and short-term activities, and most of them use neural networks and deep learning for day-ahead load forecasting.

Medium-term models address operational and strategic decisions that affect the energy system (e.g., planning power plant maintenance schedules, managing fuel procurement, and analysing the impact of medium-term policies or market changes). An outstanding example is The World Energy Model (WEM), which has been used by the International Energy Agency (IEA) for medium-term energy projections (IEA, 2024).

Long-term models are used for strategic planning and scenario analysis, assessing the long-term effects of energy and climate policies (e.g., emission, renewables, and energy efficiency targets), assessing the impact of new technologies, and driving major capital investments. The aforementioned models, TIMES and LEAP, are widely used over the long term for energy planning and policy assessment. The Wien Automatic System Planning Package (WASP) model is another example of a long-term model utilised to determine optimal power generation expansion plans.

2.3 The Integrated MARKAL-EFOM System (TIMES) models' generator

Since the 1990s, the modelling tools developed within the Energy Technology Systems Analysis Program of the International Energy Agency (IEA-ETSAP) have provided a fundamental basis for strategic energy planning and the development of long-term scenarios at various spatial scales. These models are invaluable for evaluating policy pathways, technological options, and defining decarbonisation trajectories over medium- to long-term time horizons (ALEP, Annex IEA).

The Integrated MARKAL-EFOM System (TIMES) model generator was developed based on the previous MARKAL and EFOM models, combining two systematic approaches to energy modelling: a technical-engineering approach and an economic approach. It is an essential and widely used tool for long-term strategic energy and environmental policy analysis, helping decision-makers understand how to meet future energy demands and environmental goals most cost-effectively. (Loulou, 2008). The main features are summarized in Table 2.3

Table 2.3: Key Characteristics of TIMES

Characteristic	**Description**
Model Type	It is a bottom-up, technology-rich, optimization model generator that uses linear programming to find a least-cost energy system configuration.
Objective	The core function is to minimize the total discounted system cost (including investment, operation, maintenance, and fuel costs) over the entire time horizon, subject to various user-defined constraints.
Approach	It combines two systematic approaches to energy modeling: a technical engineering approach (detailing energy technologies) and an economic approach (analyzing costs and economic equilibrium).

Characteristic	Description
Scope	A TIMES model encompasses the entire energy system, from primary resources (fossil fuels, renewables) through a chain of processes (conversion, transport, distribution) to the supply of energy services demanded by consumers (e.g., heating, mobility, lighting).
Time Horizon	It is typically applied for medium to long-term scenario analysis, often in multi-year steps (e.g., 5-year periods) up to 2050 or beyond. It assumes perfect foresight, meaning investment decisions are made with knowledge of future costs and demands.
Input	Includes data on energy service demands, characteristics of existing and future technologies (costs, efficiencies, lifetimes), resource availability/potentials, and various policy/environmental constraints (e.g., CO_2, renewable penetration targets).
Output	Provides optimal results for: technology capacity and investment, fuel flows (production, trade), energy commodity prices, GHG emissions, and energy costs.
Application	It is widely used globally by governments and researchers to explore possible future energy scenarios, evaluate the impact of energy and climate policies (like emissions reduction targets or renewable energy mandates), and identify cost-optimal paths for energy system transformation.
Software	The generator is written in the GAMS (General Algebraic Modeling System) language and uses front-end software like VEDA for data management and results analysis.

The modelling platform allows for a comprehensive representation of energy systems, covering all stages from primary resources to the chain of processes that transform, transport, distribute and convert energy in the provision of energy services required by consumers. The bottom-up, technology-oriented optimisation approach (minimum cost) allows for the identification of cost-effective solutions focused on technological replacement based on efficiency, economic profitability, and the political context, ensuring the competitiveness of the energy system. Prospective analysis is carried out by defining and comparing contrasting medium- to long-term scenarios (30 to 100 years) to determine the energy technology roadmaps that support the transition to a sustainable, low-carbon energy system, in accordance with exogenous constraints (e.g., technical, political, legal, financial, market, and organisational requirements) (Loulou, 2008).

The prerequisite for starting to model any energy system is the definition of the Reference Energy System (RES), a flow diagram that represents the complex interactions between the demand sectors and the supply within the technology network. Based on the RES structure, the data for the characterization of the energy system and its constraints are gathered and elaborated to define the model data input. In this phase, the statistical reference year (base year), the time horizon of the analysis, and the time-horizon intervals are defined. An accurate description of the system in terms of resource availability (fuels and materials), macroeconomic parameters, infrastructures, physical and policy constraints is also performed, together with the characterization of technologies.

Technology characterization includes technical, economic, and environmental parameters, namely input and output fuels and materials and services (commodities), emission factors, technical and economic parameters (efficiency, market availability, operating lifetime, investment costs, operating and maintenance costs). This step is essential to allow comparison of competing technologies and to assess the feasibility of integrating new technologies, such as solar photovoltaic (PV) systems, into the existing energy system over the explored time horizon (Labriet et al., 2015).

After the quantitative characterisation of the RES components and the boundary conditions, another key step is to project final demand over the time horizon, using regression models based on economic factors and historical trends. The last step concerns the calibration of the draft model and verification of the compliance of the optimal solution with statistical data.

After the calibration the alternative scenarios are defined and quantitatively determined to model either the baseline projection of the energy system without the introduction of major new policy interventions, changes in consumer behaviour, or accelerated technological shifts beyond current, established trends (Business as Usual scenario, benchmark for comparison) and the alternative scenarios, which illustrate prospective futures that deviate significantly from the baseline Business-as-Usual (BAU) scenario by incorporating proposed, or potential changes in government policy, technology, or societal behavior. The definition and comparison of alternative scenarios is crucial for policymakers and analysts because they help evaluate the effectiveness, costs, and benefits of different actions and identify the energy-technology roadmaps for the implementation of the policy measures.

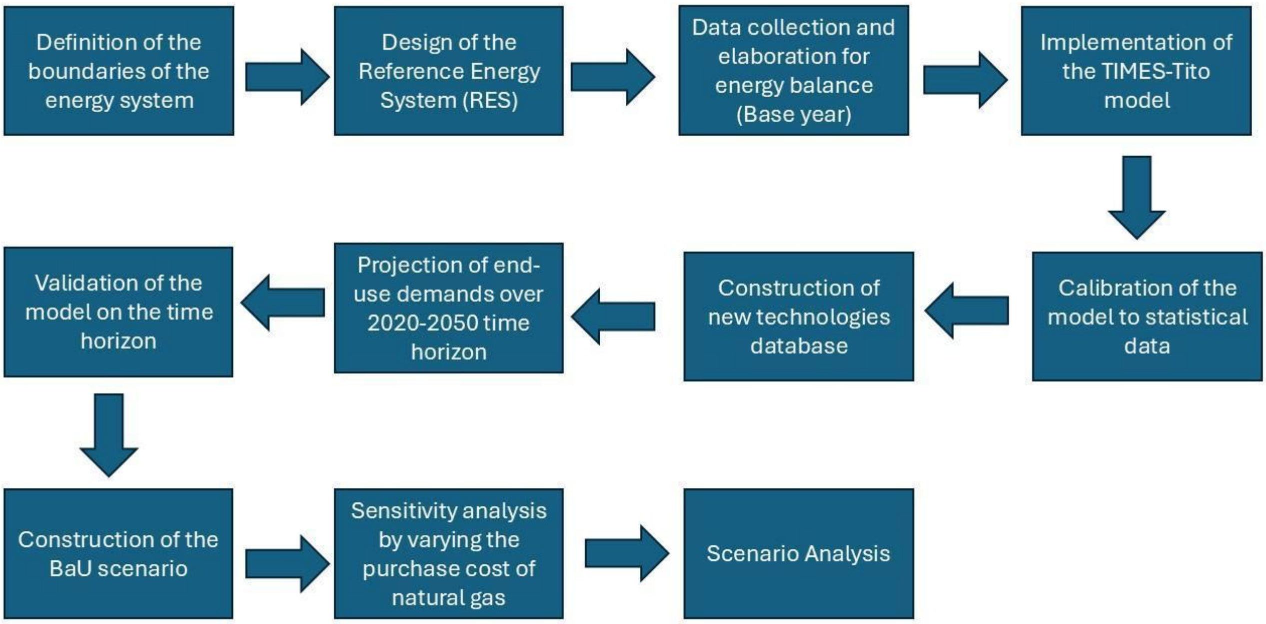


Figure 2.1: Methodological steps to build and optimize a TIMES energy model

Figure 2.1 represents the whole process of building an energy model. The model is ultimately solved using the TIMES solver, and the results are analyzed and interpreted to inform decisions. The entire process is focused on being transparent, accurate, and relevant to the stakeholder requirements.

A model interface is used to facilitate the setup of the TIMES models, enable a smart management of input and output data, and explore the results, allowing a meaningful comparison. In particular, the VEDA2.0 (Versatile Data Analyst), designed and developed by KanORS-EMR (India), is currently the most used interface to manage input and output data produced by the TIMES models, increasing efficiency and transparency.

The VEDA framework is structured into two subsystems: the Browse/Items view, which allows users to examine input data, and the Results/Reports modules, which focus on analyzing model outputs (KanORS-EMR, 2025). Data and assumptions are input into VEDA, which supplies this information to the TIMES code. VEDA accepts inputs from a range of Excel files featuring diverse yet adaptable structures, optimized for efficient processing of data-intensive models. The TIMES code operates within the GAMS environment, generating textual output that is read by VEDA. In turn, VEDA provides users with both numerical and graphical representations of the data through Excel outputs.

Operatively, each set of data files is processed by the TIMES Model Generator, the source code, which generates a matrix representing the energy system model as a mathematical programming problem. The computer programming language of the model generator is the General Algebraic Modeling System (GAMS). In turn, the matrix provides the input to the solver, a software package integrated with GAMS, that solves the mathematical programming problem and gives the solutions, which are post-processed by the TIMES Model Generator and aggregated utilising the VEDA interface

2.3.1 Mathematical formulation of the TIMES (The Integrated MARKAL-EFOM System)

TIMES (The Integrated MARKAL-EFOM System) model moves beyond simple cost minimization to compute a supply-demand equilibrium where both the energy supplies and the energy service demands are endogenously determined by the model. This equilibrium is driven by the user-defined specification of demand functions and is achieved by maximizing the net total surplus, defined as the sum of producer and consumer surpluses, which is a key metric for societal welfare in microeconomics (Loulou, 2016)

The model mathematically represents and solves the supply-demand equilibrium by transforming the economic equilibrium problem into a mathematical optimization problem. The core mathematical approach is rooted in the economic theory that the supply/demand equilibrium corresponds to the maximization of the net total surplus. The Equivalence Theorem, which serves as the basis for the computational method, states that an economic equilibrium is reached when the sum of the producers' and consumers' surpluses is maximized (Loulou, 2016). This computed equilibrium captures a major element of feedback effects not previously accounted for in standard bottom-up energy models. The equilibrium is driven by user-defined demand functions, which determine how the demand for each energy service varies based on its market price.

TIMES assumes that each demand has a constant own-price elasticity in each time period, and that cross-price elasticities are zero. The demand function for each demand category i is defined as:

$$DM_i\,/DM_i^0 \;= (\,p_i\;/\,p_i^0\,)^{E_i} \qquad 2.1$$

The inverse demand function determines price as a function of demand:

$$p_i = \;p_i^0\,.\,(DM_i\,/DM_i^0)^{1/E_i} \qquad 2.2$$

The superscript “0” indicates a reference case, and the elasticity **E_i** is negative, having different values, one for upward changes and the other for downward changes.

The pure cost minimization problem (inelastic demand) can be written as

$$Min\;\; C.X \qquad 2.3$$

$$st.\;\; \sum_k VAR\_ACT_{\mathrm{k,i}}(t)_. \;\geq\; DM_i\,(t) \qquad i \;=\; 1{,}2\,\ldots,I;\; t \;=\; 1,\ldots,T \qquad 2.4$$

$$\text{and } B.X \geq b \qquad 2.5$$

Where vector X represents all the TIMES variables, $VAR\,\_\,ACT$ is the activity levels of end-use technologies, DM_i and are the demand categories.

Equation (2.5) represents the set of modeling constraints (e.g., resource and technology availability, policy targets, etc.). While a pure cost minimization model (for inelastic demands) is a standard linear Program (LP), when demands are elastic, TIMES must compute the supply/demand equilibrium where demand adjusts to changes in marginal costs (prices). The linearization process adds new step-variables but generally does not add new constraints (besides upper bounds on the step variables). Therefore, incorporating elastic demands has only a very minor impact on computational time and the tractability of the resulting large Linear Program. Equations 2.6, 2.7, and 2.8 are where the objective is to maximize the net total surplus.

$$\text{Max} \sum_i \sum_t \left(p_i^0\,(t)\,.\,[DM_i^0\,(t)]^{-1/E_i}\cdot \int_a^{DM_i\,(t)} q^{1/E_i}\,.dq\right) \;-\; c.X \qquad 2.6$$

$$st.\;\; \sum_k VAR\_ACT_{\mathrm{k,i}}(t) \;-\; DM_i(t) \geq\; 0 \quad i \;=\; 1,..,I;\; t \;=\; 1,\ldots,T \qquad 2.7$$

$$and.B\;\cdot\;X\;\geq\;b \qquad 2.8$$

$DM_i(t)$ is now a vector of variables in equation 2.7, rather than a fixed demand. Equation 2.6 is computed to produce the following maximization program:

$$\text{Max} \sum_i \sum_t \left(p_i^0\ (t)\ .\ [DM_i^0\ (t)]^{-1/E_i} \cdot DM_i(t)^{1+1/E_i} \cdot / \ (1 + 1/E_i)\right)\ -\ c.X \qquad 2.9$$

$$st.\ \ \sum_k VAR\_ACT_{\mathrm{k,i}}(t)\ \geq DM_i(t) \qquad i = 1, .., I;\ t\ =\ 1, \ldots, T \qquad 2.10$$

$$and\ B\ \cdot\ X\ \geq\ b \qquad 2.11$$

NB: $[\boldsymbol{DM_i^0}\ (\boldsymbol{t})]^{-\boldsymbol{1}/E_i}$ are nonlinear expressions and not usable in a linear program

2.4 Applications of the TIMES models' generator

The TIMES modeling framework has been applied for scenario analysis and policy assessment from the global to the local scale. Many excellent examples in the literature recognise the usefulness and flexibility of TIMES-based models, some of which are listed below.

On a global scale, the ETSAP-TIAM (TIMES Integrated Assessment Model), formerly developed by (Loulou et al., 1999), currently includes 16 world regions Africa, Australia-New Zealand, Canada, Central and South America, China, European Union, Central Asia Caucasus, Other Eastern Europe, Russian Federation, India, Japan, Mexico, Middle-East, Other Developing Asia, South Korea, United States) modeling several thousand technologies in all sectors of the energy system and considering the emission coefficients for the three main GHGs: CO_2, CH_4, and N_2O. The time horizon extends to the year 2100. New features in its mathematical formulation allow greater flexibility and power to the ETSAP-TIAM in performing perspective analyses (Loulou et al., 2007). Among the numerous studies using ETSAP-TIAM, Ystanes Foyn et al. (2011) employed this model to represent a global-scale renewable energy system. Their work explored how uncertainties in climate sensitivity values can influence optimal decarbonization strategies, demonstrating TIMES' ability to provide useful information for high-stakes global climate policies. Other interesting applications concern the development and upgrade of a pan-European TIMES model in the framework of a series of EU-funded projects.

The TIMES Pan EU model of the New Energy Externalities Developments for Sustainability (Cosmi et al, 2006) has been set up in the framework of the NEEDS project (NEEDS, 2004) to analyse the role of energy technologies and their interaction for meeting European energy and climate change policy targets, and the role of energy externalities in the definition of climate policies

The TIMES Pan-EU consists of twenty-eight national models linked together in a European-scale model that considers the main energy and environmental policies at the national level. The reference database on energy technologies includes a comprehensive set of technologies and a series of predefined technological and economic parameters for Europe. Another interesting application concerns the integration within a single energy model of the TIMES global model (TIAM-World), the Pan European TIMES model (PET), and the RECOR model (REaccess CORridors) to investigate the risk associated with the possible energy corridors supplying the European countries and to assess how to increase the EU energy system security. (Kanudia et al.,2013)

Recent studies have extended the TIMES Pan European framework to current policy landscapes. (Luxembourg et al., 2025) presented the TIMES-Europe model, a pan-European system designed to evaluate the implications of the European Green Deal and REPowerEU initiatives. The model simulates energy supply-demand interactions across EU member states and supports analysis of energy security, technology deployment, and sectoral coupling strategies under decarbonization constraints.

Other applications concern the implementation of multi-region energy models in different geographical areas for different purposes, e.g., the Central Asia and Caspian region (Cassetti et al, 2023), and the Walloon Region (Coppens et al., 2022).

A multiregional model describing the whole Italian energy system through the modeling of 20 structurally consistent and electric-interconnected regional tools by the MOdello Nazionale Energetico TIMES - MONET was developed by RSE (Gelmini et al.,2012). Gaeta et al employed this TIMES-RSE model to create an energy roadmap aimed at achieving national climate neutrality by 2050. Their work identified key policy interactions, investment levels, and technology choices needed to meet Paris Agreement-aligned decarbonization targets (Gaeta et al.,2022).

Numerous national TIMES-based models have also been developed at a national scale all over the world for scenario analysis and for identifying the energy-technology roadmaps for the achievement of strategic energy and climate targets (IEA-ETSAP).

A recent application concerns a model developed for Central Asia by Zhakiyev et al. (2022) that used a MARKAL-EFOM model to optimize Kazakhstan's total energy system under decarbonization goals extending to 2060. Their study evaluated multiple cross-sectoral interventions, including energy efficiency, renewable integration, and emission reduction strategies.

Gronheit documented Denmark's collaborative use of MARKAL/TIMES within the ETSAP initiative, emphasizing its role in EU research programs and national energy policy assessments (Gronheit, 2008). Balyk et al. (2021) developed the TIMES-Ireland Model (TIM), supporting national energy strategy formulation by simulating sector-specific contributions toward long-term emission reduction.

TIMES based models are also widely used to support local energy and climate planning In fact, cities, towns and municipalities are now seen as the most important players in the energy transition, they are the ones who translate national policies into local actions to combat climate change supported by initiatives such as the EU Covenant of Mayors (2025) and the Global Covenant of Mayors for Climate & Energy (GCOM), which emphasis the effectiveness of a multilevel governance model with a shared long-term vision based on voluntary engagement.

Many examples of local-scale applications of ETSAP-TIMES can be found in the literature. In particular, a comprehensive methodology for sustainable planning based on ESAP-TIMES was implemented and tested in four European municipalities: Evora (Portugal), Nottingham (UK), Trikala (Greece) and Cesena (Italy), demonstrating the usefulness of a common approach to addressing the current and future city energy needs and to identify the cost-effective mix of short-, medium-, and long-term measures (Gargiulo et al, 2017).

Concerning the development of models for the Basilicata region, the geographical reference for our study, the ETSAP-TIMES framework was used to assess the effectiveness of the regional energy plan in compliance with the European Commission's long-term vision (Di Leo et al., 2021) optimise an industrial production system in the automotive sector (Di Leo et al., 2020) and to model the water-energy-food (WEF) nexus in agriculture (Di Leo et al, 2024). In particular, the Basilicata model, further developed and improved as part of the SMART Basilicata project (Di Leo and Salvia, 2014), forms the backbone of the energy model for the municipality of Tito.

This bibliographic review highlights the usefulness of energy system modelling tools, in particular ETSAP-TIMES, for policy assessment and strategic planning, facilitating the integration of different macroeconomic sectors and enabling the achievement of multiple economic, environmental, and social objectives, paving the way for the effective implementation of priority actions to support the transition to green energy.

In this context, thanks to scenario analysis and a minimum cost optimisation approach, the TIMES model is also extremely well suited to assessing the effectiveness and feasibility of decentralised energy systems such as Renewable Energy Communities (RECs), exploring the possibilities of increasing renewable use at the municipal level, and reducing energy dependence and energy bills.

Although numerous policy studies have been conducted in northern and western European countries, where research and adoption of RECs have been carried out, there are still no examples of modelling decentralised, community-led energy systems with ETSAP-TIMES. Given the growing interest of local authorities in decentralised energy production, which contributes to achieving national and EU targets for decarbonisation and energy self-sufficiency, and the need to take a comprehensive view of the technological, economic, and social aspects of RECs, the ETSAP-TIMES model is particularly well suited to representing RECs and studying their technical feasibility and economic, environmental, and social sustainability.

These considerations have been substantial in setting up a local-scale model to represent a REC and evaluate its feasibility. The municipality of Tito was chosen as a pilot case considering that it is a signatory of the Covenant of Mayors since 2011 and, in 2024, signed the Climate emergency declaration, being committed to drastically reducing its GHG emissions. This pilot study will also be included as a feasibility study in the LIFE LOCAL GoGREEN project aimed at empowering local authorities of six small municipalities in Europe “to deliver, implement, and monitor ambitious short and medium-term plans for accelerating the Clean Energy Transition and achieve the 2030 target”.

Modeling renewable energy communities with ETSAP-TIMES requires a comprehensive approach that combines technical analysis, data management, and stakeholder engagement. Based on model outcomes, implementation strategies can also be defined also involving community members and policymakers in discussing results.

The TIMES-Tito energy model was therefore designed and implemented based on the Basilicata energy system (Di Leo et al., 2015) to analyse the feasibility of a REC. By comparing different economic, technological, and policy scenarios, this work seeks to expand the applications of TIMES to energy-environmental planning at the municipal level, focusing on the deployment of decentralised renewable energy production.

2.5 The Renewable Energy Communities (REC)

Decentralized electricity production through self-consumption facilities characterizes energy communities. Each member of the community has the option of using the energy produced for their own utilities, giving away any excess production to the grid, or storing it in storage systems. Energy communities include different entities, such as individuals, small and medium-sized enterprises, territorial authorities, or local authorities, which are connected to the same low-voltage (LV) transformer substation and participate without carrying out a main commercial or industrial activity in the energy sector, such as Energy Service Companies (ESCOs).

The European Renewable Energy Directive II (RED II) defines a "renewable energy community" as a legal entity that "is based on open and voluntary participation, is autonomous, and is effectively controlled by shareholders or members who are located in the vicinity of the renewable energy production facilities that are owned and developed by the legal entity in question." It further states that "shareholders or members are individuals, SMEs or local authorities, including municipal governments, whose main objective is to provide community-based environmental, economic or social benefits to its shareholders or members or to the local areas in which it operates, rather than financial profits." (MASE, 2023).

According to the RED II Directive, "self-consumers of renewable energy acting collectively" are defined as a "group consisting of at least two self-consumers of renewable energy that operate cooperatively and share the same physical site, e.g., a building or an apartment building" (MASE, 2023). Self-consumers acting collectively are a legal entity consisting of at least two or more members. The directive also requires that they share the same building. Thus, the main characteristic of collective self-consumption is closely related to the site of production and consumption, which is limited to the condominium context only.

Renewable Energy communities bring together multiple parties capable of self-producing energy through facilities close to each other, not necessarily installed in the same building. Collective self-consumption, on the other hand, concerns the same building or condominium with renewable installations; the energy produced can be shared among condominiums or co-owners, but only at the specific location where it is generated.

Renewable Energy Communities (RECs) are becoming increasingly significant in the ecological transition, particularly in the energy transition, due to the engagement of various stakeholders and the objectives they aim to accomplish. The strategic significance of RECs derives from the engagement of citizens, enterprises, and municipal authorities in the generation and distribution of renewable energy, as well as the economic, social, and environmental objectives they aim to achieve.

Within RECs, both private and public entities can act as prosumers, simultaneously producing and consuming energy from renewable sources, reaping cost reductions, and minimizing network losses due to decreased energy transit on public networks. A further advantage is the mitigation of pollution through the transition from fossil fuel sources. Specifically, the members of the REC can carry out different activities: produce, consume, distribute, sell, store, and purchase energy, while pursuing environmental, economic, or social purposes (Porporato, 2023).

2.5.1 Benefits of RECs

The benefits of renewable energy communities are numerous and include resiliency, social, economic, and environmental factors, with a primary objective to establish a green energy system. According to Sæle et al. (2022), Cuviello (2024), and Brummer (2018), its advantages include:

1. Economic benefits

- By attracting investments in renewable energy infrastructure and technologies, RECs can boost economies and promote further economic progress.
- Self-consumption of locally produced renewable energy can result in significant savings for REC members, including lower electricity costs.

- Numerous work opportunities are created by the development and upkeep of renewable energy projects inside RECs, ranging from installation and maintenance to project management and administration.
- They enable greater energy autonomy by reducing dependence on the distributor's power grid and allowing the possibility of reducing energy costs through self-consumption and energy exchange within the community.

2. Sustainable energy transition

- Future generations gain from RECs promotion of the use of renewable energy, which promotes sustainability and long-term environmental health.
- By incorporating renewable energy sources into daily life and promoting ecologically conscious actions and practices, RECs help achieve the larger objective of sustainable development.
- RECs can act as role models for other communities, showcasing the viability and advantages of renewable energy projects and promoting their broad implementation.
- Promoting RES generation and lowering dependency on fossil fuels helps with decarbonization initiatives, energy independence, and climate change mitigation in general.

3. Environmental benefits

- By supporting the transition to clean energy sources and reducing dependence on fossil fuels, the emphasis on renewable energy, such as wind, solar, and hydro power, not only decreases greenhouse gas emissions but also lessens various forms of environmental pollution associated with fossil fuel extraction and consumption.
- They bolster efforts to combat climate change while promoting the responsible use of natural resources. Renewable energy sources are inherently more sustainable and environmentally friendly than their conventional counterparts. In this regard, RECs help to safeguard ecosystems and diminish the carbon footprint, contributing to broader environmental goals.

4. Social benefits

- Through the collaboration of local businesses, organizations, and residents toward shared energy objectives, RECs promote social cohesiveness and a sense of community.
- REC gives community people a sense of control and ownership over their energy resources, which can improve their engagement and empowerment in general.
- Social justice is promoted by RECs, which guarantee the benefits of renewable energy, such as financial savings and environmental enhancements that are shared equally among all participants.

5. Energy resilience benefits

- Reducing dependency on big, centralized power grids through the decentralization of energy generation, RECs can help communities become less susceptible to interruptions and outages.
- A community's energy security can be enhanced through local renewable energy production, which offers a more steady and dependable energy source that is less vulnerable to external shocks.

2.5.2 Activities of RECs

The Regole Operative CACER (GSE, 2024) gives a detailed framework for the administrative, operational, and financial activities of RECs in Italy, expanding the Milleproroghe Decree, Decree-Law 162/19. RECs must be connected under the same primary substation, expanding on the previous “low-voltage transformer”, and it will promote community participation still upholding the local dimension necessary for balanced distributed production and grid. Shareholders or members are individuals, small and medium-sized enterprises, territorial entities, or local authorities, including municipal administrations, and participation in the renewable energy community cannot constitute the main commercial and industrial activity (Cuviello, 2024). The stakeholders and participants who work together to form REC have their activities centered on energy generation, energy storage systems, energy consumption, energy selling, and energy sharing (Ahmed et al.,2023). The REC must be made up of customers, people, companies, government agencies, and/or organizations that are all situated under the same transformer substation in the low-voltage electricity grid. The operation of a REC is simple and innovative: community members come together to produce and share renewable energy through sustainable installations such as photovoltaic panels, renewable energy is produced by both producers and consumers exploiting available natural resources, the energy generated is distributed among REC members according to their needs and if production exceeds the community's consumption, the excess energy is fed into the national grid and sold, creating an economic return for participants. Smart monitoring and management systems (smart grids) allow real-time monitoring of energy production and consumption and more efficient management of energy flows, optimising energy use within the community and reducing waste.

Renewable energy production is incentivized for installations of small to medium plants up to 1 MW. The generated energy sharing occurs through the GSE's hourly calculation of shared energy (E_CONDIVISA) across members' consumption and production profiles. The incentive mechanism under the CACER decree captures the tariff incentive for shared energy (E_CONDIVISA), the ARERA valuation, and the hourly market price for the excess electricity fed into the grid. The REC promotes the use of batteries to maximise self-consumption. The more energy that is produced and used by self-consumers and producers who are directly connected to the system, the more the cost of the variable components will be decreased, while they pay the fixed parts of the bill. The activities of various groups that make up REC may differ, but jointly they contribute to the development, management, and success of the REC. The following paragraph will highlight the entities involved in RECs.

Prosumers: They are energy producers and contribute to shared energy. They are the owners of the renewable plant and are responsible for generating and utilizing renewable energy through various technologies.

Consumers: Does not produce energy, but uses the energy shared by the REC, obtaining economic (e.g., more advantageous energy rates) and environmental benefits contributing to support the ecological transition.

Local government: They work with other stakeholders to accomplish sustainable energy goals, facilitate permits and regulations for renewable energy projects, and offer incentives and policies to promote the adoption of RE.

