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Urban & Regional Planning

Master's degree thesis:

Territorial Data Integration for National Energy Mapping:

A Multi-Regional Analysis of Energy Consumption and Production for Renewable Energy Communities in Italy

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Abstract

Decentralized renewable deployment in Italy requires high-resolution spatial energy data, yet current public databases remain largely restricted to macro-regional aggregates. Planners can learn how much electricity a province generates and uses from annual statistics, but they are unable to determine whether production and consumption occur at the same time. For Renewable Energy Communities, whose economic advantage is determined hourly under Italian law, this divergence is crucial.

This thesis develops a building-level energy database for five Italian regions: Abruzzo, Basilicata, Sardegna, Trentino-Alto Adige, and Valle d'Aosta. For the four provinces of Abruzzo, the workflow downscales annual energy balances into hourly time series as the main case study. Developed using PostgreSQL and PostGIS, the database links municipal footprints, ISTAT census indicators, ARERA withdrawal profiles, and GSE power plants. A standardized building classification combined with tiered height calculations determines building volumes for roughly 600,000 spatial records. ARERA provincial benchmarks, a residual technique for services, and proportionate downscaling from ENEA regional totals are used to estimate annual consumption for the residential, services, industries, and agricultural sectors. Using GSE registered capacity and province-specific utilization hours, renewable production is computed plant by plant and then broken down into hourly profiles using normalized lookup coefficients.

With Self-Sufficiency Index values ranging from 20.7% in Teramo to 40.4% in L'Aquila and Self-Consumption Index values of 100% confirming that all locally produced electricity is fully absorbed by local demand, all four Abruzzo provinces consistently experience an annual energy deficit. According to monthly analysis, Teramo's nearly complete reliance on solar energy results in the flattest profile, never rising above 24%, while L'Aquila and Chieti attain peak self-sufficiency in February and March due to wind generation. On an hourly basis, the midday window of four to five hours is where renewable production is concentrated, and in every area and season, the evening consumption peak is still unexplored.

Three self-sufficiency scenarios aimed at 40%, 75%, and 100% SSI are assessed. The most balanced planning horizon is determined to be a target of 75% SSI, which calls for additional capacity ranging from 367.9 GWh in L'Aquila to 775.3 GWh in Teramo. Teramo's reliance on solar energy indicates that wind diversification is the most strategically advantageous investment, according to source-type disaggregation. By proving that hourly resolution yields planning-relevant information that annual statistics are unable to provide, the thesis adds to the Urban Energy Atlas of Italy.

Keywords: Territorial Data Integration; Urban Energy Atlas; Renewable Energy Communities; Building-Level Energy Modeling; Electricity Consumption; Renewable Energy Production

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Chapter 1: Introduction

1.1 Background and Context

Installing large-scale renewable energy plants is only one aspect of decarbonizing energy networks; another is reorganizing systems to accommodate local generation and demand. Renewable Energy Communities (RECs) were created at the EU level by the Renewable Energy Directives (RED II and RED III) to enable residents, local companies, and municipalities to produce, distribute, and use green energy within predetermined borders.

Implementing these local initiatives requires detailed spatial datasets far beyond standard national or regional aggregates from ISTAT or Terna. Assessing REC feasibility, estimating potential demand coverage, and selecting priority zones all depend on granular building-level data, including building footprint, volume, use type, and on-site generation capacity. Urban Building Energy Models (UBEMs) directly address this requirement by aggregating physical building characteristics into bottom-up territorial energy profiles.

In Italy, building-level modeling faces significant spatial data inconsistencies. Because each of the twenty regions maintains its own GIS repositories independently, datasets vary widely in their typology codes, survey years, and availability of building heights. A regional technical map (Carta Tecnica Regionale) from Piemonte and one from Sicilia may both describe "buildings," yet use incompatible category labels, different minimum mapping units, and different vintages of aerial survey. Consequently, any attempt to build a national or even multi-regional picture of building-level energy demand and supply must begin by resolving this heterogeneity before a single consumption value can be estimated.

It is against this background that the present thesis is situated. The work forms part of a broader collaborative effort between the Politecnico di Torino and the Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA), aimed at constructing a harmonized, building-level Urban Energy Atlas of Italy. Section 1.3 describes that collaborative project in more detail; the remainder of this chapter defines the specific problem addressed by this thesis and the objectives pursued within it.

1.2 Problem Statement and Research Gap

This thesis is motivated by three gaps. Building classification is the first. The wide legal-administrative categories (residential, agricultural, industrial, and commercial) used to categorize structures in existing Italian regional datasets do not clearly correlate with energy consumption patterns. Conventional schemes classify both a church and a bank branch as tertiary-sector buildings, although their daily load profiles, heating and cooling needs, and occupancy patterns are very different. In the absence of a categorization system that separates buildings based on energy-relevant usage rather than administrative category, any downstream consumption estimate inherits this imprecision.

Building height is the subject of the second disparity. Volume is the primary input for bottom-up energy demand forecast, and the characteristic that is most commonly missing or inconsistent in regional datasets is height. While some places just provide the number of floors or neither, others directly provide a height property. Global datasets, like the Global Human Settlement Layer, provide height estimates at the continental scale. However, as reported in Chapter 3, these values were found to consistently underestimate height for a significant portion of the Italian building stock, falling below the 2.7 m minimum plausible floor height. Therefore, rather than depending on a single dataset, a defensible height-estimation technique must hierarchically integrate several sources.

The third gap focuses on the demand-supply relationship itself. The annual totals of production and consumption supplied by regional or provincial energy statistics are sometimes used to compute an annual self-sufficiency indicator, the ratio of local output to local consumption. However, a yearly ratio obscures the temporal disparity between the production and use of renewable electricity. A province with an annual self-sufficiency ratio close to unity may nevertheless experience large hourly deficits during winter evenings, when solar output is at its lowest and heating demand is at its peak. Existing regional energy assessments in Italy, including ENEA's own annual efficiency reports, are structured around annual and monthly aggregates and do not resolve this hourly mismatch at sub-regional scale.

These three gaps are addressed with different scopes in this thesis. The building classification and height-estimation methodologies were developed collaboratively as part of the wider ENEA-PoliTo project and are described in Chapter 3 as inherited methodology, applied here to the case study region of Abruzzo. The temporal demand-supply analysis, by contrast, constitutes the original contribution of this thesis: it extends the annual, production-consumption balance already computed for all Italian regions into an hourly resolution for the four provinces of Abruzzo, and it introduces a set of scenario-based targets for provincial self-sufficiency that were not part of the original group project. The following section situates this distinction more precisely within the structure of the broader Urban Energy Atlas project before Section 1.4 states the thesis objectives in full.

1.3 The Urban Energy Atlas Project

This thesis originates within a larger research effort carried out at the Politecnico di Torino, in collaboration with ENEA, between March 2025 and July 2026. The project, referred to throughout this thesis as the Urban Energy Atlas, set out to construct a harmonized, georeferenced database of buildings across all twenty Italian regions, integrating four categories of information for each building: functional use, physical geometry, estimated energy consumption, and, where applicable, actual renewable energy production. The atlas was designed as an open resource to facilitate policy research and energy planning at various scales, from the individual building to the entire country.

Under the academic guidance of Prof. Guglielmina Mutani, a group of master's students collaborated on the project, which was structured around five components. The first part resolved the terminological and structural problems mentioned in Section 1.2 by harmonizing regional building databases into a single classification system.

The second addressed building height, applying a hierarchical, multi-source estimation procedure to fill gaps left by incomplete regional attributes. The third and fourth components calculated, respectively, annual and hourly building-level energy consumption across the residential, agricultural, industrial, and service sectors, and annual and hourly actual energy production from registered renewable plants. A fifth component generated synthetic Digital Surface Models for the twelve regions lacking an official one, a task to which the present author contributed by producing the DSMs for three regions, intended to support solar potential modeling in later stages of the wider project; these DSM outputs are not used in the analysis presented in this thesis.

The present writer mainly contributed to this group effort by working on the building height estimation and, more centrally, by taking independent responsibility for six regions within the larger dataset: Abruzzo, Basilicata, Puglia, Trentino-Alto Adige, Valle d'Aosta, and Sardegna (for Puglia, the current author was in charge of building classification and actual energy production, while another team member handled consumption modeling). Puglia was subsequently excluded from the present thesis owing to computational constraints associated with processing its building dataset, leaving five regions from which the case study developed here was ultimately narrowed to Abruzzo, for the reasons given in Section 1.5.

It is important to distinguish clearly from this point onward between the methodology inherited from the group project and the analysis original to this thesis. The building classification system, the height-estimation hierarchy, and the annual consumption and production calculation pipelines described in Chapter 3 were developed jointly with the project team and are applied here, not re-derived. On top of that shared infrastructure, this thesis adds a temporal and scenario-based layer of analysis that is specifically applied to Abruzzo. It does this by breaking down annual production and consumption into hourly profiles, quantifying the demand-supply mismatch at sub-annual resolution, and creating a series of self-sufficiency scenarios that assess the additional generation capacity each province would need to meet predetermined policy targets. Section 1.4 states this contribution as a set of explicit objectives and research questions.

1.4 Objectives and Research Questions

The general objective of this thesis is to assess the extent to which the four provinces of Abruzzo can meet their electricity demand from local renewable generation, at a temporal resolution fine enough to reveal mismatches concealed by annual balances, and to evaluate what additional generation capacity would be required to close that gap under alternative policy targets.

This general objective is pursued through four specific objectives:

1. To document and critically evaluate the building classification and height-estimation methodology applied to the Abruzzo building stock, assessing its coverage and data quality as a foundation for provincial energy analysis.

2. To quantify annual electricity consumption and actual renewable production for each of the four Abruzzo provinces, disaggregated by sector and by source, and to compute the resulting annual self-sufficiency indicator for each province.
3. To disaggregate annual consumption and production into hourly profiles for each province and season, and to characterize the resulting pattern of energy deficit across the day and across the year, including its monthly variation.
4. To define and evaluate a set of self-sufficiency scenarios, quantifying the additional renewable generation capacity each province would need to reach specified self-sufficiency thresholds.

These objectives translate into the following research questions, which the analysis in Chapter 4 is structured to answer:

RQ1. How do annual electricity consumption and renewable production vary across the four provinces of Abruzzo, and what does this imply for their current levels of energy self-sufficiency?

RQ2. At what times of day and in which seasons is the mismatch between local consumption and local production most severe, and does this pattern differ systematically among the four provinces? Does the degree of self-sufficiency also vary across the months of the year, and if so, which months and which provinces show the greatest departure from the annual average?

RQ3. How much additional renewable generation capacity would each province require to reach 40%, 75%, and 100% annual self-sufficiency, and how does this requirement relate to each province's current renewable energy mix?

The first research question is addressed through the annual balance calculations described in Chapter 3 and reported in Section 4.2. The second research question is addressed in two parts: the hourly and seasonal demand-supply mismatch analysis reported in Section 4.4, and the monthly self-sufficiency profiles reported in Section 4.3. The third depends on the scenario framework introduced in Section 4.5, which constitutes the most direct original contribution of the thesis relative to the wider Urban Energy Atlas project. Section 1.5 introduces the case study area to which these questions are applied.

1.5 Case Study Area: Abruzzo

The analysis developed in this thesis focuses on Abruzzo, a region of central Italy comprising four provinces: L'Aquila, Teramo, Pescara, and Chieti. Abruzzo was selected from among the five regions initially available to the present author (Section 1.3) for three reasons.

First, the region combines substantial internal heterogeneity with a manageable number of administrative units. Its four provinces span a mountainous, sparsely populated interior (L'Aquila) and a densely built Adriatic coastal strip (Teramo, Pescara, Chieti), producing meaningfully different consumption and production profiles within a single region rather than requiring a cross-regional comparison to observe variation. Second, preliminary inspection of the province-level data summarized in Table 4.1 showed that all four Abruzzo provinces present

annual production below annual consumption, placing the region as a whole in an energy deficit position; this makes Abruzzo a relevant, rather than a merely illustrative, case for the self-sufficiency scenario analysis pursued in Chapter 4. Third, the regional building dataset and the DSM/DTM sources available for Abruzzo were sufficiently complete to support the hourly disaggregation procedure without requiring extensive additional gap-filling, which was not the case for all five regions initially considered.

The percentage of renewable energy in Abruzzo varies around the region. As shown in Chapter 4, Chieti and Pescara rely on a more balanced mix of solar, wind, and biomass, but Teramo is mostly dependent on solar power. Because of its relatively lower consumption and better balanced solar-wind generation mix in relation to its demand, L'Aquila obtains the greatest provincial self-sufficiency ratio in the region despite having the lowest overall production of the four provinces. This internal variation is treated in Chapter 4 as the central empirical basis for comparing how province-level generation mix relates to the pattern and severity of hourly energy deficit. A fuller territorial and data-source description of the region, including the specific building classification and height-estimation choices applied to its dataset, is given in Chapter 3.

1.6 Structure of the Thesis

The remainder of this thesis is organized into four chapters.

The theoretical foundation for the analysis is reviewed in Chapter 2. It describes building stock characterization and Renewable Energy Communities as the policy context driving building-level energy assessment, introduces Urban Building Energy Models as the general methodological family to which this work belongs, and examines current methods for generating digital surface models and modeling solar potential. The chapter concludes by placing the current effort in the context of ongoing energy atlas projects in Italy and other countries.

The materials and approach are explained in Chapter 3. It records the sources of data used for building geometry, classification, and energy statistics; the hierarchical process used to estimate building height in cases where regional characteristics are either unreliable or missing; and the computation pipelines used to obtain production and consumption values on an annual and hourly basis. This is made clear when a method was created collaboratively within the larger Urban Energy Atlas project and applied to Abruzzo; it is also indicated when a method is unique to this thesis, primarily the hourly disaggregation and scenario methods.

Chapter 4 presents the results of the analysis and discusses their implications. It reports the annual energy balance for the four Abruzzo provinces, the hourly consumption-production mismatch and its seasonal variation, and the self-sufficiency scenarios defined in response to RQ3. Results are discussed in relation to each province's renewable energy mix and territorial characteristics as introduced in Section 1.5.

Chapter 5 concludes the thesis. It summarizes the principal findings in relation to the three research questions stated in Section 1.4, discusses the limitations of the methodology and data

used, and outlines directions for future work, including the extension of the present scenario framework to the remaining Italian regions covered by the wider Urban Energy Atlas project.

Chapter 2: Theoretical Framework

2.1 Urban Building Energy Models (UBEM)

2.1.1 Top-down vs. Bottom-up Modeling Approaches

Estimating the energy consumption of a building stock, whether at the scale of a neighborhood, a city, or an entire region, requires a modeling strategy that matches the resolution of the data available and the questions the model is meant to answer. A review of residential energy consumption modeling (Swan & Ugursal, 2009) highlighted the fundamental distinction in this subject, which divides techniques into two major categories: top-down and bottom-up.

The building sector is viewed as an overall energy sink in top-down models. They estimate consumption using historical, sector-wide data, such as macroeconomic indices (gross domestic product, employment, energy prices), meteorological conditions, and patterns in residential building or demolition, without considering specific structures or their architectural characteristics. Within this category, there are two primary subtypes: technological models, which link consumption to more general developments in the housing stock, like appliance ownership, and econometric models, which are predominantly influenced by price and income variables (Swan & Ugursal, 2009). Because of its low data requirements and dependence on past consumption levels, top-down modeling has an inherent stability for short-term forecasting. Its main flaw is the opposite of this strength: because the models are based on past trends, they are unable to accurately depict abrupt changes in the built environment or technological advancements, and they are unable to pinpoint the precise building types or end-uses that are driving consumption.

Bottom-up models take the opposite route. They calculate energy consumption at the level of individual buildings, or representative groups of buildings, and then extrapolate these results to the regional or national scale using appropriate weighting factors. Bottom-up approaches are divided into statistical methods, which regress metered consumption data against building and household characteristics, and engineering methods, which calculate consumption directly from the physical properties of buildings using heat transfer and thermodynamic principles (Swan & Ugursal, 2009). Engineering methods are further split into three techniques: distribution-based approaches, which combine national appliance-ownership statistics with typical ratings; archetype-based approaches, which classify the stock into representative building types; and sample-based approaches, which model a large, representative set of individual buildings drawn from an existing database. Because engineering methods do not depend on historical metered data, and because they explicitly model the physical characteristics of buildings, they are the only approach capable of estimating the impact of a technology or retrofit measure that has no consumption history of its own, which makes them the natural fit for evaluating future scenarios such as building retrofits or the integration of renewable energy sources.

This top-down/bottom-up framework, now more than fifteen years old, has become something close to the standard reference point for the field, but it has also drawn criticism for no longer fully capturing how urban-scale modeling is practiced. In a systematic review of 56 UBEM studies published between 2001 and 2021, it is argued that the original classification was formulated in 2009, before urban building energy modeling had properly emerged as its own area of dynamic urban energy planning, roughly around 2016, and that treating residential building modeling as representative of the full range of urban systems is no longer adequate (Kong et al., 2023). A revised mapping is proposed in which the top-down category is now dominated by data-driven statistical methods, while the bottom-up category is better described as splitting into physics-based approaches, now the most commonly used, and a smaller but growing set of reduced-order approaches that simplify the physical modeling to cut computational cost (Kong et al., 2023). This shift toward physics-based bottom-up modeling as the dominant contemporary approach is corroborated independently in a separate review of urban building energy modeling tools, which likewise treats bottom-up, physics-based simulation as the state of the art for large-scale energy assessment precisely because it is the only approach detailed enough to evaluate specific retrofit or renewable-integration interventions (Ferrando et al., 2021). Under either framing, though, the underlying logic that motivated the original split still holds: models built from aggregate historical data trade detail for simplicity, while models built up from individual buildings trade computational cost for the ability to represent new interventions and finer spatial and temporal detail.

The distinction matters directly for a project such as the Urban Energy Atlas, which needs to estimate current energy consumption across an entire region while also supporting forward-looking scenarios, retrofit interventions, renewable energy integration, and self-sufficiency targets, that a purely historical, aggregate model could not represent. This points the Atlas methodology toward an engineering, bottom-up approach, and the tools and workflows built specifically to support that approach at urban scale are discussed next.

2.1.2 UBEM Tools: A Comparative Overview

Once the choice falls on a bottom-up, physics-based approach, the practical question becomes which of the many existing software tools, if any, is fit for the task. The most detailed user-oriented comparison currently available reviews eight bottom-up physics-based UBEM tools: CitySim, SimStadt, umi (the urban modeling interface), CityBES, OpenIDEAS, CEA (City Energy Analyst), URBANopt, and TEASER (Ferrando et al., 2021). Before comparing the tools themselves, a distinction is made that is worth carrying over into any UBEM-adjacent project: UBEM is conceptually separate both from land-use and transport modeling and from urban system energy modeling, or USEM, tools such as HOMER, EnerGIS, or PVGIS, which focus on optimizing energy networks and supply systems rather than characterizing the building stock itself (Ferrando et al., 2021). The two are complementary rather than competing, since USEM tools typically need UBEM-level output as an input to properly size and design the energy systems they optimize, and the more recent UBEM tools increasingly try to fold both functions together.

Comparing the eight tools across five categories, required inputs, generated outputs, modeling workflow, applicability, and intended users, the review finds that despite sharing a common physics-based foundation, the tools diverge substantially in how they handle geometry, data integration, and the level of geometric detail supported (Ferrando et al., 2021). Nearly all of the reviewed tools rely on standard GIS formats, chiefly CityGML and GeoJSON, to import building geometry, and nearly all simplify each building to a single extruded volume based on its footprint and height, corresponding to the lowest level of geometric detail (LoD1) defined for CityGML files. A smaller subset, specifically SimStadt, CityBES, and TEASER, support a higher level of detail (LoD2) that captures features such as saddle roofs when that information is available in the source data. Thermophysical characterization, in every one of the eight tools, depends on archetypes: representative prototype buildings assigned to each entry in the geometry based on simple, generally available attributes such as construction period, intended use, and building typology. This near-universal reliance on archetypes reflects a practical reality rather than a design preference, since collecting building-specific thermal data for every structure in a city-scale dataset is rarely feasible, but it comes at a documented cost: archetype-based characterization smooths over real variation within the building stock, an issue explored further in Section 2.2.

A set of unresolved challenges shared across the reviewed tools is also identified, several of which speak directly to why building a bespoke pipeline can be the more defensible choice for a project with regionally heterogeneous data (Ferrando et al., 2021). These include the challenge of accounting for local microclimate effects and building-to-building heat exchange at scale, the difficulty of representing occupant behavior and movement realistically rather than through fixed schedules, the ongoing gap between UBEM and USEM in jointly optimizing building demand and energy system design, and the reliance on calibration methods, most promisingly Bayesian approaches, which still require significant computational effort and consistently structured input data to be effective. A similar conclusion is reached from a broader systematic review, finding that insufficient and inconsistent input data represents the single greatest constraint on UBEM accuracy across the literature, regardless of which specific tool or engine is used (Kong et al., 2023).

Taken together, these two reviews describe a field where the available tools are powerful but were largely built around case studies with relatively complete, standardized municipal or national datasets, of the kind more readily available in some European contexts than others. This heterogeneity in tool design, and the recurring finding that data availability, not modeling theory, is the binding constraint on accuracy, is precisely the gap that motivated the Urban Energy Atlas project to build a custom PostgreSQL/PostGIS pipeline tailored to the specific and often incomplete building datasets available across Italian regions, rather than adopting one of the existing tools wholesales.

2.1.3 GIS-based UBEM Workflows

Because the accuracy of any bottom-up model depends so heavily on the quality of its input data, and because that data is rarely collected with energy modeling in mind, a substantial share of applied UBEM work is really about reconciling incomplete, inconsistent GIS datasets into

something a physical model can actually use. Two case studies, one Canadian and one Italian, show how this reconciliation effort is carried out.

This problem is described in depth for Kelowna, Canada, where no single dataset was comprehensive enough to support UBEM independently (HosseiniHaghighi et al., 2022). Three distinct municipal data sources were integrated into the workflow: a manually surveyed address-point dataset, an unclassified building footprint layer produced from orthophoto images, and a parcel-level property dataset (Model City). Each came with its own limitations: missing building identifiers, building heights that were inconsistent with the recorded number of storeys for more than 40% of the dataset, and parcels containing more than one building whose properties could not always be disaggregated correctly. These inconsistencies were resolved using a combination of spatial join operations, centre-point intersection logic to correctly associate footprints with parcels, and rule-based filtering to separate heated, occupied buildings from accessory structures such as garages and sheds (HosseiniHaghighi et al., 2022). The resulting harmonized dataset was then fed to a procedurally generated 3D city model in CityGML format, and archetype-based heating demand estimates calibrated against this model came within 2.5% of measured regional energy data, a level of accuracy attributed directly to the care taken in the data harmonization stage rather than to the sophistication of the simulation engine itself.

A structurally similar, though methodologically distinct, precedent comes from Italy. A GIS-based methodology was developed for the city of Milan by overlaying two very different kinds of data: the National Census cartography maintained by ISTAT, which records population, housing, and construction-period information aggregated at the census-tract level, and a municipal buildings map derived from aerial photogrammetric survey, which records the dimensional characteristics of individual buildings, such as footprint area and eaves height, but says nothing about their age or use (Caputo et al., 2013). Neither dataset alone could support energy modeling: the census data lacked building-level geometry, and the buildings map lacked any information about construction period or thermal characteristics. By linking the two datasets spatially, each building could be assigned both a prevailing construction-period class and a geometric form factor, from which four archetype categories were derived (a small detached form, a five-storey line-block form, a ten-storey tower form, and a four-storey central-patio form) and their heating, cooling, and other energy demands simulated using EnergyPlus (Caputo et al., 2013). When aggregated to the city level and compared against the independent SIRENA regional energy database, the resulting total energy estimate differed by only 4%.

What both cases show, despite operating in entirely different national data environments, is that the modeling step itself, once representative archetypes and a harmonized geometry are in place, is often the more straightforward part of the process. The harder and more time-consuming task is almost always upstream: identifying which combination of incomplete datasets can be layered together to compensate for what any single source is missing, and designing a defensible rule set for resolving the inevitable conflicts between them. This is precisely the challenge the Urban Energy Atlas project confronts at a larger and more heterogeneous scale, working across multiple Italian regions whose underlying cadastral,

census, and geometric data sources are not uniformly available or uniformly structured, and the specific data harmonization strategy adopted for the Atlas is described in full in Chapter 3.

2.2 Building Stock Characterization

2.2.1 Classification Criteria and Building Attributes

Before an archetype can be assigned to a building, or a building simulated at all, the stock has to be sorted into groups on the basis of attributes that are both energy-relevant and realistically obtainable at scale. A small set of criteria (construction period, building type, geometric shape, and intended use) recur consistently throughout the research, although which qualities are employed and how finely the stock is split vary from study to study.

Building regulations, construction methods, and thermal insulation requirements all change over time in ways that leave a lasting impact on a building's energy performance, which is why construction period is nearly always considered the key categorization variable. The Milan building stock was classified into seven construction-period bands, drawn from the categories used in the Italian National Census, with envelope construction technologies assigned to each period based on established Italian technical literature (CNR, 1982) and the reference values in UNI TS 11300-1 (Caputo et al., 2013). Working with the Energy Performance Certificate (EPC) database for Turin, eight construction-period classes were used, spanning from before 1918 to after 2006, and the thermal transmittance values and system efficiencies calculated for each class tracked a clear and expected trend: buildings from later construction periods, particularly those built after 1980, showed markedly lower transmittance and higher system efficiency than older stock, a trend that became still more pronounced once retrofitted buildings were considered separately from the general stock (Mutani & Todeschi, 2021).

Geometric form, which measures how exposed or compact a building's shape is in relation to its volume, is the second significant axis of classification. This is often expressed using the surface-to-volume ratio, or S/V; it is also sometimes called a form factor. Using S/V thresholds, Milan's buildings were divided into four archetype shapes, with extended line-block buildings having an S/V closer to 0.36 and compact semi-detached structures having an S/V near to 0.7 (Caputo et al., 2013). Todeschi et al. (2021) demonstrate that this goes beyond straightforward categorization: self-consumption and self-sufficiency outcomes for rooftop photovoltaic systems varied significantly with building compactness when comparing two residential districts in Turin with very similar construction periods and generally compact building shapes. This is because a shorter, less compact building directly limits the amount of solar potential available per family, whereas a taller, more compact building focuses more inhabitants' demand onto the same limited roof surface.

Building typology and intended use round out the classification criteria, and their role is largely to separate the stock into categories that behave differently enough to warrant separate treatment: residential typologies (flats versus detached houses, in the terminology used by Mutani and Todeschi (2021), or single-family, semi-detached, and low-rise apartment categories elsewhere) as distinct from commercial, office, or industrial uses. How classification often has to work around what the available identifying data will actually support is well

illustrated by the Kelowna dataset, which carried a municipal "Actual Use Code" field capable of distinguishing 24 separate housing types, yet eight classes of single-family dwelling accounted for such a dominant share of the low-rise residential stock, roughly 90%, that these eight classes alone were treated as representative of the whole for archetype purposes, with the remaining, much smaller typologies folded in where their characteristics closely matched (HosseiniHaghighi et al., 2022).

2.2.2 Archetype Modeling Principles

Classification is only useful once it feeds into archetype modeling, the step where each group of similar buildings is assigned a single representative energy profile rather than requiring every individual building to be separately characterized. Archetype modeling is described as one of three engineering techniques available to bottom-up models, alongside distribution-based and sample-based approaches, with its central appeal being practical: it reduces both the data collection burden and the simulation time required to model a large building stock, since a limited number of archetype descriptions can stand in for thousands or millions of individual buildings (Swan & Ugursal, 2009).

An archetype, by definition, is not supposed to resemble any individual real edifice. The core reasoning is delineated explicitly in a critique of archetype-oriented investigations (Swan & Ugursal, 2009): a representative account is constructed for each significant category identified during classification, and this account, instead of the particulars of any individual structure, acts as the input for the energy simulation. The technique operates successfully at the aggregate level because the errors caused by classifying unlike buildings as equivalent typically neutralize when a large enough number of buildings are totaled, given that the classification process accurately clustered buildings with comparable energy behaviors. This is precisely why the classification criteria discussed in 2.2.1, construction period, form factor, typology, matter so much: an archetype built on a poorly chosen classification will carry that error straight through to the aggregate result.

How many archetypes a study defines, and how that number is arrived at, is itself a consequential modeling decision, and the literature shows real variation in approach. Four archetypes were considered sufficient for the whole of Milan, on the reasoning that four distinct building forms, combined with seven construction periods and two use categories (residential and office), was enough to capture the dominant variation in the city's stock without multiplying the number of required EnergyPlus simulations unnecessarily; the resulting 56-archetype matrix, once validated against the independent SIRENA database, came within 4% of the actual regional energy total (Caputo et al., 2013). A rather different scale of ambition is documented in a review of the Canadian national residential model developed by Farahbakhsh, Ugursal, and Fung, which combined only 16 base archetypes with data from 8,767 individual sampled houses drawn from a national survey, using the archetypes to fill gaps and the sample data to preserve real variety, an approach that sits between pure archetype modeling and the more data-intensive sample-based technique (Swan & Ugursal, 2009). What both examples share is a trade-off made explicit rather than left implicit: fewer archetypes are cheaper to simulate but risk collapsing genuine diversity in the stock, while more archetypes, or a hybrid

of archetypes and sampled real buildings, capture more of that diversity at a proportionally higher computational and data cost.

A caution about this trade-off worth carrying forward comes from the broader UBEM literature: although the archetype approach substantially improves modeling efficiency and remains the dominant strategy in bottom-up UBEM, in practice it "substantially underestimates the actual diversity of the existing building stock" (Kong et al., 2023), a concern echoed independently in the observation that even the eight leading UBEM software tools reviewed rely almost entirely on archetypes assigned from simple attributes such as construction year and intended use, with the differences that exist within a single archetype category in the real city effectively lost in the aggregation (Ferrando et al., 2021). Neither review treats this as a reason to abandon archetype modeling, since the alternative, fully individualized building-by-building characterization, remains computationally impractical at urban scale, but both frame it as a known and durable limitation rather than a solved problem, one that calibration against independent measured data, discussed next, is the primary available tool for managing.

2.2.3 Input Data and Calibration Challenges

An archetype-based model is only as reliable as the data used to build it and, just as importantly, the data used to check it afterward. This is where much of the genuinely difficult work in UBEM happens, and where the literature is most consistent in identifying a shared limitation. Insufficient and inconsistent input data are found, across a systematic review of 56 studies, to represent the single greatest constraint on UBEM modeling accuracy (Kong et al., 2023), a finding echoed in the observation that municipal and national datasets are collected for administrative rather than energy-modeling purposes and therefore routinely lack consistent building identifiers, standardized attribute formats, or complete geographic coverage, forcing modelers to reconcile GIS layers, census records, and technical registries that were never designed to be combined (Ferrando et al., 2021).

Calibration, the process of checking archetype-based estimates against independent measured data and correcting the underlying assumptions where they diverge, is the primary mechanism the literature relies on to compensate for this uncertainty, and Energy Performance Certificate (EPC) databases have proven to be an especially valuable calibration resource precisely because they contain measured or officially assessed energy performance values rather than assumptions drawn from generic literature. This is demonstrated directly for Turin, where an existing GIS-based monthly engineering model had originally relied on thermal transmittance and system-efficiency values drawn from standard Italian technical literature rather than the real characteristics of the local stock (Mutani & Todeschi, 2021). Reprocessing over 182,000 EPCs issued for the city between 2009 and 2015, discarding anomalous records using median-based statistical filtering and normal-distribution testing, and recalculating transmittance and efficiency values separately for generic, retrofitted, and renewable-technology-equipped buildings within each construction-period class, substituting these EPC-derived values for the original literature-based ones reduced the model's relative error from roughly 9% to 5% for the combined heating and domestic-hot-water model, and from around 17% to 13% for the heating-only model (Mutani & Todeschi, 2021). This illustrates a broader point: calibration is not a

one-time validation step performed after modeling is complete, but an iterative correction that can be built directly into a model's input data.

A comparable logic operating with a different kind of calibration data is illustrated by the Kelowna case (HosseiniHaghighi et al., 2022). The initial archetype-based heating demand estimates, built from five base archetypes drawn from a national simulation tool's internal library, showed deviations from measured regional data ranging from 4% to as much as 41% depending on construction vintage. A confidential energy audit of single-family homes carried out in Kelowna itself and smart-thermostat data covering heating and cooling setpoints and occupancy patterns for the same city were two more, more locally specific data sources that were layered in to close this gap (HosseiniHaghighi et al., 2022). The final calibrated model only came within 2.5% of the measured regional heating usage after applying these local changes and further splitting the five base archetypes into eight construction-vintage variants.

A pattern common to both cases, and to the calibration methodology described more generally elsewhere (Kong et al., 2023; Ferrando et al., 2021), is that no single dataset is treated as sufficient on its own. A reliable archetype model, in practice, tends to draw on at least two genuinely independent data sources: one used to define the initial building and construction characteristics, and a second, ideally consisting of real measured performance data such as an EPC record, a utility bill, or an audit, used specifically to check and correct the resulting energy estimates. This two-step logic, define first, then calibrate against independent measurement, is one of the more directly transferable lessons from the literature for the building classification and consumption estimation methodology developed for the Urban Energy Atlas, and the specific calibration strategy adopted for that project is described in Chapter 3.

2.3 Renewable Energy Communities (RECs)

2.3.1 Regulatory and Policy Context

A Renewable Energy Community, or REC, is a legal structure that allows a group of citizens, small businesses, or local authorities to jointly produce, share, and consume renewable energy, typically generated close to where the members live or operate. The idea was first legally articulated at the European level rather than in national legislation. The Renewable Energy Directive II (RED II, Directive 2018/2001/EU), which incorporated RECs into EU law in 2018, and its later revision, RED III (Directive 2023/2413/EU), which was adopted in October 2023 and increased the EU's legally binding renewable-energy target to at least 42.5% by 2030 and mandated an additional 1.6% annual increase in renewable deployment (Zhu et al., 2025).

Italy's national transposition of these directives proceeded in distinct phases rather than as a single legislative act. Three are identified: an initial experimental phase from 2018 to 2020, in which Italy introduced the concept of collective self-consumption through Legislative Decree 162/2019 and set a restrictive capacity cap of 200 kW per plant; a consolidation phase from 2021 to 2022, guided by Legislative Decree 199/2021, which expanded the regulatory framework and clarified energy-sharing rules under the Integrated Text on Collective Self-Consumption (TIAD); and a more recent expansion phase from 2023 onward, in which Ministerial Decree 414/2023 raised the capacity threshold to 1 MW and introduced incentive

tariffs and capital subsidies specifically targeted at municipalities with fewer than 5,000 inhabitants (Zhu et al., 2025). Synthesizing the wider international literature on REC regulation, Corasaniti et al. (2025) note that Italy defines the geographic proximity requirement for REC membership in electrical rather than physical terms, meaning members must be connected to the same high-voltage to medium-voltage primary substation, in contrast to countries such as France and Greece, which instead interpret proximity as physical distance from the renewable energy source itself.

With Regional Law 12/2018, Piedmont became the first region in Italy to enact laws particularly for energy communities. Energy communities must demonstrate an annual self-consumption rate of at least 70%, of which at least half must come from locally available renewable sources, and annual electricity consumption across the community must exceed 0.5 GWh. These requirements are described as a template that subsequent national regulations would follow (Mutani et al., 2021). This 70% threshold recurs directly as a design constraint, rather than merely a reporting requirement, in later feasibility studies discussed in Section 2.3.2.

The Italian case is situated within a much broader international picture, drawing on more than 170 studies spanning Europe, the Americas, Africa, Asia, and Australia (Corasaniti et al., 2025). Despite a shared EU legal foundation, national implementation of RED II and RED III has varied considerably, with Germany accounting for more than half of the EU's roughly 9,000 energy communities as of 2020, followed by the Netherlands and Denmark, while Italy, though an early and active adopter at the policy level, remains comparatively early in its practical rollout (Corasaniti et al., 2025). This unevenness across countries, and the fact that regulatory particulars such as the definition of geographic proximity differ meaningfully even among EU member states, is part of why country-specific and even region-specific REC research, of the kind reviewed throughout the remainder of this section, continues to be necessary rather than something a single EU-wide framework could substitute for.

2.3.2 REC Design and Feasibility Studies

Once the regulatory conditions for forming a REC are established, the practical work becomes sizing and designing one, and a substantial body of feasibility research has grown up around specific Italian case studies, most of it associated with the same research group whose UBEM and atlas methodologies were discussed in Section 2.1. This body of work has a concrete starting point: Magliano Alpi, a small agricultural municipality in the province of Cuneo, Piedmont, is identified as the first REC formally established in Italy, launched in 2020 in the aftermath of the COVID-19 pandemic as a new business and financial model developed with the involvement of the Energy Center of Politecnico di Torino (Mutani et al., 2025).

One of the earliest detailed feasibility studies in this line of work examines a nascent REC in Villar Pellice, a small alpine municipality near Turin (Mutani et al., 2021). Working with hourly consumption and production data for a mix of municipal buildings, a residential user, public lighting, and a local company, seven progressively more ambitious intervention scenarios were tested, from individually metered users with no energy sharing through to a fully constituted REC combining storage, LED retrofits of public lighting, and an expanded membership base.

Even in the best-performing scenario, annual self-sufficiency did not exceed roughly 0.5, a ceiling attributed to the strong seasonal mismatch between winter heating demand and summer solar generation in an alpine climate, a mismatch that storage, sized only for short-term daily balancing, could not resolve (Mutani et al., 2021). A comparable design logic was applied to a very different climate and building type by Mutani and Usta (2022): a single eight-apartment condominium in Cagliari, Sardinia, evaluated both at the condominium scale and as part of a hypothetical REC formed with a neighbouring building. Using the new ENEA-developed simulation tool IES-iVN, combining building envelope retrofits with a 40 kWh battery raised the self-sufficiency index by between 26% and 36% depending on configuration, while reducing greenhouse gas emissions by 23% to 28%, though this improvement still fell well short of full energy independence for the community (Mutani & Usta, 2022).

Not every REC design study centers on photovoltaic generation and storage sizing alone. How far building form and district-scale aggregation, rather than technology choice, can push self-consumption and self-sufficiency outcomes is instead the focus of a comparison of two socioeconomically distinct residential districts of Turin, Crocetta and Arquata (Todeschi et al., 2021). Applying the Piedmont regulatory threshold of at least 70% self-consumption as a binding design constraint, and optimizing photovoltaic and battery sizing against it, moving from individual building-level analysis to district-level aggregation allowed self-sufficiency values of 53% to 67% to be reached with comparatively modest photovoltaic and battery capacity per household, a result that would not have been achievable at the single-building scale for either district (Todeschi et al., 2021). The range of technologies considered is extended still further in an examination of the underused potential of geothermal energy for Italian RECs (Chicco et al., 2024). Reviewing an existing simulation of a geothermal-based energy community in the Pisciarelli district of Pozzuoli, near Naples, self-consumption and self-sufficiency indices of 85% and 89% respectively are reported, alongside an 81.2% reduction in carbon dioxide emissions, figures substantially higher than those typically reported for solar-only REC configurations, though Italy's geothermal resources remain concentrated in a small number of regions and social acceptance of geothermal technology, largely due to limited public understanding of how it works, remains a meaningful barrier to wider adoption (Chicco et al., 2024).

The Termoli REC in Molise was created through a school-led "living lab" initiative involving about a hundred students and teachers working alongside ENEA and the municipal government, as opposed to a purely technical feasibility exercise. Tundo et al. (2024) present a REC feasibility case that differs from the others in framing rather than technology. The resulting community reached 74 committed members and a combined committed capacity of 276.6 kW, and preliminary modeling using ENEA's RECON tool indicated that the REC could achieve 70% to 80% self-consumption through virtual energy sharing even without battery storage, with a projected return-on-investment of 3.3 to 6.4 years depending on the financing structure adopted (Tundo et al., 2024). This case is framed explicitly within the UNI/TC058 technical standard on sustainable cities and communities, which calls for buildings to be evaluated not only on their own individual performance but on their "horizontal" connections to neighbouring buildings, energy communities, and the wider city, a holistic framing that

positions REC feasibility work as one component of a broader sustainable-urban-development agenda rather than a purely energy-engineering exercise. Beyond Termoli, a variety of other significant Italian REC configurations are included in this same institutional and pilot-project landscape, as reported by Mutani et al. (2025). These include territorial-scale RECs that span multiple municipalities, such as those in the Garda Bresciano and Biellese areas; Lignano Sabbiadoro, which stands out because of its mainly tourism-oriented consumer base; Anguillara Sabazia, which was developed primarily as a "solidarity REC" aimed at social inclusion; and a cluster of fifteen RECs with public-sector and school-based drivers.

Across these studies, spanning an alpine village, a Mediterranean condominium, two socioeconomically distinct urban districts, a geothermal case, a school-driven community project, and this wider set of pilot configurations, a consistent pattern holds: REC feasibility work combines local resource assessment, whether solar, geothermal, or building-form-driven, with the specific regulatory constraints described in Section 2.3.1, since a technically optimal configuration carries little practical weight if it falls outside what current Italian law permits for a single community.

2.3.3 Digital Tools and Platforms for RECs

As the number of REC feasibility studies has grown, so has interest in digital tools capable of supporting REC planning at scale, rather than requiring a fully bespoke technical study for every new community that forms. ENEA's Department of Energy Technologies and Renewable Sources has developed a suite of such tools, organized around what is termed a progression from RECs toward "smart energy communities," in which digital infrastructure and citizen engagement extend the basic concept of energy sharing into something closer to a broader participatory energy ecosystem (Meloni et al., 2025). A national geoportal and the Public Energy Living Lab (PELL) support territorial screening and data collection at municipal to national scale; RECON is a free web-based simulator for initial technical, economic, and financial feasibility assessment of a proposed REC configuration; and CruISE and SIMUL are tools for REC operators to monitor real-time performance and simulate a "digital twin" of community energy behavior (Meloni et al., 2025; Mutani et al., 2024). This institutional infrastructure has recently been formalized at the national standards level through UNI 11973:2025, which sets out a methodological model for the integration and interconnection of buildings, neighbourhoods, and energy communities within a smart and resilient city (Mutani et al., 2025).