Local businesses: They participate by making investments in renewable energy projects, offering products and services associated with clean energy technologies, and promoting long-term, steady growth.

Cooperatives/Community Organizations: They encourage community members to work together, pool resources, and make decisions collectively to carry out and sustain Renewable energy projects.

Investors: They provide investments used in establishing the REC. They actively support the growth of the REC and may include banks, financial institutions, and other strategic investors in addition to private citizens and landlords.

The GSE calculates shared energy (E_CONDIVISA) hourly as the minimum value between the total renewable production and total consumption of participating members within the same substation (GSE, 2024).

2.5.3 Energy sharing in RECs

In renewable energy communities, energy sharing entails the cooperative distribution and use of locally produced distributed renewable energy resources. When there is excess energy generated, the participants divide it among themselves, promoting a decentralized and sustainable strategy (Herenci´c et al. 2022). Individual consumers become prosumers through energy sharing within communities, which enables them to distribute excess energy to other community members.

Energy planning at the community level provides a better opportunity to customize established energy systems to local conditions and limits. This strategy makes it easier for the community to use these RESs sustainably and with more efficiency. (Ruparathna et al.,2017).

To maximize the use of RESs, foster a sense of community involvement, improve energy resilience, and encourage self-sufficiency in sustainable energy practices, sharing could take place through a variety of mechanisms, such as community microgrids, peer-to-peer energy exchanges (Mehrjerdi, 2020; Duvignau et al, 2021), or collective energy storage projects. Shared energy is defined, in each hour, as the minimum between the sum of the electricity input and the electricity withdrawn from the grid at the level of the entire condominium (ARERA, 2020):

$$E_{shared,t} = \min\left(\sum_{i=1}^{n} E_{injected,t\_i} \,;\, \sum_{i=1}^{n} E_{withdrawn,t\_i}\right) \qquad 2.12$$

Where:

$E_{shared,t}$ is the energy shared in hour t (and remunerated)

$E_{injected,t\_i}$ is the energy put into the grid in hour t from connection point i

$E_{withdrawn,t\_i}$ is the energy withdrawn in hour t from connection point i

n is the number of connection points that are part of the collective self-consumption scheme

The determination of incentives depends on the calculation of shared energy, which is performed by the GSE on an hourly and monthly basis.

Figure 2.2 displays a diagram illustrating an energy community and collective self-consumption model within a condominium, focusing on a photovoltaic (PV) system.

Energy Flow: It shows how energy is produced by a PV system, how it's consumed within the condominium (self-consumption), and how excess energy is fed into the public grid, or energy is drawn from it when needed.

Metering Points: Key metering points are identified, including a production counter (M2) for the PV system and an exchange counter (M1) for interactions with the public grid.

Shared Energy Calculation: Shared energy is calculated hourly based on the minimum of energy produced and energy consumed by the individual apartments and common utilities.

Components: The system includes a PV system, condominium meters for individual apartments, a production counter, and an exchange counter, all interacting with the public grid.

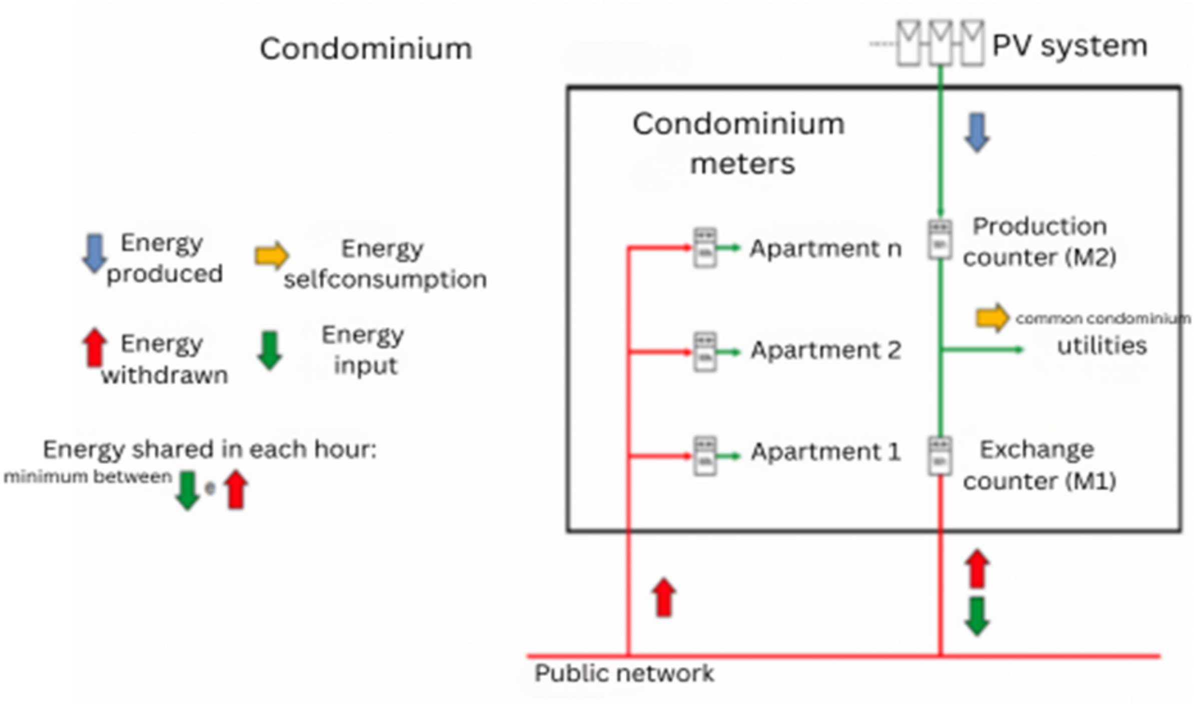


Figure 2.2: Schematic diagram of a hypothetical condominium of three apartments and a PV system installed on common uses, under virtual self-consumption. (GSE, 2023)

- Produced energy represents the energy generated by the PV system and is measured by the (if any) production meter.

- Self-consumed energy represents the energy produced and instantaneously consumed by a utility connected directly to the PV system. Self-consumed energy results in reduced absorption from the grid and thus a direct reduction in the bill.

- Energy withdrawn represents the energy absorbed from the grid and is measured by PODs; it is important for the calculation of shared energy for self-consumption, which is incentivized through a premium tariff.

- Energy injected represents the energy that is sold to the grid and is measured by the exchange meter. This amount of energy is made available to the producer, who can sell it through a dedicated withdrawal. Dedicated withdrawal is a simplified mechanism for selling energy, which avoids the producer from participating in the electricity market.

2.5.3.1 Principle of operation of collective self-consumption

The collective self-consumption scheme enables owners of photovoltaic (PV) systems, referred to as prosumers, to utilize self-generated energy for their immediate energy needs. This process, characterized as physical self-consumption, results in significant cost savings on utility bills. Under this scheme, only the electricity that exceeds the physical self-consumption and is necessary to satisfy physical demands is recorded in the fiscal Point of Delivery (POD). In cases where energy production exceeds total consumption, any surplus energy can be stored in designated storage systems, contingent upon the system's installation capability. However, if the batteries reach their capacity during peak production periods, the excess energy is exported to the grid. Within the framework of energy communities, this surplus energy can be distributed among the community's users, with allocation proportional to each user’s consumption during the hours of production. This arrangement incentivizes community members to optimize their energy usage by aligning it with periods of high prosumer energy generation.

In Italy, before the development of energy communities, self-consumption was allowed through the “one-to-one” scheme, that is, a production unit serving a consumption unit. An example of a “one-to-one” scheme is the case of self-consumption in condominiums, where there is a common production plant serving only common consumers. Common utilities refer to the electrical loads of the non-private parts of the condominium (lights and motive power in common areas such as stairs and hallways, elevator power supply, TV system power supply, autoclave, etc.). The supply of equipment serving the district heating connection system is to be understood as included in common utilities; likewise, a heat pump serving the condominium and not private units is to be considered.

2.5.3.2 Economic Sustainability

Physical self-consumption

Physical self-consumption refers to the energy produced by the PV system that is instantly consumed by the loads connected to it; this amount of energy, which does not pass through the meter, is not recorded on the bill. This aspect makes physically self-consumed energy the most substantial economic benefit, as the total energy cost on the bill in the last two quarters ranges between 200 and 250 Euro/MWh (GSE, 2023). Table 2.4 shows for each quarter the total amounts of energy purchased in the last five years (2021-2025).

Table 2.4: Cost of electricity in the last 5 years (GSE, 2025).

quarterly	**expenditure on energy matters (cEuro/kWh)**	**expenditure on transportation and meter operation (cEuro/kWh)**	**expenditure on system charges (cEuro/kWh)**	**taxes (cEuro/kWh)**	**total amount (cEuro/kWh)**
I 2021	9.24	4.01	4.18	2.63	20.06
II 2021	9.94	4.01	4.18	2.70	20.83
III 2021	13.55	4.01	2.44	2.89	22.89
IV 2021	22.18	4.01	0.00	3.51	29.70
I 2022	37.20	3.84	0.00	4.99	46.03
II 2022	32.93	3.84	0.00	4.57	41.34
III 2022	33.08	3.85	0.00	4.58	41.51
IV 2022	55.36	3.85	0.00	6.80	66.01
I 2023	43.49	3.99	0.00	5.63	53.11
II 2023	13.77	3.99	3.03	2.96	23.75
III 2023	14.01	3.99	2.89	2.97	23.86
IV 2023	13.78	3.99	3.03	2.96	23.75
I 2024	14.37	4.53	3.24	3.1	25.24
II 2024	9.2	4.53	3.86	2.65	20.24
III 2024	11.8	4.53	3.86	2.91	23.1
IV 2024	13.75	4.53	3.86	3.1	25.24
I 2025	18.17	5.01	3.22	3.52	29.92
II 2025	17.58	5.01	3.13	3.46	29.18
III 2025	18.07	5.01	3.13	3.5	29.71
IV 2025	15.91	5.01	3.13	3.29	27.34

Sale of Energy

The sale of energy covers the energy that is fed into the grid via the Point of Delivery (POD), specifically the output generated by the photovoltaic (PV) system. This sale applies to all energy producers, including producers within a collective consumption group.

Crucially, the energy generated remains under the producer's control, enabling them to sell it to the GSE through a dedicated take-back mechanism. The compensation provided to producers is subject to variation based on the type of energy plant and any supplementary incentives that may be applicable. For facilities with a peak power output of less than 100 kW, there is an opportunity to request the application of the guaranteed minimum price (Prezzo Minimo Garantito, PMG), which is established annually by the Autorità di Regolazione per Energia Reti e Ambiente (ARERA). Conversely, for plants with a capacity exceeding 100 kW but under 1 MW, the remuneration corresponds to the hourly zonal price (Prezzo Zonale Orario, PZO). This price is determined by the energy market and fluctuates based on the specific time slot during which the energy is fed into the grid as well as the geographical zone of the plant.

In 2023, ARERA set the guaranteed minimum price for PV systems with an annual production of less than 1,500 MWh at 44 Euro/MWh (ARERA, 2023). The PZO is significantly influenced by geographic location and the timing of energy sales; accordingly, the GSE regularly updates and publishes monthly average prices, stratified by time of day and market zones. Data presented in Table 2.5 illustrates the PZO for May, June, July, and August 2025, with price values expressed in Euro/MWh.

Table 2.5: PZO summer 2025 (Euro/MWh) (GSE, 2025).

	May 2025	June 2025	July 2025	August 2025
North	78.91	109.22	106.86	101.19
Center	107.07	108.80	107.40	101.60
South	76.43	108.98	100.49	102.14

Data presented in Table 2.6 illustrates the PZO for May, June, July, and August 2024, with price values expressed in Euro/MWh.

Table 2.6: PZO summer 2024 (Euro/MWh) (GSE, 2024).

	May 2024	June 2024	July 2024	August 2024
North	94.16	101.39	107.61	124.47

Center	95.63	105.94	118.03	113.49€
South	93.97	105.94	118.03	131.49

Data presented in Table 2.7 illustrates the PZO for May, June, July, and August 2023, with price values expressed in Euro/MWh.

Table 2.7: PZO Summer 2023 (Euro/MWh) (GSE, 2023)

	May 2023	June 2023	July 2023	August 2023
North	104.82	106.26	112.87	104.57
Center	107.07	107.07	112.83	105.01
South	104.60	104.60	112.57	102.40

These amounts are strongly influenced by significant geopolitical events, such as the conflict in Ukraine. To highlight the relative difference in hourly zonal prices due to the outbreak of war, rates for the year before the war (2021) are shown in Table 2.8. In contrast, Table 2.9 shows the values for the year when the conflict erupted (2022).

Table 2.8: PZO summer 2021 (Euro/MWh).

	May 2021	June 2021	July 2021	August 2021
North	74.20	88.84	108.93	113.63
Center	74.40	88.61	108.72	117.21
South	70.14	88.41	109.28	117.09

Table 2.9: PZO summer 2022 (Euro/MWh)

	May 2022	June 2022	July 2022	August 2022
North	231.14	293.37	518.10	549.41
Center	230.62	297.07	520.38	554.90
South	224.68	278.10	424.24	528.54

2.5.3.3 Premium tariff

The premium tariff is the actual incentive for shared energy and is provided by the GSE.

$$Tariff\ Premium = \frac{Incentives}{E_{shared}} \tag{2.13}$$

Below is the incentive mechanism described in the MASE implementing decree.

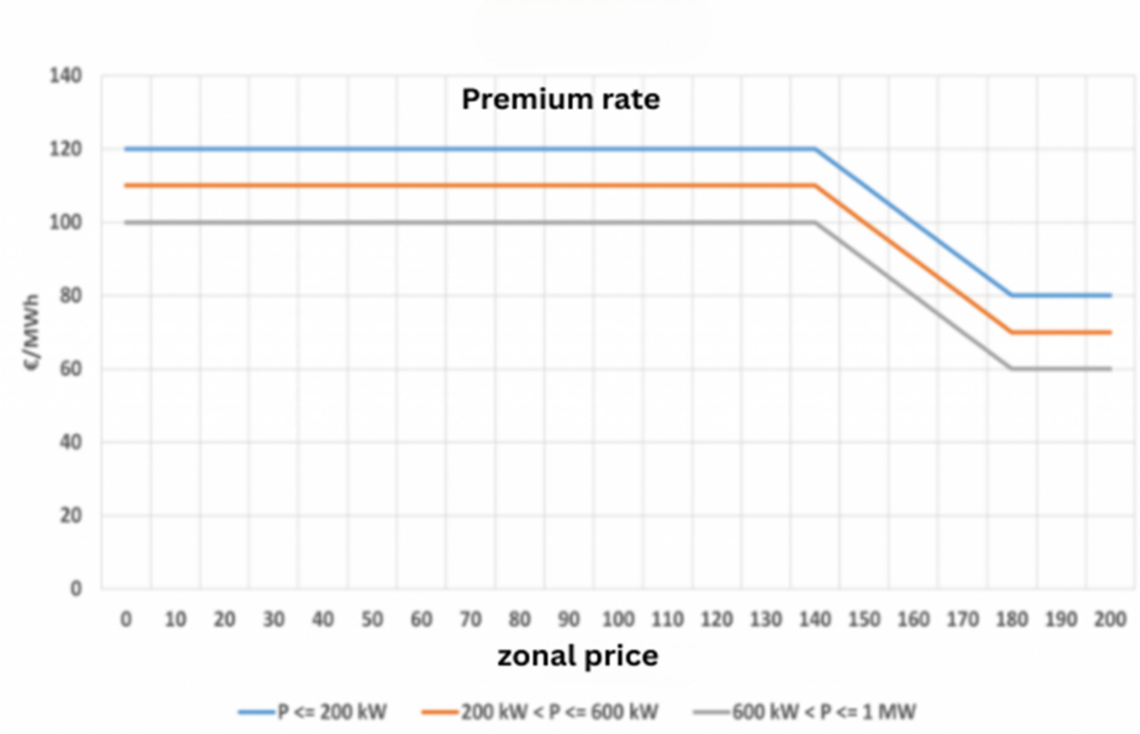


Figure 2.3: Premium tariff.

The tariff consists of a fixed part (equal to 60, 70, or 80 Euro/MWh) that varies depending on the size of the plant and corresponds to the minimum incentive, and a variable part that decreases as the zonal price increases until it is cancelled when it is worth 180 Euro/MWh.

$$C_{sh} = \min\ [C_{sh,p,O,}C_{sh,p} + \max(\,0, 180\ -\ P_z)] + C_{sh,g} \tag{2.14}$$

Where C_{sh} the premium tariff, $C_{sh,p}$ and $C_{sh,p,O}$ represents the total power capacity of the PV plants, $C_{sh,g}$, and the geographic location of the plant.

- For plants of 200 kW or less:

Premium tariff =80+max (0; 180-Pz), with a maximum of 120 Euro/MWh

- For plants with power between 200 kW and 600 kW:

Tariff Premium=70+max (0; 180-Pz), with a maximum of 110 Euro/MWh

- For plants with a capacity between 600 kW and 1 MW:

Tariff Premium=60+max (0; 180-Pz), with a maximum of 100 Euro/MWh

The decree, currently (June 2024) in effect, provides for a correction of the premium tariff for regions with lower isolation. Specifically, 4 Euro/MWh is added for PV systems installed in Central Italy (Lazio, Marche, Toscana, Umbria, and Abruzzo). For PV systems installed in Northern Italy (Emilia-Romagna, Friuli-Venezia Giulia, Liguria, Lombardia, Piemonte, Trentino-Alto Adige, Valle d'Aosta, and Veneto), the increase is 10 Euro/MWh (GSE, 2023).

2.5.3.4 Reimbursement of avoided grid costs

A further enhancement of shared energy concerns the reimbursement of avoided grid costs. Indeed, collective self-consumption results in less use of the public grid and consequently a reduction in grid losses. The fact that consumers continue to pay grid loss charges on the bill even though they do not exist for the shared energy share motivates the refund of the charges. For this reason, it is expected that the GSE will calculate the shared energy hour by hour and return the fee related to the enhancement to the user.

For a collective self-consumption scheme, valorization depends on both the connection point of the generating plant and the zonal price. This value is around 10 Euro/MWh; the precise value of the calculation depends on formulas defined in the GSE document “Operational rules for access to the service for diffuse self-consumption and PNRR contribution” (GSE, 2023).

2.5.3.5 Annual costs for plant operation

Administrative costs, plant maintenance, and insurance are part of the annual costs for plant operation. The GSE imposes a fee to cover administrative costs. This is composed of a fixed fee and a variable fee based on the capacity of each plant that is part of the collective self-consumption configuration. The fees are shown in Table 2.10.

Table 2.10: GSE administrative costs.

Power (kW)	Fixed fee (Euro/year)	Variable fee (Euro/kW)
$P \leq 3$	0	0
$3 < P \leq 20$	15	0
$20 < P \leq 1000$	15	1

In addition, an additional fee of 4 Euro/year must be paid to the GSE (again for administrative costs) for each connection point that is part of the collective self-consumption configuration.

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Model tool and available download website

IEA-ETSAP. Available online: https://iea-etsap.org/index.php/etsap-tools/model-generators/markal

OSeMOSYS. Available online: http://www.osemosys.org/

Homer. Available online: https://ndcpartnership.org/knowledge-portal/climate-toolbox/hybrid-optimization-multiple-energy-resources-homer-model

EnergyPLAN. Available online: https://energyplan.eu/

RETScreen. Available online: https://natural-resources.canada.ca/maps-tools-publications/tools applications/

GEM-E3: Available online: https://e3modelling.com/modelling-tools/gem-e3/

LEAP. Available online: https://www.i2am-paris.eu/detailed_model_doc/leap

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Chapter 3 CASE STUDY

3.1 The Tito Municipality and its energy system

Tito is an Italian municipality with approximately 7,162 inhabitants (2020 ISTAT census) located in the province of Potenza, in Basilicata, southern Italy. The territory is essentially divided into two parts: the town of Tito, where most of the inhabitants live, home to the Town Hall and other services, and the industrial and commercial area of Tito Scalo, where numerous companies from Potenza have established their headquarters.

Geographically, it lies at approximately 40.5838°N latitude and 15.677°E longitude, covering an area of about 70.59 square kilometers. The town is situated at an elevation of 650 meters above sea level in the Apennine Mountain range, with a mountain Mediterranean climate characterized by cold winters and hot summers, and favorable to the deployment of solar power due to the high levels of solar irradiance (ISTAT, 2021). The town's strategic location near Potenza, the regional capital, enhances its connectivity and accessibility. The town is bound by several municipalities, including Abriola, Picerno, Pignola, Potenza, Sant'Angelo Le Fratte, Sasso di Castalda, Satriano di Lucania, and Savoia di Lucania, each contributing to the region's cultural and social tapestry. (Figure 3.1) (Comune di Tito, 2025)

In line with national trends and like most municipalities in Basilicata, energy supply is still heavily based on fossil fuels, taking advantage of a discount on gas granted to Lucanian citizens as environmental compensation for hydrocarbon extraction in the region (Basilicata Regional Law, 2022). However, growing concern about climate change and air quality is promoting the transition to cleaner energy sources at both the municipal and regional levels to reduce environmental impact and improve energy security, in line with European Union policies. Currently, Tito ranks first in Basilicata in terms of installed photovoltaic capacity (18,775 kW), second in terms of installed photovoltaic capacity per km^2 (263 kW/km^2), and third in terms of installed photovoltaic capacity per inhabitant (2.64 kW/inhabitant) (Energy service manager Atlaimpianti, 2024). The electricity produced locally by photovoltaics is distributed through infrastructure connected to the national grid.

In recent decades, the municipality of Tito has distinguished itself by its focus on environmental issues. In 2011, the municipality of Tito joined the European Commission's Covenant of

Mayors initiative and in 2012 issued its Sustainable Energy Action Plan (SEAP) (Covenant of Mayor, 2012). It is currently one of six pilot municipalities in the LIFE CET Local Go Green project, which aims to accelerate the transition to clean energy at the municipal level. As part of this project, the municipal council recently approved a climate emergency declaration (CED), making concrete commitments to tackle climate change and promote renewable energy sources. Another important initiative is the promotion of a Renewable Energy Community (REC) in accordance with national legislation, which will involve citizens in a new system of production and self-consumption of energy produced from renewable sources and is aimed at providing a concrete response to the challenges of the ecological transition (Commune Tito, 2025).

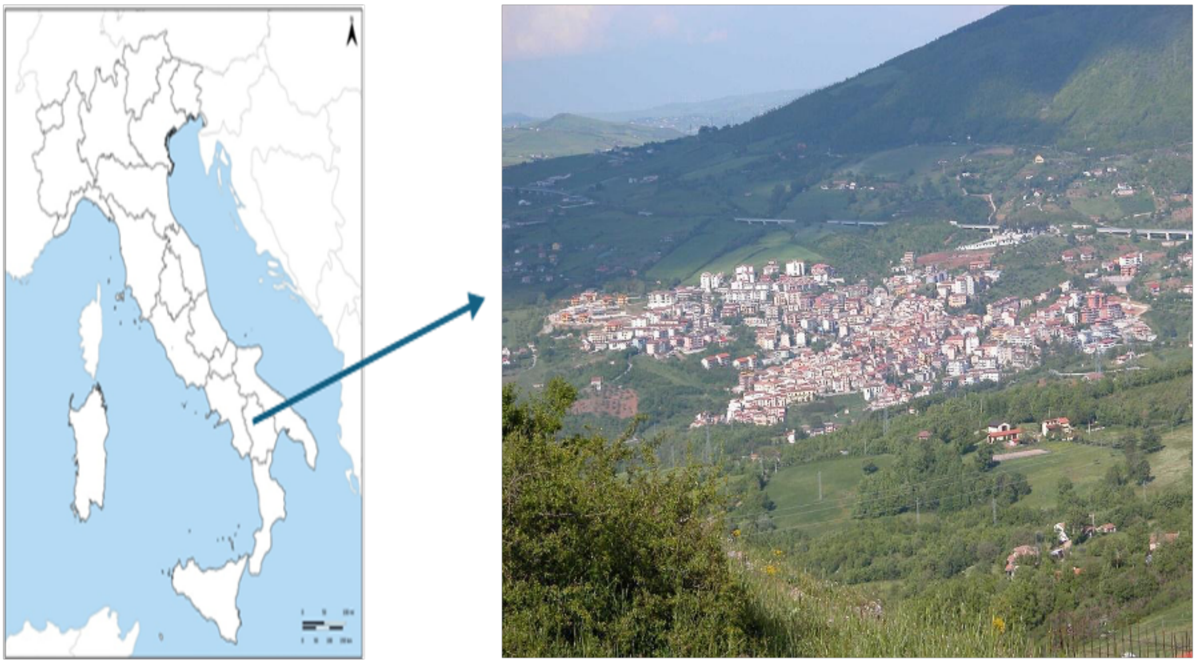

Figure 3.1: Location of Tito Municipal

Based on these premises, the TIMES-Tito model has been implemented to analyze the municipal energy system to assess the capacity to reach the renewable energy and CO_2 emissions targets set by the EU and to support the implementation of a REC within a local energy-climate plan.

Tito's energy system analysis focuses on Residential and Tertiary, two sectors that can greatly benefit from the photovoltaic electricity generation to help meet energy supply.

Therefore, the end-use demands considered are related to the services that can be satisfied by electricity as an alternative to other fuels. Regarding the tertiary sector, seven sub-sectors have been defined based on the economic activities defined by the ATECO 2007 classification

(ISTAT, 2023). Starting with the ATECO 2007 classification, some sub-sectors required reworking, which in some cases involved a subdivision of activities and in Other Uses, an aggregation of activities. For example, the item “Accommodation and Food service activities” has been divided into two sub-sectors: “Food” for Food service activities and “Accommodation”. Instead of Private Offices, it was necessary to aggregate the economic activities ‘financial and insurance activities, real estate activities, administrative and support services, information and communication, postal and courier, professional scientific and technical activities, arts and other service activities. Instead of Healthcare, we aggregated human health and social work activities, and School was aggregated for education.

In Table 3.1, the end-use demands by sector are reported, along with the corresponding TIMES model codes and units of measure.

Table 3.1: End-use demands by sector

Description	**TIMES Code**	**Unit of measure**	**Description**	**TIMES Code**	**Unit of measure**
Residential			Tertiary – Accommodation		
Space heating	DRSH	Mm^2	Space heating	DTASH	Mpresences
Water heating	DRWH	Mlitres	Water heating	DTAWH	Mpresences
Space cooling	DRSC	Mm^2	Space cooling	DTASC	Mpresences
Cooking	DRCO	Munit	Other electric uses	DTAOEU	Mpresences
Lighting	DRLG	Glumen			
Other electric uses	DROEU	PJ			
Tertiary – Food			Tertiary – Public Buildings		
Space heating	DTCSH	MEmployees	Space heating	DTPSH	Mm^3
Water heating	DTCWH	MEmployees	Water heating	DTPWH	Mm^3
Space cooling	DTCSC	MEmployees	Space cooling	DTPSC	Mm^3
Other electric uses	DTCOEU	MEmployees	Other electric uses	DTPOEU	Mm^3

Tertiary – Private Offices			Tertiary – Shopping Buildings		
Space heating	DTPOSH	MEmployees	Space heating	DTSBSH	Mm^2
Water heating	DTPOWH	MEmployees	Water heating	DTSBWH	Mm^2
Space cooling	DTPOSC	MEmployees	Space cooling	DTSBSC	Mm^2
Other electric uses	DTPOOEU	MEmployees	Other electric uses	DTSBOEU	Mm^2
Tertiary – Health care			Tertiary – Schools		
Space heating	DTHSH	MEmployees	Space heating	DTSSH	Mm^3
Water heating	DTHWH	MEmployees	Water heating	DTSWH	Mm^3
Space cooling	DTHSC	MEmployees	Other electric uses	DTSOEU	Mm^3
Other electric uses	DTHOEU	MEmployees			

In Appendix A, the classification of processes and commodities in TIMES is reported.

3.2 Building the TIMES - TITO: the Reference Energy system

As explained above, the definition of a customized Reference Energy System (RES) is essential to provide a disaggregated graphical representation of the supply and demand sectors and the technology network, which synthetically describes the current configuration of the energy system under consideration and helps understand the dynamics and interactions between energy production, distribution, and consumption technologies (Cosmi et al.,2009).

In the following section, the RES developed for the Tito municipality is illustrated in detail regarding supply, electricity production, the Residential sector, and the Tertiary subsectors.