Of these tools, the one most directly relevant to the interpretation of this thesis's own results is SIMUL-REC, an ENEA-developed simulation tool applied to an 88-member REC in Lignano Sabbiadoro, a coastal tourist town in northeastern Italy whose membership spans residential users, hotels, restaurants, beach resorts, and various commercial and service operators (Petrovich et al., 2025). Beyond the case study itself, the tool's principal contribution is a mathematical proof that a REC's total self-consumption and self-sufficiency rates depend, under reasonably general conditions, on the ratio of total production to total consumption alone, rather than on the absolute scale of either quantity, provided the underlying hourly production and consumption profile shapes remain broadly similar across communities being compared

(Petrovich et al., 2025). This result matters well beyond the specific case study it was derived from, because it means that self-sufficiency and self-consumption are not simply properties of how much capacity a community happens to have installed, but of the ratio between what it produces and what it consumes, and of how closely the shape of the production curve tracks the shape of the demand curve over time. Framed this way, the same underlying logic extends naturally from a single REC to a broader territorial unit such as a province: an SSI value calculated at province scale, at whatever annual or hourly resolution it is computed, reflects that same production-to-consumption relationship rather than an absolute measure of installed renewable capacity, which is directly relevant to how the annual and hourly self-sufficiency results for Abruzzo are interpreted in Chapter 4.

Read together, these tools point toward a workflow that is increasingly standard in REC-related digital infrastructure: broad, atlas-style platforms are used to screen and prioritize candidate areas at a coarse resolution, while detailed, parametrized simulation tools such as SIMUL-REC are reserved for refining the design of specific communities once a promising site has already been identified. This layered logic, screen broadly, then simulate precisely, closely parallels the intended relationship between the province-scale Urban Energy Atlas developed in this thesis and the more detailed hourly demand-supply matching analysis built on top of it, a relationship discussed further in Chapter 3.

2.4 Self-Sufficiency and Self-Consumption Indicators

2.4.1 Definitions and Indices

Measuring how well a Renewable Energy Community meets its own energy needs requires standardized metrics, and while the literature converges on a shared underlying logic, the exact notation and terminology used to express that logic varies meaningfully from one research group, and sometimes one paper, to the next.

The two foundational quantities are self-sufficiency and self-consumption, and one of the clearest formal definitions attributes the framework explicitly to Luthander, Widén, Nilsson, and Palm (2015) rather than presenting it as original (Mutani et al., 2021). The Self-Sufficiency Index (SSI) is defined as the share of a community's total consumption met by locally self-consumed energy, expressed as SSI = (SC + CSC) / TC, where SC is direct self-consumption, CSC is collective self-consumption shared among REC members, and TC is total consumption. The Self-Consumption Index (SCI), by contrast, is defined as the share of total local production that ends up self-consumed rather than exported to the grid, expressed as SCI = (SC + CSC) / TP, where TP is total production. The two indices capture different failure modes of a REC design: a low SSI means the community still depends heavily on grid imports regardless of how much it produces, while a low SCI means a large share of what is produced goes unused locally and is instead exported, typically at a lower economic return than direct consumption would provide. This identical SCI/SSI formulation, though defined directly in the methodology section rather than attributed to Luthander et al., is applied to a Cagliari condominium, confirming that the framework transfers without structural modification across two markedly different climates, from an alpine village to a Mediterranean coastal city (Mutani & Usta, 2022).

A separate notation for the same underlying concepts appears in a study of self-consumption and self-sufficiency in Turin, which describes its indicators as SC/P, for self-consumption, and SC/C, for self-sufficiency (Todeschi et al., 2021). Despite the different labels, the quantities measured are structurally equivalent to SCI and SSI: SC/P is production-relative and SC/C is consumption-relative. This paper adds a methodological refinement worth noting explicitly, since it clarifies why the two indices cannot both be maximized simultaneously without external constraints. Because SC/P rises as installed capacity falls relative to demand, while SC/C requires exactly the opposite, greater installed capacity relative to demand, Piedmont's regulatory 70% SC/P threshold is shown to function as a genuine design trade-off rather than a formality: once that self-consumption floor is imposed, the achievable self-sufficiency ceiling is determined by how much additional capacity, and consequently how much battery storage, can be added before self-consumption drops back below the regulatory minimum (Todeschi et al., 2021).

The most mathematically developed treatment of this relationship formalizes the SCI/SSI trade-off using the notation SCRtot (total self-consumption rate) and SSRtot (total self-sufficiency rate), while further decomposing self-consumption into two distinct physical components: direct self-consumption (SCdir), energy produced and consumed by the same member at the same location, and shared energy (SE), the virtual exchange occurring when one member exports to the grid at the same hour another member withdraws from it (Petrovich et al., 2025). This decomposition matters because SCdir and SE have different economic consequences in the Italian regulatory system: SCdir principally benefits the individual prosumer through reduced private energy bills, while SE generates the community-level incentive tariff that Italian law attaches specifically to shared, rather than directly self-consumed, energy. A more general mathematical result is additionally proven: provided a REC's hourly production and consumption profile shapes remain broadly stable and no battery storage is present, SCRtot and SSRtot depend only on the ratio of total annual production to total annual consumption (Ptot/Ctot), not on the absolute scale of either quantity (Petrovich et al., 2025). This allows the point where SCRtot equals SSRtot, termed the Net Zero Energy Point by direct analogy with the established concept of a Net Zero Energy Building, to be identified as occurring precisely where Ptot/Ctot = 1.

What unites all of these formulations, regardless of notation, is that they are fundamentally problems of temporal matching. Self-consumption and self-sufficiency can only be calculated meaningfully once a time resolution has been chosen, whether annual, monthly, or hourly, and that choice materially affects the resulting values, since production and demand that appear balanced when summed over a year can still be badly mismatched hour by hour or season by season. This temporal dimension, addressed directly in the case study applications discussed next, is also central to the hourly demand-supply matching analysis carried out later in this thesis.

2.4.2 Empirical Applications and Temporal Sensitivity

The case studies introduced in Section 2.3.2 are revisited here specifically to examine how the SSI and SCI values they report are shaped by the temporal resolution and spatial scale of analysis, aspects that were secondary to the design focus of the preceding section.

Applying these indices to real, or realistically modeled, communities makes clear how strongly the resulting values depend on climate, generation technology, storage availability, and above all the time resolution at which the balance is calculated.

In Villar Pellice, even the most favourable of seven tested scenarios, combining battery storage, LED retrofits of public lighting, and an expanded membership, kept annual SSI below roughly 0.5, a limitation traced directly to the alpine climate's strong seasonal mismatch between winter heating demand and summer solar production, a mismatch that daily-cycle battery storage, sized for short-term balancing rather than seasonal shifting, could not meaningfully close (Mutani et al., 2021). A comparatively more favourable outcome is reported for the Cagliari condominium case, where combining envelope retrofits with a 40 kWh battery raised SSI by 26% to 36% depending on configuration, reflecting the region's stronger and more evenly distributed solar resource, though even in the best-performing scenario the community remained some distance from full energy independence (Mutani & Usta, 2022).

The clearest illustration of how sensitive these indices are to spatial scale specifically, independent of climate or technology choice, comes from a comparison of individual-building analysis against district-level aggregation for the same two Turin neighbourhoods, Crocetta and Arquata (Todeschi et al., 2021). Self-sufficiency values reached 53% in Crocetta and 67% in Arquata once buildings were aggregated at the district scale and modeled as a shared REC, outcomes that individual building-level analysis alone could not approach given the same underlying photovoltaic and battery budget. Notably, the lower-income Arquata district achieved a higher self-sufficiency ceiling than the wealthier Crocetta, a result attributed to Arquata's lower per-household electricity consumption relative to its available roof area for photovoltaic installation, a reminder that self-sufficiency outcomes are driven as much by the demand side of the ratio as by the supply side (Todeschi et al., 2021).

A further layer of nuance is added by a study of roof-integrated photovoltaic technologies for Turin residential buildings, which examines how a single design choice, whether to use only south-facing roof surfaces or to also exploit north-facing ones, interacts with self-sufficiency outcomes (Mutani & Todeschi, 2021). Working with seven residential buildings of varying size and orientation, installing panels across two roof orientations rather than one raised SSI by an average of 8.5%, though the maximum achievable SSI still varied considerably by building scale: 41.8% for small condominiums, 41.5% for medium condominiums, and only 35.7% for large condominiums, since larger buildings concentrate more residents' demand onto a comparatively smaller available roof area per household, echoing the same demand-per-roof-area dynamic identified at the district scale by Todeschi et al. (2021).

The clearest empirical demonstration of the temporal-resolution problem described in Section 2.4.1 comes from the Lignano Sabbiadoro case (Petrovich et al., 2025). For this 88-member

REC, an overall annual SCRtot of 76.1% and SSRtot of 39.8% are reported, of which direct self-consumption accounts for 18.6% of total production and shared energy for a further 57.5%, making shared, rather than direct, self-consumption the dominant contributor to the community's overall performance. Critically, this annual figure is shown to conceal sharply different behaviour across seasons and even across the day: the daily self-consumption rate reaches close to 100% during summer months, when local demand and photovoltaic output are both high and closely aligned, but falls to around 50% during spring and autumn, when consumption drops while production remains comparatively stable, illustrating precisely the risk that an annual energy balance can overstate how well a community's generation and demand genuinely align in practice (Petrovich et al., 2025). At the national scale, a consistent version of this same finding is reported using the geoportal platform: a baseline scenario reflecting Italy's current renewable energy mix produces an SCI near 1 but an SSI of only about 0.09, since the very limited existing renewable capacity is almost entirely absorbed locally but covers only a small fraction of overall demand, while a solar-expansion scenario excluding historic centres raises SSI to roughly 50% but drops SCI to only 30% to 31%, and REC scenarios that add explicit energy sharing between different building sectors improve SCI to between 45% and 56% while holding SSI in a comparable 35% to 44% range (Mutani et al., 2024). This shows that, once a self-consumption floor is established, energy sharing is what significantly improves results across yet another scale and dataset.

When combined, these case studies provide a consistent lesson: self-sufficiency is a value that varies highly depending on the time resolution of study, the spatial scale at which sharing is allowed, and the presence or absence of storage. This is directly relevant to the self-sufficiency scenarios developed later in this thesis, which are calculated at both the annual and hourly level specifically to capture the kind of mismatch these case studies reveal, and are discussed further in Chapters 3 and 4.

2.5 Digital Surface Models: Geometry, Resolution, and Implications for Building Energy Modeling

Estimating rooftop solar potential or building height at scale both depend on the same underlying input: an accurate representation of the built surface. Digital Surface Models (DSMs), which capture the elevation of buildings and vegetation rather than bare ground alone, are the standard geometric input for this kind of analysis, and the accuracy of the underlying DSM propagates directly into the reliability of anything calculated from it. This dependency is traced through the full modeling chain in a state-of-the-art review of urban solar potential modeling: a coarse or outdated DSM can misrepresent building heights and shadow geometry badly enough to distort downstream calculations regardless of how sophisticated the modeling approach built on top of it is, and DSM sources themselves vary considerably in origin, from airborne LiDAR to photogrammetric reconstruction from stereo aerial imagery, each carrying its own trade-offs between spatial resolution, vertical accuracy, and how frequently the data is updated (Freitas et al., 2015). A direct illustration of how DSM resolution choices propagate into downstream results comes from a comparison of a coarse 5-metre DSM against a finer 0.5-metre DSM for the same block of Turin buildings, where the coarser dataset was found to

systematically underestimate values because its lower resolution blended rooftop pixels together with adjacent non-roof surfaces, while the finer DSM more accurately isolated genuine building geometry from the surrounding urban surface, directly affecting the self-sufficiency estimates ultimately derived from it (Mutani & Todeschi, 2021).

Atmospheric conditions add a further layer of uncertainty specific to solar applications: high-resolution DSM data combined with Earth-observation atmospheric datasets for two municipalities in Athens show that clouds, not building shadows, are the dominant source of rooftop irradiance attenuation across most of the year, with shadowing effects consistently suppressed once cloud or aerosol cover is already present (Hou et al., 2025).

The same dependency on accurate surface geometry that makes DSMs critical for solar potential modeling makes them equally important for building height estimation at scale, since both tasks ultimately rely on correctly distinguishing a building's true elevation from the surrounding terrain and adjacent structures. This is the more directly relevant application for the present thesis: while the Urban Energy Atlas project does not construct or apply DSM outputs for solar potential modeling within the scope of the analysis carried out here, the building height estimation hierarchy documented in Chapter 3 depends on exactly the kind of DSM-DTM elevation differencing described in this section, making DSM quality, resolution, and source heterogeneity a live methodological concern for this thesis even though solar potential itself is not.

2.6 Existing Urban Energy Atlases and Related Initiatives

2.6.1 Italian Case Studies

Italy has produced a substantial and closely interconnected body of work on urban and regional energy atlases, much of it emerging from the same research group whose broader UBEM and REC methodologies were discussed in Sections 2.1 through 2.4, which makes these atlases particularly direct precedents for the Urban Energy Atlas developed in this thesis.

The Turin Urban Energy Atlas, first described by Mutani and Todeschi (2019), is the most extensively documented and iteratively developed of these precedents. The atlas, which is based on a top-down engineering model that simulates space heating and domestic hot water consumption at a monthly time step for groups of buildings within a 1 km² mesh, includes two urban morphology variables not commonly found in single-building energy models: the canyon height-to-distance ratio (H/W), which characterizes how enclosed a street or block is by surrounding buildings, and the sky view factor, which captures the proportion of sky visible from a given point and thus how much thermal radiation is lost skyward. Validated against three consecutive heating seasons of measured district-heating consumption across roughly 40 km² and 500,000 inhabitants, the model's accuracy was found to decrease as the spatial scale of application increased, though this decline was partially offset in areas where a higher share of buildings were both residential and served by the district heating network, since the model's underlying assumptions hold most closely for that combination of conditions (Mutani & Todeschi, 2019). This same atlas was subsequently extended with a substantially expanded Energy Performance Certificate (EPC) database, reprocessing over 182,000 certificates issued

for Turin between 2009 and 2015 to replace literature-derived thermal transmittance and system efficiency values with real, measured values specific to the local stock, an extension that moved the atlas from a primarily descriptive tool toward one capable of testing and quantifying specific retrofit scenarios, ultimately estimating that combined envelope insulation and window replacement across the district-heating-served residential stock could yield annual energy savings of 79,064 MWh and a corresponding greenhouse gas reduction of 12,097 tonnes of CO2 equivalent (Mutani & Todeschi, 2021).

At the regional scale, the Clean Energy Atlas for the Piedmont Region expanded the geographic scope from a single city to an entire region and explicitly incorporated renewable energy production potential, drawn from solar, wind, hydroelectric, and biomass sources, alongside building energy demand (Mutani et al., 2020). Defining self-consumption simply as the ratio of local production to local consumption at the municipal level, the resulting atlas was used to identify which of Piedmont's 33 Areas of Territorial Integration could plausibly meet the region's 70% self-consumption threshold for REC formation, a direct precedent for using an atlas as a screening tool for REC feasibility across many municipalities simultaneously, rather than for a single city or district in isolation (Mutani et al., 2020). This same atlas-based logic is built on in subsequent work on geothermal energy for Italian RECs, using existing regional atlas infrastructure as the starting point from which to identify areas where geothermal resources could plausibly support a level of community self-sufficiency well beyond what solar-only configurations typically achieve (Chicco et al., 2024).

Atlas-based methodologies have also been adapted to more localized planning contexts that extend well beyond the atlas as a standalone technical deliverable. The account of the Termoli REC is situated within a wider suite of ENEA-developed digital tools, including RECON, DHOMUS, and CruISE, treating atlas-style building and energy data as one input among several feeding a broader, school-led sustainable-city initiative aligned with the UNI/TC058 technical standard, rather than as an end in itself (Tundo et al., 2024). Most recently, this same underlying atlas logic was scaled to the national level with a geoportal for RECs, a place-based platform allowing users to screen self-consumption and self-sufficiency potential for any location across the country, representing the broadest geographic extent among the Italian atlas initiatives discussed here and incorporating six distinct categories of territorial constraint, technical, environmental, landscape, hydrogeological, economic, and governance, into its screening logic (Mutani et al., 2024).

A related, though methodologically distinct, precedent comes from outside this particular research group. An energy assessment methodology developed for Milan functions in essentially the same way as an atlas, even though the term itself is not used: it links national ISTAT census cartography with a municipal buildings map to construct a georeferenced database of building-level energy performance, later validated against the independent regional SIRENA energy database with a discrepancy of only 4% (Caputo et al., 2013). The underlying structure, a georeferenced building-level energy database built by combining national statistical infrastructure with locally sourced geometric data and used to support city-scale policy scenarios, closely parallels the Turin and Piedmont atlases described above, and its independence from that research group reinforces that the broader atlas approach reflects a

genuine methodological convergence within Italian urban energy research, rather than one team's particular working style.

2.6.2 International Case Studies

Comparable atlas-style initiatives exist outside Italy as well, and comparing them to the Italian examples helps clarify which aspects of the approach are broadly transferable across data environments and which are shaped by locally specific infrastructure, such as ISTAT census records or Italy's electrical-proximity definition of REC membership.

The most directly comparable international example is the Kelowna case study, already discussed in Sections 2.1 and 2.2 for its GIS data harmonization workflow (HosseiniHaghighi et al., 2022). Although the term "atlas" is not used in the precise sense adopted by the Turin or Piedmont initiatives, it serves a functionally equivalent purpose: it generates a georeferenced, building-level digital twin of a city's housing stock in CityGML format, supporting both baseline energy demand estimation and, in the retrofit scenario later modeled, forward-looking planning for decarbonization by combined heat-pump and photovoltaic interventions. The comparison with the Italian atlases is instructive precisely because the underlying data infrastructure differs so substantially between the two national contexts. Where the Turin and Piedmont atlases draw heavily on centralized Italian statistical sources such as ISTAT census records and the national EPC database, the Kelowna study had to construct its harmonized dataset almost entirely from disparate municipal GIS layers, since no equivalent national building census existed to anchor the work (HosseiniHaghighi et al., 2022). That both approaches nonetheless converge on a broadly similar end product, a georeferenced, archetype-based building energy database capable of supporting scenario analysis, suggests that the general atlas methodology is transferable across quite different data environments, even where the specific data sources and harmonization steps required to reach that end product are not.

Taken as a whole, the Italian and international examples reviewed in this section show urban and regional energy atlases maturing from single-city descriptive tools into platforms capable of supporting REC feasibility screening, retrofit scenario testing, and systematic comparison of candidate sites across an entire country.

2.7 Research Positioning and Identified Gaps

The literature reviewed in this chapter shows that Urban Building Energy Modeling has matured considerably as a field, from early top-down statistical approaches toward increasingly detailed bottom-up, physics-based methods capable of representing individual buildings and their surrounding urban context (Sections 2.1 and 2.2). This maturation has been paralleled by the growth of Renewable Energy Communities as both a regulatory mechanism and an object of technical study (Section 2.3), and by the development of standardized self-sufficiency and self-consumption indicators that allow REC and territorial energy performance to be compared across studies (Section 2.4). At the applied, atlas scale, Italian and international initiatives alike have demonstrated that georeferenced, building-level energy databases can be built from heterogeneous administrative and statistical data sources, and that such atlases can support increasingly sophisticated applications, from retrofit scenario testing to REC feasibility

screening to, at the national geoportal scale, systematic candidate-site comparison (Section 2.6).

What remains unresolved, across the literature surveyed here, is the integration of hourly-resolution demand-supply matching into an atlas-style platform operating at provincial or regional scale. The self-sufficiency literature reviewed in Section 2.4 demonstrates convincingly, across REC case studies ranging from a single alpine village to an 88-member coastal tourist community, that annual self-sufficiency figures can conceal substantial hourly, daily, and seasonal mismatch between local production and local consumption. Yet this temporal sensitivity has, to date, been demonstrated almost exclusively at the scale of individual buildings, condominiums, or small RECs, rather than at the scale of a province or region, and the atlas initiatives reviewed in Section 2.6, including the Turin atlas, the Piedmont Clean Energy Atlas, and the national REC geoportal, operate predominantly at annual or, at most, monthly temporal resolution.

This thesis addresses that gap directly by extending the annual, province-level production-consumption balance already computed for the Abruzzo region within the wider Urban Energy Atlas project into an hourly resolution, applied specifically to the region's four provinces. In doing so, it applies the same underlying logic demonstrated at building and REC scale in Section 2.4, that self-sufficiency depends on the temporal alignment of production and demand and not merely on their annual totals, to a spatial and administrative scale, the province, that has not yet been examined at this resolution in the reviewed literature. The scenario-based self-sufficiency targets introduced in Chapter 3 and evaluated in Chapter 4 extend this contribution further, translating the hourly mismatch findings into a concrete assessment of the additional renewable generation capacity each Abruzzo province would require to close that gap under alternative policy benchmarks.

Chapter 3: Materials and Methodology

3.1 Data Sources and Pre-processing

3.1.1 Building Geometry and Classification Data

Any attempt to estimate energy consumption at the building level across an Italian region must begin with a choice that is more consequential than it might initially appear: which geometric dataset to use, and what to do when that dataset was produced for administrative rather than analytical purposes. For Abruzzo, the building geometry was obtained from the Geoportale Regionale Abruzzo, specifically the D.B.T.R. (Database Topografico Regionale) vector layer at 1:25,000 scale, edition 2007, available at opendata.regione.abruzzo.it. This dataset provided building footprint polygons with associated thematic attributes describing functional use within the regional classification system, and, critically for the height estimation procedure described in Section 3.1.2, a direct building height attribute column derived from the regional three-dimensional vector dataset. The availability of this height attribute for Abruzzo reduced the reliance on indirect estimation methods that proved necessary for regions lacking such information.

Building datasets for the other four regions processed within the broader Urban Energy Atlas project were obtained from comparable regional sources. Basilicata's building layer came from the CTR vettoriale per Comune distributed through the regional spatial data infrastructure at rsdi.regione.basilicata.it; Sardegna is from the DBGT at 1:10,000 scale via the Sardinian geoportal at sardegnageoportale.it; Trentino-Alto Adige from the Carta Tecnica Provinciale at 1:10,000, which is kept independently by the autonomous provinces of Trento and Bolzano; and Valle d'Aosta from a 2024 update of the "Edifici e Viabilità da Ortofoto 2018" layer on the regional geoportal at geoportale.regione.vda.it. There is no direct connection between these five datasets. They differ in how they define a building footprint, in the granularity of their use-category legends, and in whether they carry any height-related attributes. Resolving these differences, which had to be addressed before any energy calculation could begin, accounted for most of the pre-processing effort.

Three additional datasets were integrated at the pre-processing stage to support the consumption and production modeling pipelines. The first was the Sezioni di Censimento boundary shapefiles for Abruzzo (region code R13) for both the 2011 edition (R13_11) and the 2021 edition (R13_21), which were downloaded in EPSG:32632 from the ISTAT Basi Territoriali portal at istat.it. This dataset provided census-section boundaries and socioeconomic variables E8 through E20 describing the stock of residential buildings. The second was the 2011 ISTAT Industry and Services Census, which yielded information on non-residential economic activity at the census-section level. This information was imported into the PostGIS database and utilized to weight the spatial distribution of commercial and industrial energy demand throughout the study area. The third was the ENEA Rapporto Annuale sull'Efficienza Energetica 2025, Schede Regionali, specifically the regional energy balance tables known as the Bilancio Energetico Regionale di Sintesi for Abruzzo, available at

efficienzaenergetica.enea.it. These tables were structured in tabular format and imported into the spatial database as a top-down regional baseline for sector-level consumption calibration. Values in these tables were originally expressed in kilotonne of oil equivalent and were converted to gigawatt-hours using the standard conversion factor of 1 ktep equal to 11.63 GWh prior to import. The primary substation service area boundaries, represented by the Cabine Primarie layer primary_cabins2025, were also integrated as a GeoPackage, providing the grid-topology framework required for sub-provincial spatial disaggregation and relevant to the REC membership proximity rules established under Italian ARERA and GSE regulations.

Before starting any classification or height calculation, a consistent filtering choice was used in each of the five regions. Buildings with a footprint of less than fifty square meters were classified as "No Energy Use" and were not included in any further study. Polygons below this level almost always represent agricultural outbuildings, equipment shelters, or transformer cabins rather than residential buildings. This threshold is close to the minimum floor space required for a legally habitable residence under Italian building standards. The proportion of excluded buildings varies substantially across the five regions, reflecting the very different densities of small ancillary structures in each regional building stock.

Table 3.1: Data Sources Used in the Construction of the Building-Level Energy Database for Abruzzo and the Four Additional Study Regions

Typology	Input Data	Sub-category	Source	License
Building geometry and classification				
Built-up environment / Type of users / Building classification	D.B.T.R. Regione Abruzzo, edition 2007	Vector building footprint layer with height attribute and use classification	http://opendata.regione.abruzzo.it/content/dbtr-regione-abruzzo-scala-125000-edizione-2007	Open Data - Regione Abruzzo
	CTR vettoriale per Comune - Basilicata	Vector building footprint layer with use classification	https://rsdi.regione.basilicata.it/viewGis/?project=f8f85db9-54f9-4a61-90f3-49fcaf31a1b2	Open Data - Regione Basilicata
	DBGT 1:10,000 - Sardegna, edition 2022	Vector building footprint layer with use classification	https://www.sardegnageoportale.it/index.php?xsl=2420&s=40&v=9&c=95645&na=1&n=10&esp=1&tb=14401	Open Data - Regione Sardegna
	Edifici e Viabilità da Ortofoto 2018, update 2024 - Valle d'Aosta	Vector building footprint layer with use classification	https://geoportale.regione.vda.it/dati-nuovi/?id_categoria=0&testo_libero=Uso+del+suolo%3A+Fabbricati+2024&cerca=Cerca	Open Data - Regione Valle d'Aosta
	Carta Tecnica Provinciale 1:10,000 - Trentino-Alto Adige, edition 2020	Vector building footprint layer with use classification	https://www.provincia.tn.it/News/Approfondimenti/Carta-Tecnica-Provinciale-CTP	Open Data - Autonomous Provinces of Trento and Bolzano
Census and demographic data				
Census section boundaries	ISTAT - Sezioni di Censimento, SHP and XLS format (2011 and 2021)	Spatial boundaries of census sections for Abruzzo (R13_11 for 2011, R13_21 for 2021) in EPSG:32632; used as the spatial unit for all demographic and building-stock downscaling operations	https://www.istat.it/notizia/basi-territoriali-e-variabili-censuarie/	Open Data - ISTAT
Socioeconomic characteristics	ISTAT - Censimento della Popolazione e delle Abitazioni, XLS/CSV format (2011 and 2021)	Building stock variables E8–E20 describing construction period and floor count (2011) and variable A8 recording total dwellings per census section (2021)	https://www.istat.it/notizia/basi-territoriali-e-variabili-censuarie/	Open Data - ISTAT

Typology	Input Data	Sub-category	Source	License
Non-residential economic activity	ISTAT - Censimento dell'Industria e dei Servizi, TXT format (2011)	Number of employees by ATECO economic sector code at census section level; used to weight the spatial distribution of industrial, commercial, and agricultural energy demand	https://www.istat.it/notizia/basi-territoriali-e-variabili-censuarie/	Open Data - ISTAT
Digital terrain and surface models				
Digital Terrain Model	TINItaly DTM, 10 m resolution	National bare-ground elevation model derived from LIDAR; used as DTM baseline across all five regions	https://tinitaly.pi.ingv.it/Download_Area1_1.html	CC BY - INGV
Digital Surface Model	Regional DSMs - where available	Valle d'Aosta: 2 m; Trentino-Alto Adige: 0.5–3 m; Basilicata: 5 m; Sardegna: 1 m (partial); Abruzzo: not available at sufficient coverage	Regional geoportals (see Section 3.1.3)	Various - Open Data / CC-BY (Italian Regions)
Energy consumption data				
Residential electricity consumption	ARERA - Prelievo medio dei clienti domestici	Average annual electricity consumption per residential customer per province (yearly_kwh); reference year 2024; used to calculate building-level residential consumption	https://reporting.arera.it/SASVisualAnalytics/?reportUri=%2Freports%2Freports%2Fff58199d-f010-4cfd-a5d1-32c1d6359c05&sso_guest=true&reportViewOnly=true&reportContextBar=false&sas-welcome=false	Open Data - ARERA
Hourly electricity consumption profiles - all sectors	ARERA - Prelievo medio dei clienti domestici	Monthly average hourly withdrawal coefficients per province for residential, agricultural, industrial, and service sectors; separate profiles for working days (FR) and non-working days (FS); compiled into the provincial hourly profile lookup table	https://reporting.arera.it/SASVisualAnalytics/?reportUri=%2Freports%2Freports%2Fff58199d-f010-4cfd-a5d1-32c1d6359c05&sso_guest=true&reportViewOnly=true&reportContextBar=false&sas-welcome=false	Open Data - ARERA

Typology	Input Data	Sub-category	Source	License
Regional energy balance	ENEA - Rapporto Annuale sull'Efficienza Energetica 2025, Schede Regionali	Bilancio Energetico Regionale di Sintesi for Abruzzo: civil, industrial, and agriculture and fisheries sector electricity totals in ktep, converted to GWh at 1 ktep equal to 11.63 GWh	https://www.efficienzaenergetica.enea.it/vi-segnaliamo/rapporto-annuale-sull-efficienza-energetica-2025-schede-regionali.html	Open Data - ENEA
Administrative boundaries	ISTAT - Provincial boundaries (prov_2024)	Vector layer of Italian province boundaries used for spatial aggregation of consumption results	https://www.istat.it/notizia/basi-territoriali-e-variabili-censuarie/	Open Data - ISTAT
Infrastructure	National primary electrical cabin service areas (primary cabins_2025)	Polygon layer of primary substation service areas used for sub-provincial spatial disaggregation	Provided by project supervisor	Internal project dataset
Actual energy production by RES				
Registered renewable plants	GSE - Atlaimpianti portal	Point layer of registered renewable energy plants, reference date 18 October 2021; attributes include plant ID, municipality, energy source type (ai_fonte), and installed capacity in kW	https://www.gse.it/dati-e-scenari/atlaimpianti	Database pursuant to art. 1 L. 22/4/1941 n. 633
Utilization hours	Province-level utilization hours per RES type	Equivalent full-load hours per year by energy source and province	Internal project dataset	Internal project dataset

Sources: Regional building datasets from official regional geoportals (Regione Abruzzo, Regione Basilicata, Regione Sardegna, Regione Valle d'Aosta, Province Autonome di Trento e Bolzano). Census data from ISTAT Basi Territoriali e Variabili Censuarie (istat.it). Electricity consumption profiles and residential benchmarks from ARERA (reporting.arera.it). Regional energy balance from ENEA RAEE 2025 Schede Regionali (efficienzaenergetica.enea.it). Renewable plant registry from GSE Atlaimpianti (gse.it), processed and provided by the project PhD supervisor. Utilization hours compiled from GSE statistical reports by the project PhD supervisor. National DTM from TINItaly, INGV (tinitaly.pi.ingv.it). Primary substation boundaries provided by the project supervisor. Table structure adapted from Mutani et al. (2023).

3.1.2 Height Estimation Sources and Hierarchy

Building height is indispensable to the volumetric consumption estimation described in Section 3.3.1, and its availability across Italian regional building datasets ranges from directly measured to absent. A hierarchical strategy is therefore the only defensible approach, proceeding through four levels applied in sequence until a usable value is established for each building.

The first and most reliable level is the regional dataset itself. Where the building layer includes a measured height attribute, as is the case for Abruzzo where the D.B.T.R. vector dataset carries a direct height column, this value is used following a quality check. Any height value below 2.7 metres is flagged as implausible. This threshold corresponds to the minimum floor-to-ceiling height required under Italian building regulations for a habitable room, and a record below it almost certainly reflects a digitization artifact or an attribute mismatch rather than a real inhabited structure. Buildings failing this check proceed to the second level.

The second level draws on the ISTAT building-stock indicator variables E17 through E20 from the census dataset described in Section 3.1.1. These variables record, at the census-section level, the distribution of buildings by number of floors: E17 for single-storey buildings, E18 for two storeys, E19 for three storeys, and E20 for four or more storeys. The modal floor count for the census section containing each building is identified as the category with the highest recorded frequency, and height is then estimated as:

$$H_ISTAT = N_floors \times h_floor$$

where N_floors is the modal floor count for the census section, and h_floor is an inter-floor height of 3.3 metres for buildings predominantly constructed before 1970, reflecting the higher ceiling standards typical of older Italian construction, and 3.0 metres for buildings predominantly constructed after 1970, with the predominant construction period determined from indicators E8 through E16. This approach assigns the same floor count to all buildings within a census section, which is a known simplification, but it is grounded in official statistical data and is preferred over the DSM-based approach at the third level precisely because it is more interpretable and less susceptible to the geometric artifacts that affect remote-sensing-derived height estimates in topographically complex areas.

The distinction between a digital surface model and a digital terrain model is used at the third level. Building height is approximated as follows when the regional dataset yields no useable height, and ISTAT floor-count data is either unavailable or implausible:

$$H_DSM = \text{mean}(DSM) - \text{mean}(DTM)$$

where each building footprint's matching raster pixel is used to derive both values. For the same reasons as at the previous level, values less than 2.7 meters from this computation are regarded as improbable. An important disadvantage is that pixels that cross footprint boundaries might sample surrounding surfaces (like highways, vegetation, or open spaces) instead of the building roof. In rural and peri-urban areas, this might lead to underestimates, especially for small or isolated structures. The DSM-based estimation was only used for a small subset of buildings

in Abruzzo, where the regional building layer carried a direct height attribute, whose regional height values failed the 2.7-meter quality check and for which ISTAT floor-count data was either implausible or unavailable.

Buildings classified as "No Energy Use" and omitted from energy modeling on the grounds that there is insufficient evidence to treat them as occupied structures are placed in the fourth category when all three of the sources produce implausible or null data.

The Global Human Settlement Layer building height product, GHS-OBAT R2024A, is one source that was specifically assessed and left out of this hierarchy. From 54% in Trentino-Alto Adige to 75% in Puglia, a consistently high percentage of GHS-derived height readings fell below 2.7 meters in each of the five regions evaluated for this project. The GHS raster's coarse spatial resolution in relation to Italian building footprint geometry is reflected in this consistent underestimation, especially in old urban centers and scattered rural settlements where building footprints are small and irregularly shaped.

The decision to exclude it was taken early in the project, and it plays no role in any of the estimates presented in this thesis.

3.1.3 Digital Surface and Terrain Models

Two raster products support the third level of the height hierarchy: a Digital Terrain Model for bare-ground elevation and a Digital Surface Model for the elevation of the highest surface feature at each raster cell, including buildings, vegetation, and infrastructure. These are sourced separately because no single provider supplies both at consistent resolution across the full extent of the five study regions.

The DTM baseline for the entire project is TINItaly. It is a continuous terrain model at 10-meter resolution. It is made by the Istituto Nazionale di Geofisica e Vulcanologia using LIDAR data and is freely available at tinitaly.pi.ingv.it. This source was selected for its consistent national coverage and its derivation from sufficiently recent data collection to be representative of current terrain conditions across the entire topographic range of the study regions, from the flat Adriatic coastal plain of Pescara and Chieti to the high Apennine plateaus of L'Aquila. In regions like Valle d'Aosta where a regional authority provides a higher-resolution local DTM at two meters, the regional product replaces TINItaly.

The five regions have different DSM situations. Depending on the provincial collection effort, Trentino-Alto Adige offers DSM ranging from 0.5 to 3 meters. Valle d'Aosta offers a 2-meter DSM at its regional geoportal, and Basilicata offers a 5-meter DSM with its INSPIRE-compliant geoportal. Abruzzo, by contrast, does not provide an official regional DSM of sufficient coverage, meaning that the DSM-minus-DTM height estimation at level three of the hierarchy could not be systematically applied for this region. Buildings in Abruzzo that required height estimation beyond the regional attribute and ISTAT fallback were therefore assigned to the fourth level and labeled accordingly. This is one reason why Abruzzo shows a slightly higher proportion of buildings without a usable height value than regions with complete DSM coverage, though the availability of the direct regional height attribute substantially

limited the number of records reaching this stage of the hierarchy. All DSM and DTM sources, their resolutions, acquisition years, and download links are consolidated in Table 3.1.

3.1.4 Spatial Database and Processing Infrastructure

All geometry, thematic, and statistical data sources described in the preceding sections were integrated into a single PostgreSQL relational database extended with the PostGIS spatial extension, queried and managed through the DBeaver client interface. This infrastructure choice was driven by the scale of the datasets involved. Abruzzo's building layer consists of over 617,000 polygon records. Sardegna approaches 500,000, and Puglia exceeds 1.3 million. Spatial join operations between building footprints and census-section boundaries or plant-location points and province and primary-cabin polygons would be almost complex in a GIS environment but efficient in a properly indexed PostGIS database. The GiST spatial index structure applied to all geometry columns is what makes the repeated proximity queries involved in household allocation and plant mapping feasible at run times compatible with an iterative development workflow.

QGIS served two distinct purposes alongside the database. The first was visual inspection and quality control of intermediate outputs, since a map of spatially implausible results is generally faster to interpret than a table of numerical anomalies. The second was the production of the cartographic outputs presented in Chapter 4, including the building land-use map, the renewable energy plant distribution map, and the provincial self-sufficiency and scenario maps. GRASS GIS modules were used for raster operations, specifically for the DSM-minus-DTM differencing described in Section 3.1.2. A consistent coordinate reference system was maintained throughout: EPSG:32632 for all five study regions.

3.2 Building Stock Harmonization and Characterization

3.2.1 Unified Classification System

The five regional building datasets described in Section 3.1.1 arrive with their own local classification legends, each reflecting the administrative and cartographic conventions of the region that produced it. A building labeled "edificio civile" in the Abruzzo dataset, "residenziale" in the Basilicata dataset, and "Civile" or "Civile1" in the Trentino dataset all refer to the same functional category, yet appear under entirely different labels. On the other hand, some regional datasets combine entire sectors into a single label, while others identify dozens of subcategories. Without first resolving this heterogeneity into a common system, direct cross-regional comparison is not feasible.

To address this, the classification system created for the Urban Energy Atlas simultaneously arranges buildings along two dimensions: an energy consumption typology that divides categories whose daily and seasonal demand profiles differ significantly even when they belong to the same administrative sector, and the traditional Italian sectoral grouping that distinguishes Residential (R), Primary (P), Secondary (S), and Tertiary (T) uses. Although both a church and a hospital are classified as tertiary-sector buildings in Italy, their energy consumption patterns are nearly opposed: the church has low and sporadic consumption concentrated on particular days and hours, while the hospital operates continually at high

intensity. No methodological rigor elsewhere in the pipeline could repair the error that would be introduced into any downstream consumption estimate if both were collapsed into a single tertiary category.

The resulting system assigns each building one of ten codes, each encoding both sector membership and energy demand typology. Table 3.2 presents the full classification with examples and a brief characterization of the energy behavior associated with each category.

Table 3.2: Unified Building Use Classification System developed for the Urban Energy Atlas of Italy

New Code	Sector (R/P/S/T)	Energy Consumption Type	Examples	Energy Characteristics
RL (Residential - Low Demand)	R (Residential)	Only residential	Apartments, houses, dormitories	Pure residential: morning and evening peaks, low daytime demand
RM (residential mixed)	R (Residential)	Mixed-use residential	Student dorms, residential buildings with ground-floor commercial units, mixed-use residential with offices, shops on lower floors	High demand. Like RL, but with higher daytime consumption due to mixed residential and commercial use. HVAC
PA (Primary - Agriculture & Extraction)	P (Primary)	Agriculture, Mining, Fishing	Farms, greenhouses, fisheries, mines	Seasonal peaks, heating, irrigation, refrigeration
SP (Secondary -Production & Industry)	S (Secondary)	Manufacturing & Heavy Industry	Factories, refineries, warehouses	Heavy machinery, continuous or shift-based operation
TC (Tertiary - Commercial & Public Services)	T (Tertiary)	Shops, offices, government, museums, places of culture, military, hotel, religious, medical outpatient	Shops, banks, offices, administrative buildings, supermarkets, gyms, cinemas, church, military, police station, prison, dental clinic, family practice	Daytime peak (offices, shops). High HVAC and lighting demand; stable operation of IT and service systems. Some facilities (e.g., churches, police stations) operate also during weekends.
TT (Tertiary - Transport)	T (Tertiary)	Transport hubs	Train stations, airports	Large transport hubs operate daily or 24/7. Main energy uses: lighting, HVAC. The load pattern follows passenger traffic.
TI (Tertiary – Intermittent Use)	T (Tertiary)	Entertainment, stadium	Theatres, auditoriums, stadiums, sports fields, tennis court	Very high peak loads during events, but low or near-zero Otherwise, usage concentrated on specific hours/days (e.g., concerts, sports).

New Code	Sector (R/P/S/T)	Energy Consumption Type	Examples	Energy Characteristics
TS (Tertiary - School)	T (Tertiary)	Schools	Primary and secondary schools, universities, training centers	Daytime use, HVAC, lighting, no weekend use, seasonal
TH (Tertiary - Healthcare)	T (Tertiary)	Hospitals	General hospital, specialized hospital, children's hospital	Continuous 24/7 use. High demand from lighting, air conditioning, medical devices, and support systems, high hot water demand
Others	-	Infrastructure or undefined features (non-building)	Telecom towers, open equipment areas, and track platforms, technical shafts, or elements with NULL attributes	There is no use of energy, or it isn't a building

Source: Developed by the Urban Energy Atlas project group, Politecnico di Torino, in collaboration with ENEA (2025).