3.2.1. Supply

The supply sector of Tito municipality is based on a mix of conventional and renewable energy sources, including natural gas (SUPGAS), liquefied petroleum gas (SUPLPG), diesel (SUPDIE), biomass (SUPBIO), and solar thermal (SUPTHES). Electricity (SUPELC) is mainly imported from the national grid (IMPELC20). The supply sector RES shows how imported and locally produced energy sources are converted into input energy commodities of the tertiary and residential sectors by fictitious (dummy) technologies (Figure 3.2)

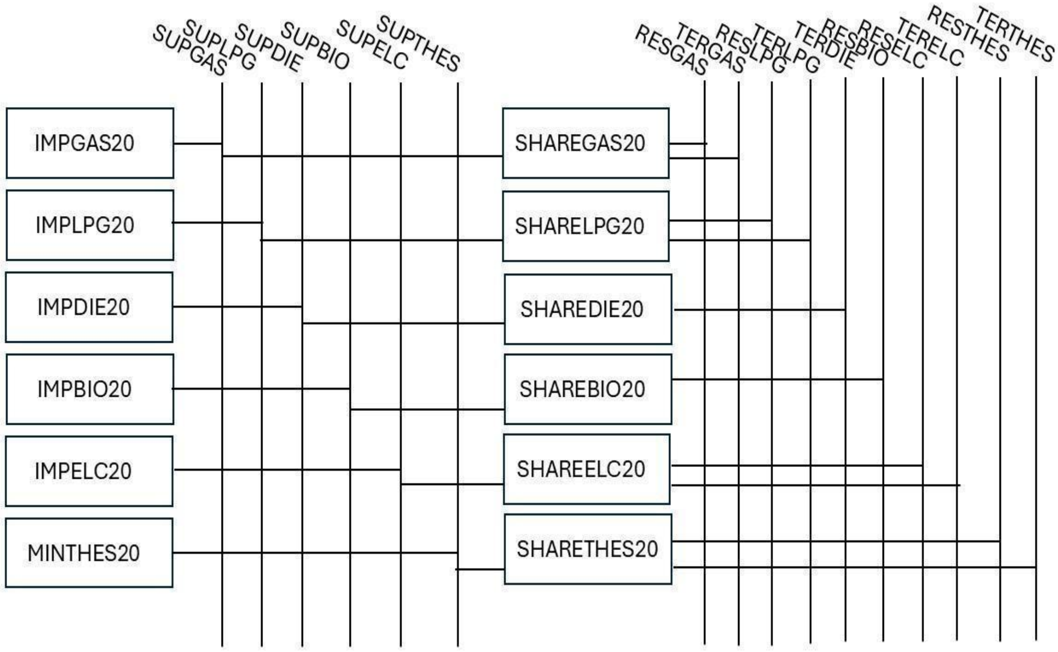

Figure 3.2. RES of the supply sector (RES- Supply)

A more detailed reference system is designed for electricity production by photovoltaic systems, as extensively explained in the next section.

3.2.2. Electricity

As concerns electricity. photovoltaic endogenous production integrates imports from the national transmission grid, helping to meet energy demand either in residential or tertiary sectors. The electricity produced by photovoltaic systems is partly self-consumed and partly sold to the national electricity grid.

The reference system for electricity (RES-E) highlights the transformation of the endogenous source (MINELCSOL) into electricity from solar sources (ELCSOLRI) that powers the photovoltaic systems serving homes (ERESSOLRI1) and tertiary buildings (ETERSOLRI1) as well as the excess production fed into the national electricity grid (ELCT and ELCR).

The scheme shows the electricity produced by photovoltaic systems in the residential (ELCRESD) and tertiary (ELCTERD) sectors (Figure 3.3). It distinguishes between the two energy vectors used for self-consumption (RESELC and TERELC) and the amount transferred to the national grid (ELCR and ELCT).

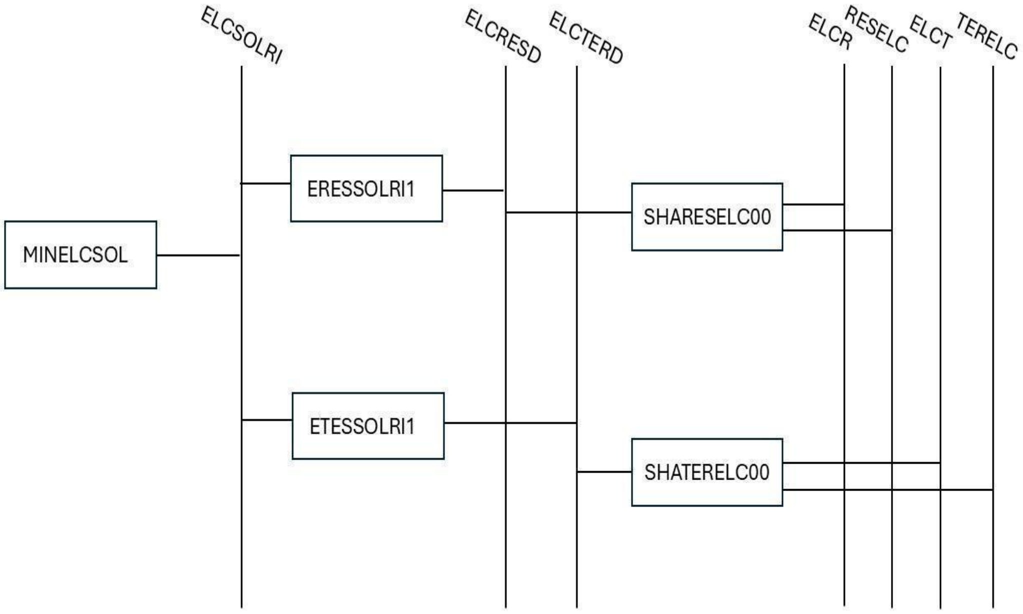

Figure 3.3: RES of electricity production from photovoltaic systems (RES-E).

3.2.3. Residential

Six end-use demand categories were taken into consideration when modelling the Residential sector: Space Heating, Space Cooling, Water Heating, Cooking, Lighting, and Other Electric Uses, including in the reference network the in-use technologies by category. Multiple and single outputs were also considered for Space Cooling, Water Heating, and Space Heating technologies (such as heat pumps and dual boilers) and single end-use technologies (such as single boilers, heaters, etc.) as shown in Figure 3.4.

The energy sources natural gas (RESGNA), liquefied petroleum gas (RESLPG), biomass (RESBIO), solar thermal (RESTHES), and electricity (RESELC) are inputs of the in-use technologies that produce, in turn, useful energy for space heating (RESSH), water heating (RESWH), and space cooling (RESSC). As the demands for services are expressed in different units of measure (respectively Mm^2 for space heating (DRSH) and space cooling (DRSC), G-Litres for water heating (DRWH)), dummy technologies (RDRSHD101, RDRWHD101, RDRSCD101) were modeled to convert the useful energy into end-use demands.

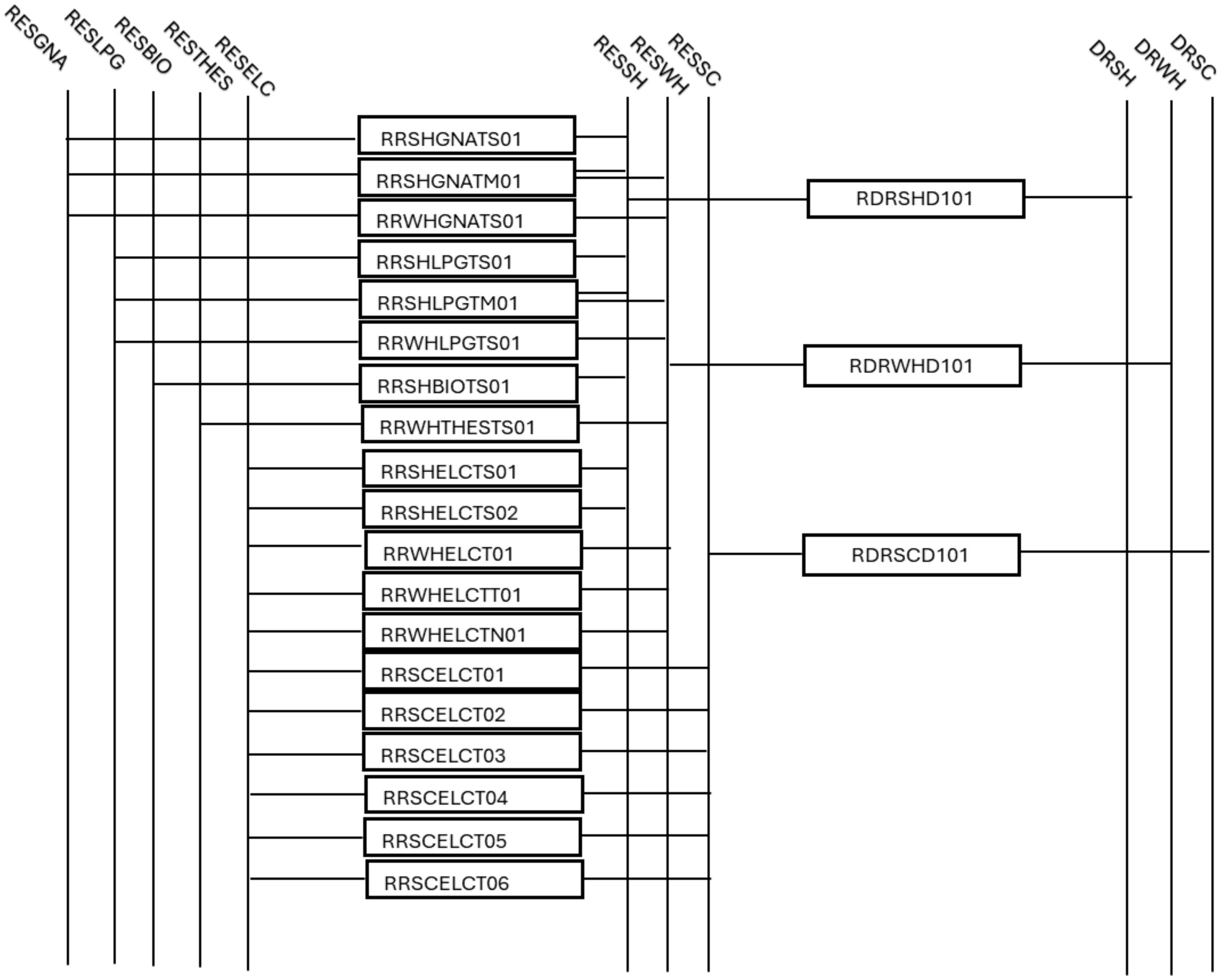

Figure 3.4: RES for Space Heating, Water Heating, and Space Cooling of the Residential sector.

Cooking, Lighting, and Other Electric Uses, whose technologies have a direct link with the final use demand, have a very simple schematization (Figure 3.5). Lighting includes incandescent, halogen, and compact fluorescent lighting lamps.

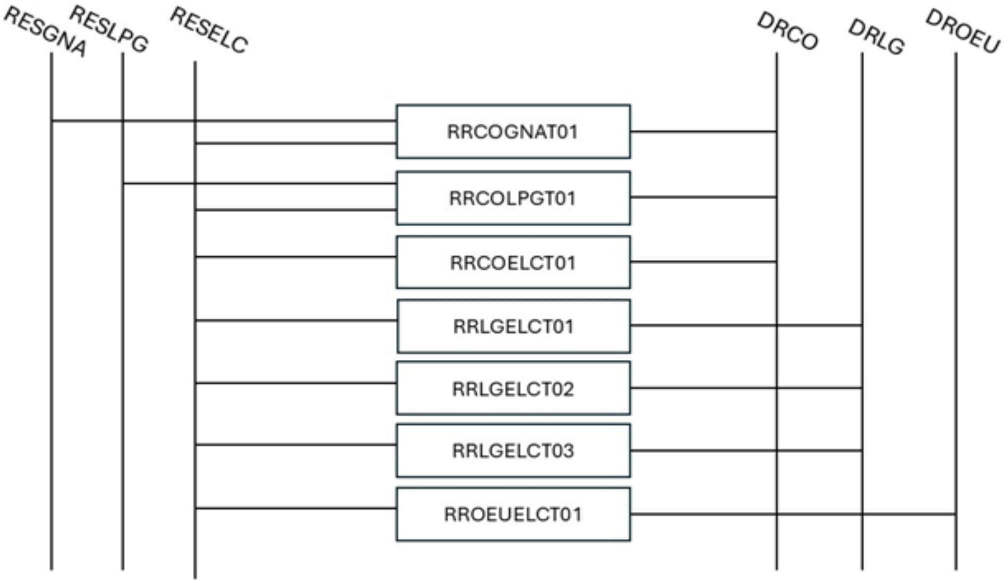

Figure 3.5. RES for cooking, lighting, and other electrical uses of the Residential sector.

3.2.4. Tertiary sector

The seven subsectors of the tertiary sector have a similar representation: input fuels feed end-use technologies whose outputs provide useful energy in PJ to fulfil space heating and water heating demand. Dummy technologies convert the useful energy in PJ into the end-use demand units. Space Cooling and Other Electric Uses are modelled through technologies that have as output directly the end-use demands. In the reference model, the space cooling demand of Schools was not considered, due to the current infrastructure and the school calendar (from September to June). This assumption could be reconsidered in the light of the increasing rise in temperature due to climate change and possible modification of the school calendar.

Figure 3.6 shows an example of the RES for the Food subsector, in which the processes convert energy sources into useful energy for space heating (TERCSH) and water heating (TERCWH), and the dummy technologies (TDCSHD101 and TDCWHD101) convert the useful energy in PJ into end-use demands for space heating (DTCSH) and water heating (DTCWH), both expressed in MEmployees. The end-use demand for space cooling (DTCSC) and other electric uses (DTCOEU) has a very simple schematization since their technologies have as their output directly the final use demand, and both are expressed in MEmployees.

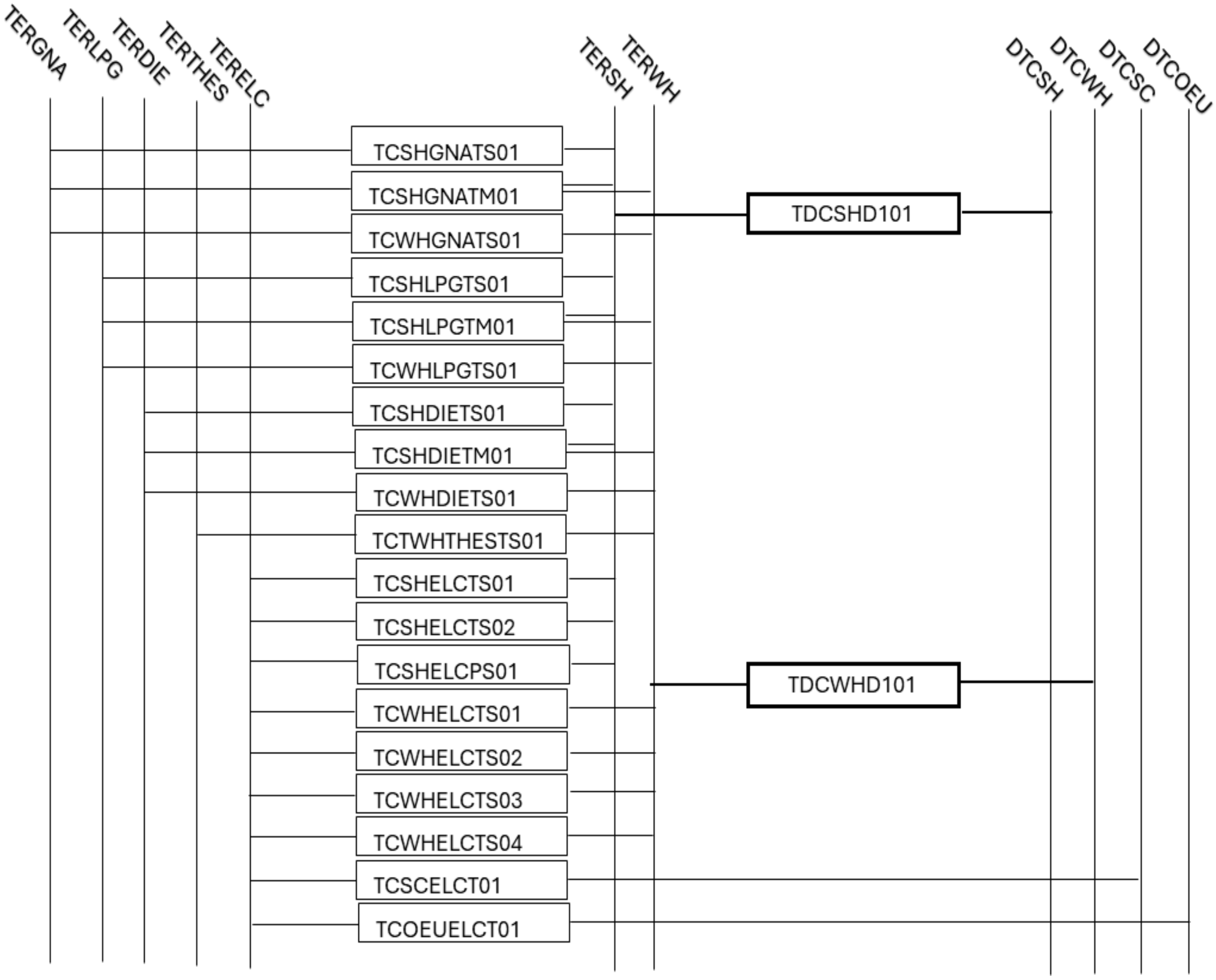

Figure 3.6: RES of the Food subsector in the Tertiary sector

The RES schematizations of the remaining subsectors of the tertiary sector are very similar and reported in Appendix B.

3.3 The TIMES-TITO energy model data input

3.3.1 The model spreadsheets

The structure of the input data of the TIMES-TITO energy model consists of several interrelated spreadsheets, each serving a specific purpose.

1. Base Year Templates: These are the primary data files consisting of four Excel spreadsheets that establish the basic structure of the TIMES-TITO energy system and include the base year data (2020) and the data for modelling energy flows along the time horizon.

- Energy Supply: The energy mixes over the time-horizon (primary energy mining and import, with reference to both renewables and fossil fuels)
- Electricity Production: Data on sources and technologies for electricity generation
- Residential: Energy consumption patterns of residential sector end-uses and technology network
- Tertiary: Energy consumption patterns of tertiary sector end-uses and technology network

2. Database of New Technologies: This database catalogues alternative and emerging energy technologies for the future. It includes data on their market availability, technical and economic performance, and potential environmental impacts, allowing the model to select the most suitable ones to meet energy needs and optimize the energy system in the expected time horizon, based on scenario assumptions. (Cosmi et al.,2009). The new technological options included in the TIMES Tito model are related to the alternative for the key sectors of electricity generation (ELE), residential (RES), and tertiary (TER).

3. Scenario files: These files contain assumptions about the future development of the energy system: demand projections, changes in socioeconomic factors, technology penetration rates, and policy and environmental targets. A range of scenarios can be modelled, from "business-as-usual" to pathways to accelerate decarbonisation and energy transition. Emission factors for greenhouse gases (GHG) and local air pollutants have been included in Tito's energy system scenario files to explore mitigation strategies and evaluate the impacts on air quality.

A visual representation of the model structure is shown in Figure 3.7

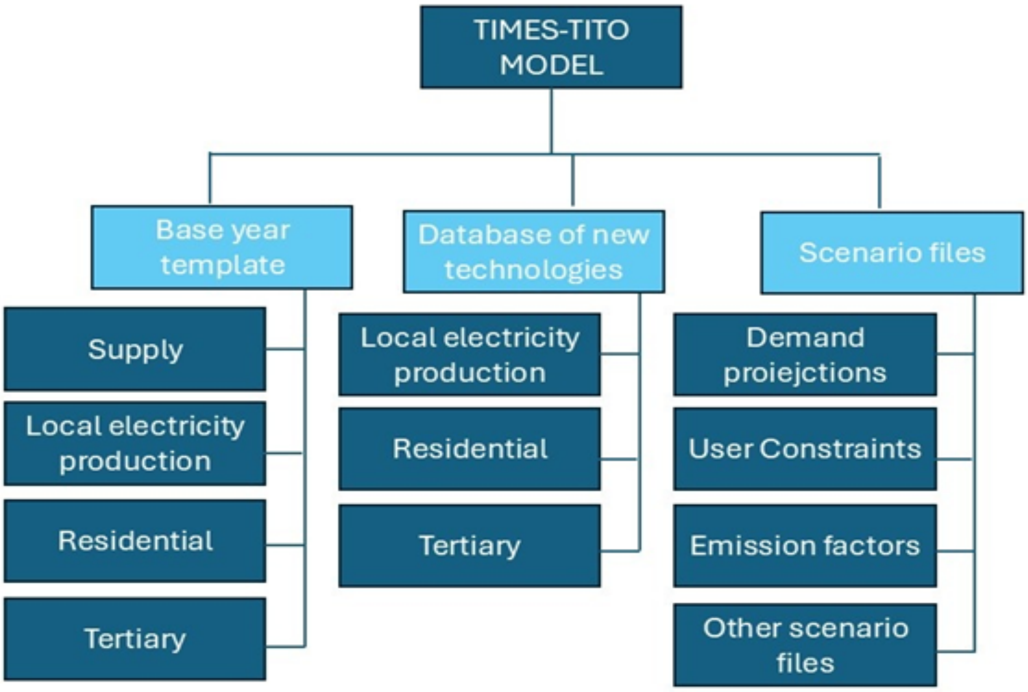

Figure 3.7: TIMES-TITO energy model structure

3.3.2 Input data collection and elaboration

The TIMES-Tito model analyses the energy system of the Municipality of Tito over a thirty-year time horizon, from 2020 to 2050, focusing on the residential and tertiary sectors. The analysis is based on the year 2020 (the statistical reference year) and the key years 2021, 2025, 2030, 2035, 2040, 2045, and 2050 as milestones along the time horizon. The energy mix includes renewable and conventional energy sources, dominated by biomass, natural gas, and electricity, partly produced by photovoltaic plants.

An important aspect in modeling a local-scale energy system concerns the data collection process and the construction of the energy balance for the reference year.

As highlighted by Unluturk and Riekkola (Unluturk et al.,2021), the collection and processing phase of TIMES energy models at the municipal scale is one of the major challenges for modelers and is key to guarantee realistic and reliable model outputs and to devise robust solutions from optimized scenarios. Furthermore, in general, there are no official databases available at the municipal scale as a reference for building the energy balance. Therefore, it is necessary to process heterogeneous data from multiple sources by formulating a series of assumptions and using appropriate proxy variables to estimate the energy consumption of the various sub-sectors.

In this study, SEAP 2012 data were used to estimate the order of magnitude of certain parameters in the residential and tertiary sectors and to fine-tune the data. The calculation procedure is explained in detail below.

3.3.2.1 Energy consumption of the residential sector

The procedure applied to estimate energy consumption for the Residential sector is shown in Figure 3.8, differentiating the proxy variables for electricity consumption from the other energy sources.

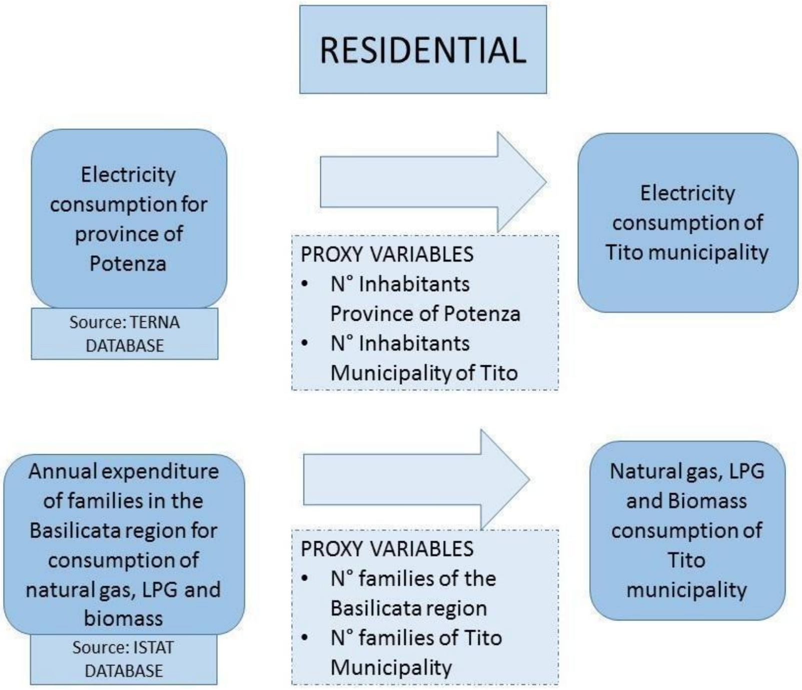

Figure 3.8: Calculation procedure for Residential data

Electricity consumption of the province of Potenza (TERNA, 2020) was downscaled to the municipal level by using proxy variables, specifically, the number of inhabitants in the province and the number of inhabitants in the Municipality of Tito. In addition, average annual household expenditure in the Basilicata region for natural gas, LPG, and biomass was used to estimate consumption for the Municipality of Tito (ISTAT, 2021).

$$Electricity\ consumption\ for\ Tito = \frac{Electricity\ consumption\ for\ the\ province\ of\ Potenza}{Potenza\ Inhabitant} * Tito\ Inhabitant \quad 3.1$$

$$\text{Other energy consumption for Tito} = \frac{annual\ expenditure\ for\ family\ (Euro)}{cost\ per\ unit\ of\ measure} * number\ of\ household \quad 3.2$$

The estimated reference costs for energy consumption in the municipality of Tito per family are respectively Euro 533 for natural gas, Euro 60 for LPG, Euro 163 for firewood, and Euro 97 for pellets (ISTAT, 2023), considering an average cost of Euro139 per tonne for wood and Euro 245 per tonne for pellets. Considering an average number of 2,847 households in 2020 for the municipality of Tito (AdminStat. Italia, 2025) and the end-use categories included in the TIMES Basilicata model (Di Leo et al., 2015) the breakdown of energy consumption by fuel and end-uses (e.g., Space heating, Water heating, Space cooling, Lighting, Cooking, and Other electric uses) was estimated (Table 3.2).

Table 3.2: Energy consumption for the Residential sector in 2020 (TJ)

	Natural gas	**LPG**	**Solar Thermal**	**Biomass**	**Electricity**	**Total**
Space Heating	61	3.5		104	0.5	169
Water Heating	26	1.8	1.2		3.3	32.3
Space Cooling					0.7	0.7
Lighting					3.2	3.2
Cooking	13	1.8			0.9	15.7
Other Electric Uses					15	15
Total	**100**	**7.1**	**1.2**	**104**	**23.6**	**235.9**

As highlighted, biomass is the most widely used energy source in the residential sector for space heating (62%), followed by natural gas (36%). Natural gas is the prevailing energy source for cooking (83%) and water heating (80%), while space cooling is fulfilled only by electricity, which on the whole accounts for 10%. LPG and solar thermal contributions overall are respectively 3% and 1%. Different hypotheses were formulated to estimate end-use demand in the base year of the six subsectors in the Residential sector. The space heating demand, expressed in Mm^2, was estimated using data provided by the Italian Revenue Agency, considering the total number of premises at the municipal level for each residential cadastral category, multiplied by the average floor area per room (about 20 square meters), and considering the percentage of uninhabited houses during the year.

The water heating demand, expressed in liters, was estimated considering an average need of 40 liters per day per inhabitant (Hot water association, 2025) and multiplying this daily need by the number of inhabitants of the municipality of Tito and the number of days per year.

$$Water\ heating\ demand = 40\ litres\ per\ person * 7162\ inhabitants * number\ of\ days\ in\ a\ year \quad 3.3$$

The cooling demand, as for the heating demand, was related to the surface area of the dwellings, assuming a 50% penetration of cooling technologies in accordance with national data (ISTAT, 2021).

The demand for cooking is estimated considering the number of inhabitants (7,162) of the Tito municipality and the average national data.

The lighting demand was estimated by assuming an average lighting demand of 150 lumens per square meter (Sypher Solutions Pty Ltd, 2025) and considering the total number of square meters of residential dwellings in the municipality of Tito.

The demand for other electrical uses for the reference year was estimated by considering the average annual requirement per household (290 MJ/household) (Borgarello et al.,2010) and the number of households in the municipality of Tito (2,847).

$$Other\ electric\ uses\ demand = Average\ annual\ per\ household * number\ of\ household \quad 3.4$$

Table 3.3 shows the estimated demand for end-use category for the year 2020

Table 3.3: Sectoral end-use demands in Residential - year 2020

End-use demands	Unit of measure	Values
Space heating	Mm^2	0.423
Water heating	Mlitres	104.6
Space cooling	Mm^2	0.212
Cooking	Munit	0.0072
Lighting	Glumen	0.064
Other electric uses	PJ	0.00083

3.3.2.2 Energy consumption of the tertiary sector

The procedure applied to estimate energy consumption for the Tertiary sector is shown in Figure 3.9.

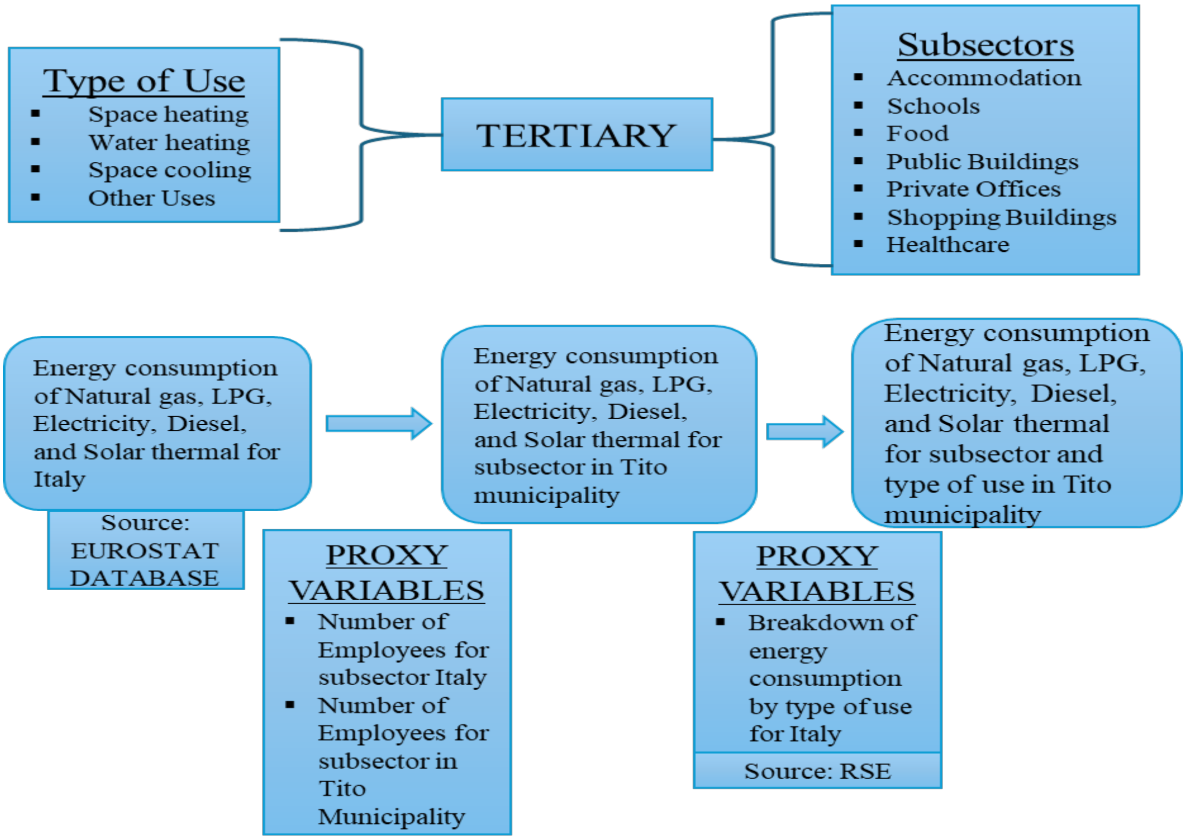

Figure 3.9: Calculation procedure for Tertiary data

Energy consumption of the tertiary sector for the Tito municipality was estimated considering the number of employees as proxy variables (ISTAT, 2020). The energy consumption of the tertiary sector was estimated based on the total national energy consumption (Eurostat, 2020), considering the ratio between the employees of the Municipality of Tito (2,204) and the total employees in Italy (15,099,495), using direct knowledge of the local situation to make some corrections to the estimated value. In this way, the estimated energy consumption of the tertiary sector for the municipality of Tito in 2020 was equal to 83.72 TJ divided by fuel as follows: 40.88 TJ natural gas, 39.48 TJ electricity, 2.66 TJ LPG, 0.48 TJ diesel, and 0.21 TJ solar thermal energy.

$$Energy\ consumption\ for\ Tito = \frac{Energy\ consumption\ for\ Italy}{Total\ No.of\ employees\ for\ Italy} * Total\ No.of\ employees\ for\ Tito \qquad 3.5$$

In the second step, the percentage of employees for each sub-sector was used to estimate the total energy consumption by category (Table 3.4).

Table 3.4: Number of employees and energy consumption of the tertiary subsectors – year 2020

	Number of Employees	Energy consumption (TJ)
Accommodation	18	0.75
Food	107	4.36
Schools	115	4.09
Public Buildings	142	5.25
Private Offices	1042	38.03
Shopping Buildings	704	28.22
Healthcare	76	3.02
Total	2,204	83.72

In the third phase, energy consumption per sub-sector was broken down by end use, considering space heating, water heating, space cooling, and other electrical uses (Table 3.5) based on the national distribution provided by the RSE study (Besagni et al.,2020).

Table 3.5: Energy consumption of different sub-sectors for type of end-use – year 2020 (TJ)

	Space Heating	**Water Heating**	**Space Cooling**	**Other Electric Uses**	**Total**
Accommodation	0.24	0.06	0.11	0.34	0.75
Food	1.40	0.37	0.60	2.00	4.36
Schools	3.48	0.01	0.00	0.60	4.09
Public Buildings	3.53	0.01	0.70	1.00	5.25
Private Offices	28.34	0.09	5.90	3.70	38.03
Shopping Buildings	11.68	0.64	8.10	7.80	28.22
Healthcare	1.15	0.07	0.20	1.60	3.02
Total	49.82	1.25	15.61	17.04	83.72

Finally, for each subsector and end-use, the average consumption by fuel was estimated considering average energy consumption percentages by source of the Tito municipality. (Table 3.6).

Table 3.6: Energy consumption of tertiary sub-sectors by end-use and energy source – year 2020 (TJ)

	Natural gas	**Electricity**	**LPG**	**Diesel**	**Solar thermal**	**Total**
Accommodation	**0.23**	**0.49**	**0.02**	**0.003**	**0.01**	**0.75**
Space heating	0.21	0.02	0.01	0.002		0.24
Water heating	0.03	0.02	0.002	0.0003	0.01	0.06
Space cooling		0.11				0.11
Other uses		0.34				0.34
Food	**1.37**	**2.83**	**0.09**	**0.02**	**0.06**	**4.36**
Space heating	1.21	0.10	0.08	0.01		1.40
Water heating	0.16	0.13	0.01	0.002	0.06	0.37
Space cooling		0.60				0.60
Other uses		2				2
Schools	**2.81**	**1.07**	**0.18**	**0.03**	**0.002**	**4.09**
Space heating	2.80	0.47	0.18	0.03		3.48
Water heating	0.01	0.004	0.0003	0.0001	0.002	0.01
Space cooling						
Other uses		0.60				0.60
Public Buildings	**2.85**	**2.18**	**0.19**	**0.03**	**0.002**	**5.25**
Space heating	2.84	0.47	0.18	0.03		3.53
Water heating	0.01	0.005	0.0003	0.0001	0.002	0.01
Space cooling		0.70				0.70
Other uses		1.00				1.00
Private Offices	**22.84**	**13.42**	**1.48**	**0.27**	**0.02**	**38.03**

Space heating	22.80	3.79	1.48	0.27		28.34
Water heating	0.04	0.03	0.003	0.0005	0.02	0.09
Space cooling		5.90				5.90
Other uses		3.70				3.70
Shopping Buildings	**9.81**	**17.54**	**0.64**	**0.12**	**0.11**	**28.22**
Space heating	9.54	1.41	0.62	0.11		11.68
Water heating	0.28	0.23	0.02	0.003	0.11	0.64
Space cooling		8.10				8.10
Other uses		7.80				7.80
Healthcare	**0.97**	**1.96**	**0.06**	**0.01**	**0.01**	**3.02**
Space heating	0.94	0.14	0.06	0.01		1.15
Water heating	0.03	0.03	0.002	0.0004	0.01	0.07
Space cooling		0.20				0.20
Other uses		1.60				1.60
Total	**40.88**	**39.48**	**2.66**	**0.48**	**0.21**	**83.72**

3.3.2 3. Tertiary end-use demand

End-use energy consumption of the tertiary sector is expressed in PJ and is estimated considering the selected proxy variables by subsector.

For accommodation facilities, the proxy variable is the number of registered presences (total number of nights spent by customers), available at the municipal level on the website of the Basilicata Region Tourist Promotion Agency (Territorial Promotion Agency of Basilicata, 2020). For Food, Private offices, and Healthcare, the number of employees for each subsector was used, based on data provided by the ISTAT database.

To estimate the end-use demands of Schools, Shopping Buildings, and Public Buildings, the values provided by the Revenue Agency based on the cadastral categories of the buildings were used.

Specifically, for Public Buildings (cadastral category B4) and Schools (cadastral category B5), the volumetric values were used, while for Shopping Buildings (cadastral category C1), the available surfaces were considered. Table 3.7 summarizes the values of the final tertiary demand by subsector for the base year.

Table 3.7: Tertiary sector demand by subsector - year 2020

Tertiary subsectors	Unit of measure (proxy variables)	Values
Accommodation	Mpresences	0.0172
Food	Memployees	0.000107
School	Mm^3	0.0262
Public buildings	Mm^3	0.0088
Private office	Memployees	0.001
Shopping buildings	Mm^2	0.045
Health care	Memployees	0.00076

3.3.2 4. Electricity production on the local scale

The electricity production modeled in the Tito energy system is related to photovoltaic production serving both residential and tertiary buildings. For this study, large ground-mounted photovoltaic plants and wind farms are not considered, since the electricity produced by them is sold directly to the Energy Services Manager (GSE) and fed directly into the national electricity grid.

The total number of photovoltaic systems (n. 164) and the total installed power (18,775 kW) of the municipality of Tito in 2020 were obtained from the Atlaimpianti database which provides a detailed description of the installed renewable energy systems (Atlaimpianti,2020) Further elaborations were carried out to differentiate the photovoltaic systems based on their location: Residential, Tertiary, and Industrial-Ground. In particular, the Industrial-Ground location refers to medium-high photovoltaic systems typically serving industrial plants or ground-based systems to produce electricity sold to the national electricity transmission grid.

The use of PVGIS software allowed us to estimate the production of electricity from photovoltaic systems for each sector based on their installed capacity (European Commission, 2025).

Considering the national data relating to the percentage of self-consumption (30% for Residential and 52% for Tertiary), the values of self-consumed electricity and sold to the national transmission network were estimated (Table 3.8).

Table 3.8: Local electricity production from photovoltaic plants

Localization	**Capacity (kW)**	**Electricity Production (TJ)**	**Self-consumption (TJ)**	**Transferred to the national grid (TJ)**
Residential	367	1.5	0.4	1
Tertiary	466	1.9	1	0.9
Industrial-Ground	17,942	72.4		72.5
Total	18,775	75.8	1.4	74.4

The electricity produced by ground-mounted photovoltaic systems and those serving industrial buildings is not considered in this scenario. In fact, in the first case, the electricity produced is fed into the national electricity grid, while in the second case, the electricity produced and self-consuming is related to a non-modeled sector. For the tertiary and residential sectors, the electricity produced and fed into the grid is considered an export.

3.3.3 Energy balance of the base year

The reference energy balance for the base year was obtained considering the local production of electricity and the imports of other fuels necessary to satisfy the energy demand of the residential and tertiary sectors. Both fossil fuels (natural gas, liquefied petroleum gas, and diesel) and biomass (wood and pellets) are imported, which satisfy the energy demand for heating of the residential sector. The electricity produced by photovoltaic systems sold to GSE was considered an exported commodity. Table 3.9 shows the energy balance for the reference year.

Table 3.9: Energy balance (TJ) – year 2020.

Flow/ Product	**Natural gas**	**LPG**	**Diesel**	**Electricity**	**Biomass**	**Solar thermal**	**Total**
Import	141	9.73	0.48	62	104		317.2
Local production				3.4		1.4	4.8

Export				2			2
Residential Consumption	100	7.07		23.6	104	1.2	235.9
Tertiary Consumption	40.88	2.66	0.48	39.48		0.21	83.72

3.4 Demand projections

Relevant category-specific drivers were identified to estimate demand projections over the time horizon (2020-2050) through a statistical approach. For the residential sector, population and household projections at the municipal level were used. The 20-year demographic trend provided by the National Institute of Statistics (ISTAT) was used, which estimates a population decline from 7,147 in 2022 to 6,389 in 2042 (ISTAT, 2025). This assumption was also used to project the demographic trend to 2050 by identifying an appropriate mathematical function for extrapolation. The negative population trend shown in Table 3.10 is typical of small municipalities in Southern Italy and in the internal areas of the Italian Apennines. On the contrary, the number of families residing in Tito in the last twenty years has recorded an increase from 2003 to 2023 (from 2323 to 2873) with a decrease in the average number of members per family (from 2.81 in 2003 to 2.45 in 2023) (AdminStat Italia, 2025). Based on the statistical data of the period 2003-2023, the trend of the average number of members per family in the period 2024-2050 was estimated, and, consequently, the trend of the number of families in the period 2020-2050 (obtained as the ratio between the population and the average number of members per family).

Table 3.10: Demographic drivers of end-use demand.

Year	**2020**	**2021**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Population	7162	7147	7083	6941	6740	6497	6333	6142
Average number of members per family	2.52	2.49	2.44	2.36	2.28	2.20	2.12	2.03
Families	2847	2868	2901	2941	2958	2957	2993	3020

Table 3.11 summarizes the end-use demand projections for the period 2020-2050 in the residential sector

Table 3.11: Demand Projection by end-use in the residential sector (2020-2050).

	Unit	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Space heating	Mm^2	0.423	0.431	0.437	0.440	0.440	0.445	0.449
Water heating	MLitres	105	116	127	123	119	116	112
Space cooling	Mm^2	0.212	0.215	0.218	0.220	0.220	0.222	0.224
Cooking	MUnit	0.0072	0.0071	0.0069	0.0067	0.0065	0.0063	0.0061
Lighting	Glum	0.063	0.065	0.066	0.066	0.066	0.067	0.067
Other electric uses	TJ	0.83	0.84	0.85	0.86	0.86	0.87	0.88

Table 3.12 summarizes the energy demand projections of different tertiary sectors. In the tertiary sector, the trend of energy demand for different end uses is not directly related to demographic parameters. Based on the available statistical data, a trend line was identified for each subsector and, using this information, the demand projection over the 2020-2050 time horizon was obtained. For the public sector (Schools and Public Buildings), energy demand was considered constant over the time horizon, assuming that there is no increase in the volumes of Public Buildings and that the decrease in population does not affect consumption.

Table 3.12: Energy demand Projections of the tertiary subsectors.

	Unit	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Accommodation	MPresence	0.017	0.022	0.023	0.024	0.025	0.026	0.027
Food	MEmployees	0.000107	0.000103	0.000105	0.000107	0.000109	0.000111	0.000113
Schools	Mm^3	0.0262	0.0262	0.0262	0.0262	0.0262	0.0262	0.0262
Public building	Mm^3	0.0088	0.0088	0.0088	0.0088	0.0088	0.0088	0.0088
Private office	MEmployees	0.0010	0.0012	0.0013	0.0014	0.0016	0.0017	0.0018
Shopping building	Mm^2	0.045	0.047	0.050	0.052	0.055	0.057	0.060
Health care	MEmployees	0.00008	0.00010	0.00013	0.00016	0.00018	0.00021	0.00024

3.5 Modeling of the Renewable Energy Community

The modeling of the Renewable Energy Community (REC) model within the ETSAP-TIMES framework involves defining the modalities for generating, sharing, self-consumption, and sale of electricity within the local energy system. The model structure is based on the creation of a detailed Reference Energy System (RES) that describes the flow of electricity from photovoltaic (PV) generation through various "fictitious (dummy) technologies" representing the operations and market mechanisms of the REC. Figure 3.11 and Figure 3.12 show the operational diagram of the REC respectively for residential users and tertiary users.

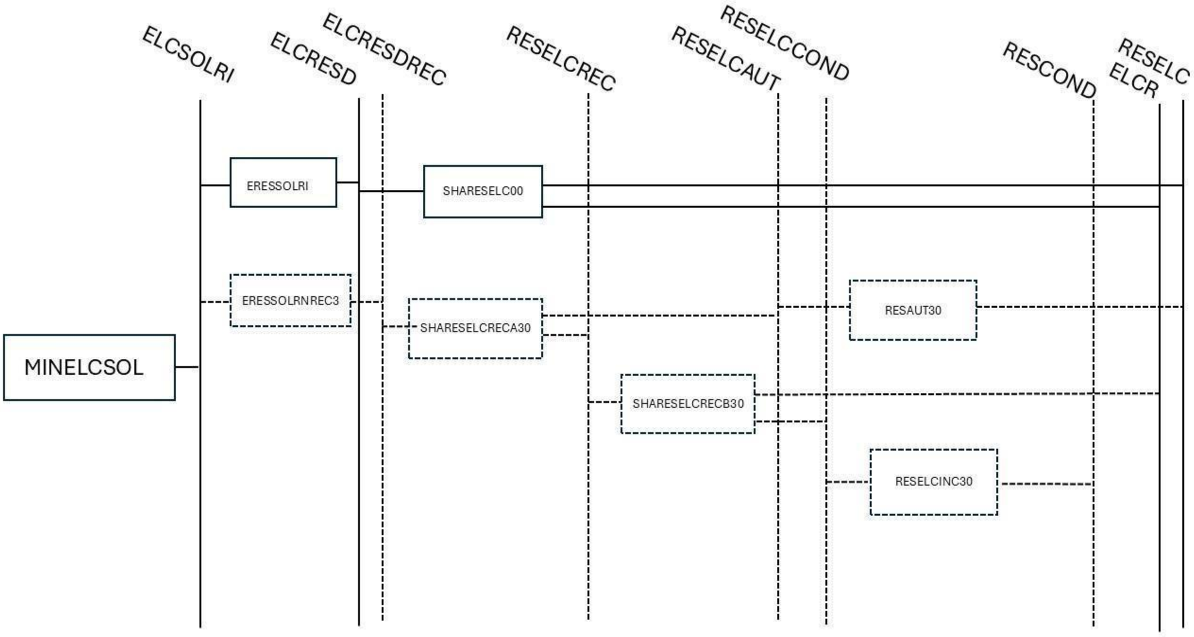

Figure 3.11: Operational diagram of the REC for residential users.

The section represented by dotted lines outlines the REC scheme for the Residential sector~~.~~ The photovoltaic technologies installed for REC's electricity production are represented by the ERESSOLRNEC3 box. These systems are designed to meet part of the residential sector's electricity demand through collective self-consumption and shared use. The fictitious technology SHARESELCRECA30 is introduced to divide the electricity produced by photovoltaic systems connected to the REC into:

- Self-consumption: assumed to be 50% of production, used directly within the residential sector.

- Shared Virtual energy: the remaining 50% of electricity is available to be shared among REC members, simulating a cooperative energy exchange within the community.

The RESAUT30 process manages the self-consumption, which allocates energy to residential users at zero cost, representing the direct on-site use of electricity without transaction or network costs. The SHARESELCRECB30 process manages the distribution of shared electricity among community members and has two output commodities: RESELCCOND and ELCR. If the REC is perfectly calibrated, i.e., all the electricity produced by prosumers is consumed by REC users, RESELCCOND coincides with RESELCREC, benefiting from the incentive tariff. If not all the electricity produced by prosumers is consumed by REC users, the excess electricity (ELCR) is sold to the national grid at the hourly zonal price.

The RESELCINC30 process represents the fictitious technology that aggregates all financial inflows associated with shared energy, including:

- The incentive tariff set by the CACER Decree [Decreto CACER]
- The hourly zonal market price
- The ARERA valuation (national energy regulator adjustment).

Finally, the RESCOND commodity represents the energy purchased by end-users (consumers) participating in the community at full purchase price.

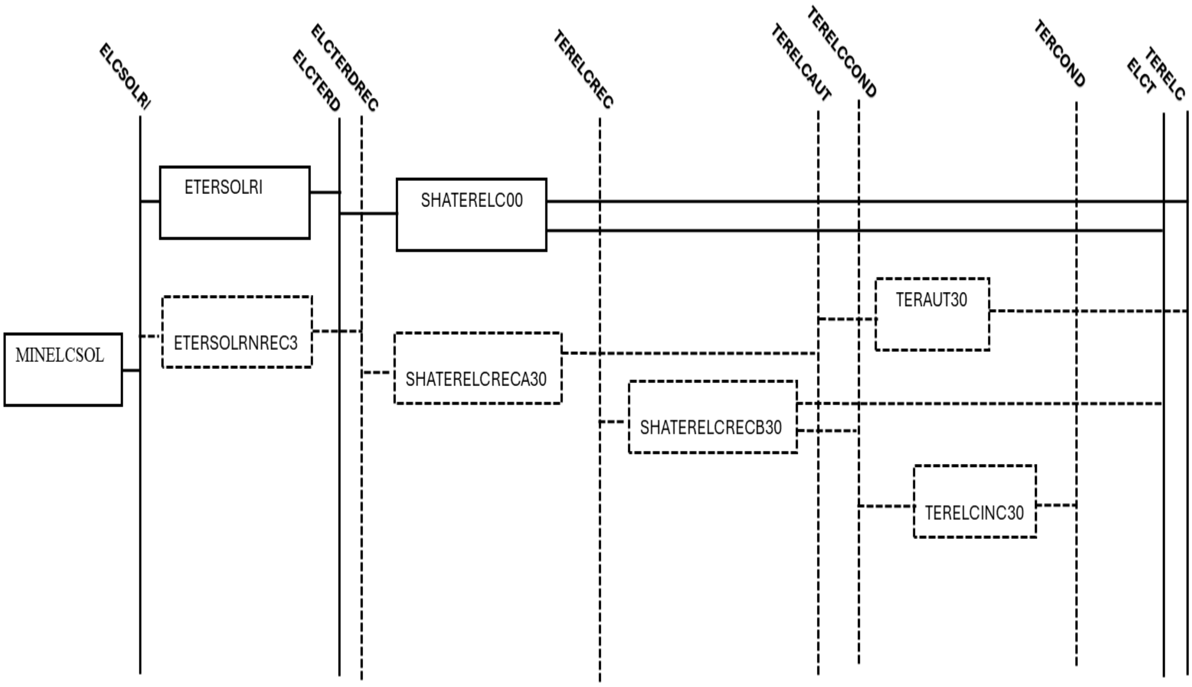

Figure 3.12: Operational diagram of the REC for tertiary users.

The operational diagram of the REC for the tertiary users is similar to that of the residential users. The final commodity for the tertiary is TERCOND, which represents the energy purchased by end-users (consumers).

Three REC sizes were considered: 500 kW, 1 MW, and 10 MW. For each of these, the PNRR option (40% of the contribution for investment in PV and a 50% reduction in the incentive tariff) and the non-PNRR option with the full incentive tariff on investment were considered.

Table 3.13 reports the electricity production from photovoltaic plants for different REC sizes in the Tito municipality, using PVGIS software. It has been assumed that the distribution of electricity consumption produced by REC photovoltaic systems between the residential sector (34%) and the tertiary sector (66%) is proportional to their electricity consumption in 2030 in the BAU scenario.

Table 3.13: Local electricity plant production for different REC sizes

System power (kW)	Plant production (KWh)	Plant Production (TJ)	Residential (TJ)	Tertiary (TJ)
500	652,514	2.3	0.8	1.6

1000	1,305,029	4.7	1.6	3.1
10000	13,050,288	47	16	31

The electricity produced by a 500 kW PV REC covers 4% of total electricity consumption (residential and tertiary), while that produced by a 1 MW REC covers 7% of Tito's total electricity consumption, and that produced by a 10 MW REC covers 71%.

Table 3.14 lists the financial incentives that influence the profitability and attractiveness of REC and that are considered in the modelling of the REC.

Table 3.14: Tariff assumptions

	a)	b)	c)	d)	e)	f)
	Tariff according to CACER Decree with PNRR (MEuro /PJ)	**Tariff according to CACER Decree without PNRR** (MEuro /PJ)	**ARERA valorization** (MEuro /PJ)	**Hourly zonal price (HZP)** (MEuro /PJ)	**Total incentive tariff with PNRR** (MEuro /PJ)	**Total incentive tariff (CACER tariff + ARERA value + HZP) without PNRR** (MEuro /PJ)
500 kW	12.50	25	2.36	35.69	50.54	63.04
1 MW	11.11	22.22	2.36	35.69	49.16	60.27
10 MW	11.11	22.22	2.36	35.69	49.16	60.27

In the ARERA valuation, the value is constant in all scenarios (2.36 MEuro/PJ). For the hourly zonal price, the average annual value for the Centre-South area on the Energy Market Manager website was considered (35.7 MEuro/PJ). The total incentive tariff is the summation of the CACER tariff, ARERA valuation, and hourly zonal price.

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Chapter 4 THE SCENARIOS ANALYSIS

Scenario analysis is a fundamental tool for assessing the evolution of an energy system under variable technological, economic, and regulatory conditions. The building of alternative scenarios allows understanding how different infrastructure configurations, incentive measures, and market dynamics can impact energy consumption, renewable energy production, greenhouse gas emissions, and overall system costs. This approach does not aim to predict a single future, but rather to outline a series of plausible trajectories that identify strengths, vulnerabilities, and strategic opportunities. Specifically, it allows us to evaluate the effectiveness of energy policies and incentive tools, providing a basis for decision-making for local governments, energy managers, and communities. Within this framework, this study uses scenario analysis to estimate the effects of the introduction of new technologies and new organizational models on regional energy demand, production, and flows, considering both the continuation of current trends and alternatives characterized by greater use of renewable sources and electrification. From this perspective, three main scenarios were developed, each with a specific role in the evaluation process:

- Business-as-Usual (BaU) Scenario.

This represents the reference path, in which the system evolves according to current trends in terms of energy consumption, technologies adopted, and energy mix. This scenario provides the benchmark for assessing the impact of alternative measures.

- Sensitivity Analysis to Variations in Natural Gas Prices.

This scenario explores the energy system's response to the progressive increases in natural gas prices, also considering the introduction of incentives for the adoption of heat pumps. This scenario allows estimating the system's resilience to energy market volatility and analysing the effects of end-use electrification.

- Renewable Energy Community Scenario (REC Scenario).

It evaluates the effects of implementing a Renewable Energy Community through different configurations of photovoltaic systems, varying in installed capacity and the presence or absence of capital contributions. The scenario investigates the potential of RECs to promote local decarbonization, collective self-consumption, energy sharing, and the reduction of import dependence.

4.1 The Business-as-Usual scenario

The Business-as-Usual (BaU) scenario represents the baseline or reference scenario that describes how the energy system is expected to evolve in the absence of any new policies or measures beyond those already in place. It reflects the continuation of current trends in energy demand, technology deployment, resource availability, and existing policy frameworks. It is used as a benchmark against which alternative policies or mitigation scenarios can be compared to assess their economic, environmental, and technological impacts. The following assumptions were made in the BAU path:

Assumptions relating to energy supply and production

The electricity produced by ground-mounted photovoltaic systems and those serving industrial buildings is not considered in this model. In fact, in the first case, the electricity produced is fed into the national grid, while in the second case, the electricity produced and self-consumed is related to a sector that is not modelled. For the tertiary and residential sectors, the electricity produced by photovoltaic plants and not self-consumed is sold to the national grid. It is modeled through an export process.

Assumptions relating to Technology

In the tertiary sector, a minimum increase of 10% in the use of technologies with combined outputs (e.g., space heating and hot water) was assumed with respect to the base year.

Assumptions relating to emissions and costs

Revenues from environmental compensation paid on gas consumption, subject to the exploitation of oil fields, were considered unchanged until 2050.

Costs of energy commodities were assumed to be constant over the time horizon.

4.2 The REC scenario assumptions

The REC scenario was based on a series of technical and economic assumptions that represent the functioning of REC within the ETSAP-TIMES model generator. The following assumptions were used in the REC path:

- For each REC, it was assumed that 50% of the photovoltaic production is self-consumed by members, while the remaining 50% represents the shared energy.
- It has been assumed that 5% of the energy produced by the REC is virtually not consumed by its members and represents excess electricity fed into the grid at the hourly zonal price.
- The REC electricity output was allocated as 34% to the residential sector and 66% to the tertiary sector.
- In the case of a 10 MW size, 10 RECs of 1 MW size are considered, 1 MW being the maximum size.

4.3 The model optimisation and scenarios results

4.3.1 BAU scenario results

The section presents the results of the Business-as-Usual scenario, focusing on electricity production, energy supply, total energy consumption, air pollutant emissions, and sensitivity.

4.3.1.1 Electricity production

Electricity production from photovoltaic (PV) (Figure 4.1) increases by 99% in the considered time horizon, going from 3.4 TJ in 2020 to 6.7 TJ by 2050, highlighting a strong commitment to the development of solar power, which is essential to meet energy needs and, at the same time, support the achievement of sustainability goals.

56% of photovoltaic electricity is produced by the tertiary sector and 44% by the residential sector, demonstrating the equal importance of both sectors in the development of photovoltaic energy.