The classification was applied to each regional dataset by constructing a keyword dictionary mapping every unique original label in the regional legend to the corresponding unified code. This method covered every label in each dataset and needed careful study of regional metadata documentation where a label's textual meaning was unclear. The resulting dictionaries are recorded in the project tracking spreadsheet and serve as the definitive reference for the reclassification step applied to each region. For Abruzzo specifically, the regional legend is relatively compact: seven distinct use labels are present in the D.B.T.R. dataset, each mapping unambiguously to one of the ten unified codes. The full classification mapping applied to the Abruzzo building stock is reported in Section 4.2 alongside the spatial distribution of building categories across the four provinces.

One classification decision warrants explicit justification. Mixed-use residential buildings, assigned to the code RM, are treated differently from purely residential buildings (RL) in the volumetric allocation step described in Section 3.2.2. In mixed-use buildings with residential and commercial or office uses, the lower floors are presumed to be non-residential. Then it is removed from residential volume calculations. The number of floors dedicated for non-residential use follows a model drawn from Italian urban building practice: two to four storeys, one floor; four or more floors, two floors. This heuristic is a simplification, since actual mixed-use configurations vary considerably even within a single urban block, but it is applied consistently across all buildings in the RM category and its effect on total provincial consumption estimates is small given that RM buildings represent a modest share of the overall stock.

The complete classification dictionaries mapping original regional labels to unified codes for all five study regions are provided in Appendix A.

3.2.2 Height Assignment and Volume Calculation

Once each building has been assigned a classification code, the next step is to establish its volume, which serves as the primary geometric variable for distributing household counts and employee counts across the building stock within each census section. Volume is calculated as the product of footprint area and building height, and the height assignment follows the four-level hierarchy described in Section 3.1.2.

For Abruzzo, the majority of buildings received their height value directly from the regional D.B.T.R. attribute column, subject to the 2.7-metre plausibility check described in Section 3.1.2. Buildings whose regional height value failed this check, and buildings for which the attribute was null, proceeded to the ISTAT floor-count estimation at the second level of the hierarchy. The floor count assigned at this level is the modal value among indicators E17 through E20 for the census section containing the building, where E17 records single-storey buildings, E18 records two-storey buildings, E19 records three-storey buildings, and E20 records buildings of four or more storeys. The inter-floor height applied to convert floor count to estimated building height depends on the predominant construction period of the census section, determined from indicators E8 through E16: 3.3 metres is used for sections where the modal construction period falls before 1970, and 3.0 metres for sections where it falls after 1970. These values reflect the historically higher ceiling standards of pre-war and early post-war Italian construction relative to the more standardized heights introduced in later decades (Caputo et al., 2013).

Once a height has been established through whichever level of the hierarchy applied, building volume is calculated as:

$$V = A \times H$$

where A is the footprint area in square meters and H is the assigned building height in meters. For mixed-use residential buildings in the RM category, the total volume is partitioned into a residential component and a non-residential component before the household allocation step, using the floor-ratio logic described in Section 3.2.1:

$$V_{res} = A \times H \times (N_{res} / N_{total})$$

$$V_{non\text{-}res} = A \times H \times (N_{non\text{-}res} / N_{total})$$

The total floor count is N_total, whereas N_res and N_non-res are the residential and non-residential floors. Total volume V equals V_res for residential buildings (RL). All volume of non-residential buildings in categories PA, SP, TC, TT, TI, TS, and TH is assigned to the applicable sector.

Based on the building's categorization code, non-residential volume is divided into three sectors. PA buildings contribute their full non-residential volume to agricultural volume, SP buildings to industrial volume, and TC, TH, TI, TS, or TT to service volume. Mixed-use buildings with a non-residential use attribute have their non-residential volume assigned directly to the sector. Where the non-residential function is unspecified, the non-residential

volume defaults to the service sector, consistent with the predominance of commercial and public-service ground-floor uses in Italian urban mixed-use buildings.

These sectoral volumes then serve as the denominators in the spatial downscaling procedure described in Section 3.3.1, where both household counts and employee counts are distributed across individual buildings in proportion to each building's share of the total sectoral volume within its census section. The logic is clear: based on its sector-relevant volume, a larger structure is assumed to house a proportionately larger fraction of the workers or population recorded for that census part. This proportionality assumption is the most reasonable allocation rule given the data constraints of the project. It provides statistical consistency across spatial scales by ensuring that the total of all building-level estimates within each census section exactly matches the census-section total published by ISTAT. However, it simplifies actual occupancy patterns because floor area per household and per employee varies in practice.

3.3 Electricity Consumption and Actual Renewable Production Estimation

3.3.1 Building-Level Electricity Consumption Estimation

Estimating electricity consumption at the building level requires connecting three categories of information that are held in entirely separate datasets: the physical and functional characteristics of buildings, established through the classification and volumetric procedures described in Section 3.2; the demographic and economic composition of the population occupying those buildings, drawn from ISTAT census sources; and the temporal distribution of electricity demand, derived from ARERA provincial withdrawal data. The methodology connects these three through a sequence of spatial downscaling steps, each of which distributes a census-section-level aggregate down to the individual building using the sectoral volumes calculated in Section 3.2.2 as allocation weights. The full pipeline was implemented as a series of SQL queries executed within the PostgreSQL/PostGIS environment described in Section 3.1.4.

Residential sector

The residential consumption calculation proceeds in two stages. In the first, the number of dwellings recorded for each census section is divided among the residential buildings in that section. Variable A8 of the 2021 ISTAT Population Census, which counts the number of homes per section regardless of occupancy status, is used to determine the total number of residences for each census section. A rate from the 2011 census is used to modify this total for vacancy, and it is computed as follows:

$$\mathbf{r_empty = A6 / (A2 + A3)}$$

where A2 is the number of occupied dwellings, A3 is the number of secondary or unoccupied dwellings, and A6 is the number of vacant dwellings listed in the 2011 census section. Then, each building's number of occupied residences is:

$$\mathbf{DW_active = (V_res_building / V_res_section) \times A8_section \times (1 - r_empty)}$$

where A8_section is the total number of dwellings for that section, V_res_building is the residential volume of each individual building, and V_res_section is the total residential volume of all energy-relevant buildings within the same 2021 census section. In order to maintain statistical consistency with the ISTAT source data, this proportionate allocation makes sure that the overall number of active homes across all buildings within a census section precisely equals the census-section total adjusted for vacancy.

The following formula is used to determine the annual residential electricity usage per building:

$$\mathbf{C_res = DW_active \times kWh_province}$$

where kWh_province is derived from the ARERA prelievo medio dei clienti domestici dataset for the reference year 2024 and represents the average yearly electricity consumption per residential customer for the province that contains the building. The actual variations in home consumption patterns among the four Abruzzo provinces, which are influenced by household size, appliance ownership, and climate, are reflected in this value, which differs per province.

Service sector

The residual approach, which divides the amount of regional civil-sector power not accounted for by residential consumption among service-sector buildings according to their estimated employee counts, is used to estimate the consumption of the service sector. Start with the ENEA RAEE 2025 regional energy balance's total civil-sector power for Abruzzo in GWh and converted to kWh. After removing residential building consumption, civic energy used for non-residential service activities is the remaining. The per-employee consumption factor is then calculated:

$$\mathbf{k_ser = (C_civil_total - C_res_total) / W_ser_total}$$

where C_civil_total is the total civil-sector electricity in kWh from ENEA, C_res_total is the sum of all residential building consumption assigned in the preceding step, and W_ser_total is the total number of service-sector employees across all energy-relevant buildings in the region. Annual service consumption per building is then:

$$\mathbf{C_ser = W_ser_building \times k_ser}$$

where W_ser_building is the number of service-sector employees assigned to the building through the ATECO-based downscaling procedure described below.

Industrial and agricultural sectors

Industrial and agricultural consumption are estimated through direct proportional downscaling of the regional sectoral totals reported in the ENEA RAEE 2025 energy balance. The regional total for each sector is distributed across energy-relevant buildings in proportion to each building's share of the regional sectoral workforce:

$$\mathbf{C_ind = (W_ind_building / W_ind_total) \times C_ind_total}$$

$$\mathbf{C_agr = (W_agr_building / W_agr_total) \times C_agr_total}$$

where C_ind_total and C_agr_total are the regional industrial and agricultural electricity totals from ENEA converted to kWh, W_ind_total and W_agr_total are the sums of industrial and agricultural employees across all energy-relevant buildings in the region, and W_ind_building and W_agr_building are the employees assigned to each individual building.

Employee downscaling from census sections to buildings

The employee counts used in the service, industrial, and agricultural consumption formulas are derived from the ISTAT Industry and Services Census 2011 through a two-step procedure. In the first step, the raw employee records are classified into three macro-sectors using ATECO economic activity codes: agriculture corresponds to ATECO divisions 1 through 3; industry corresponds to divisions 5 through 43; and services correspond to divisions 45 through 99. In the second step, the macro-sector employee totals aggregated at census-section level are distributed across individual buildings within each section in proportion to each building's share of the corresponding sectoral volume:

$$W_{sector,building} = (V_{sector,building} / V_{sector,section}) \times W_{sector,section}$$

where V_sector_building is the sectoral volume of the individual building, V_sector_section is the total sectoral volume across all energy-relevant buildings in the census section, and W_sector_section is the total employees in that sector recorded for the section. As with the residential downscaling, this proportional allocation ensures that the sum of employees across all buildings within a section exactly reproduces the census-section total, maintaining consistency with the ISTAT source data at every spatial scale.

3.3.2 Actual Renewable Electricity Production Estimation

The actual production component of the energy model estimates the current annual electricity output of all registered renewable energy plants within the five study regions, at the individual plant level, disaggregated by energy source type, province, and primary substation service area. Five source types are modeled: solar photovoltaic, wind, hydroelectricity, biomass, which encompasses biogas, liquid biomass, solid biomass, and waste-to-energy plants, and geothermal. The calculation pipeline was implemented in PostgreSQL/PostGIS following a structure parallel to the consumption workflow described in Section 3.3.1.

Spatial assignment

Each plant in the GSE registry is first assigned to its containing province and primary substation service area through a spatial join between the plant point geometry and the province and primary cabin polygon layers. Where a plant falls outside all polygon boundaries due to minor geometric inconsistencies at administrative boundary edges, a nearest-neighbour assignment is applied as a fallback, ensuring that every plant receives a valid province code and cabin code before the production calculation proceeds.

Annual production

Annual electricity production for each plant is calculated as:

$$E_{annual} = P_{installed} \times U_h$$

where P_installed is the installed capacity in kilowatts taken from the potenza attribute of the GSE plant registry, and U_h is the province-specific equivalent full-load hours per year for the corresponding source type, taken from the abruzzo_actual_plants_utilization_hour lookup table compiled from GSE statistical reports. The source type label recorded in the GSE registry field ai_fonte uses Italian terminology and is normalized to a standard English label at this stage: SOLARE becomes solar, EOLICA becomes wind, IDRAULICA becomes hydroelectricity, BIOGAS, BIOMASSE LIQUIDE, BIOMASSE SOLIDE, and RIFIUTI all become biomass, and GEOTERMICA becomes geothermal. Table 3.3 reports the province-specific utilization hours applied for each source type in Abruzzo.

Table 3.3: Province-Specific Equivalent Full-Load Utilization Hours for Renewable Energy Sources

Region	Province	Solar (h/yr)	Wind (h/yr)	Biomass (h/yr)	Hydroelectricity (h/yr)	Geothermal (h/yr)
Abruzzo	Chieti	1138	1799.851	3729.642	1554.839	0
	L'Aquila	1229	1799.851	3729.642	1554.839	0
	Pescara	1159	1799.851	3729.642	1554.839	0
	Teramo	1142	1799.851	3729.642	1554.839	0
Basilicata	Matera	1261	1857	3089.6	2842	0
	Potenza	1209	1857	3089.6	2842	0
Sardegna	Cagliari	1188	1609.526	4992	982.2041	0
	Nuoro	1199	1609.526	4992	982.2041	0
	Oristano	1217	1609.526	4992	982.2041	0
	Sassari	1155	1609.526	4992	982.2041	0
	Sud Sardegna	1154	1609.526	4992	982.2041	0
Trentino-Alto Adige	Bolzano	951	0	3695.698	5720.223	0
	Trento	894	0	3695.698	5720.223	0
Valle d'Aosta	Aosta	983	1615.4	3419.4	2832	0

Source: Compiled from GSE statistical reports by the project supervisor.

The utilization hours show the real differences in resource availability among the four provinces. Solar hours are highest in L'Aquila at 1,229 hours per year and lowest in Chieti at 1,138 hours per year since the inland mountain regions receive more sunlight than the coastal plain. Wind, biomass, and hydroelectricity use uniform regional benchmark values throughout all four provinces because the reference statistics did not provide province-level distinction for these sources.

3.3.3 Hourly Demand-Supply Disaggregation

The annual consumption and production totals calculated in Sections 3.3.1 and 3.3.2 are disaggregated into hourly profiles to support the temporal analysis reported in Chapter 4. The disaggregation uses pre-computed lookup tables of normalized hourly distribution coefficients, one for consumption and one for production, both organized by province, month, hour of day, and day type.

Day type classification

Each calendar day is classified as either a working day, abbreviated FR from the Italian feriale, or a non-working day, abbreviated FS from the Italian festivo, encompassing weekends and Italian national public holidays. This classification is directly reflected in both lookup tables and is according to the official Italian public holiday calendar for the reference year.

Consumption disaggregation

For every combination of province, month, hour, and day type, the sector-specific hourly coefficient is multiplied by the yearly building-level consumption to calculate the hourly consumption for each sector:

$$C_sector[h, m, d] = C_sector_annual \times coeff_cons[h, m, d, sector, province]$$

where h is the hour from 1 to 24, m is the month from 1 to 12, d is FR or FS, and coeff_cons is the normalized coefficient from the ARERA provincial withdrawal data-derived abruzzo_consumption_hourly_profile_lookup database. Individual coefficient profiles describe the daily demand pattern of the residential, agricultural, industrial, and service sectors. The hourly disaggregation matches the annual total since the sum of all coefficients for a sector and province across all hours and months equals unity.

The results at building level are stored as 24-element arrays of hourly consumption values for each month and day type combination. For the provincial-scale analysis presented in Chapter 4, building-level arrays are aggregated to province level by summing across all buildings within each province.

Production disaggregation

Hourly production for each plant is calculated in an analogous manner:

$$E_plant[h, m, d] = E_annual \times coeff_prod[h, m, d, type_res, province]$$

where coeff_prod is the normalized coefficient from the abruzzo_actual_production_hourly_profile_lookup table, indexed by source type rather than sector. Each renewable source's known temporal patterns are reflected in the production coefficients: solar coefficients are concentrated during the day and vary significantly by month, wind coefficients are more evenly spread throughout the day with only slight seasonal variation, and biomass and hydroelectricity coefficients are comparatively flat throughout the day, indicating the more continuous and dispatchable nature of these sources. Since there is no recorded geothermal capacity in the region, all Abruzzo provinces have zero geothermal utilization hours.

Monthly self-sufficiency disaggregation

In addition to the hourly disaggregation, a monthly self-sufficiency profile is computed for each province to support the analysis reported in Section 4.3. Monthly consumption for each province is estimated by summing the hourly coefficients within each month separately for each sector and multiplying by the corresponding annual total:

$$C_cons_m = \Sigma_buildings\ [\ C_res \times f_res_m + C_agr \times f_agr_m + C_ind \times f_ind_m + C_ser \times f_ser_m\ ]$$

where f_sector_m is the sum of all working-day hourly coefficients for that sector and month, representing the fraction of annual consumption falling in month m for each sector. Monthly production is calculated analogously using the production lookup coefficients summed within each month. The monthly self-sufficiency index is then:

$$SSI_m = \min(E_prod_m, E_cons_m) / E_cons_m \times 100$$

The hourly distribution coefficients used for monthly disaggregation are derived from the ARERA provincial dataset. Province-specific monthly variation is fully captured for the residential sector, whose coefficients reflect real seasonal differences in household electricity withdrawal across the twelve months of the year. For the industrial, service, and agricultural sectors, the ARERA dataset does not provide the same level of province-specific monthly differentiation, and the resulting coefficients show limited variation across months. This means that seasonal variation in the monthly consumption profiles presented in Section 4.3 is driven primarily by the residential sector, while the non-residential sectors contribute a relatively uniform monthly distribution. A more accurate representation would require sector-specific monthly distribution factors derived from national sources such as Terna monthly electricity statistics, which document distinct seasonal patterns for each sector including the August industrial consumption dip associated with factory closures and the winter heating-related increase in service sector demand. This refinement is identified as a direction for future work in Section 5.4.

3.4 Self-Sufficiency Scenario Framework

3.4.1 Indicator Definitions and Threshold Justification

The analytical comparison between electricity consumption and renewable production at provincial scale is structured around two complementary performance indicators introduced in the literature on Renewable Energy Communities and place-based energy modeling: the Self-Sufficiency Index (SSI) and the Self-Consumption Index (SCI). Both are defined and applied in this thesis following the formulations established by Mutani et al. (2021) in their feasibility study of the Villar Pellice energy community, and subsequently adopted across a wider set of Italian REC case studies reviewed in Section 2.4.

The Self-Sufficiency Index measures the share of local electricity demand that is covered by local renewable production. At the provincial scale, it is calculated as:

$$SSI = \min(E_production, E_consumption) / E_consumption \times 100$$

where E_production is the total annual renewable electricity produced within the province by all registered plants, and E_consumption is the total annual electricity consumed within the province across all sectors. The numerator takes the minimum of the two quantities because only production that does not exceed consumption can substitute for grid withdrawal. Overproduction is fed back into the national grid rather than locally self-consumed.

Self-Consumption Index evaluates the complementary dimension: the share of local renewable generation absorbed by local demand rather than exported to the grid. The calculation is:

$$\mathbf{SCI = min(E_production, E_consumption) / E_production \times 100}$$

where the numerator is again the lowest of production and consumption, but as a fraction of total production. An SSI of 100% with a low SCI indicates a territory that produces more than it consumes but exports a large share of that production, while an SSI below 100% with a 100% SCI indicates an energy deficit where every kilowatt-hour produced is locally absorbed and none is wasted.

The two metrics together better describe a territory's energy balance. A province with high SSI and SCI meets most local demand and consumes most of its output for power. As seen in Chapter 4, all four Abruzzo provinces have low SSI and high SCI, resulting in a structural deficit: local supply is entirely absorbed but only partially meets demand, with the rest coming from the national grid.

For the scenario analysis described in Section 3.4.2, three SSI threshold values are used to define planning targets. The first is 40%, which corresponds approximately to the current best-performing province in Abruzzo and represents the minimum threshold above which a territory can be considered to have achieved a meaningful degree of electrical self-reliance. The second is 75%, which falls within the High sufficiency class and is broadly consistent with the scale of renewable capacity expansion implied by Italy's National Integrated Energy and Climate Plan (PNIEC) targets for 2030, which project a roughly doubling of total installed renewable capacity relative to the 2023 baseline (Ministero dell'Ambiente e della Sicurezza Energetica, 2023). The third is 100% electrical self-sufficiency, where local renewable generation meets annual provincial electricity demand. These three criteria give a structured basis for comparing investment effort throughout the four provinces, from a near-term feasible improvement to a medium-term policy-aligned aim to a long-term aspirational benchmark.

3.4.2 Target Self-Sufficiency Scenarios

Three scenarios are defined, each corresponding to one of the SSI threshold values established in Section 3.4.1. For each scenario and each province, the additional renewable generation capacity required to reach the target SSI is calculated as the difference between the production level that would achieve the target and the current actual production:

$$\mathbf{E_additional = (SSI_target \times E_consumption) - E_production_current}$$

where SSI_target is the target expressed as a decimal (0.40, 0.75, or 1.00), E_consumption is the current annual provincial electricity consumption, and E_production_current is the current annual renewable production. Where E_additional is negative or zero, the province already meets the target and no additional capacity is required.

The additional production required under each scenario is distributed across renewable source types in proportion to the existing installed mix of each province, following what is termed here a proportional expansion assumption. This implies that each province's renewable energy mix is maintained while its overall output is increased. For example, a province that currently

produces 46.6% of its energy from solar and 44.1% from wind, like L'Aquila, would add new solar and wind capacity in those same proportions to meet its goal. There are two reasons why the proportionate expansion assumption is used. First, it considers the infrastructure orientation and resource endowment that have already been developed in each province, viewing current capacity as proof of the best conditions for each technology. This analysis does not make assumptions about future technology costs, land availability, or regulatory constraints because a full optimization of the future renewable mix would require site-specific data and engineering assessments that the provincial-scale database developed here cannot support.

The incremental production for each source type under each scenario is computed as:

$$E_{additional_source} = E_{additional} \times (E_{source_current} / E_{production_current})$$

where E_source_current is the current annual production from that source type and E_production_current is the current total production. The resulting source-type breakdown allows the scenario results to be interpreted not only in terms of total additional capacity needed but also in terms of which technologies would need to expand most in each province, a distinction that is analytically meaningful given the very different renewable mixes across the four Abruzzo provinces documented in Chapter 4.