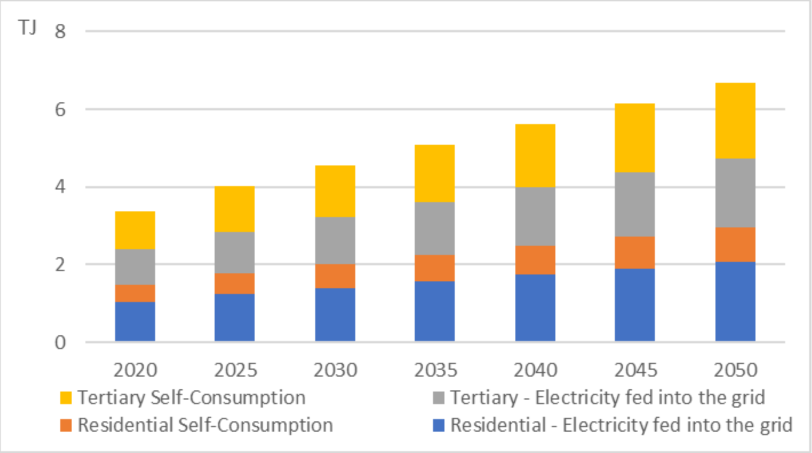


Figure 4.1: Electricity Production from Photovoltaic (TJ)

Investing in photovoltaics is a measure that, on the one hand, provides electricity from renewable sources and, on the other, reduces CO_2 emissions, objectives contained in the PNIEC (Santos et al., 2025). In the year 2020, 42% of the electricity produced by photovoltaic is self-consumed (1.4 TJ), while the remaining 58% (1.9 TJ) is sent to the national distribution grid.

4.3.1.2 Energy supply

Figure 4.2 shows the energy mix from 2020 to 2050, highlighting the important role of natural gas and electricity, which, in the long term substitute all fuels, In particular, natural gas reaches its maximum in 2035 (214 TJ) while biomass, and LPG are gradually phased out by 2040, replaced by electricity, which increases to 64 TJ in 2050, representing 24% of the energy supply. Biomass decreases from 104 TJ in 2020 to 6.1 TJ by 2035. There is a small contribution of Diesel from 0.5 TJ in 2020 and will be gradually phased out by 2035. Electricity experienced a decrease from 2025 to 2030, followed by a steady increase from 52 TJ in 2035 to 63 TJ by 2050. Natural gas increased from 141 TJ in 2020 to its apex of 216 TJ by 2045, then decreased to 204 TJ by 2050. LPG decreases from 9.7 TJ in 2020 to near zero by 2035. The total energy supply decreases by almost 16% between 2020 and 2050, which could be because of increased energy self-consumption or decentralization.

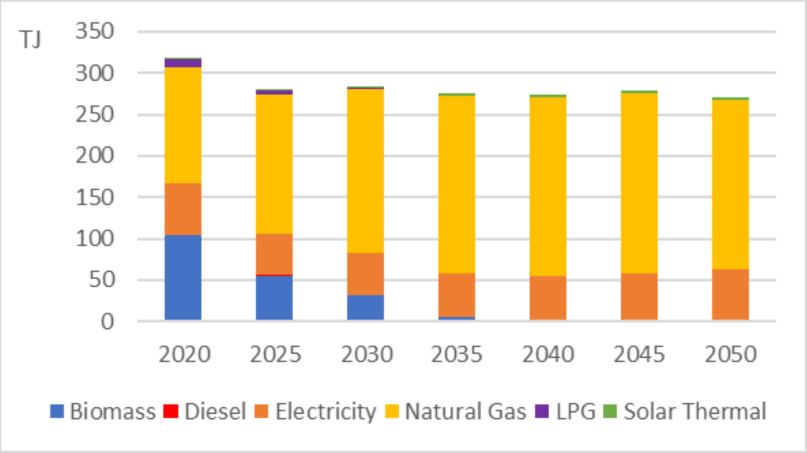


Figure 4.2: Energy supply (TJ)

4.3.1.3 Energy consumption

Total energy consumption from 2020 to 2050 (Figure 4.3) decreases by 15% and shows a significant change in energy use patterns, driven by the decline of biomass and the increase in natural gas consumption (+ 44% in 2050 compared to 2020). Biomass is used only in the Residential sector and, together with LPG, is gradually phased out in 2040.

Diesel follows a similar trend, being phased out by 2035. Electricity consumption, after an initial decrease from 63 TJ in 2020 to 52 TJ in 2025, increases by 5% over the time horizon, reaching 66 TJ in 2050.

Solar thermal energy shows a significant growth (+187% by 2050), even if it still represents a minimal part of the energy consumption, driven by investment in renewable energy to meet climate goals (IEA, 2024). Electricity consumption overall is about 20% in 2020 and 24 % in 2050, with a minimum of 52 TJ (18%) in 2030, being mainly used in the tertiary sector (62% in 2020 and 73% in 2050 of the total electricity available). Natural gas consumption remains constant over the period considered in both the residential (71%) and tertiary (29%) sectors, while LPG consumption, which also remains constant until 2040, accounts for 73% in the residential sector and 27% in the tertiary sector, before being phased out by 2040.

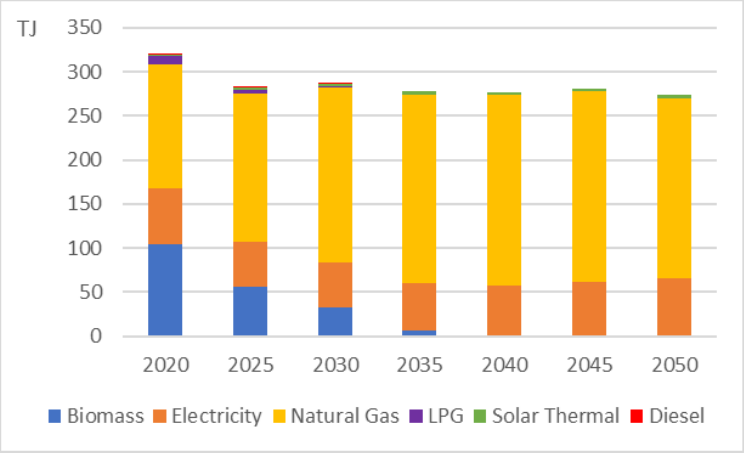


Figure 4.3: Total energy consumption (TJ)

4.3.1.3 1 Energy consumption– Residential sector

Energy consumption in the residential sector decreases 30% by 2050 due to the replacement of base year technologies with more efficient ones. Biomass, the prevailing fuel in 2020 (44%), is phased out by 2040, being entirely substituted by natural gas (88%). Electricity consumption decreases by 6 TJ in 2050 compared to the base year, while its percentage contribution to total residential is almost constant (around 10% for the whole time horizon). Solar thermal increases from 1.2 TJ in 2020 to 3 TJ by 2050, contributing to fulfill around 2% of the energy demand of Residential in 2050 (Figure 4.4).

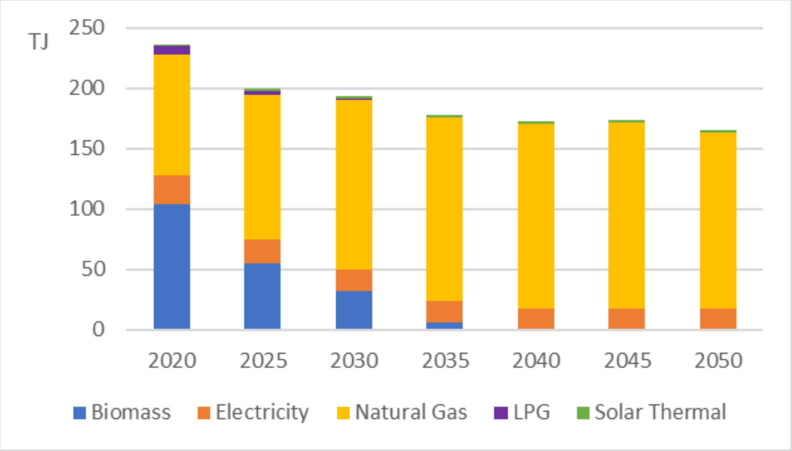


Figure 4.4: Total fuel consumption – Residential sector (TJ)

Solar thermal increases by 133% on the time horizon (from initially 1.2 TJ in 2020 to 3 TJ by 2050), contributing from 1% to 2% to fulfill the energy demand of Residential.

The demand for Space Heating, initially met by natural gas, biomass, and LPG (52%, 45% and 3% respectively), is entirely covered by natural gas from 2040 onwards, decreasing by about 4% on the time horizon (Figure 4.5). Over the 2020-2050 time horizon, energy demand remains stable, despite a 6% increase in heated surface area. This is due to improved energy efficiency, with a reduction in specific energy consumption (energy per unit area).

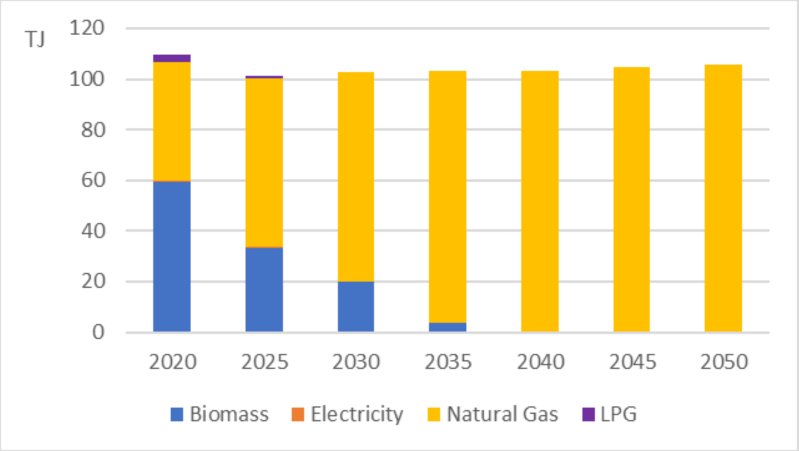


Figure 4.5: Space heating demand – Residential sector (TJ)

Water heating increases 7% over the time horizon, being fulfilled in 2020 by natural gas (82%), Electricity (11%), LPG (5%), and solar thermal (2%), while in 2050 by natural gas (95%) and solar thermal (5%) (Figure 4.6). In the 2020–2030 decade, an increasing volume of water is heated without significantly increasing energy consumption. After 2030, the amount of heated water decreases, while energy demand remains virtually unchanged: this implies a slight increase in specific energy requirements.

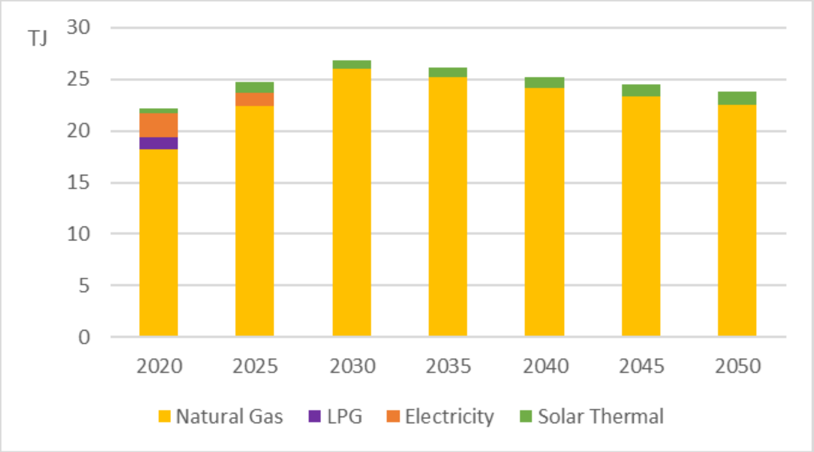


Figure 4.6: Water heating demand – Residential sector (TJ)

Space cooling is entirely fulfilled by electricity, accounting for 3% of electric uses, including lighting, and other electric appliances, with a 25% increase for lighting in 2050 compared to the base year (Figure 4.7).

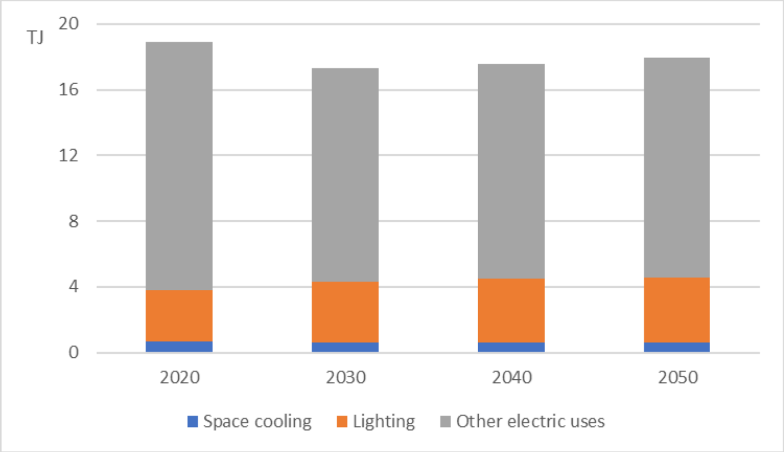


Figure 4.7: Electricity consumption for space cooling, Lighting, and other electric uses – Residential sector (TJ)

In the case of space cooling, the cooled surface grows by 5.7% from 2020 to 2050, while the share of electricity used for cooling remains very low and almost constant over time. This indicates that the efficiency of air conditioning systems has improved significantly. In the case of lighting, the end-use demand increases slightly from 0.063 to 0.067 Glumen, but the energy used remains almost unchanged, especially due to the introduction of LED technologies.

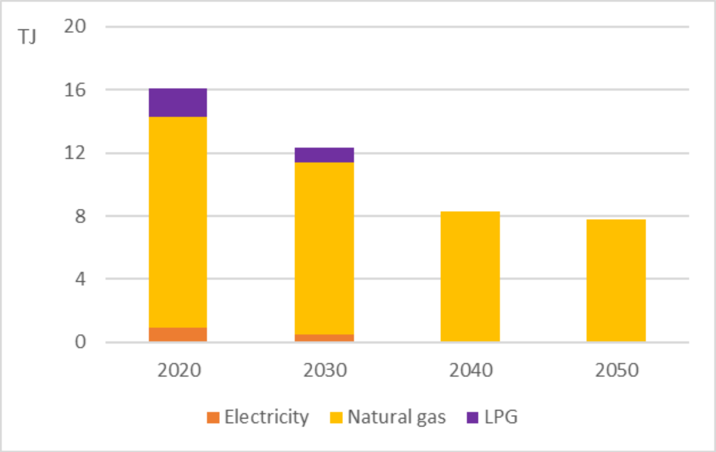


Figure 4.8: Fuel consumption for cooking – Residential sector (TJ)

Cooking demand, initially fulfilled by natural gas (83%), LPG (11%), and electricity (6%), is fully met by natural gas by 2040, with a decrease of 51% of end-use demand (Figure 4.8). By 2035, Electricity (2.3%) and LPG (4.3%) phased out, with Natural gas (93.4%) substituted

100% by 2050. It is due to the replacement of the technologies used in the base year with new, more efficient natural gas technologies.

4.3.1.3 2 Energy consumption – Tertiary sector

Energy consumption in the tertiary sector increases by 30% over the period considered, i.e. +22% for electricity, +45% for natural gas, and a significant increase in solar thermal energy (from 0.2 to 1.3 TJ), which replaces LPG and diesel, gradually phased out from 2030 onwards. In 2050, the energy demand of the tertiary is fulfilled by natural gas (55%), electricity 44% and solar thermal (1%) (Figure 4.9).

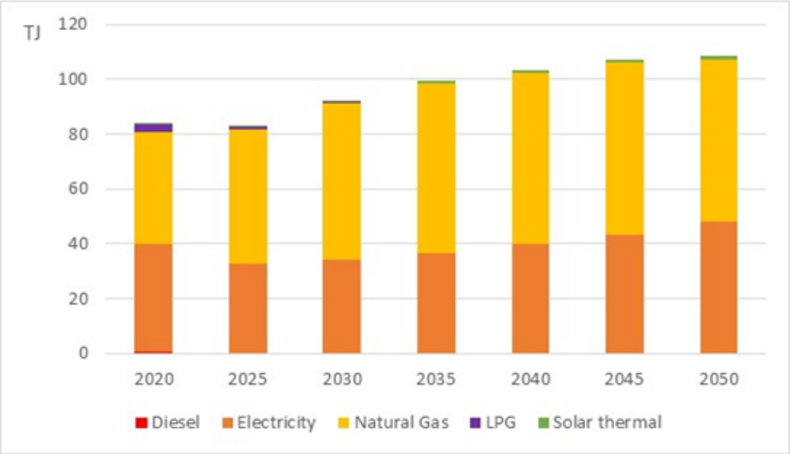


Figure 4.9: Total fuel consumption – Tertiary sector (TJ)

Total energy consumption by subsector provides further insights, as shown in Figure 4.10. Energy consumption in the Tertiary increases 30% over the time horizon. In 2020, Private Offices and Shopping Centers accounted for 47% and 34%, respectively, followed by Food, Public Buildings, and Schools (around 5 % each). In 2050, a remarkable increase in the Healthcare and Accommodation subsectors is expected (+190% and + 78% respectively), while Schools and Public Buildings will consistently reduce their consumption (-37% and -12% respectively), due to efficiency interventions on building structures. Food shows a 30% increase in the time horizon in line with the expected growth in the number of employees, accounting for about 5% of the entire time horizon.

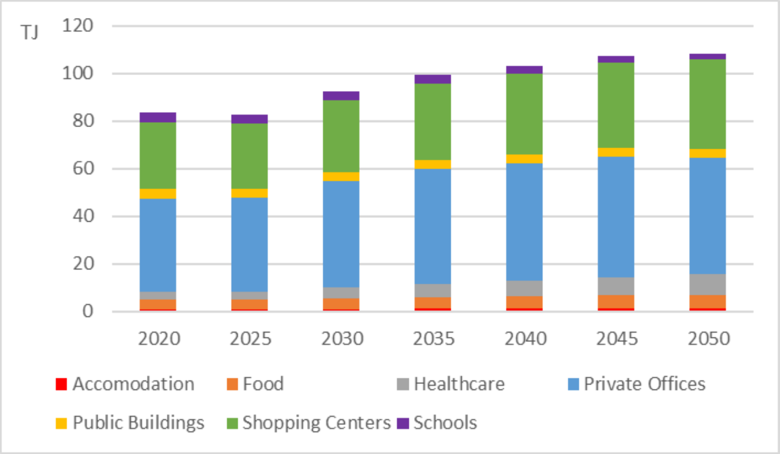


Figure 4.10: Total fuel consumption per subsector– Tertiary sector (TJ)

Figure 4.11 shows the consumption of natural gas by subsectors over the time horizon. In 2020, Private Offices and Shopping Centers showed the highest levels of consumption, accounting for 56% and 24% respectively. Public buildings and Schools each constitute 7% of total consumption, while Food, Health Care, and Accommodation represent 3%, 2%, and 1%, respectively.

In 2050, Private Offices anticipate a 7% decrease in their share of total natural gas consumption (from 56% in 2020 to 49% in 2050). On the other hand, Shopping Buildings show a 6% increase in their share of natural gas consumption (from 24% in 2020 to 30% in 2050). Analyzing the breakdown of natural gas consumption of all subsectors, an increase is observed for Food and Healthcare (2% and 4% respectively), while the share of School consumption decreases by 4% (from 7% in 2020 to 3% in 2050).

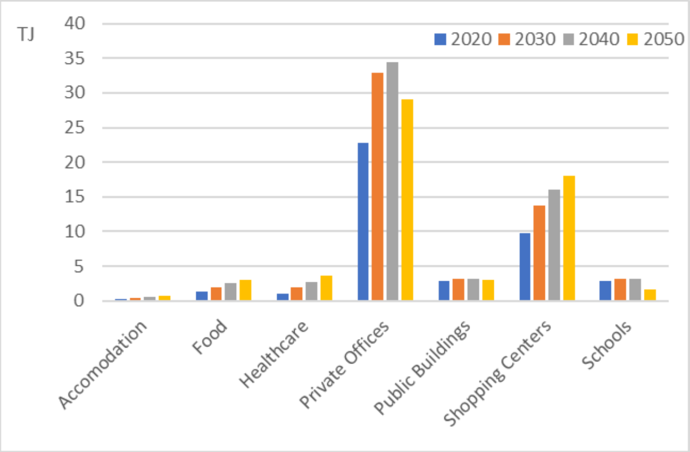


Figure 4.11: Natural gas consumption per subsector (TJ)

Figure 4.12 shows the electricity consumption by subsectors along the time horizon. Private Offices and Shopping Centers have the highest consumption. In 2020, Private Offices account for 37%, while Shopping Centers account for 44%. In 2050, the share of the total electricity consumption increases by 4% (from 37% in 2020 to 41% in 2050). There is a 4% decrease in their share of electricity consumption (from 44% in 2020 to 40% in 2050). In the same period, for this subsector, electricity consumption increases from 18 TJ to 19 TJ. Healthcare and Private Offices increase their share + 5% and 4% respectively, while other subsectors decrease their share from 5% to 1%.

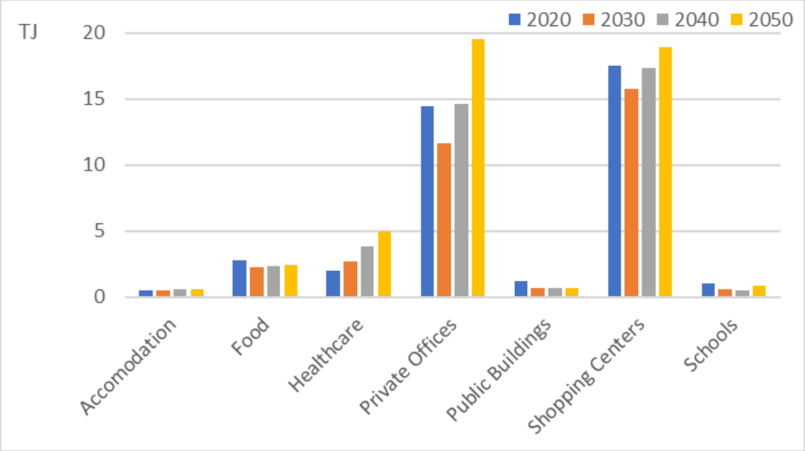


Figure 4.12: Electricity consumption per subsector (TJ)

Figure 4.13 illustrates the consumption of thermal solar across various subsectors over the time horizon. It is evident that Shopping Centers and Food subsectors show the highest consumption. In 2020, Shopping Centers accounted for 51% of total consumption, while Food represented 29%. In 2050, the share of thermal solar in the Shopping Centers subsector increased by 8% (from 51% in 2020 to 59% in 2050). The food subsector is anticipated to experience a decrease of 67% in its share of thermal solar consumption (from 29% in 2020 to 23% in 2050).

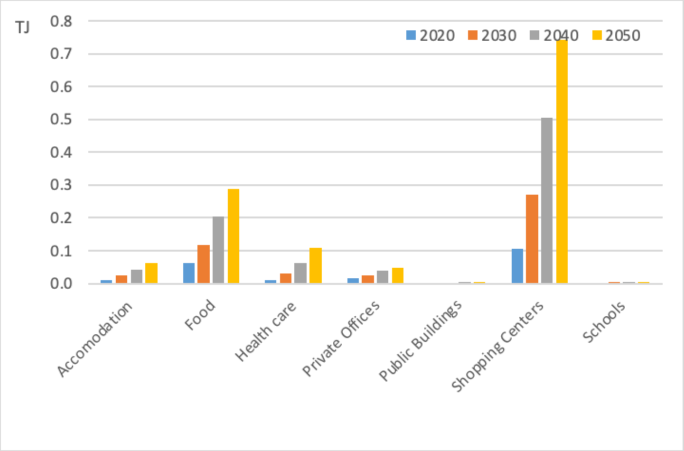


Figure 4.13: Thermal solar consumption per subsector (TJ)

Important considerations can be obtained by analyzing the trends in natural gas and electricity consumption and the trend in demand for use for each subsector. In Accommodation, the growth in presence leads to increased energy demand. However, natural gas consumption increases more rapidly than electricity, indicating greater thermal dependence and poor electrification. Food demand remains nearly stable, but natural gas consumption grows significantly, and the subsector becomes more energy intensive. The reduction in electricity and the increase in gas consumption indicate a shift toward thermal uses. School demand is constant, while the decline in consumption indicates improvements in energy efficiency, characterizing it as the subsector with the most advanced transition. In Public Buildings, characterized by unchanged demand, electricity consumption is reduced due to system optimization, but gas remains predominant for heating. In Private Offices, electricity and gas consumption both increase, but less so than end-use demand, implying an improvement in specific energy efficiency. Shopping centers are characterized by an increase in consumption, especially of natural gas, at a percentage higher than the growth in end-use demand. Finally, in healthcare, consumption growth follows that of end-use demand, but with a strong increase in natural gas.

4.3.2 Sensitivity analysis

A sensitivity analysis was carried out by gradually increasing the purchase cost of natural gas to assess the behavior of the energy system in terms of fuel use and technology configuration. A progressive increase (+20%, 30%, 50% and 100%) in the cost of natural gas of the reference year along the time horizon was therefore considered to assess the response to both moderate changes and extreme conditions that could occur in the event of geopolitical instability.

The total cost of the energy system represents the total amount of energy production and consumption expenditure over 30 years, discounted to the base year. It includes fuel purchase costs, investment costs for new technologies, operating and maintenance costs for infrastructure and conversion and end-use technologies, minus any profits from energy sales or incentives.

Figure 4.14 shows an increase in the total system cost due to the variations in natural gas prices. The cost increase goes from 2.5% to 5.2% compared to the BAU scenario. The variation between +2.5% and +5.2% in total system costs suggests that, despite a sharp increase in gas costs (up to 100%), the energy system has a good adaptive capacity and is not excessively vulnerable to such market shocks.

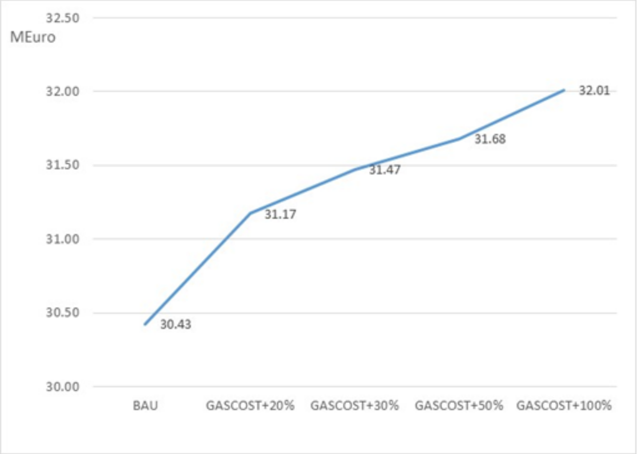


Figure 4.14: Total energy system cost

Figure 4.15 shows the natural gas supply trends, highlighting the decrease due to the increase in purchasing costs, which are more evident in the long term.

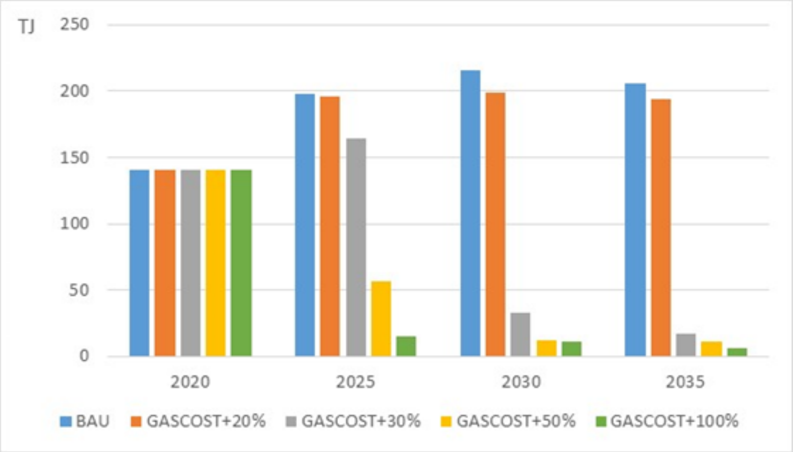
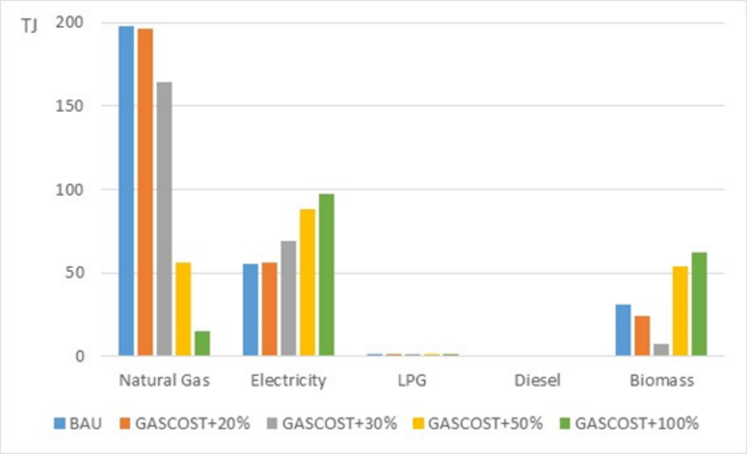
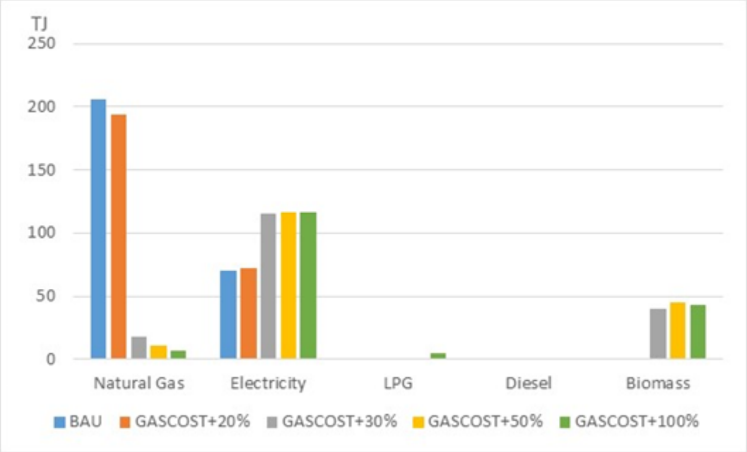


Figure 4.15: Natural gas supply (TJ)

A 20% increase in natural gas price is almost ineffective on consumption, which decreases in the consumption ranges from 1% in 2030 to 8% in 2040. In the GASCOST+30% case, the reduction is significant, ranging from -71% to -95% in 2040. Doubling the natural gas costs (case GASCOST+100%), the reduction in the long term is -97%. Energy supply variations highlight the effects of the increase in natural gas prices on the fuel mix (Figure 4.16).



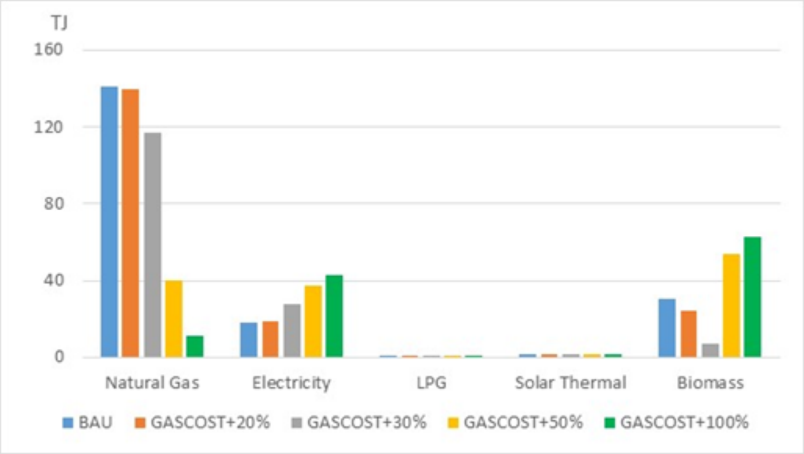
a) Year 2030



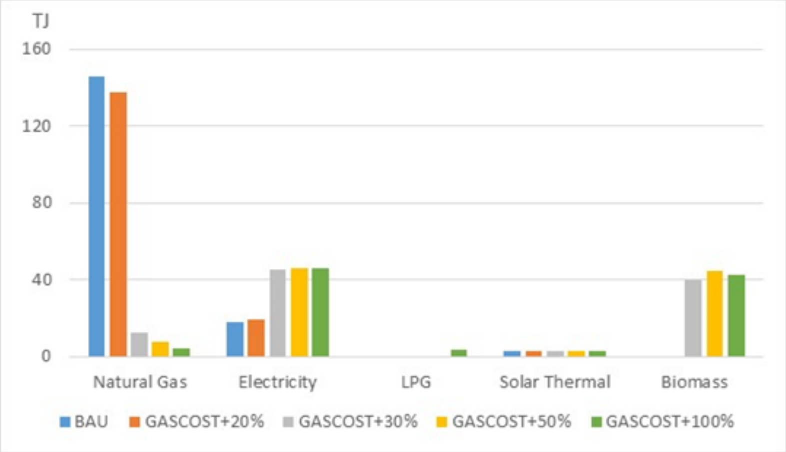
b) Year 2050

Figure 4.16: Fuel Supply variations at increasing natural gas costs – a) year 2030 and b) year 2050

Natural gas is mainly substituted by electricity and biomass. In 2030, electricity increases range from 2% to 75%, while biomass decreases in the GASCOST+20% and GASCOST+30% cases, increasing up to 103% in the case GASCOST+100%, achieving 62.5 TJ (Figure 4.16a). In 2050, electricity increases from 3% to 67%, while biomass and LPG contributions achieve 43 TJ and 45 TJ, respectively, in the case GASCOST+ 100%. Fuel mix in Residential areas at increasing natural gas costs is reported in Figure 4.17.



a) Year 2030



b) Year 2050

Figure 4.17: Residential fuel mix a) year 2030 and b) year 2050

In 2030 (Figure 4.17a), natural gas drops to 92% (GASCOST+100% case), being substituted by electricity (+141%) and biomass (+103%). LPG and solar thermal contributions are constant, being respectively 10 TJ and 2 TJ. In 2050, Electricity consumption increases by +157% and biomass 138%. Solar thermal is constant (around 3 TJ), and LPG is zero in all cases except GASCOST+100%, which achieves 3 TJ, contributing 3% to total residential energy consumption.

The increase in electricity consumption, which compensates for the decline in natural gas consumption, is linked in particular to the use of heat pumps for space and water heating as also demonstrated by the increase in space electricity consumption per square meter, which goes from 2.3 TJ (BaU) to a maximum of 140 TJ (GASCOST+100% case, year 2040) ((Figure 4.18).

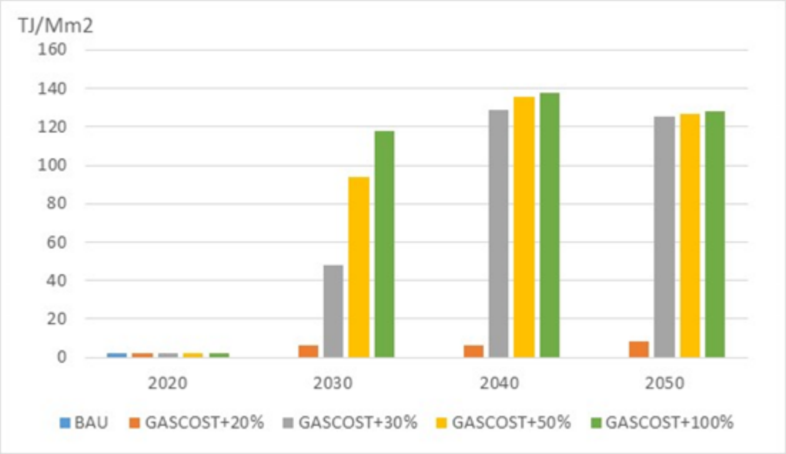


Figure 4.18: Electricity consumption for space heating (TJ/Mm^2)

Biomass also contributes to meeting space heating demand, showing a downward trend and gaining importance in 2040 and 2050, when the price of gas increased by at least 30% (Figure 4.19).

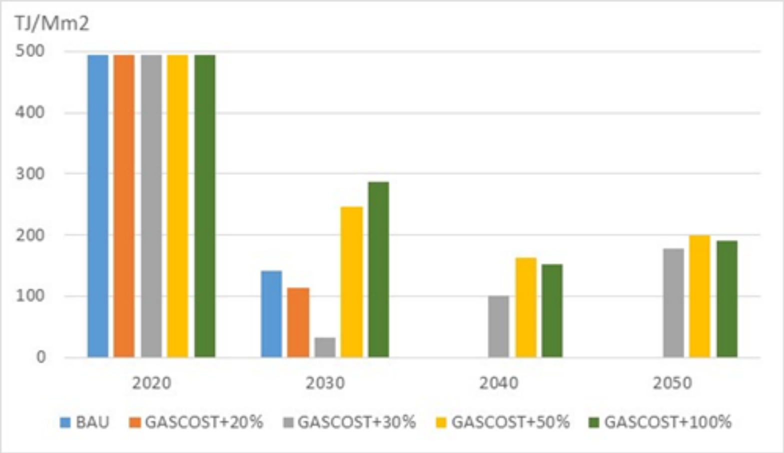


Figure 4.19: Biomass consumption for space heating (TJ/Mm^2)

In the tertiary sector, the increase in electricity consumption driven by the rise in natural gas prices is lower than in the residential sector, achieving + 29% in 2050 when the natural gas price is doubled (GASCOST100% case) (Figure 4 20).

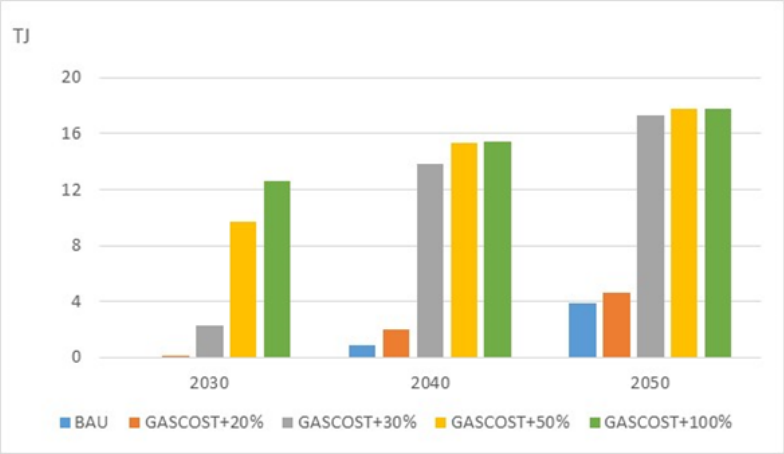


Figure 4.20: Electricity consumption in the tertiary sector (TJ)

Figure 4.21 shows the expected distribution among sub-sectors in 2050. Private offices and public buildings still account for the largest share (84%), while schools and public buildings account for about 4% each, Food and healthcare about 3% each, and accommodation 0.15%.

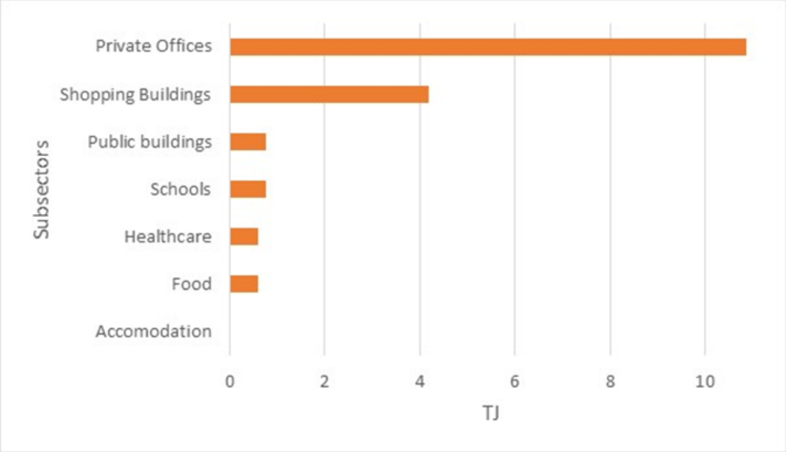


Figure 4.21: Electricity consumption by subsectors- Year 2050 (TJ)

Considering the results of the sensitivity analysis, further investigation was conducted under the assumption of a 50% non-repayable grant for the purchase of heat pumps in both the residential and tertiary sectors, alongside a gradual increase in natural gas purchase costs (Table 4.1).

Table 4.1: Sensitivity analysis with an increase in natural gas costs and a 50% reduction in heat pump investment costs

Cases	Increase in the purchase cost of natural gas	Investment costs for heating pumps
GASCOST+20%_50_HP	+20%	-50%

GASCOST+30%_50_HP	+30%	-50%
GASCOST+50%_50_HP	+50%	-50%
GASCOST+100%_50_HP	+100%	-50%

Figure 4.22 shows the trend in total system costs considering a 50% reduction in investment costs of heat pumps and a gradual increase in the purchase cost of natural gas. In all four cases, the total system's cost is lower than the cost of the BaU scenario. The lowest total system cost (29.19 MEuro) is obtained in the GASCOST+20%_50_HP case, corresponding to a 50% reduction in heat pump investment cost and a 20% increase in the purchase cost of natural gas. The total cost of the system reaches 29.70 MEuro in the GASCOST+100%_50_HP case, corresponding to a 100% increase in the purchase cost of natural gas and a 50% reduction in the heat pumps investment cost.

The 50% incentive on the purchase of heat pumps is an effective solution to mitigate the economic impact of an increase in the cost of natural gas, bringing the total cost of the system to be even lower than the BAU scenario. The 50% incentive on the purchase of heat pumps is an effective solution for mitigating the economic impact of an increase in the cost of natural gas, resulting in total system costs that are even lower than in the BAU scenario. The results suggest that incentives for energy efficiency technologies, such as heat pumps, can reduce overall energy system costs, even in un-favorable scenarios of rising gas prices. This provides a strong argument for public policies that promote energy efficiency improvements at various scales.

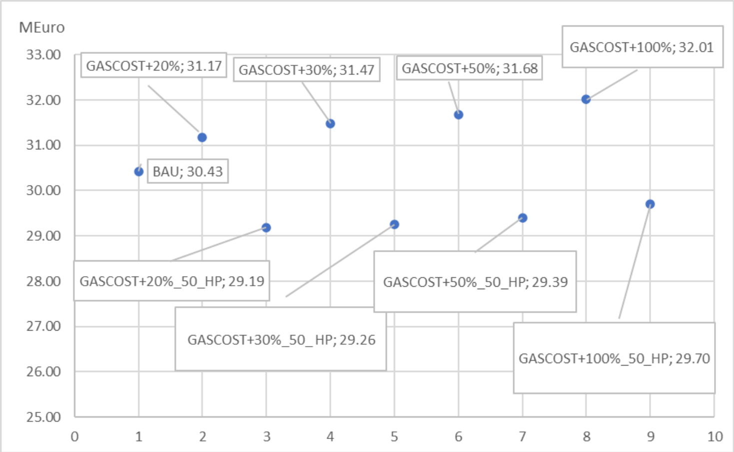


Figure 4.22. Total energy system cost (MEuro)

The following figures show the results of the GASCOST+20%_50_HP and GASCOST+30%_50_HP cases in which the cost of natural gas increased by 20% and 30%. The results obtained with a further increase in the cost of gas are comparable to those obtained in the GASCOST+50% and GASCOST+100% cases, with no reduction in the purchase cost of heat pumps. When the investment cost of heat pumps is halved, biomass boilers, formerly selected as the most economical technology without any reduction in the price of heat pumps, from a 30% increase in the cost of natural gas, are discarded. Biomass is therefore no longer used for space heating in the residential sector, as illustrated in Figure 4.23.

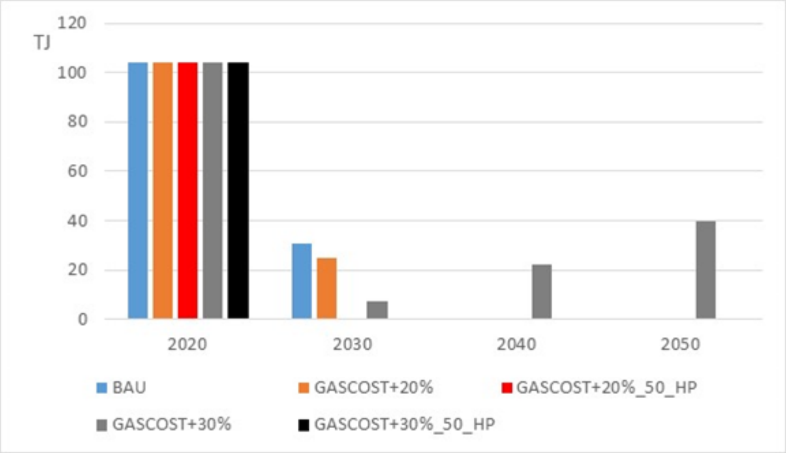


Figure 4.23. Supply of biomass (TJ)

The reduction in heat pump investment costs leads also to a more rapid reduction in natural gas consumption, as shown in Figure 4.24, which shows the trend in gas consumption considering a 20% and 30% increase in natural gas purchase costs with and without the reduction in heat pump investment costs (GASCOST+20%, GASCOST+20%_50_HP, GASCOST+30%, GASCOST+30%_50_HP cases). In the GASCOST+20%_50_HP case, natural gas consumption is reduced by 80% in 2030 and by 94% in 2040 and 2050 compared to the GASCOST+20% case. In the GASCOST+30%_HP case, the reduction is 91% in 2030, 65% in 2040, and 37% in 2050 compared to the GASCOST+30% case. In the GASCOST+30% case, natural gas consumption is lower than in the BaU scenario as early as 2040.

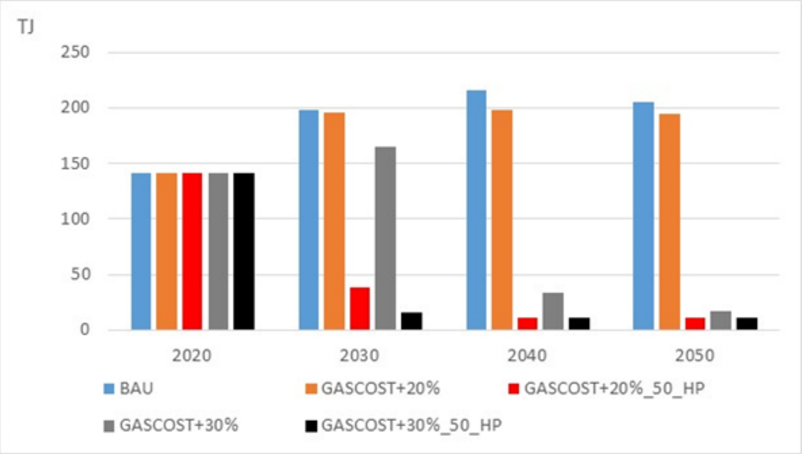


Figure 4.24. Supply of natural gas (TJ)

Concerning electricity, the GASCOST+20%_HP case, in which the cost of natural gas increases 20% and the investment cost for heat pumps is halved, shows a significant increase in electricity consumption (64% in 2030, 65% in 2040 and 55% in 2050) compared to the GASCOST+20% case whose consumption is very similar (almost identical) to that of the BAU scenario (Figure 4.25). In 2030, the increase in electricity consumption in the GASCOST+30%_HP case is 42% compared to the GASCOST+30% case. This difference is not evident in 2040 and 2050, where the trends for the GASCOST+30% and GASCOST+30%_HP cases are very similar. In the GASCOST+30%_HP case, there is a slight reduction in consumption of 1.6% in 2040 and 2.8% in 2050 compared to the GASCOST+30% case, due to the use of more efficient heat pumps than in the GASCOST+30% case, promoted by lower investment costs.

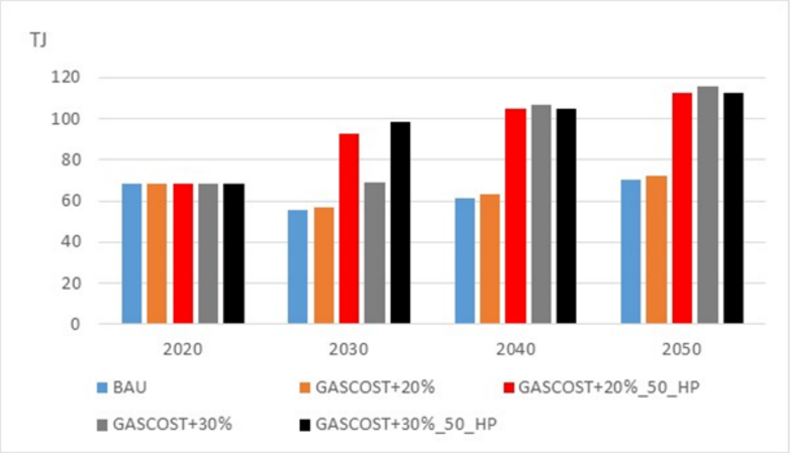


Figure 4.25. Supply of electricity (TJ)

4.3.3. Greenhouse gas emissions

The Kyoto Protocol identified seven greenhouse gases that contribute to global warming: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride (SF6), and nitrogen trifluoride (NF3), among which carbon dioxide, methane, and nitrous oxide are the main contributors. Carbon dioxide is by far the most important anthropogenic greenhouse gas, as it currently accounts for the largest share of warming associated with human activities. In fact, globally, total CO_2 emissions linked to energy use increased by 0.8% in 2024, contributing to an atmospheric CO_2 concentration of 422.5 ppm, 50% higher than pre-industrial levels. This increase was driven by the rise in natural gas emissions in 2024 (180 Mt CO_2, +2.5%), which was the main contributor to the growth in global carbon emissions. (IEA, 2025; Materi et al., 2021).

As concerns the Tito energy system, the analysis focused on CO_2 emissions, which are mainly determined by natural gas consumption in residential and tertiary sectors and a contribution associated with the electricity import.

Regarding CO_2 emissions associated to electricity import by the municipality of Tito (Table 4.2), taking into account the national fuel mix for electricity production in 2020 (Energy Services Manager, 2025) and CO_2 emission factors for each energy fuel, it is possible to estimate first of all the contribution of each fuel to imported electricity and therefore the value of total CO_2 emissions associated with electricity imports emissions in the base year (1.89 kton CO_2). Assuming the national fuel mix remains constant over the time horizon, the CO_2 emissions associated with electricity import are 1.93 kton CO_2 in 2050.

Table 4.2: CO_2 Emissions associated with electricity import in the Tito Municipality

National fuel mix 2020 (%)	**CO_2 Emission factors for fuel (ton/TJ)**	**Contribution of each fuel to electricity import (TJ)**	**Emissions (kton)**	**Contribution of each fuel to electricity import (TJ))**	**CO_2 Emissions (kton)**
		2020		2050	

Electricity import (TJ)			61.8		63.1	
Renewable sources	44.3		27.4		28.0	
Natural gas	45.9	56	28.3	1.59	28.9	1.62
Coal	4.8	95	2.9	0.28	3.0	0.28
Petroleum products	0.6	78	0.4	0.03	0.4	0.03
Other sources	4.5		2.8	0	2.8	0
Total CO_2 emissions (kton)				1.89		1.93

The values obtained are added to CO_2 emissions from residential and tertiary sectors, so that the emissions value in 2050 is 13.4 kton compared to 10.5 kton in the base year.

Residential accounts for 61%, highlighting its main contribution, while Tertiary emits for 25% and the electricity supply accounts for the remaining 14%.

As shown in Figure 4.26, CO_2 emissions increase till 2045 (+ 33%) and start declining by 2050 with an overall increase of around 28% with respect to 2020. Residential accounts for 61%, highlighting its main contribution, while Tertiary emits for 25% and the electricity supply for the remaining 14%. These percentages remain constant over the time horizon. The slight decrease in the last time period is mainly due to a decrease in natural gas consumption.

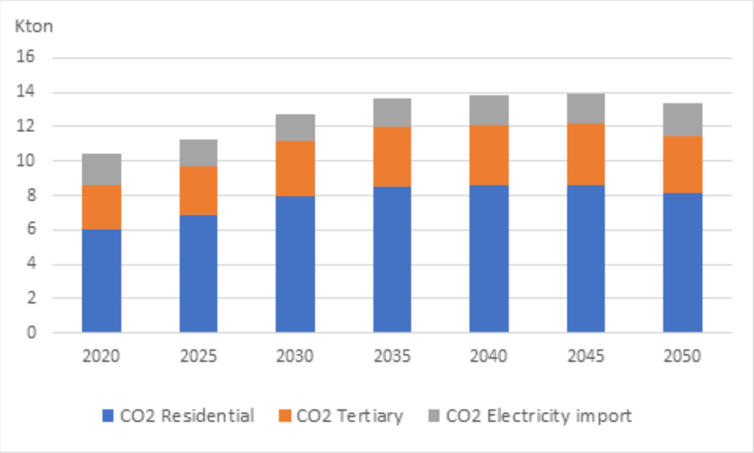


Figure 4.26. CO_2 emissions - BaU scenario (Kton)

As for scenario BAU, in the sensitivity analysis, the fuel mix for electricity supply is assumed to be similar to that of the base year in order to estimate the associated CO_2 emissions. The decrease in natural gas consumption due to the increasing gas prices drives a decrease in CO_2 emissions (Figure 4.27).

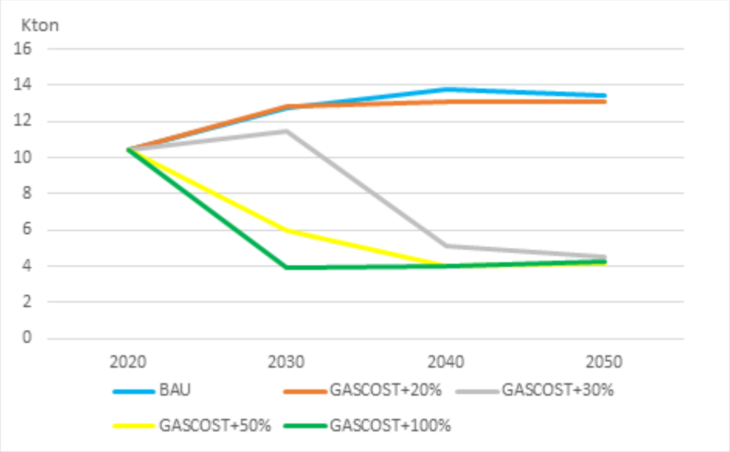


Figure 4.27. Total CO_2 emissions (kton)

In 2030, the decline will be significant when the price of natural gas is at least 50% higher than the current selling price (-53% compared to emissions in the BaU scenario). By 2040, a 30% increase will already be effective (-63%), while in 2050, the reduction in CO_2 emissions will vary from 66% (GASCOST30% case) to 68% (GASCOST50% and GASCOST100% cases). This confirms the effectiveness of a 30% increase in the price of natural gas in the long term in bringing about a steady decrease in CO_2 emissions.

Analyzing the cases with the reduction in heat pump investment costs (Figure 4.28), it is possible to see a reduction in CO_2 emissions of 60% by 2030, 70% by 2040, and 69% by 2050 in the GASCOST+20%_HP case compared to the GASCOST+20% case. In the

GASCOST+30%_HP case, CO_2 emissions are reduced by 65% compared to the GASCOST+30% case in 2030, while in subsequent periods the values are very similar, with a difference of -1.3 kton in 2040 and -0.5 kton in 2050.

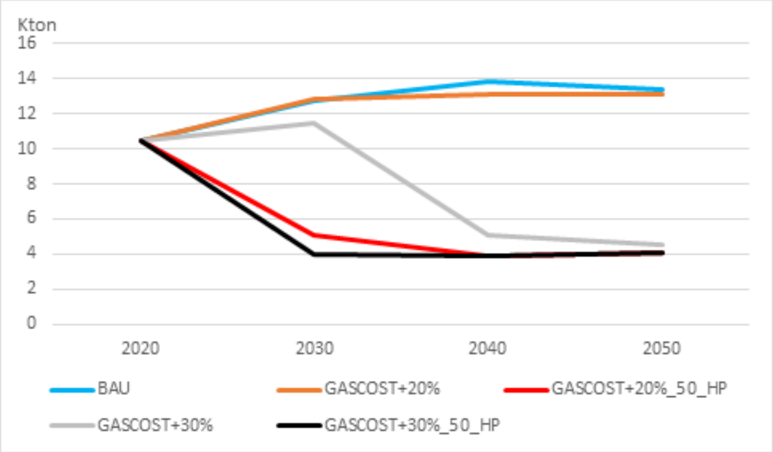


Figure 4.28. Total CO_2 emissions (Kton)

4.4 The REC scenario results

The section presents the results of the REC scenarios, analyzing their impacts from both an energy, economic, and environmental perspective. The goal is to provide a comprehensive overview of the system's evolution, as installed capacity and the presence or absence of incentives provided by the PNRR vary.

The total cost of the system (Figure 4.29) for the alternative scenarios is always lower than the cost of the BAU scenario. In particular, the case of introducing the REC by exploiting the PNRR contribution is always lower than the case where the PNRR contribution is not expected. For the same capacity, the installation of the PV system alone is always less cost-effective than the case where the REC is introduced.