Keep in mind what these scenarios are not. They do not include investment costs, economic optimization, physical constraints on renewable installation like rooftop area, suitable land, grid capacity limits, or regulatory exclusion zones, or engineering feasibility studies. They are analytical targets intended to quantify the production gap that would need to be closed to reach each self-sufficiency level, providing a structured basis for comparing the relative effort required across provinces and discussing the implications for territorial energy planning. A full scenario optimization incorporating constraints and costs would require the spatial constraint mapping and future production modeling components of the broader Urban Energy Atlas project, which lie outside the scope of this thesis as noted in Section 1.3.

The scenario results are reported and discussed in Section 4.5, where the additional capacity requirements are compared across the four provinces and interpreted in relation to each province's current renewable energy mix, territorial characteristics, and the temporal demand-supply mismatch patterns identified in Section 4.4.

3.5 Limitations and Sources of Uncertainty

Every modeling exercise of the kind described in this chapter operates under constraints imposed by the data available, the assumptions required to fill gaps in that data, and the spatial and temporal scale at which the analysis is conducted. This section documents the principal limitations of the methodology honestly, distinguishing between limitations that are inherent to the approach and those that reflect specific data gaps in the Italian context, and discusses their likely direction and magnitude of effect on the results presented in Chapter 4.

Scope: electricity only

The most significant boundary condition of the entire analysis is that it addresses electricity consumption and production exclusively. Space heating and cooling supplied through natural

gas, district heating, liquid petroleum gas, or solid biomass combustion falls entirely outside the scope of the model. In Italy, and particularly in the colder provinces of the study regions, thermal energy for space heating represents a substantial share of total building energy demand, often exceeding electricity consumption in absolute terms. For a mountain province such as L'Aquila, where heating degree-days are among the highest in central Italy, the exclusion of thermal energy means that the self-sufficiency indicators reported in Chapter 4 substantially overestimate the true degree of energy independence of that province relative to its total energy needs. This limitation is not a methodological weakness that could have been avoided with different choices, but a consequence of the data infrastructure available: the ARERA consumption profiles cover electricity withdrawal only, and the GSE plant registry covers electricity-generating plants only. Extended analysis to thermal energy would require a different data architecture using gas distribution records, heating plant registries, and thermal consumption surveys that are not available at the spatial resolution needed for building-level modeling across multiple Italian regions.

Annual consumption anchoring and sectoral calibration

The residential consumption estimations are based on the ARERA province averages, which are reliable at the provincial aggregate level because they reflect actual electrical billing data. However, the volumetric proportionality assumption, which assumes that buildings are proportional to their residential volume and ignores variation in dwelling size, occupancy rate, or per-capita consumption within a census section, adds uncertainty to the allocation process at the building level. This assumption is standard in bottom-up modeling at regional scale and is well documented in the literature reviewed in Section 2.2, but it means that individual building estimates carry a level of uncertainty that provincial aggregates do not.

Because the service sector estimations come from a residual method rather than a direct measurement, they are more unpredictable. Any inaccuracy in the residential total immediately affects the service estimate. The residual is the difference between the ENEA regional civil-sector total and the entire amount of residential consumption that has already been assigned. The ISTAT 2011 employee counts, which are over ten years old and may not accurately reflect the current distribution of economic activity across census sections, especially in provinces that have seen substantial industrial restructuring or demographic change since 2011, are the basis for the industrial and agricultural estimates.

Building height estimation

In buildings where the ISTAT floor-count estimate was used, and the regional height attribute was either unavailable or implausible, the assigned height represents the modal floor count for the whole census sector rather than the actual floor count of the specific building. This creates a smoothing mistake that overestimates low buildings and underestimates tall ones in census regions with significant internal variation in building height. At the census-section level, the effect on volumetric allocation is somewhat self-correcting because underestimates for some buildings balance out overestimates for others, but at the individual building size, it still causes real uncertainty. Compared to areas without a direct height attribute, Abruzzo, where the

regional height attribute was available for most buildings, is less exposed to this source of uncertainty.

Renewable production estimation

The production estimates depend on province-level utilization hours compiled from GSE statistical reports by the project supervisor. These equivalent full-load hours represent averages derived from historical generation data and may not accurately reflect the production of individual plants, which varies with local wind resource, shading conditions, plant age, and maintenance status. The uniform application of regional benchmark values for wind, biomass, and hydroelectricity across all four Abruzzo provinces, as noted in Section 3.3.2, introduces a further simplification: In fact, wind resources differ significantly between the milder terrain of the coastal provinces and the high Apennine ridges of L'Aquila. Another restriction is the July 2021 plant registry reference date, which means that plants erected or decommissioned after that date are not included in the production projections. As a result, the registered capacity as of late 2021 rather than the current operational fleet is represented.

Temporal disaggregation

Production and consumption are broken down hourly using lookup table coefficients derived from province averages. These coefficients capture the typical daily and seasonal patterns of electricity supply and demand, but they do not take into consideration year-to-year weather variability, which can drastically change both production (due to variations in irradiance and wind speed) and consumption (due to temperature-driven heating and cooling demand). Therefore, rather than being forecasts for any particular year, the monthly self-sufficiency profiles presented in Section 4.3 are better understood as descriptions of typical seasonal activity. A further limitation of the monthly disaggregation concerns the non-residential sectors. The ARERA provincial dataset provides robust monthly variation only for residential electricity withdrawal. For the industrial, service, and agricultural sectors, the monthly distribution coefficients available in the dataset show limited seasonal differentiation, which results in a flatter seasonal consumption profile than would be expected from real measured sector-level data. This limitation affects the monthly consumption profiles in Section 4.3 and the seasonal hourly profiles in Section 4.4, where the contrast between winter and summer consumption is somewhat understated relative to what sector-specific monthly data would produce. The annual totals, self-sufficiency indicators, and scenario analysis results are not affected by this limitation as they are anchored directly to ARERA and ENEA annual statistics.

Scenario analysis

The three self-sufficiency scenarios defined in Section 3.4 are subject to all the uncertainties of the baseline consumption and production estimates on which they are built. Additionally, the proportional expansion assumption treats the current renewable mix as a fixed constraint on future capacity additions, which is a simplification: in practice, future investment decisions will respond to technology cost trends, regulatory incentives, land availability, and grid needs in ways that may shift the mix substantially relative to the current baseline. The scenario results are therefore most appropriately interpreted as indicative of the order of magnitude of

additional capacity required under a given self-sufficiency target, rather than as precise investment plans. For Teramo in particular, where the proportional expansion assumption implies adding very large amounts of solar capacity to reach higher SSI targets, the qualitative argument for diversification toward wind is strong and is discussed in Section 4.5.

Chapter 4: Results and Case Study Analysis

4.1 Introduction to the Results

The results of the energy balance analysis described in Chapter 3 are presented in this chapter for the five Italian regions for which building databases, consumption models, and real data on renewable energy production were processed as part of this project. There are two separate but related layers to the analysis.

See Section 4.2 for the first layer's wide view. It covers all five regions and their provinces, comparing power consumption across industries, renewable generation by source type, and annual energy balances. This comparative overview places the Abruzzo case study in a larger Italian context and shows the striking diversity of energy conditions across territories with a national regulatory framework but vastly different climate, building stock, and renewable resource endowment.

The second layer focuses solely on Abruzzo and spans Sections 4.3 through 4.5. The hourly temporal analysis, the spatial mapping of building stock and renewable infrastructure, and the self-sufficiency scenario framework were all created especially for the four Abruzzo provinces, and it is at this scale that the work's original analytical contribution is most fully realized. This decision reflects the structure of the thesis itself. Section 4.3 looks at how each province's self-sufficiency percentage changes over the course of the year, exposing seasonal characteristics that yearly averages invariably hide. The primary territorial and temporal analysis is presented in Section 4.4, which includes the spatial distribution of buildings and renewable plants as well as the hourly correlation between local renewable supply and energy consumption across the four seasons. These results are then translated into a forward-looking scenario framework in Section 4.5, which quantifies the extra capacity for renewable production that each province would require to meet three more challenging self-sufficiency goals. Throughout the chapter, all energy quantities are expressed in gigawatt-hours unless otherwise noted, and all results pertain exclusively to electricity. The exclusion of thermal energy from the scope of this analysis, and its implications for interpreting the self-sufficiency indicators reported here, were discussed in Section 3.5 and should be kept in mind when reading the provincial results that follow.

4.2 Overview of the Study Regions

4.2.1 Building Stock Characterization across Study Regions

The five study regions collectively encompass a building stock of considerable scale and heterogeneity. Across Abruzzo, Basilicata, Valle d'Aosta, Trentino-Alto Adige, and Sardegna, the total number of building records processed exceed 1.6 million, spanning a geographic range from the high Alpine valleys of the northwest to the Mediterranean coastlines of the south and the islands. Before any energy calculation could be performed, each regional dataset was harmonized into the unified classification system described in Section 3.2.1, resolving the

terminological differences between regional legends into a consistent set of ten functional categories.

As would be expected given that apartments and homes make up most of the Italian building fabric rather than commercial or industrial structures, residential buildings in the RL category numerically dominate the stock throughout all five regions. However, there are significant regional variations in the relative weight of non-residential categories, which reflects true territorial character distinctions. Given the region's substantial agro-forestry and alpine farming traditions, Trentino-Alto Adige has a proportionally larger representation of agricultural structures compared to the overall number of buildings. Basilicata has a large agricultural building share due to its rural and low-density interior. In contrast, Sardegna's urbanized coastal areas, especially Cagliari, feature more service-sector buildings. Abruzzo is midway. The hilly heart of L'Aquila's building stock is mostly residential and agricultural, but around the Adriatic coast of Pescara, Teramo, and Chieti, it's more mixed with residential, commercial, and industrial uses.

The spatial distribution of building use categories across Abruzzo is shown in Figure 4.7 in Section 4.4.2, where the territorial gradient from mountain to coast is discussed in greater detail. For the purposes of the regional overview presented in this section, the relevant observation is that non-residential building volume, aggregated across the SP, TC, TH, TI, TS, TT, and PA categories, constitutes a disproportionately large share of total built volume relative to building count in all five regions. Industrial, commercial, and agricultural structures are typically larger in footprint and taller than residential ones. This has a direct consequence for the consumption estimates: despite being numerically fewer, non-residential buildings contribute substantially to total provincial electricity demand, as the sectoral breakdown in Section 4.2.2 confirms.

4.2.2 Annual Electricity Consumption by Sector

The sectoral composition of electricity demand varies considerably across the fourteen provinces of the five study regions, reflecting differences in economic structure, settlement density, and land use that are as much a product of geography and history as of energy policy. Figure 4.1 presents this breakdown for each province, disaggregated into residential, agricultural, industrial, and service consumption.

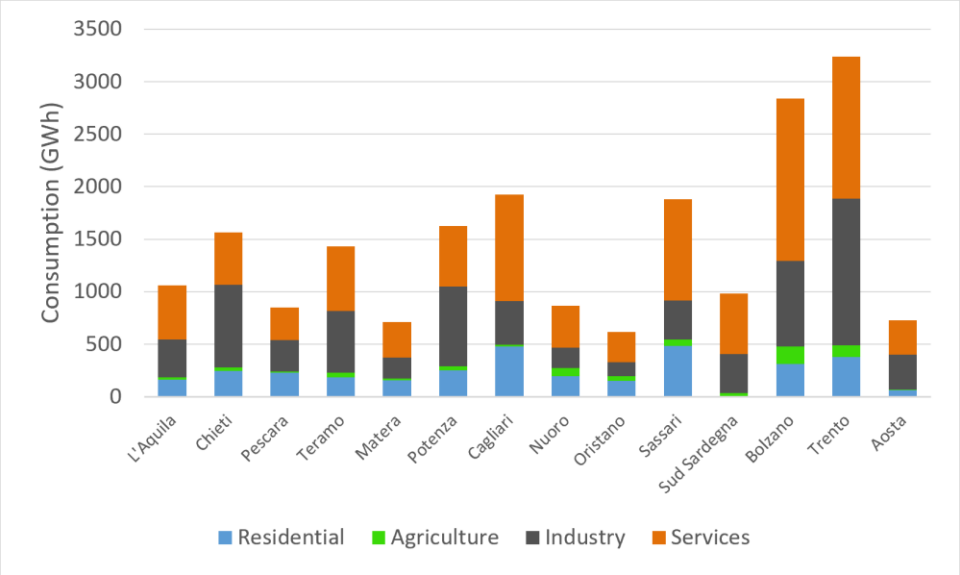


Figure 4.1: Annual Electricity Consumption Breakdown by Sector across Study Provinces (GWh)

The industrial and service sectors together account for most of the electricity demand across virtually every province in the dataset, regardless of region. This is most pronounced in the alpine provinces of Bolzano and Trento, where combined industrial and service consumption reaches 2,362 GWh and 2,747 GWh respectively. These figures represent South Tyrol and Trentino's energy-intensive industry base and extensive tourism and hospitality infrastructure. Cagliari, the metropolitan capital of the island, has the highest service-sector consumption in the dataset at 1,013.51 GWh, reflecting its unique concentration of financial, administrative, and commercial activities.

One Table 4.1 data point needs clarification. Sud Sardegna's domestic consumption is a dash. The province of Sud Sardegna was created through the 2016 administrative reorganization of Sardegna, but building records within its current boundaries remain classified under the historical Cagliari province code in the ISTAT census database used for household allocation. As a result, residential consumption for Sud Sardegna cannot be independently disaggregated from the Cagliari figure. The remaining sectoral consumption values for Sud Sardegna, covering agriculture, industry, and services, are correctly assigned, and the total consumption and production figures for the province are not affected by this limitation.

Within Abruzzo, the industrial sector is particularly dominant in Chieti and Teramo, at 785.87 GWh and 586.42 GWh respectively, consistent with the concentration of manufacturing activity in the Val di Sangro and Val Pescara industrial corridors. In Pescara and L'Aquila, where the service economy and public administration provide a different mix of demand than in the more industrialized coastal provinces in the north and south, residential consumption is proportionately more substantial. All four of the Abruzzo provinces have moderate agricultural consumption, never rising above 46.05 GWh. This is due to the region's small number of energy-intensive agricultural enterprises as well as the very small proportion of irrigated and greenhouse farming compared to dryland cultivation.

Compared to the other research locations, Basilicata offers an intriguing contrast. Potenza province exhibits a significant industrial consumption of 759.50 GWh despite being one of the least populated regions. This is because the Val d'Agri basin, one of the biggest onshore hydrocarbon production regions in Western Europe, has infrastructure for oil extraction, and its energy needs fit within the model's industrial sector classification.

4.2.3 Actual Renewable Energy Production by Source

The source composition of renewable electricity production differs even more sharply across the study regions than the consumption structure, driven primarily by natural resource endowment rather than by policy choice or investment intensity alone. Figure 4.2 shows the annual production of each province broken down by source type: solar photovoltaic, wind, hydroelectricity, and biomass.

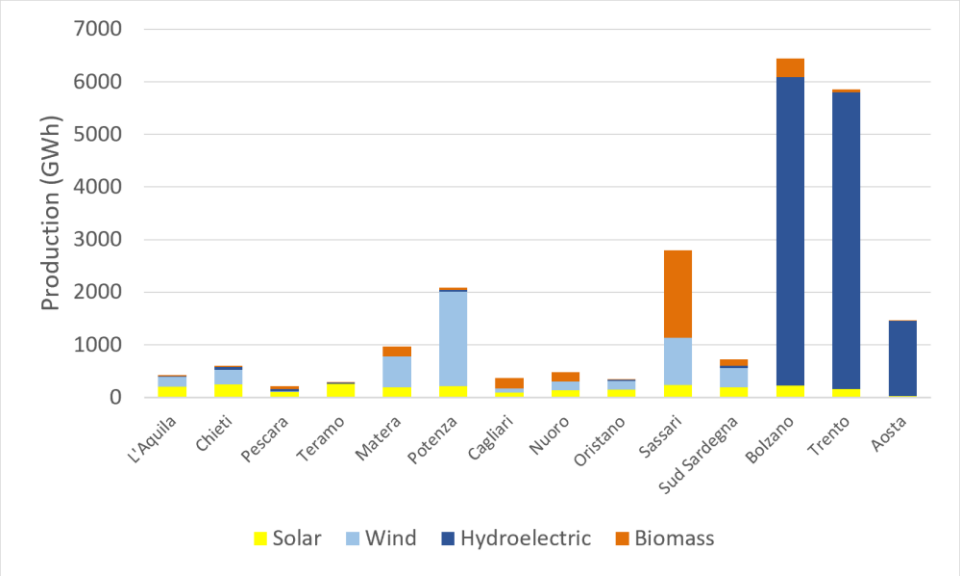


Figure 4.2: Annual Renewable Electricity Production Breakdown by Source across Study Provinces (GWh)

The most striking feature of Figure 4.2 is the complete dominance of hydroelectricity in the alpine regions. Trento generates 5,640.72 GWh, Bolzano 5,863.32, and Valle d'Aosta 1,426.06 GWh from hydroelectric sources. These numbers surpass every other province in the dataset and represent the Alpine watersheds' high concentration of run-of-river and reservoir hydropower infrastructure. Solar and wind contribute 3% to 7% of productivity in each alpine province.

Basilicata represents the opposite extreme of the renewable energy spectrum. Both Potenza and Matera are wind-heavy. Matera generates 578.06 GWh from wind, while Potenza generates 1,799.71 GWh, roughly three times its solar production. Over the past two decades, Basilicata has developed large-scale wind farms on the Apennine ridgelines and plateaus due to excellent

wind resources and regional policy incentives, making it one of the most wind-dense regions per unit area in the Italian south.

With a remarkably high biomass output of 1,670.10 GWh, Sassari stands out among the provinces of Sardinia. As mentioned in Section 3.5, this number should be interpreted cautiously. It may not correctly reflect real generation because it is based on registered plant capacity and consistent regional utilization hours. In keeping with the island's Mediterranean irradiance and its exposed coastline and plateau terrain, the other regions of Sardinia exhibit more balanced solar and wind profiles.

The production mix of Abruzzo demonstrates distinct geographic heterogeneity. With 262.17 GWh out of a total production of 296.39 GWh, or 88.4% of the provincial total, Teramo is nearly totally dependent on solar photovoltaic. Given the province's mixed coastal and Apennine topography, Teramo's nearly total lack of wind generation is noteworthy. This could be due to either actual local wind resource limitations at the locations where installations would otherwise be feasible or landscape protection restrictions that prevent wind installations in the province's picturesque areas. Similar solar dominance is seen at Pescara, with a more varied secondary contribution from biomass and hydroelectricity on the Pescara River. In contrast, the solar-wind profiles of L'Aquila and Chieti are truly balanced. The excellent wind resources of the Apennine ridges and the broad valley floors that enable big photovoltaic installations are reflected in Chieti's 41.3% solar and 45.0% wind production, compared to L'Aquila's 46.6% solar and 44.1% wind.

4.2.4 Annual Energy Balance and Self-Sufficiency Indicators

Placing consumption and production side by side reveals the degree to which each province is able to meet its electricity needs from local renewable sources. Figure 4.3 presents this comparison for all fourteen provinces, showing the relationship between total annual consumption and total annual renewable production at a glance.

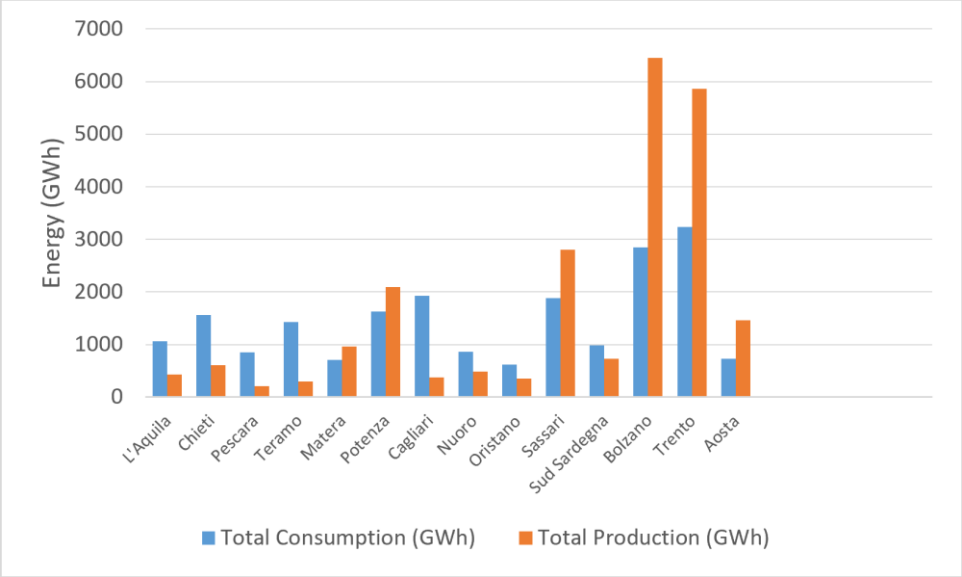


Figure 4.3: Comparison of Annual Total Electricity Consumption and Renewable Energy Production by Province (GWh)

The numerical detail underlying Figure 4.3 is presented in Table 4.1, which provides the complete provincial breakdown including sectoral consumption, source-type production, the resulting surplus or deficit in GWh, and the Self-Sufficiency Index and Self-Consumption Index for each province calculated following the methodology of Section 3.4.1.

Table 4.1: Annual Electrical Energy Balance and Self-Sufficiency Indicators across the Five Study Regions

Region	Province	Total Consumption (GWh)	Residential (GWh)	Agriculture (GWh)	Industry (GWh)	Services (GWh)	Total Production (GWh)	Solar (GWh)	Wind (GWh)	Hydroelectric (GWh)	Biomass (GWh)	Surplus / Deficit (GWh)	SSI (%)	SCI (%)
Abruzzo	L'Aquila	1062.50	162.62	24.40	359.25	516.23	429.03	199.93	189.00	15.18	24.92	-633.48	40.40	100.00
	Chieti	1562.70	245.27	32.00	785.87	499.57	605.00	250.12	272.33	57.52	25.03	-957.70	38.70	100.00
	Pescara	850.67	230.99	11.58	296.74	311.36	210.98	103.78	7.89	49.89	49.41	-639.70	24.80	100.00
	Teramo	1428.93	182.12	46.05	586.42	614.35	296.39	262.17	0.05	13.32	20.85	-1132.54	20.70	100.00
Basilicata	Matera	709.10	157.35	16.03	202.30	333.41	966.42	197.56	578.06	4.18	186.62	257.32	100.00	73.40
	Potenza	1626.20	250.78	38.63	759.50	577.30	2090.05	213.82	1799.71	24.12	52.40	463.85	100.00	77.80
Sardegna	Cagliari	1923.78	477.21	19.30	413.75	1013.51	370.65	96.90	74.72	3.04	195.99	-1553.13	19.30	100.00
	Nuoro	864.03	196.50	74.73	195.45	397.35	485.37	134.92	162.76	4.23	183.46	-378.66	56.20	100.00
	Oristano	618.64	151.04	43.71	134.46	289.43	351.77	148.90	163.61	28.80	10.47	-266.87	56.90	100.00
	Sassari	1883.12	484.80	59.98	369.88	968.47	2799.03	232.77	896.15	0.00	1670.10	915.91	100.00	67.30
	Sud Sardegna	981.34	-	34.88	371.61	574.84	727.96	194.74	357.90	47.42	127.89	-253.38	74.20	100.00
Trentino-Alto Adige	Bolzano	2841.40	314.76	162.76	816.78	1547.09	6447.29	222.08	0.00	5863.32	361.89	3605.89	100.00	44.10
	Trento	3236.42	379.41	110.54	1395.24	1351.24	5858.16	162.52	0.00	5640.72	54.92	2621.75	100.00	55.20
Valle d'Aosta	Aosta	729.42	63.73	3.57	330.90	331.22	1465.23	23.35	4.17	1426.06	11.65	735.81	100.00	49.80

Note: Negative Surplus/Deficit values indicate energy deficit (consumption exceeds production); positive values indicate energy surplus (production exceeds consumption). Residential consumption for Sud Sardegna is shown as a dash; see Section 4.2.2 for explanation. SSI = Self-Sufficiency Index; SCI = Self-Consumption Index, calculated following Mutani et al. (2021).

Source: Author's own elaboration

The findings show that the research regions are clearly divided structurally. With significant absolute surpluses of 735.81 GWh for Aosta, 3,605.89 GWh for Bolzano, and 2,621.75 GWh for Trento, Valle d'Aosta and both provinces of Trentino-Alto Adige attain SSI values of 100%. Hydroelectric output, which vastly outpaces local electricity demand, is the primary source of these surpluses. Their SCI values, however, are relatively modest at 49.8%, 44.1%, and 55.2%, respectively, indicating that roughly half of the electricity these territories produce is fed into the national grid rather than consumed locally. This low SCI is structurally inevitable given the nature of large hydroelectric production, which operates on seasonal water flow cycles largely independent of local demand patterns and generates substantial over-production relative to what any local community could absorb without grid exchange.

Basilicata similarly achieves SSI of 100% in both provinces, with Potenza generating a surplus of 463.85 GWh and Matera 257.32 GWh. Their SCI values are higher than the alpine regions at 77.8% and 73.4% respectively, suggesting that wind energy, despite being intermittent, aligns somewhat better with local demand patterns than hydroelectric baseload production does. The temporal basis for this observation is explored further in the analysis of Section 4.4.

Among the Sardinian provinces, the results are the most heterogeneous of all five regions. Sassari achieves SSI of 100% with a surplus of 915.91 GWh driven by its large biomass and wind production, while Cagliari records the lowest SSI in the entire dataset at 19.3%. This low figure reflects the very great service-sector demand of the metropolitan province and its relatively limited installed renewable capacity. Nuoro and Oristano occupy intermediate positions at 56.2% and 56.9% SSI, respectively, and Sud Sardegna reaches 74.2%, approaching the High sufficiency class threshold defined in Section 3.4.1.

All four Abruzzo provinces are in annual energy deficit, with SSI values ranging from 20.7% in Teramo to 40.4% in L'Aquila. Every province shows SCI of 100%, confirming that all locally produced renewable electricity is absorbed by local demand with no over-production at the annual scale. This combination of low SSI and maximum SCI is the characteristic signature of an energy-deficit territory: local production is fully and efficiently utilized, but it covers only a fraction of what the territory consumes. The amount of electricity that each province must currently import from the national grid is represented by the difference between current output and consumption, which ranges from 633.48 GWh in L'Aquila to 1,132.54 GWh in Teramo. The scenario analysis in Section 4.5 aims to measure and close this exact gap.

The stark discrepancy between Abruzzo and nearby Basilicata shows how geography and the history of renewable investment may result in drastically different energy outcomes at similar latitudes and within the same regulatory framework. Although both Basilicata and Abruzzo share Apennine topography with abundant wind and solar resources, Basilicata exports power while Abruzzo imports it. The size and timing of wind energy investments are the main areas of variance. While Abruzzo's more moderate renewable deployment has left its provinces still severely dependent on grid supplies, Basilicata's extensive wind growth over the past 20 years has produced a production base that now significantly exceeds regional demand. This regional contrast, grounded in the annual data of Table 4.1, provides the essential backdrop against

which the detailed temporal and spatial analysis of Abruzzo presented in Sections 4.3 and 4.4 can be most meaningfully interpreted.

4.3 Monthly Self-Sufficiency Variation across Abruzzo Provinces

The annual SSI values reported in Table 4.1 provide a useful summary of each province's overall energy balance, but they inevitably conceal the temporal dynamics that determine when and how severely a province depends on grid imports. A province with an annual SSI of 40% is not uniformly 40% self-sufficient throughout the year: it may approach or exceed self-sufficiency in some months while falling well below that level in others, depending on how seasonal renewable production patterns interact with seasonal demand variation. Resolving this temporal structure is the first step toward understanding whether the deficit is a chronic year-round condition or a seasonal phenomenon concentrated in specific periods.

Figure 4.4 presents the monthly energy balance for each of the four Abruzzo provinces across the twelve months of the year, showing average daily electricity consumption and production as paired bars alongside the monthly Self-Sufficiency Index as a line on the secondary axis. All values are computed from working-day profiles, consistent with the approach applied throughout the hourly analysis of Section 4.4.

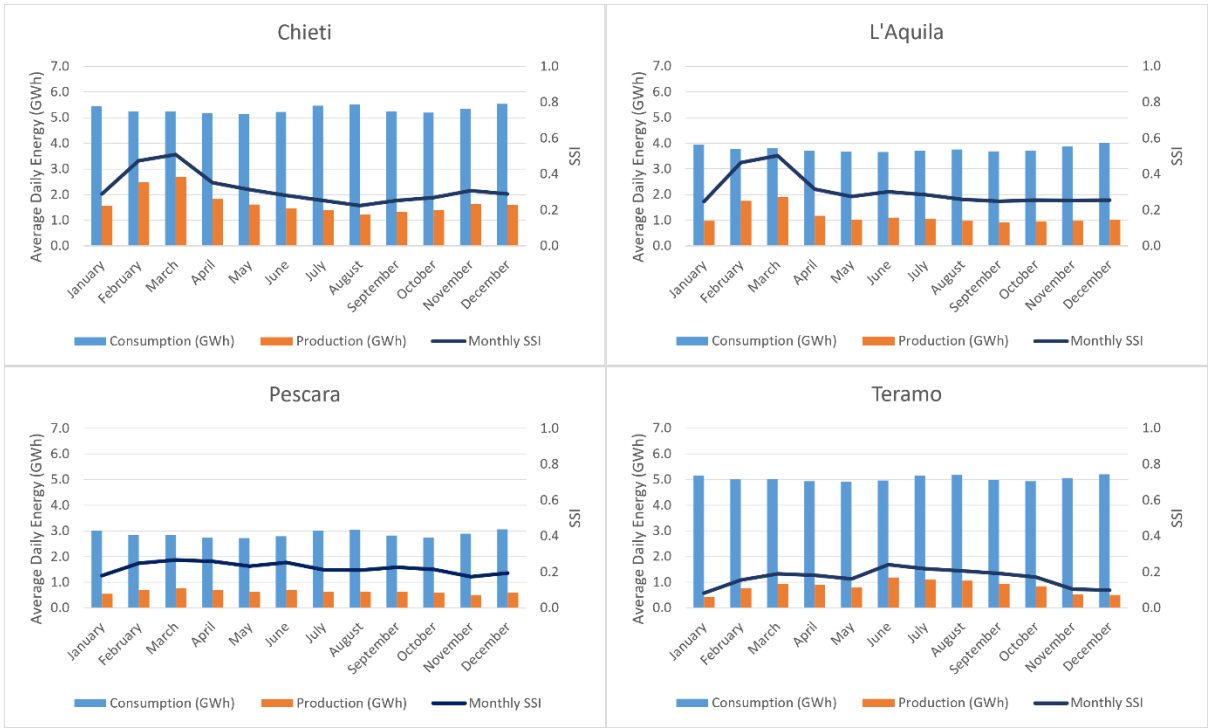


Figure 4.4: Monthly Average Daily Electricity Consumption and Production with Self-Sufficiency Index - Abruzzo Provinces, Working Days

Several findings emerge clearly from Figure 4.4 and deserve careful attention before the deeper hourly analysis of Section 4.4 is presented.

The first and most consistent finding is that no province achieves monthly SSI values approaching or exceeding 100% in any month of the year. Even in the most favorable months, the best-performing province, L'Aquila, reaches a monthly SSI of only 50.2% in March. This confirms that the annual deficit reported in Table 4.1 is not merely an averaging artifact produced by a summer surplus offsetting a winter deficit. All four provinces are in energy deficit in every single month, and the variation in SSI across months reflects differences in the magnitude of that deficit rather than transitions between surplus and deficit conditions.

The second finding concerns the seasonal structure of self-sufficiency across the four provinces, and here a meaningful divergence between the provinces becomes visible. L'Aquila and Chieti both show their highest SSI values in February and March, at 46.4% and 50.2% for L'Aquila and 47.4% and 51.0% for Chieti respectively. This winter-to-spring peak is unusual relative to what one would expect from a solar-dominated generation mix, since solar production is typically lowest in winter and peaks in summer. The explanation lies in the wind component of production in these two provinces. Wind generation in L'Aquila and Chieti is substantial and relatively uniform across seasons, and in the early months of the year it combines with moderate solar production to create the most favorable supply conditions of the year. At the same time, consumption in these months, while high due to heating-related electricity demand, does not yet reach the elevated levels of the peak winter weeks in January and December. The resulting February-March SSI peak is therefore a wind-driven phenomenon rather than a solar-driven one, and it illustrates the analytical value of resolving the energy balance at monthly rather than annual resolution.

Teramo tells a very different story. Of the four provinces, its SSI line in Figure 4.4 is the lowest and flattest throughout the year, never climbing above 24% in any month and falling to 8.2% in January and 9.8% in December. Teramo's almost total reliance on solar production is directly responsible for the lack of any evident February-March upturn in L'Aquila and Chieti. There is no winter wind component to counteract the low solar irradiation of the cold months because wind barely makes up 0.05 GWh of the province's production total each year. Nearly exactly in line with the solar irradiance cycle, Teramo's monthly SSI rises gradually from its January minimum through spring, peaks modestly in June at 24%, and then drops once more throughout the second half of the year. The reason for the small range of variation is that the more diverse generation portfolios of L'Aquila and Chieti are characterized by seasonal diversity that cannot be produced by a single intermittent source without a complementary technology.

Pescara is situated between the balanced profiles of L'Aquila and Chieti and the solar-only profile of Teramo. In most months, its monthly SSI is greater than Teramo's due to its more varied production mix, which includes biomass and hydroelectricity in addition to solar. However, because its wind contribution is likewise minimal, it does not exhibit a February-March upturn like L'Aquila and Chieti. Pescara's best month is March at 26.8% SSI, and its worst month is November at 17.5%. The relatively narrow range across the year suggests that the diversification provided by hydro and biomass adds temporal stability to the production profile without dramatically shifting seasonal peaks.

Chieti's monthly profile is the most dynamic of the four, ranging from 22.5% SSI in August to 51.0% in March. This wide range reflects a production mix in which wind, solar, and hydroelectricity all contribute meaningfully and each has a different seasonal profile. June, July, and August have the maximum solar irradiation of the year, yet Chieti's SSI drops to 28.1%, 25.3%, and 22.5%. Summer consumption rises faster than solar generation due to cooling demand in the province's coastal and interior urban centers. The interaction between rising summer demand and rising but insufficient summer production creates a widening deficit precisely in the months when one might naively expect the solar-rich summer to perform best.

Taken together, the monthly profiles in Figure 4.4 establish three key findings that motivate the more granular hourly analysis presented in Section 4.4. First, the energy deficit in Abruzzo is a persistent year-round condition, not a seasonal phenomenon. Second, the severity and temporal structure of the monthly deficit differ substantially across the four provinces depending on their renewable energy mix, with wind-bearing provinces showing a different seasonal pattern than solar-only ones. Third, the summer months, despite their high solar irradiance, do not necessarily represent the best self-sufficiency conditions for provinces with significant cooling demand, because demand growth in summer can outpace production growth. These findings set the analytical context for examining not just how much energy is produced and consumed, but when within the day that production and consumption occur and how well the two align at the hourly scale.

4.4 Case Study: Abruzzo

4.4.1 Study Area Description and Territorial Context

Abruzzo is a region of central-eastern Italy covering approximately 10,800 square kilometers, bordered to the west by Lazio and to the north by Marche, with a long Adriatic coastline to the east and Molise to the south. Its distinctive geographic feature is the sharpness of its internal gradient: the terrain shifts from the highest peaks of the central Apennines, including the Gran Sasso massif at 2,912 meters above sea level, to a narrow but densely populated coastal plain along the Adriatic shore within a horizontal distance of about 150 kilometers. Such a considerable variation in elevation, climate, and settlement morphology within a single administrative boundary is uncommon in comparable-sized Italian regions. Figure 4.5 shows the location of Abruzzo within the Italian peninsula, situating the study area geographically within the broader national context.

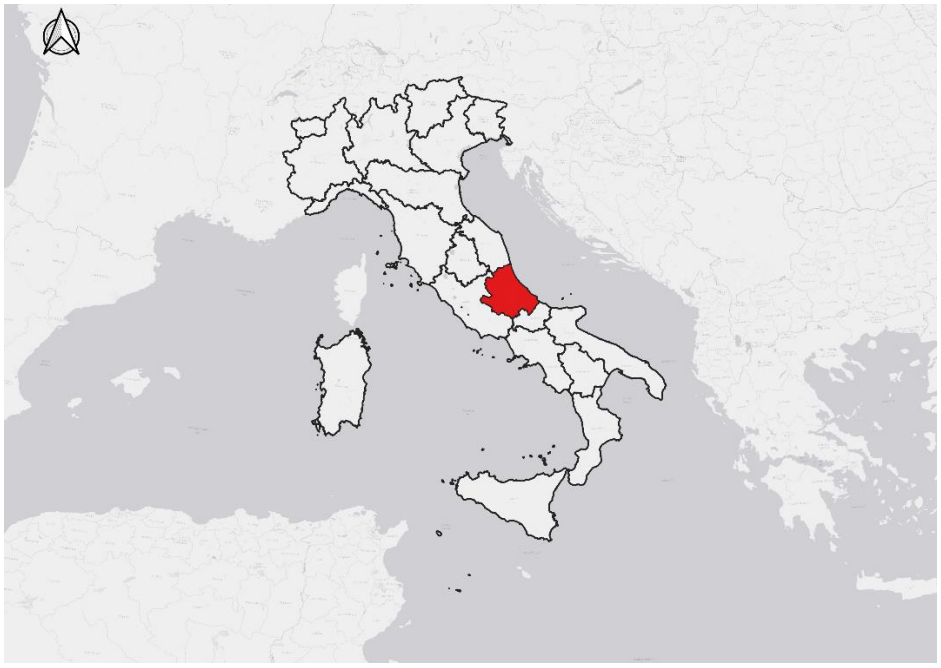


Figure 4.5: Location of Abruzzo within the Italian Peninsula

Source: *Basemap: OpenStreetMap contributors.*

The region is divided into four provinces whose boundaries reflect both the physical geography of the territory and the historical administrative organization of central Italy. Figure 4.6 presents these boundaries alongside the principal urban centres within the region.

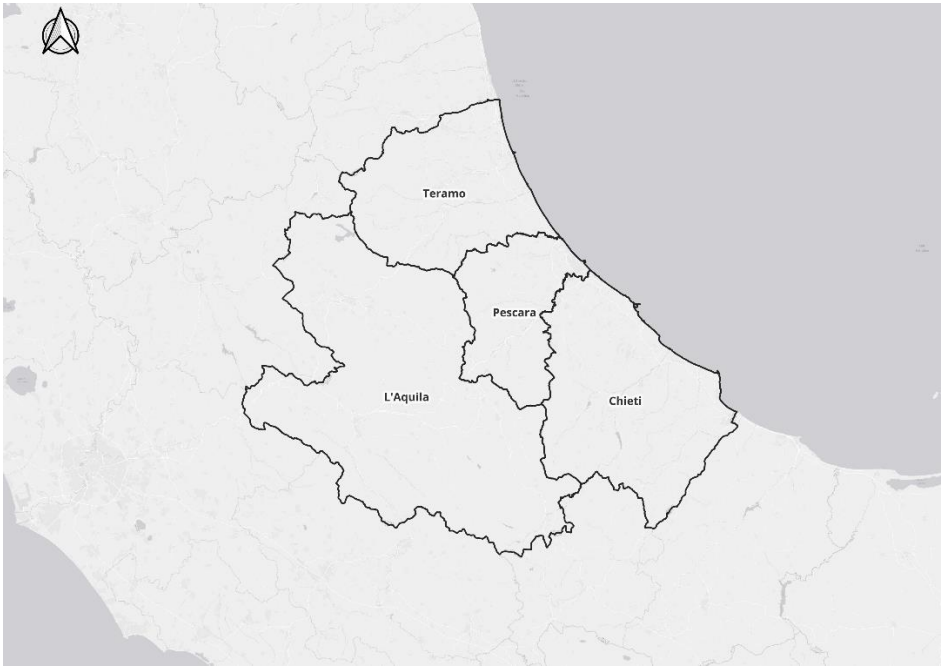


Figure 4.6: Administrative Boundaries and Major Urban Centers of Abruzzo

Source: *Basemap: OpenStreetMap contributors.*

The territorial and demographic characteristics of the four provinces demonstrate this regional variation. With the Gran Sasso and Majella national parks as well as most of the upper Apennine region, L'Aquila is the largest province in terms of area. With a settlement pattern of tiny, historic mountain communities dispersed over the inner plateaus and valleys, it is also the least populous. The province's capital, L'Aquila, experienced massive renovation following the April 2009 earthquake that caused significant damage. During the analysis's reference period, a significant amount of its building stock was either pending consolidation or had been reconstructed in accordance with post-2009 construction regulations. Teramo is in the northeastern region, where the Adriatic coast meets the Apennine foothills. It has a more varied economic character than L'Aquila since it has a flourishing agricultural plain, a coastline tourist strip, and a dispersed industrial base in the mountains. Pescara is the most urbanized province in terms of area, with a continuous coastal urban fabric that joins with the municipality of Montesilvano to the north. Chieti, the southernmost province, extends from the Maiella mountain in the west to the Adriatic coast in the east. It boasts the biggest concentration of manufacturing industry in the area, particularly in the Val di Sangro, which is home to a major hub for the automotive supply chain.

There are clear energy implications to this territorial variety. The climatic gradient between the mountains and the shore results in noticeably different heating and cooling needs: L'Aquila, which has one of the highest heating degree-day counts among Italian provincial capitals, has energy demand patterns that are significantly impacted by cold-season heating loads, whereas Pescara and the coastal part of Chieti experience a more Mediterranean pattern with considerable summer cooling demand. The morphological gradient also shapes the availability of renewable resources: wind resources are strongest on the exposed Apennine ridges of L'Aquila and western Chieti, while solar irradiance is more uniform throughout the region but reaches its maximum productive potential on the level, south-facing terrain of the coastal and foothill areas. The provincial variations in energy balance and self-sufficiency discussed throughout this chapter are caused by these geographic considerations.