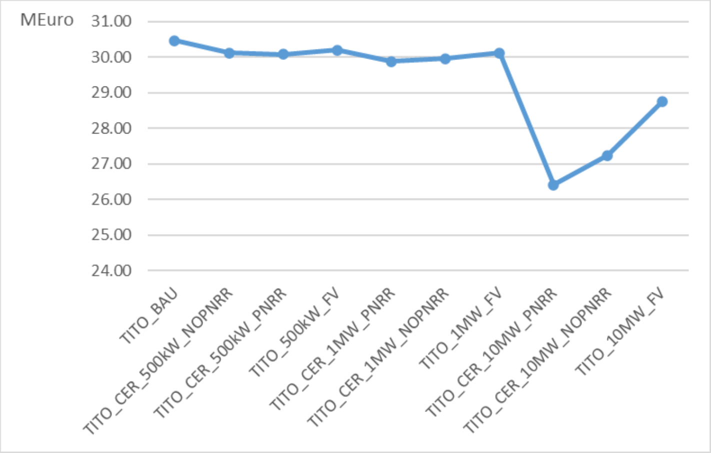


Figure 4.29: Total system cost values (MEuro)

4.4.1 Energy and environmental results

As shown in Figure 4.30, the BAU scenario represents a reference baseline showing the evolution of Tito's local energy system without structured Renewable Energy Community integration. For both TITO_CER_500kW_NOPNRR and TITO_CER_500kW_PNRR, the total production increases from 3.4 TJ (2020) to 6.4 TJ (2030–2040), stabilizing at 6.7 TJ by 2050. There is a short-term boost in renewable electricity generation due to REC integration, and there is no significant difference between PNRR and NOPNRR scenarios in physical energy terms.

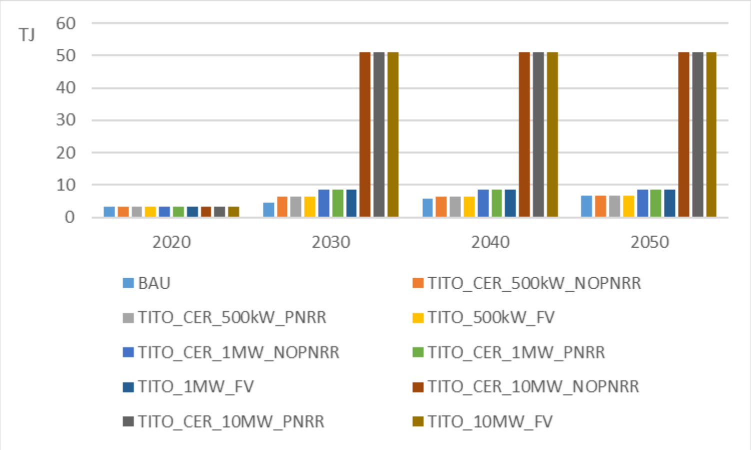


Figure 4.30: Electricity production from photovoltaic plant (TJ)

Figure 4.31 shows the electricity importation from the national grid to meet local demand. TITO_CER_500kW_NOPNRR, TITO_CER_500kW_PNRR, and TITO_500kW_FV import levels decreased when compared to BAU (from 57 TJ in 2030 compared to 58 TJ in BAU), showing that a small-scale PV system has little impact on import dependency. With the installation of 10 MW photovoltaic systems, there is a reduction in total electricity imports of -32% in the TITO_10MW_FV scenario, -31% in TITO_CER_10MW_PNRR, and -31% in

TITO_CER_10MW_NOPNRR by 2050 compared to BAU. The capital contribution of the PNRR does not significantly alter the level of imports, which are instead strongly determined by installed capacity rather than by the incentive mechanism.

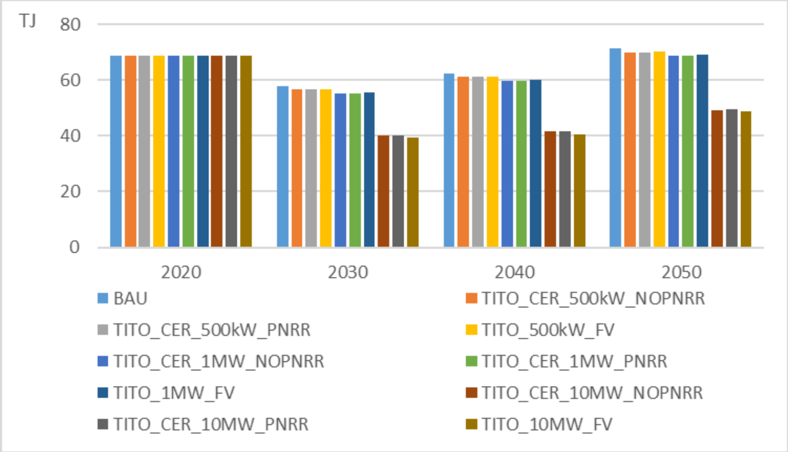


Figure 4.31. Electricity importation (TJ)

Figure 4.32 shows the result of electricity consumption, which increases by 5.4% in the TITO_CER_10MW_PNRR scenario and by +5% in the TITO_CER_10MW_NOPNRR scenario compared to BAU. In the photovoltaic-only scenario, a 1% increase in electricity consumption is observed. There are no significant changes in electricity consumption compared to BAU in the other scenarios with the 1 MW and 500 kW sizes. In the case of PV alone, 50% of production is sold to the grid, while the 50% for self-consumption does not change consumption in the BAU scenario but only reduces imports.

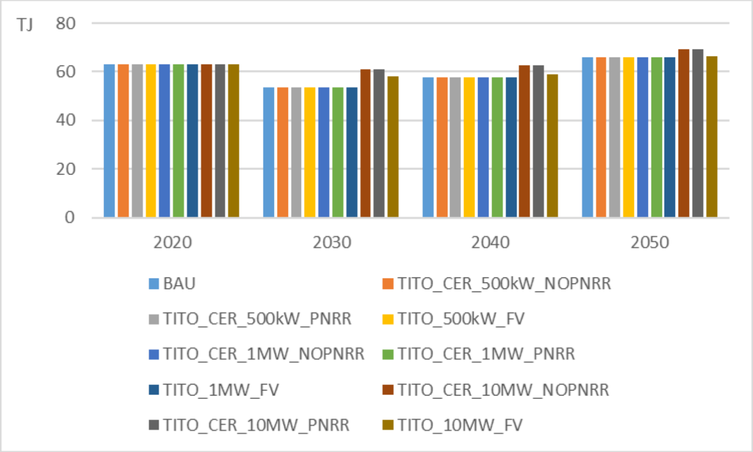


Figure 4.32: Total Electricity Consumption (TJ)

The electricity produced by a 500 kW PV REC covers 4% of total electricity consumption (residential and tertiary), while that produced by a 1 MW REC covers 7% of Tito's total electricity consumption, and that produced by a 10 MW REC covers 71%.

The increase in electricity consumption results in a 6% decrease in natural gas consumption in both REC scenarios (with and without PNRR) with a 10 MW photovoltaic system, as seen in Figure 4.33. In the other scenarios, there are no significant changes in natural gas consumption.

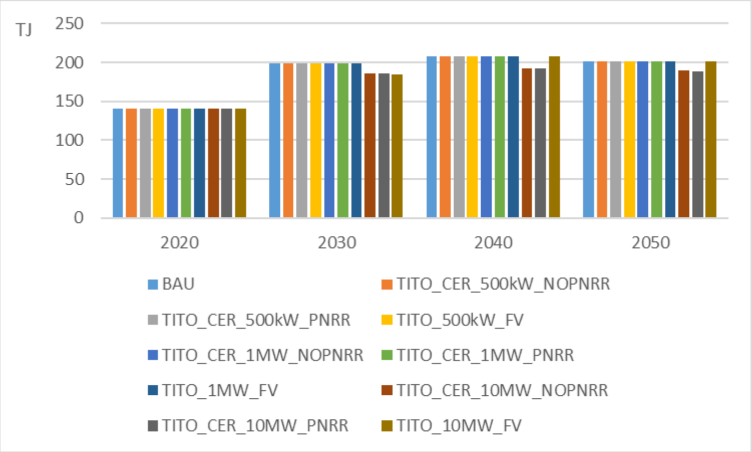


Figure 4.33: Total Natural Gas Consumption (TJ)

As regards the trend of CO_2 emissions, it is possible to observe a significant decrease in the case of CERs with 10 MW photovoltaic plants (Figure 4.34). They decrease by 9.9% in the TITO_CER_10MW_NOPNRR scenario and by 10.3% in the TITO_CER_10MW_PNRR scenario compared to BAU. This is due both to lower electricity imports and, consequently, to the lower quantities of CO_2 associated with them and to lower natural gas consumption. In the TITO_10MW_PV scenario, CO_2 emission reductions are 5% compared to the BAU scenario, and they are due exclusively to lower electricity imports. Small-scale interventions (500 kW and 1 MW) do not have a noticeable impact on the overall emissions of the system.

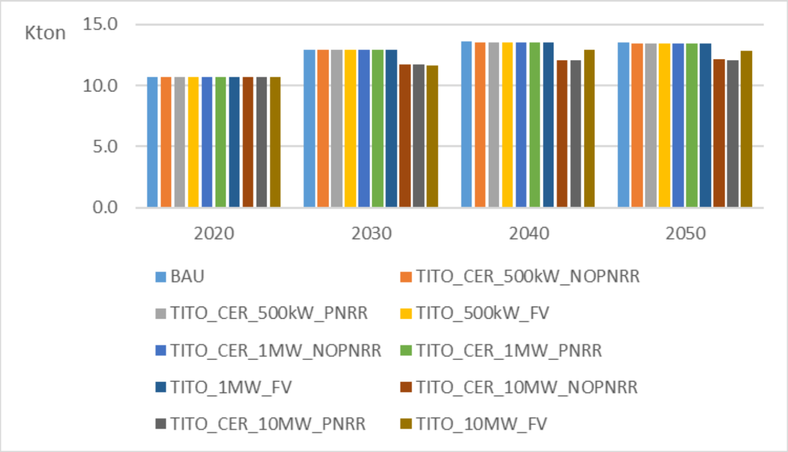


Figure 4.34: CO_2 emissions – REC scenario (Kton)

4.4.2 Economic results

Figure 4.35 presents the economic benefits generated by different plant configurations in different scenarios, with capacity ranging from 500 kW and 10 MW, considering the sum of the incentives granted to REC and revenues deriving from the sale of electricity to the grid at hourly zonal price. The smaller scenarios show limited differences, with benefits ranging from 0.67 MEuro (BaU scenario) to 1.03 MEuro (TITO_CER_500kW_NOPNRR scenario). The CER configurations with a capacity of 500 kW are more profitable than the BAU scenario and the scenario with only a photovoltaic system (TITO_500kW_FV scenario). The presence of the PNRR contribution slightly reduces the overall benefit (0.96 MEuro), taking into account the reduction in the CER incentive in the presence of a capital grant. Scenarios with a capacity of 1 MW show a significant increase in economic benefits. The CER configurations achieve values of 1.34 MEuro (without PNRR) and 1.22 MEuro (with PNRR), confirming the economic advantage of energy sharing. The TITO_1MW_FV scenario, with a benefit of 1.13 MEuro, is still more favorable than the small-scale configurations, but lower than the CER solutions with the same power output. For the 10 MW size, a marked scale effect is observed, with a significant increase in economic benefits. The CER scenarios achieve the highest results, with 7.45 MEuro in the configuration without PNRR and 6.28 MEuro with PNRR. The TITO_10MW_FV scenario presents a benefit of 5.31 MEuro, higher than the smaller sizes but lower than the CER scenarios of the same power. These results confirm that the increased electricity generation allows for the simultaneous maximization of both CER incentives and revenues from grid sales.

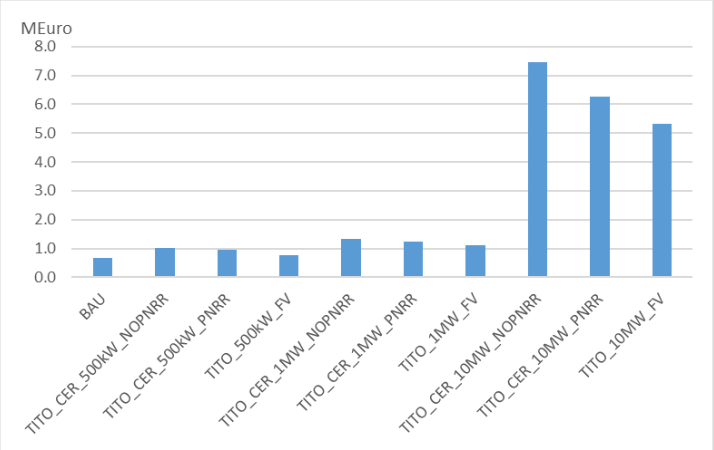


Figure 4.35: Total revenue (network sales + incentives) MEuro

Figure 4.36 shows the cumulative revenue over the period 2020-2050, from the sale of the excess electricity produced from photovoltaic plants and fed into the national grid based on the hourly zonal price. The BAU and CER scenarios up to 1 MW generate similar and relatively low profits. Scenarios featuring photovoltaic systems not connected to a CER (TITO-FV) show a clear economic advantage, with profits increasing as their size increases. The TITO_10MW_FV scenario stands out as the most profitable overall, with a profit margin more than four times higher than the other scenarios. Regardless of the presence of PNRR contributions, the CER scenarios do not show significant economic benefits related to grid sales alone, at least under the operating conditions considered.

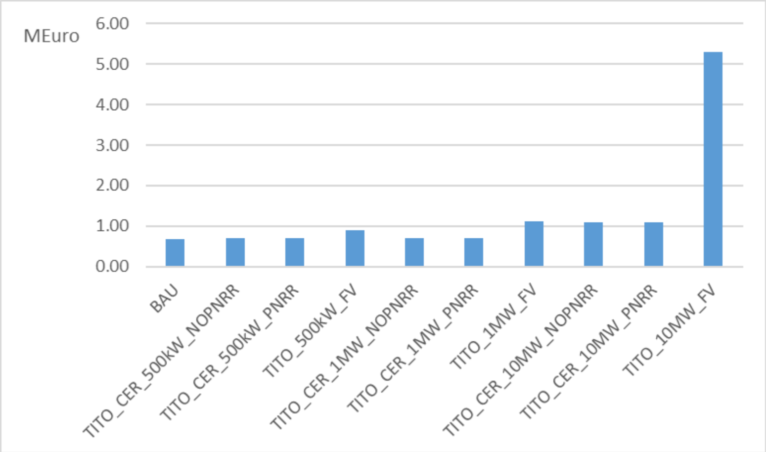


Figure 4.36: Excess electricity sold to the grid (MEuro)

Figure 4.37 shows the REC revenues for the total incentive tariff alone (CACER incentive + hourly zonal price + ARERA valuation). The REC configurations with small-scale PV systems generate modest benefits, consistent with the limited electricity production available for sharing with consumers. The benefits of CER configurations powered by 1 MW photovoltaic systems are significant, but much lower than those of 10 MW systems. All other things being equal, the relationship is almost linear; in fact, a REC configuration powered by a 10 MW system produces approximately 10 times the benefit of one powered by a 1 MW system.

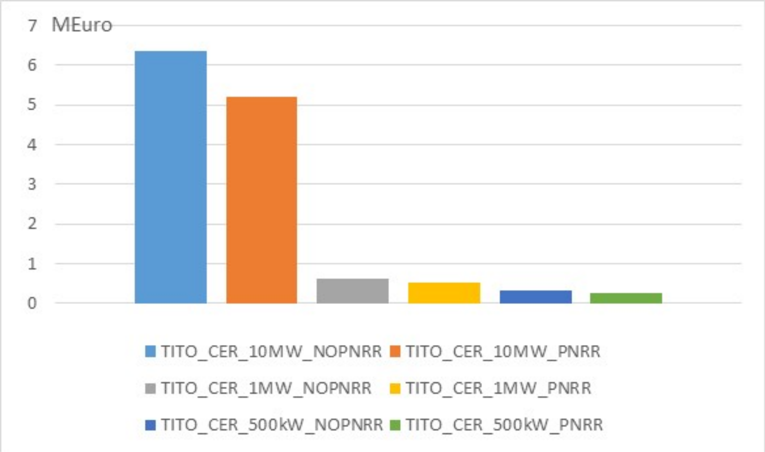


Figure 4.37: REC incentive tariff (MEuro)

Figure 4.38 shows the total revenue from the REC for the period 2030-2050. It is the sum of the incentive tariff (CACER tariff + hourly zonal price + ARERA value) and the sale of excess energy (hourly zonal price).

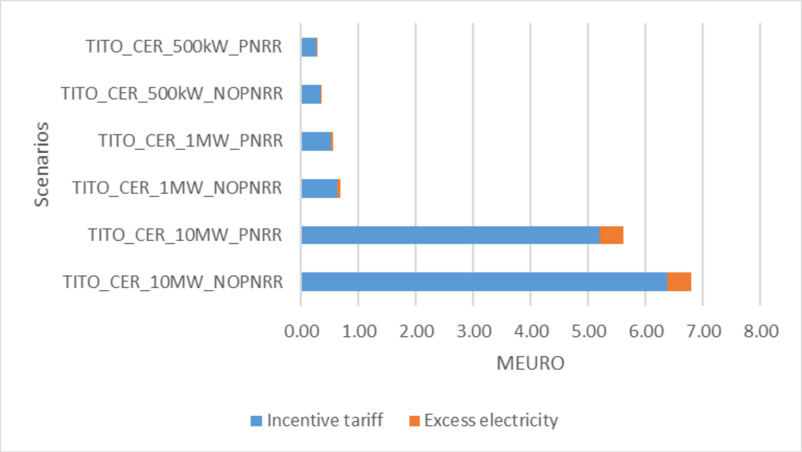


Figure 4.38: Total REC revenue (MEuro)

4.5 Scenarios comparison and policy outcomes

In both the REC scenarios (both with and without NRRP) and the PV-only scenario, installing a 10 MW capacity allows for a significant increase in electricity production, rising from approximately 6.7 TJ in the BAU scenario to 51 TJ in the alternative scenarios by 2050, an increase of more than seven and a half times the initial production. This substantial increase in local generation leads to a significant reduction in electricity imports: from 71 TJ in the BAU scenario to 49 TJ in the alternative scenarios, a reduction of 31%. This result indicates a clear shift away from external energy dependence towards greater local self-generation from renewable sources, resulting in increased energy autonomy. Despite offering significant electricity generation from renewable sources, the TITO_FV_10MW scenario features a significant level of electricity transfer to the grid (approximately 28 TJ), due to the lack of a sharing mechanism typical of RECs. This demonstrates how, given the same installed capacity, non-community-based plants do not generate comparable benefits in terms of local self-sufficiency to RECs.

In REC configurations, electricity shared and purchased by community members fosters active user participation and collective ownership of energy infrastructure, in line with European policies promoting participatory decarbonisation models.

The REC configurations, therefore, represent a step toward more local and integrated energy governance, allowing municipalities and users to directly contribute to energy resilience and the path to climate neutrality. The PNRR, however, impacts the economic feasibility of investments while not altering energy flows (consumption, imports), while installed capacity remains the determining factor in the effective contribution to the energy transition.

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CONCLUSIONS

5.1 Summary of key findings

This research highlights the strategic role of municipalities in driving the decarbonization of energy systems by enhancing the contribution of renewable energy, new technologies, energy efficiency, and sustainable planning in the context of sustainable energy-climate planning, focusing on energy system modeling and decarbonization strategies for the Municipality of Tito, Italy.

The core of the work involves implementing the ETSAP-TIMES model to analyze the local energy system, its current reliance on fossil fuels, and future demand projections on a time horizon spanning from 2020 to 2050. The implementation at the local scale of a municipal energy system model based on the ETSAP-TIMES framework has paved the way for investigating possible evolutionary paths by comparing them through scenario analysis and identifying least-cost paths for the energy transition capable of simultaneously balancing economic and environmental constraints.

In the BaU scenario, utilised as a benchmark, total energy consumption decreases by 15% by 2050. There is a significant overall decline in the use of biomass, LPG, and diesel, which are phased out by 2040 and 2035, respectively, and substantial growth in renewable energy. In particular, electricity production from photovoltaics increases by 99% in the time period considered, illustrating a shift towards renewable energy that can help align with national climate goals. Solar thermal energy is also expected to grow significantly (+ 187% by 2050), but its overall contribution is negligible in absolute terms. Despite the growth of photovoltaics, natural gas remains the dominant energy source throughout the time. This is mainly due to the financial relief on natural gas bills for households in the Basilicata region due to the presence of oil field exploitation activities. Natural gas consumption increases by 44% by 2050, being mainly used for space heating and cooking in the residential sector. In the residential sector, technological change leads to a 30% reduction in overall energy consumption by 2050, reflecting improved efficiency or behavioral shifts, but without a significant reduction in overall emissions. All residential subsectors show progress in efficiency and reduced specific consumption. In this sector, biomass, the predominant fuel in 2020 (44%), is entirely replaced by natural gas (88%) by 2040. There is limited electrification and integration with renewable sources. The energy transition process to achieve climate neutrality is therefore incomplete. Energy consumption in the tertiary sector increases by 30% over the time horizon, particularly in the Healthcare and Accommodation subsectors (by 190% and 78% respectively). The tertiary sector also shows an energy mix with a predominance of natural gas, while electricity grows moderately. Food, Shopping Centers, and Healthcare are the most energy-intensive and least efficient over time. These are priority subsectors for efficiency and decarbonization policies. The tertiary sector is not moving toward a real energy transition toward electrification. On the contrary, the increase in gas prices suggests that the tertiary sector is not reducing its dependence on fossil fuels but rather combining it with increased electricity consumption. Heavy reliance on natural gas leads to a 28% increase in CO_2 emissions by 2050, peaking in 2045. The residential sector is the primary contributor, contributing 61% of these emissions. The slight decline in emissions by 2050 highlights the effect of increased energy efficiency due to technological shifts.

The sensitivity analysis aims to highlight the impact of gas prices and subsidies on investment costs to promote technological innovation. Increasing the price of natural gas is effective in reducing consumption and consequently related CO_2 emissions. Indeed, a 30% increase in gas price significantly reduces consumption in the long term, leading to a 66% decrease in CO_2 emissions by 2050 compared to the BaU scenario, with electricity and biomass being the main fuels to replace natural gas. Combining the increase in the price of natural gas with non-repayable contributions for heat pumps accelerates the reduction in natural gas consumption and consequently the reduction in CO_2 emissions.

A 20% increase in the price of natural gas, combined with a 50% non-repayable grant for the purchase of electric heat pumps, is already proving to be an effective strategy. These conditions allow for a drastic reduction in both natural gas consumption and CO_2 emissions by approximately 69% by 2030, with a total energy system cost lower than that of the BaU scenario.

In addition to sensitivity analysis, scenario analysis assesses the integration and feasibility of renewable energy communities (RECs) across various scenarios, examining economic, environmental, and energy resilience benefits.

In terms of renewable electricity production, the REC scenarios, with or without PNRR incentives, record an increase in photovoltaic production of 99% in the time horizon considered, more evident for plants with larger capacity (10 MW).

In the REC scenarios, electricity imports from the national grid decrease under REC configurations, especially in the 10 MW CER scenarios, which record a 31–32% reduction compared to BAU by 2050, highlighting RECs' contribution to local energy independence and resilience.

Shared energy purchased by REC consumers remains stable over the 2030–2050 time horizon, confirming the reliability of energy-sharing models as consumption decreases by about 6%, showing a substitution of fossil fuels by electricity. The implementation of a REC favors the substitution of electricity for fuels. Indeed, in the TITO_CER_10MW_PNRR scenario, electricity consumption increases by 5.4% while natural gas consumption decreases by approximately 6%.

CO_2 emissions decrease by 9.9 to 10.3% respectively in the 10 MW REC scenarios compared to the BAU scenario, confirming that RECs significantly support decarbonization efforts in line with the objectives of the EU Green Deal, Fit-for-55, and RED II Directive.

From an economic point of view, total revenues from the REC (network sales + incentives) are higher, particularly in the 10 MW REC scenario, where they increase from 0.67 MEuro of BAU to 7.45 MEuro without the PNRR incentives. The presence of the PNRR primarily influences the feasibility of investments, while installed capacity remains the determining factor for energy production and revenue generation. At the same time, the analysis of excess energy fed into the grid shows higher values in PV scenarios without sharing, highlighting the role of RECs in optimizing self-consumption.

Future research will focus on improving the TIMES-Tito model by integrating energy storage solutions and improving grid flexibility options, as well as analyzing end-use sectors relevant to achieving climate neutrality, such as transportation. Particular attention will be paid to studying energy and technological options that can drastically reduce not only CO_2 emissions but also local air pollutants, and to modeling consumer behavior.

5.2 Contributions to knowledge

This thesis demonstrates how the ETSAP-TIMES model, successfully applied to policy evaluation at the national and regional level, can provide useful insights at the municipal level for policy implementation and planning, successfully representing and enhancing local. The thesis analyses the energy system of the Municipality of Tito, through detailed analyses of supply-demand balances, technological options, and feasible long-term paths within the context of the PNRR.

The thesis also provides a detailed look at the policy framework for clean energy transition in Europe and Italy, emphasizing the role of local governance and incentive structures like PNRR contributions and various tariffs for RECs. Ultimately, the scenario analysis demonstrates that integrating RECs offers a lower total system cost and significant reductions in CO_2 emissions and natural gas consumption compared to the business-as-usual pathway.

The main contribution is to provide a replicable modeling framework based on scenario analysis that can be applied to other small municipalities across Europe, both to define the optimal conditions for implementing renewable energy communities (RECs) and to identify the most effective strategies for achieving climate neutrality. In this regard, the thesis also serves to inspire action and encourage partnerships among stakeholders committed to achieving a sustainable future for their communities.

Appendix A

Table A1. End-use demands

TIMES Code	Description	Sector	Unit of measure
DRSH	Space Heating	Residential	Mm^2
DRWH	Water Heating	Residential	Mliters
DRSC	Space Cooling	Residential	Mm^2
DRCO	Cooking	Residential	Munit
DRLG	Lighting	Residential	Glumen
DROEU	Other Electric Uses	Residential	TJ
DTASH	Space Heating	Tertiary - Accommodation	Mpresences
DTAWH	Water Heating	Tertiary – Accommodation	Mpresences
DTASC	Space Cooling	Tertiary – Accommodation	Mpresences
DTAOEU	Other Electric Uses	Tertiary - Accommodation	Mpresences
DTCSH	Space Heating	Tertiary – Food	MEmployees
DTCWH	Water Heating	Tertiary – Food	MEmployees
DTCSC	Space Cooling	Tertiary – Food	MEmployees
DTCOEU	Other Electric Uses	Tertiary - Food	MEmployees

DTPSH	Space Heating	Tertiary – Public Buildings	Mm^3
DTPWH	Water Heating	Tertiary – Public Buildings	Mm^3
DTPSC	Space Cooling	Tertiary – Public Buildings	Mm^3
DTPOEU	Other Electric Uses	Tertiary – Public Buildings	Mm^3
DTPOSH	Space Heating	Tertiary – Private Offices	MEmployees
DTPOWH	Water Heating	Tertiary – Private Offices	MEmployees
DTPOSC	Space Cooling	Tertiary – Private Offices	MEmployees
DTPOOEU	Other Electric Uses	Tertiary – Private Offices	MEmployees
DTPSH	Space Heating	Tertiary – Shopping Buildings	Mm^2
DTPWH	Water Heating	Tertiary – Shopping Buildings	Mm^2
DTPSC	Space Cooling	Tertiary – Shopping Buildings	Mm^2
DTPOEU	Other Electric Uses	Tertiary – Shopping Buildings	Mm^2
DTHSH	Space Heating	Tertiary – Healthcare	MEmployees

DTHWH	Water Heating	Tertiary – Healthcare	MEmployees
DTHSC	Space Cooling	Tertiary – Healthcare	MEmployees
DTHOEU	Other Electric Uses	Tertiary – Healthcare	MEmployees
DTPSH	Space Heating	Tertiary - Schools	Mm^3
DTPWH	Water Heating	Tertiary – Schools	Mm^3
DTPOEU	Other Electric Uses	Tertiary - Schools	Mm^3

Table A2. Commodities

TIMES Code	**Description**	**Sector**	**Unit of measure**
SUPGAS	Natural gas	Supply	TJ
SUPLPG	LPG	Supply	TJ
SUPDIE	Diesel	Supply	TJ
SUPBIO	Biomass	Supply	TJ
SUPELC	Electricity	Supply	TJ
SUPTHES	Solar thermal	Supply	TJ
RESGAS	Natural gas	Residential	TJ
RESLPG	LPG	Residential	TJ
RESBIO	Biomass	Residential	TJ
RESELC	Electricity	Residential	TJ
RESTHES	Solar thermal	Residential	TJ

TERGAS	Natural gas	Tertiary	TJ
TERLPG	LPG	Tertiary	TJ
TERDIE	Diesel	Tertiary	TJ
TERELC	Electricity	Tertiary	TJ
TERTHES	Solar thermal	Tertiary	TJ
ELCSOLRI	Solar energy for photovoltaics	Supply	TJ
ELCRESD	Electricity generated by photovoltaics – Residential	Electricity production	TJ
ELCTERD	Electricity generated by photovoltaics – Tertiary	Electricity production	TJ
ELCR	Electricity produced by photovoltaics and fed into the grid – Residential	Supply	TJ
ELCT	Electricity produced by photovoltaics and fed into the grid – Tertiary	Supply	TJ
RESSH	Useful energy for space heating	Residential	TJ
RESWH	Useful energy for water heating	Residential	TJ

RESSC	Useful energy for space cooling	Residential	TJ
TERCSH	Useful energy for space heating	Tertiary – Food	TJ
TERCWH	Useful energy for water heating	Tertiary - Food	TJ

Table A3. Processes

TIMES Code	Description	Sector	Activity	Capacity
IMPGAS20	Import of natural gas	Supply	TJ	-
IMPLPG20	Import of LPG	Supply	TJ	-
IMPDIE20	Import of diesel	Supply	TJ	-
IMPBIO20	Import of biomass	Supply	TJ	-
IMPELC20	Import of electricity	Supply	TJ	-
MINTHES20	Mining of solar thermal	Supply	TJ	-
SHAREGAS20	Infrastructure for natural gas	Supply	TJ	TJ-year
SHARELPG20	Infrastructure for LPG	Supply	TJ	TJ-year
SHAREDIE20	Infrastructure for diesel	Supply	TJ	TJ-year
SHAREBIO20	Infrastructure for biomass	Supply	TJ	TJ-year
SHAREELC20	Infrastructure for electricity	Supply	TJ	TJ-year
SHARETHES20	Infrastructure for solar thermal	Supply	TJ	TJ-year

MINELCSOL	Mining solar energy for photovoltaics	Supply	TJ	-
ERESSOLRI1	Photovoltaic plants for Residential	Electricity production	TJ	GW
ETESSOLRI1	Photovoltaic plants for Tertiary	Electricity production	TJ	GW
SHARESELC00	Infrastructure of produced electricity - Residential	Supply	TJ	TJ-year
SHATERELC00	Infrastructure of produced electricity – Tertiary	Supply	TJ	TJ-year
RRSHGNATS01	Natural gas space heating technology – single output	Residential	TJ	GW
RRSHGNATM01	Natural gas space heating technology – mixed output	Residential	TJ	GW
RRWHGNATS01	Natural gas water heating technology – single output	Residential	TJ	GW
RRSHLPGTS01	LPG space heating technology – single output	Residential	TJ	GW
RRSHLPGTM01	LPG space heating technology – mixed output	Residential	TJ	GW
RRWHLPGTS01	LPG water heating technology – single output	Residential	TJ	GW

RRSHBIOTS01	Biomass space heating technology – single output	Residential	TJ	GW
RRWHTHESTS01	Solar thermal water heating technology – single output	Residential	TJ	GW
RRSHELCTS01	Electricity space heating technology – single output	Residential	TJ	GW
RRSHELCTS02	Electricity space heating technology – single output	Residential	TJ	GW
RRWHELCTS01	Electricity water heating standard heat pump technology – single output	Residential	TJ	GW
RRWHELCTT01	Electricity water heating top heat pump technology – single output	Residential	TJ	GW
RRWHELCTN01	Electricity water heating new DWH technology – single output	Residential	TJ	GW
RRSCELCTS01	Electricity space cooling technology – single output	Residential	TJ	GW
RRSCELCTS01	Electricity space cooling portable technology – single output	Residential	TJ	GW

RRSCELCTS02	Electricity space cooling class A technology – single output	Residential	TJ	GW
RRSCELCTS03	Electricity space cooling class BC technology – single output	Residential	TJ	GW
RRSCELCTS04	Electricity space cooling class DE technology – single output	Residential	TJ	GW
RRSCELCTS05	Electricity space cooling class EF technology – single output	Residential	TJ	GW
RRSCELCTS06	Electricity space cooling technology others– single output	Residential	TJ	GW
RRCOGNAT01	Natural gas cooking technology	Residential	TJ	Munit
RRCOLPGT01	LPG cooking technology	Residential	TJ	Munit
RRCOELCT01	Electricity cooking technology	Residential	TJ	Munit
RRLGELCT01	Incandescent lighting technology	Residential	TJ	Glumen
RRLGELCT02	Halogen Lighting technology	Residential	TJ	Glumen
RRLGELCT03	Compact Fluo Lighting technology	Residential	TJ	Glumen

RROEUELCT01	Other uses technology	Residential	TJ	TJ
TCSHGNATS01	Natural gas space heating technology, single output	Tertiary - Food	TJ	GW
TCSHGNATM01	Natural gas space heating technology, mixed output	Tertiary - Food	TJ	GW
TCWHGNATS01	Natural gas water heating technology, single output	Tertiary - Food	TJ	GW
TCSHLPGTS01	LPG space heating technology, single output	Tertiary - Food	TJ	GW
TCSHLPGTM01	LPG space heating technology, mixed output	Tertiary - Food	TJ	GW
TCWHLPGTS01	LPG water heating technology, single output	Tertiary - Food	TJ	GW
TCSHDIETS01	Diesel space heating technology, single output	Tertiary - Food	TJ	GW
TCSHDIETM01	Diesel space heating technology, mixed output	Tertiary - Food	TJ	GW
TCWHDIETS01	Diesel water heating technology, single output	Tertiary - Food	TJ	GW
TCWHTHESTS01	Solar thermal water heating technology, single output	Tertiary - Food	TJ	GW

TCSHELCTS01	Electricity space heating technology 1, single output	Tertiary - Food	TJ	GW
TCSHELCTS02	Electricity space heating technology 2, single output	Tertiary - Food	TJ	GW
TCSHELCPS01	Electricity space heating heat pump technology, single output	Tertiary - Food	TJ	GW
TCWHELCTS01	Electricity water heating technology 1, single output	Tertiary - Food	TJ	GW
TCWHELCTS02	Electricity water heating technology 2, single output	Tertiary - Food	TJ	GW
TCWHELCTS03	Electricity water heating technology 3, single output	Tertiary - Food	TJ	GW
TCWHELCTS04	Electricity water heating technology 4, single output	Tertiary - Food	TJ	GW
TCSCELCT01	Electricity space cooling technology	Tertiary - Food	MEmployees	
TCOEUELCT01	Electricity equipment technology	Tertiary - Food	MEmployees	

Table A4. Dummy technologies

TIMES Code	Description	Sector	Activity

RDRSHD101	Dummy technology space heating	Residential	Mm^2
RDRWHD101	Dummy technology water heating	Residential	Mliters
RDRSCD101	Dummy technology space cooling	Residential	Mm^2
TDCSHD101	Dummy technology space heating	Tertiary - Food	MEmployees
TDCWHD101	Dummy technology water heating	Tertiary - Food	MEmployees

Appendix B

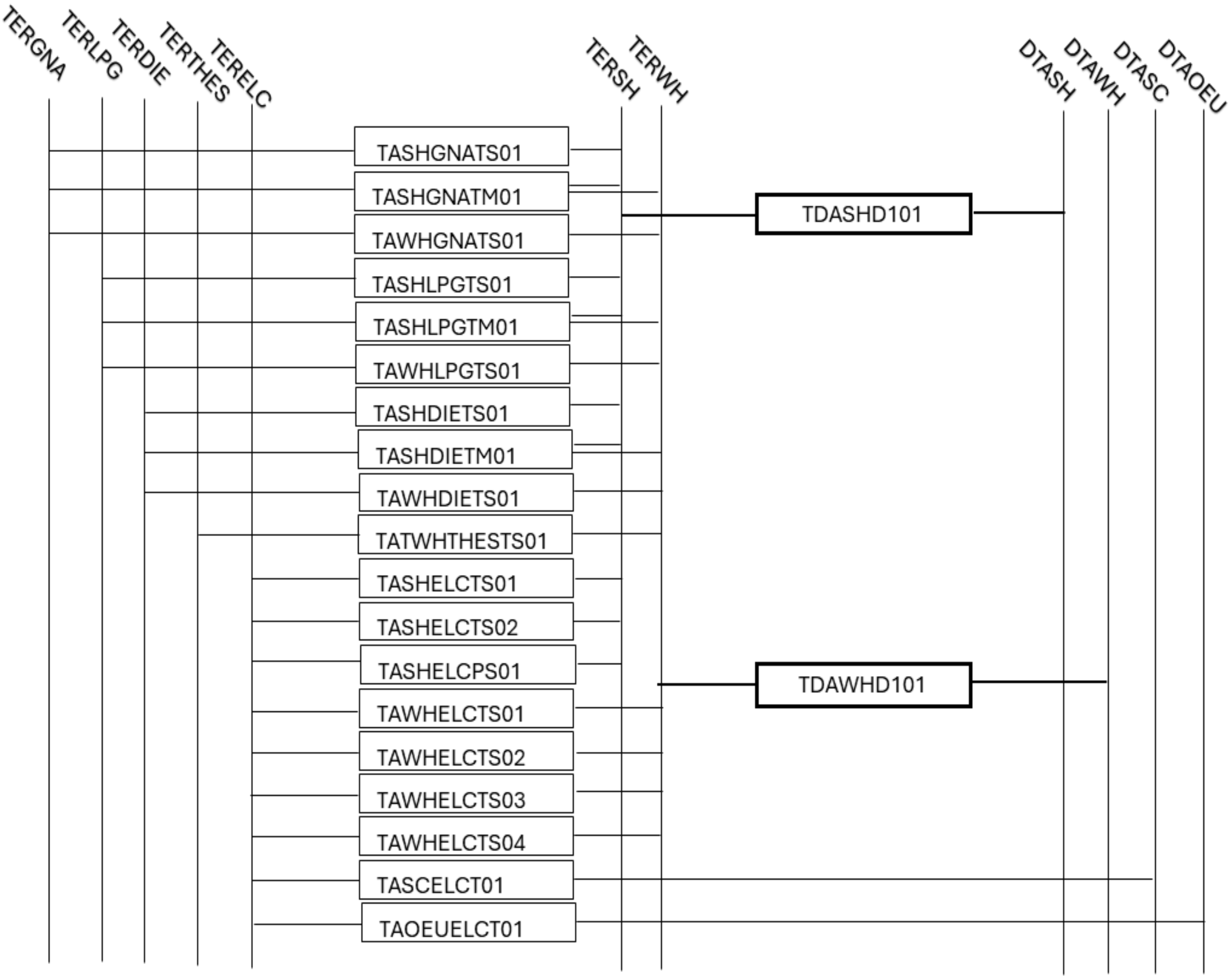

Figure B.1: RES of the Accommodation subsector in the Tertiary sector

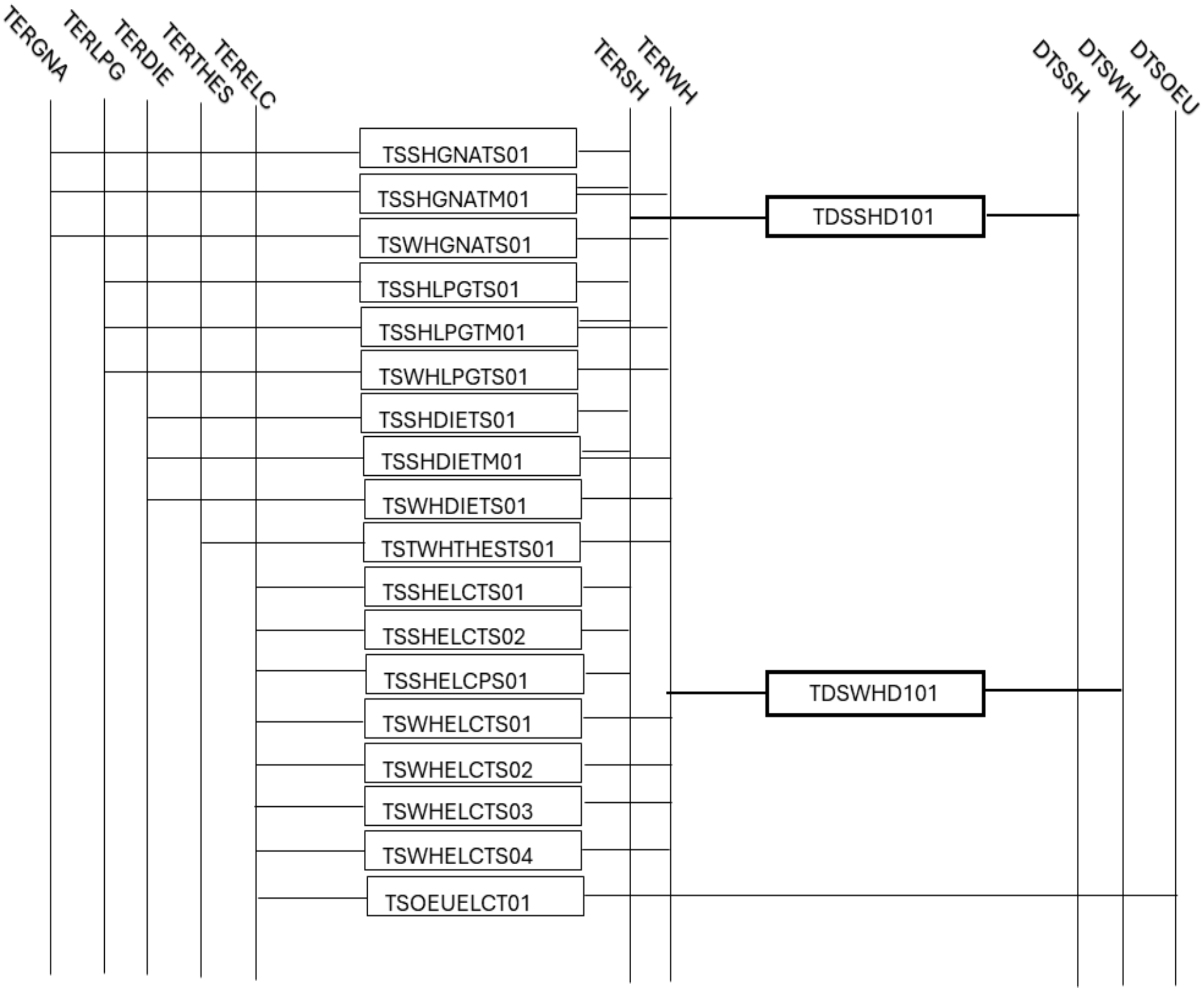

Figure B.2: RES of the School subsector in the Tertiary sector

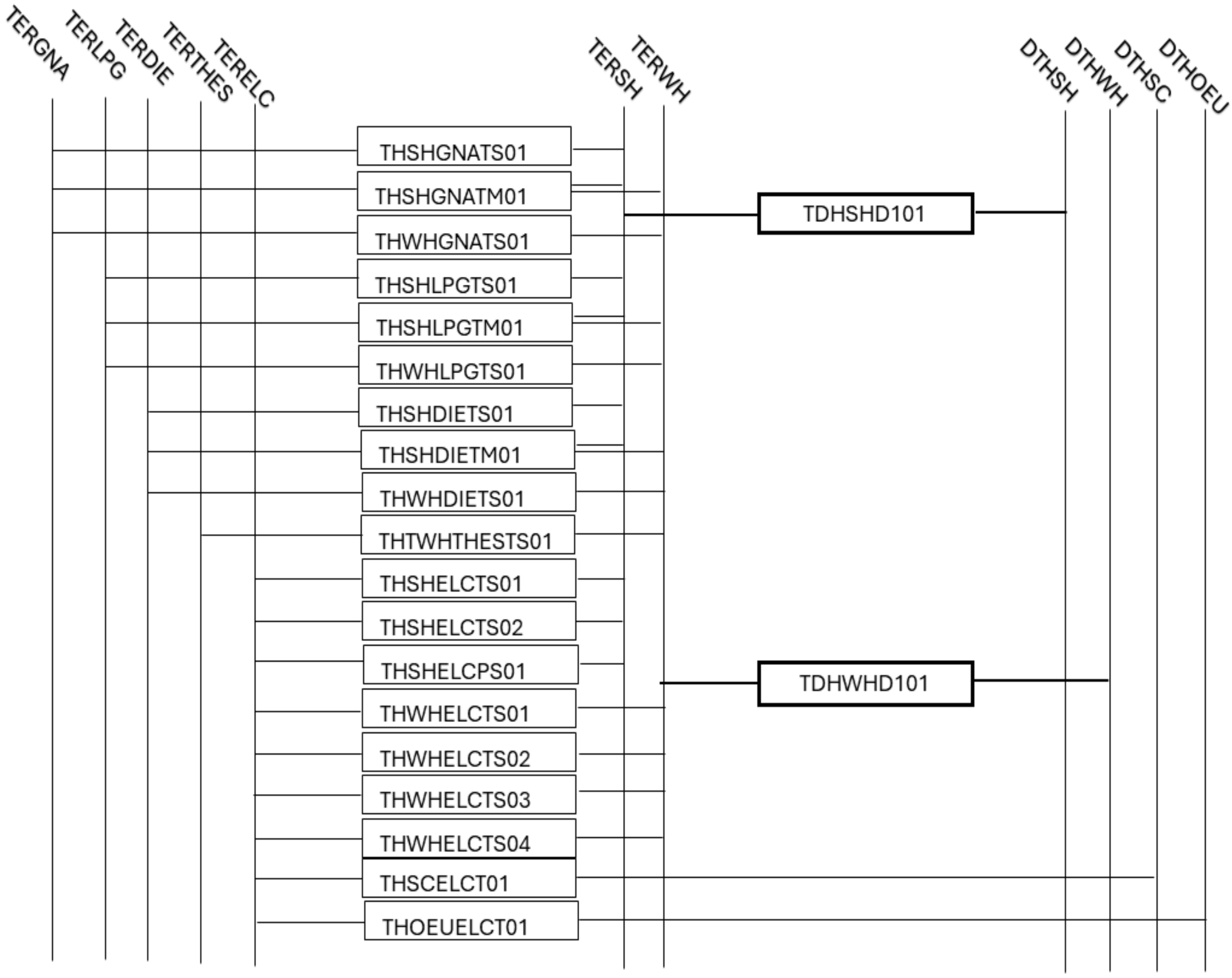

Figure B.3. RES of the Healthcare subsector in the Tertiary sector

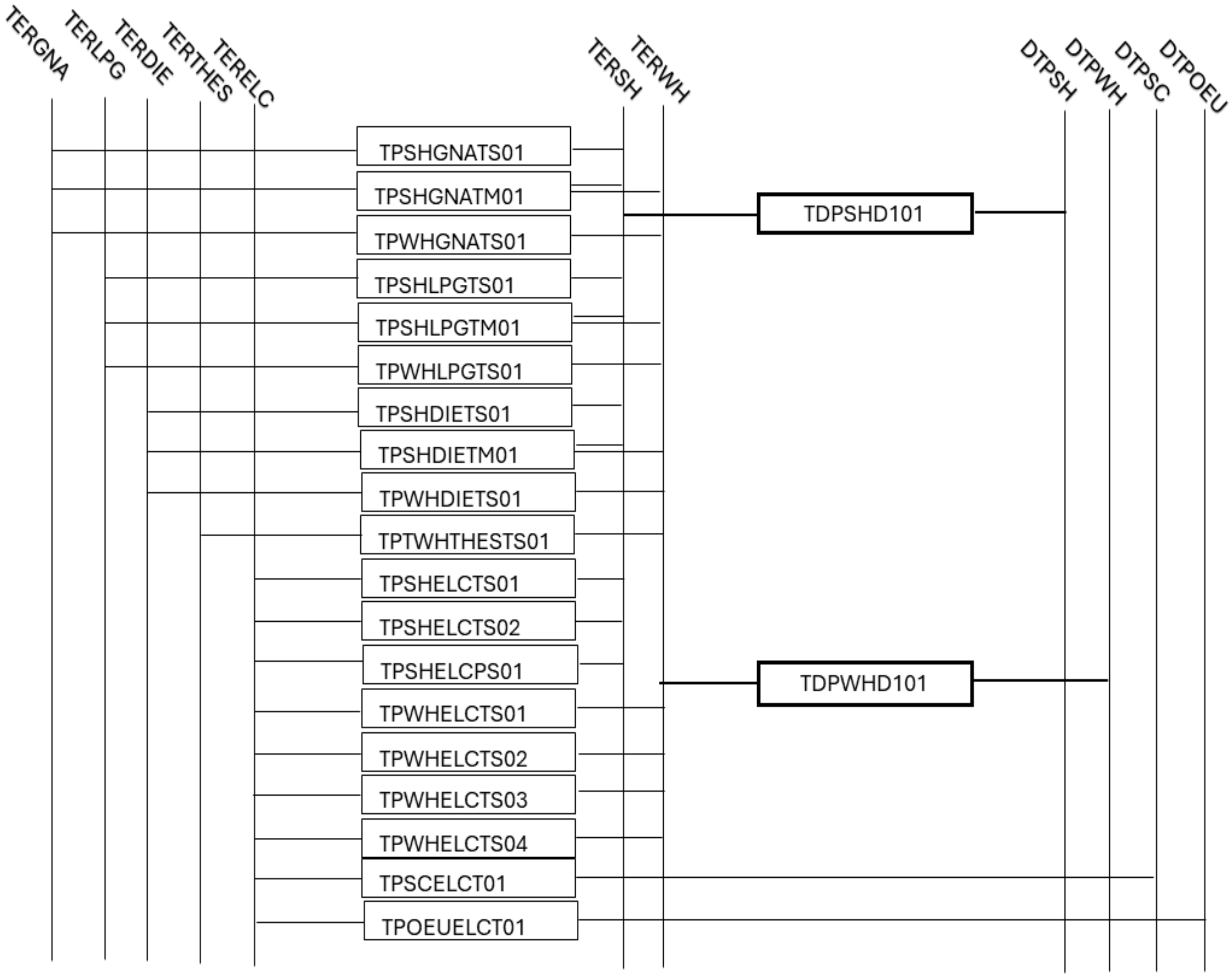

Figure B.4: RES of the Public Building subsector in the Tertiary sector

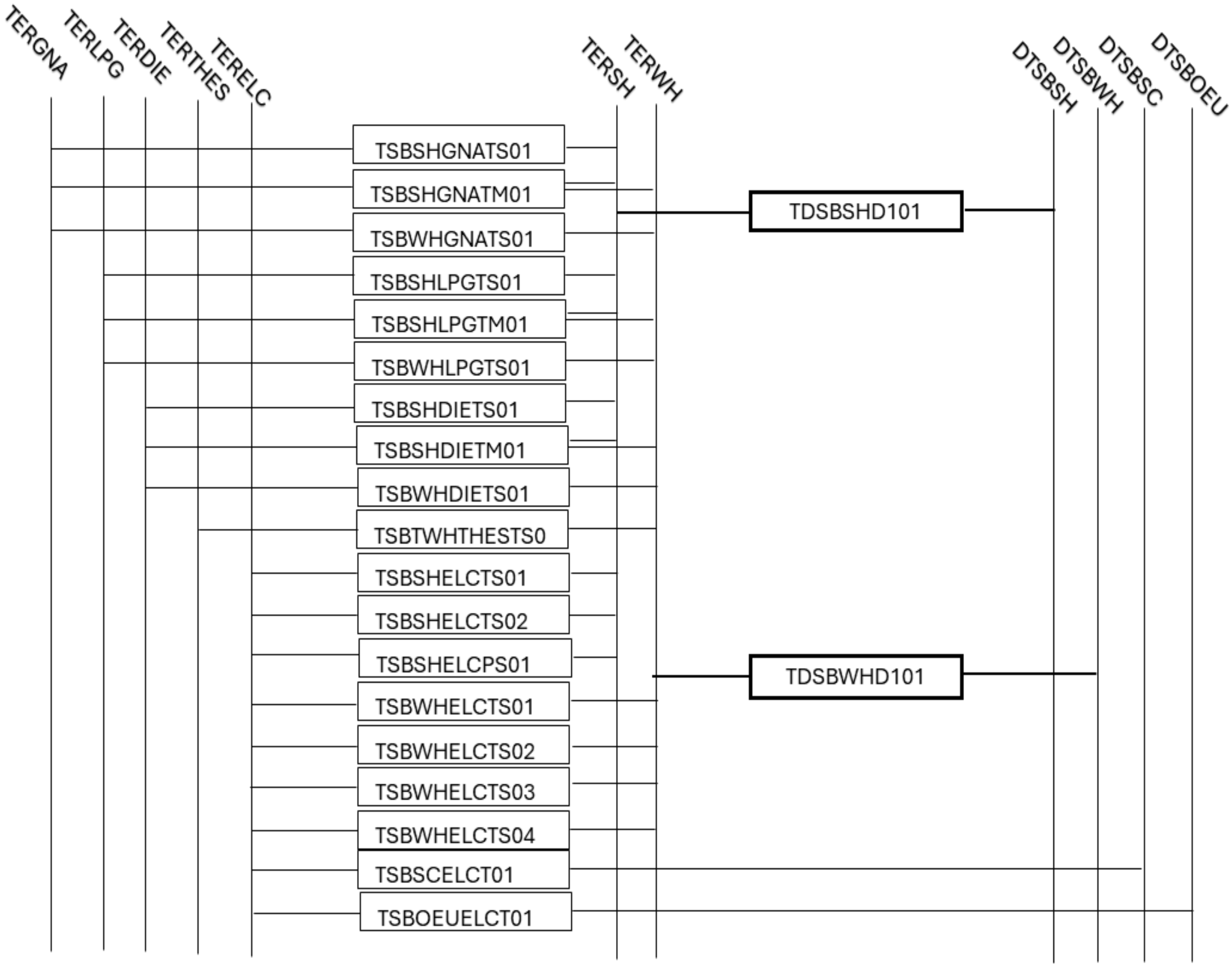

Figure B.5: RES of the Shopping Building subsector in the Tertiary sector

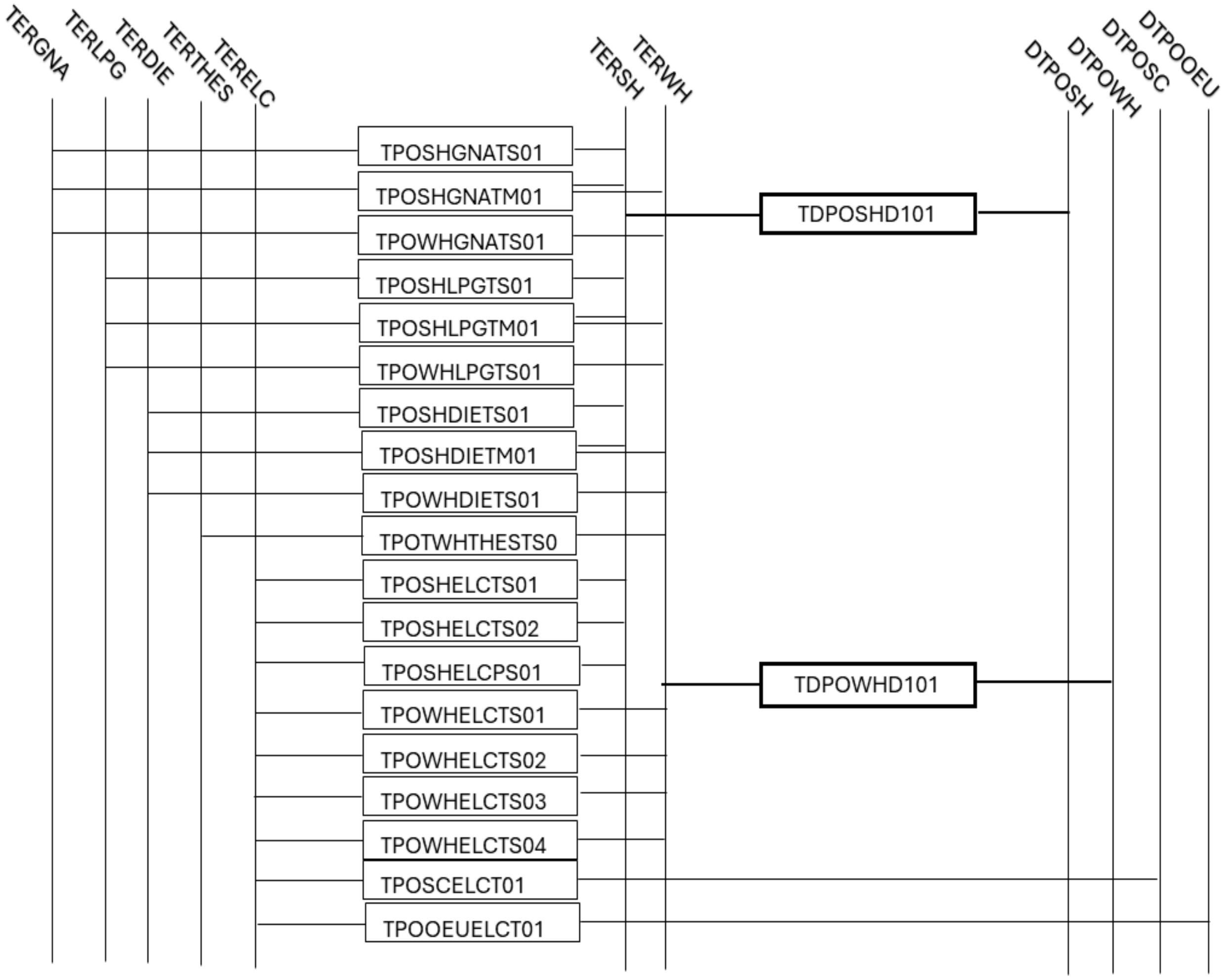

Figure B.6: RES of the Private Offices subsector in the Tertiary sector