4.4.2 Building Stock Spatial Distribution

The spatial organization of Abruzzo's building stock reflects the territorial structure described in Section 4.4.1 in a direct and visually legible way. Figure 4.7 shows the distribution of buildings across the region classified by the unified use categories described in Section 3.2.1.

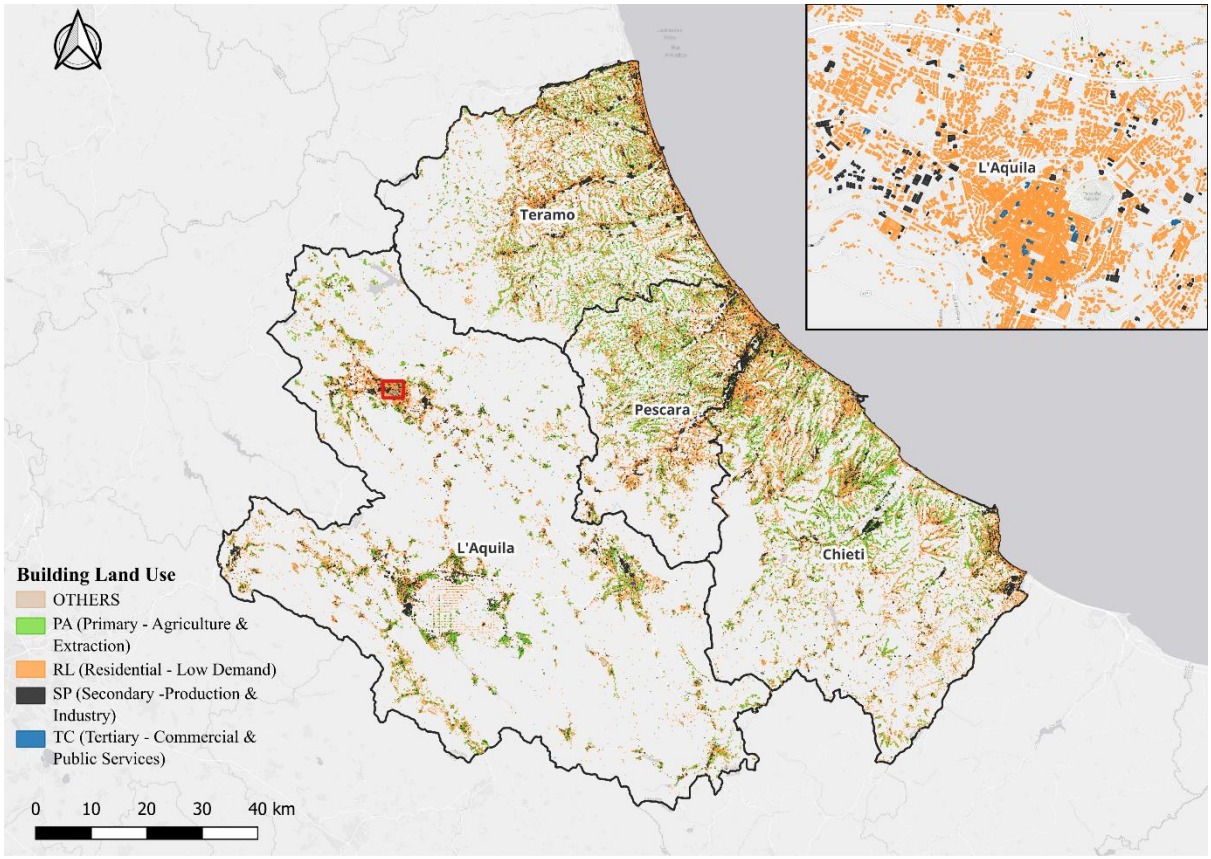


Figure 4.7: Building Use Classification across Abruzzo - Spatial Distribution of Unified Categories (Inset: L'Aquila City Center Detail)

Source: *Basemap: OpenStreetMap contributors.*

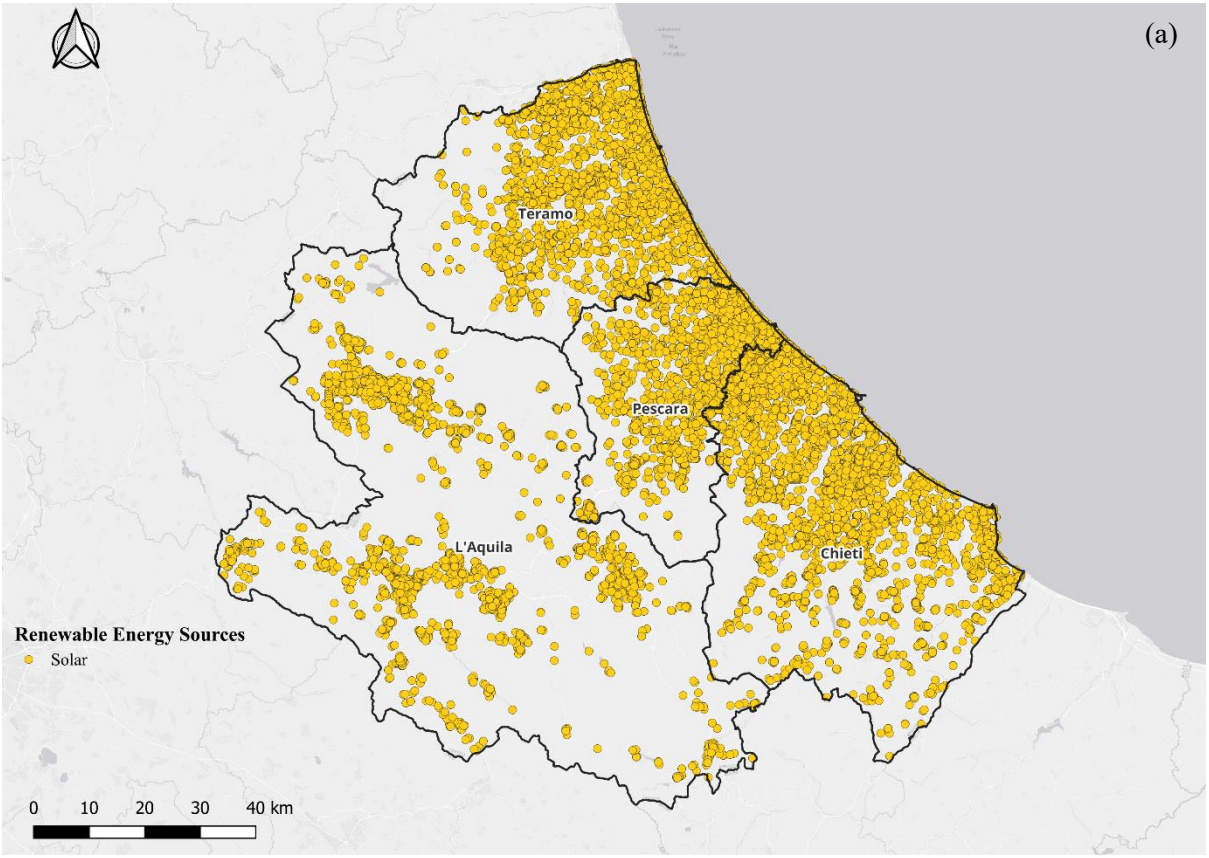
As is typical of regional building stocks in Italy, the built fabric in all four regions is dominated by residential buildings of the RL category. However, they are not evenly distributed across space. The largest density of residential buildings is found in the coastal strip that runs through Teramo and Pescara. The continuous urban fabric of these structures indicates decades of population growth and coastal urbanization driven by trade, tourism, and industrial occupations. In contrast, L'Aquila's mountain interior contains small residential clusters surrounded by huge forests and farms, with villages far apart. Dispersed mountain settlements receive different grid infrastructure configurations and have different per-building consumption profiles than dense coastal urban blocks, which affects energy demand in Abruzzo.

Agricultural buildings are most common in Teramo and Chieti's foothills, where mixed farming on the rolling terrain between the Apennines and the coast produces a large stock of rural outbuildings, storage facilities, and agricultural support structures. Industrial buildings are clustered in the region's main industrial zones: the Val di Sangro corridor in southern Chieti, the seaside industrial districts near Pescara, and the scattered Teramo foothills manufacturing locations. The highest concentrations of commercial, educational, healthcare, and public service buildings are in L'Aquila, Pescara, and the provincial capitals of Chieti and Teramo.

A zoom of the L'Aquila metropolitan region is displayed in Figure 4.7, where the building stock partially displays the post-earthquake reconstruction pattern. While the periphery districts created or rebuilt after 2009 exhibit a more regular pattern of residential blocks scattered with public facilities, the historic city center has a denser mix of residential and tertiary buildings.

4.4.3 Renewable Energy Plant Distribution

The spatial distribution of renewable energy plants across Abruzzo reflects the resource geography described in Section 4.4.1 with considerable clarity. Solar photovoltaic installations, which dominate the regional plant count numerically, are distributed across all four provinces with the highest density in the coastal and foothill areas where flat or gently sloping south-facing terrain is abundant and agricultural land use is compatible with ground-mounted installations. Figure 4.8 (a) shows the distribution of solar plants only, while Figure 4.8 (b) shows the distribution of wind, hydroelectric, and biomass plants separately, since mapping all source types together would cause solar to completely overwhelm the visual representation of the other, much smaller source types.



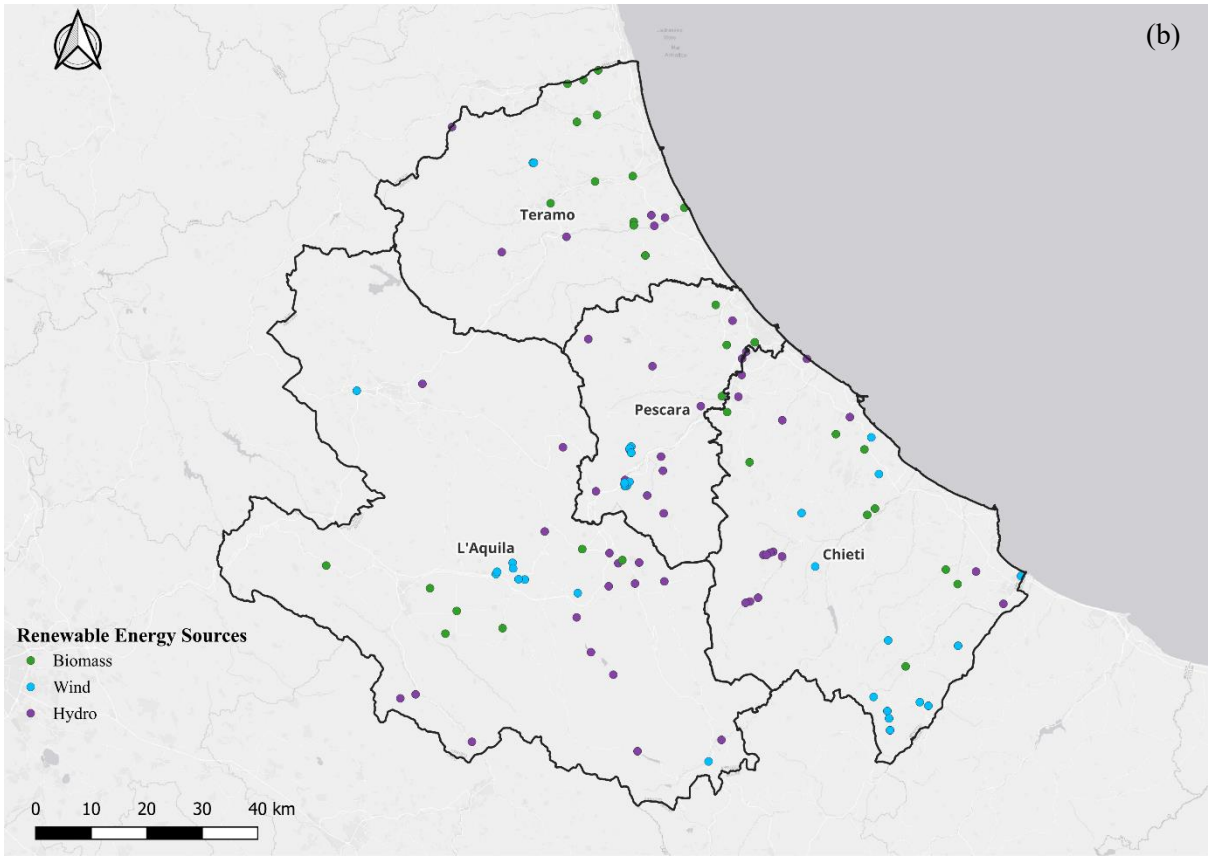


Figure 4.8: Distribution of Renewable Energy Plants across Abruzzo by Source Type (GSE Atlaimpianti, October 2021)
(a) Solar photovoltaic installations
(b) Wind, hydroelectric, and biomass installations
Source: *Basemap: OpenStreetMap contributors.*

Figure 4.8's solar distribution demonstrates that photovoltaics is almost universally present in all four provinces. According to the production figures in Table 4.1, which show that Teramo generates 262.17 GWh from solar and Pescara generates 103.78 GWh, the density is clearly higher in Teramo and Pescara than in L'Aquila. In contrast, L'Aquila's solar contribution of 199.93 GWh is more widely distributed across a larger provincial territory.

Figure 4.9 reveals the geographic concentration of the non-solar source types in a much more spatially selective pattern. Wind installations are concentrated almost entirely in L'Aquila and western Chieti, on the exposed ridgelines and plateau edges of the Apennine crest where wind resource is sufficient to justify large-scale turbine deployment. The complete absence of wind plants in Teramo and the very limited presence in Pescara confirms the production data reported in Table 4.1: Teramo generates only 0.05 GWh from wind annually, and Pescara 7.89 GWh, figures that reflect not just regulatory or economic constraints but a genuine difference in wind resource availability between the exposed mountain provinces and the more sheltered coastal and foothill terrain. Hydroelectric plants follow the river network, with the Pescara, Sangro, and Aterno-Pescara watercourses hosting most of the region's run-of-river capacity. Biomass

plants are few but spatially scattered, located primarily near agricultural and forestry activity in the foothill and piedmont areas of all four provinces.

4.4.4 Self-Sufficiency and Renewable Energy Mix

The combined map in Figure 4.9 integrates the annual SSI results from Table 4.1 with the renewable energy source mix for each province, presenting both dimensions simultaneously. The province fill color encodes the SSI value, transitioning from dark red for the lowest self-sufficiency to light yellow for the highest, while the pie chart overlaid on each province shows the proportional contribution of each renewable source type to total provincial production.

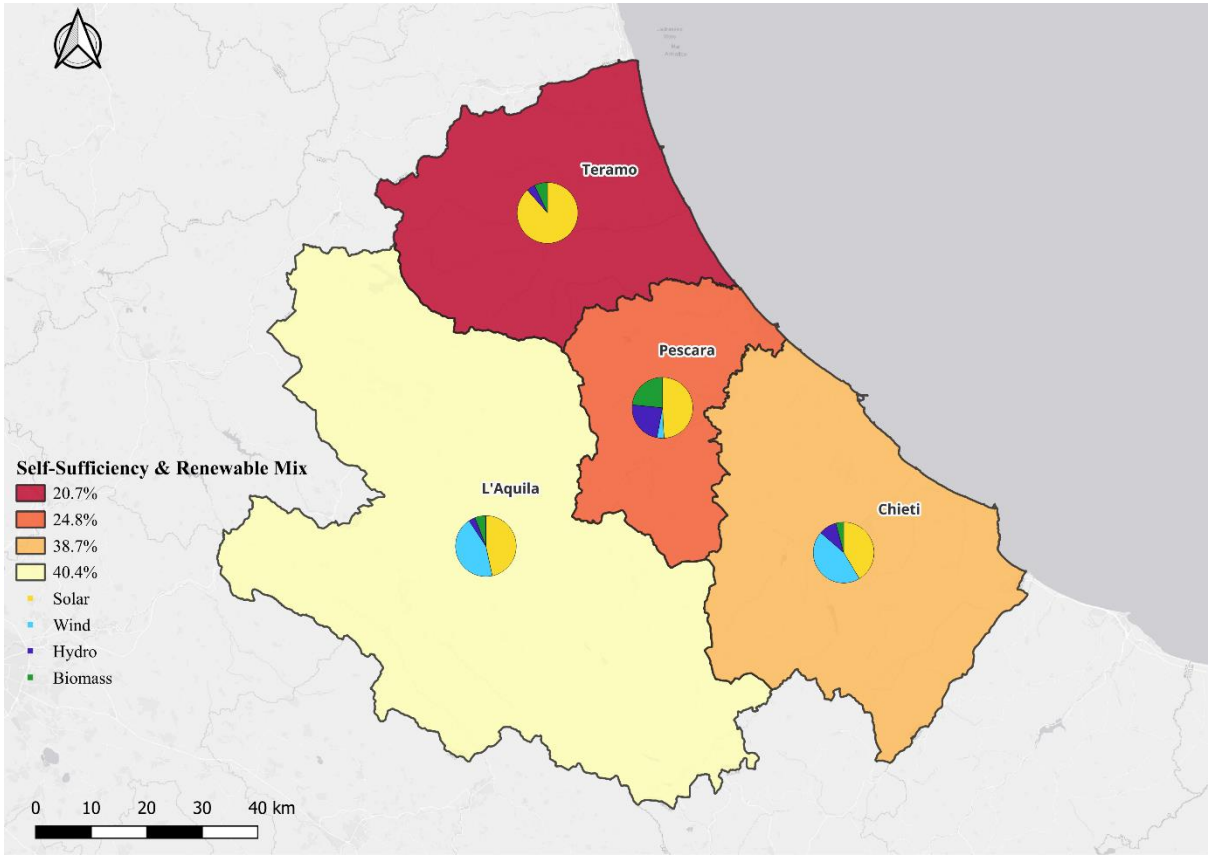


Figure 4.9: Provincial Self-Sufficiency Index and Renewable Energy Mix - Abruzzo
Source: *Basemap: OpenStreetMap contributors.*

The map makes immediately visible what the tabular data of Table 4.1 describes in numbers. Teramo, the darkest province on the map, has the lowest SSI at 20.7% and a pie chart that is almost entirely yellow, indicating near-total dependence on solar photovoltaic. L'Aquila, the lightest province, achieves the highest SSI at 40.4% and shows a nearly equal split between solar and wind in its pie chart, illustrating how the diversification of the generation mix contributes to a more favorable energy balance. Chieti's intermediate position on the SSI scale corresponds to a pie chart showing a balanced solar-wind mix supplemented by a meaningful hydroelectric contribution. Pescara's pie chart shows the most diversified production among

the four provinces, with solar, hydro, and biomass all contributing substantially, yet its SSI of 24.8% remains low because the absolute production volumes across all sources are insufficient to close the gap with its consumption.

The spatial pattern visible in Figure 4.9 suggests a geographic logic to the distribution of self-sufficiency across Abruzzo. The western, mountain-facing provinces, which benefit from both wind and solar resources, achieve higher SSI than the eastern, coastal provinces where wind is largely absent and production depends almost entirely on solar photovoltaic. This geographic gradient in renewable resource diversity, rather than any difference in the scale of investment or the regulatory environment, appears to be the primary determinant of the provincial SSI ranking at this stage of renewable development.

4.4.5 Hourly Demand-Supply Profiles and Temporal Mismatch Analysis

The annual and monthly analyses presented in Sections 4.2 and 4.3 established that all four Abruzzo provinces are in persistent energy deficit and that the severity of this deficit varies seasonally. The shape of that deficit throughout the day is what those analyzes are unable to disclose. Since the Italian REC framework's Collective Self-Consumption mechanism computes the shared energy benefit on an hourly basis, this hourly resolution is important for REC planning. Even if both provinces produce the same annual total, a province that produces well in the middle of the day but not in the evening has a fundamentally different REC potential than one whose output is more evenly spread throughout the day.

The analysis presented in this section focuses on the two most contrasting seasons: winter, which represents the most challenging conditions for local renewable supply, and summer, which represents the most favorable. Spring and autumn profiles, which show transitional patterns broadly intermediate between these two extremes, are provided in Appendix C for all four provinces.

The aggregate picture for the entire Abruzzo region across all four seasons is presented first in Figure 4.9, to establish the regional pattern before examining the individual provincial profiles in Figure 4.10.

Before examining the seasonal balance charts, it is useful to understand the temporal structure of demand. Across all four provinces combined, the consumption profile follows a consistent daily shape regardless of season: a low plateau through the early morning hours from 1 to 6, a rapid morning ramp-up beginning around hour 7 as commercial and industrial activity starts, a broad midday plateau with a slight early-afternoon dip around hour 13 reflecting the lunch-hour reduction in service and industrial activity, and a pronounced evening peak between hours 19 and 22 as residential demand combines with the tail end of commercial activity. This bimodal daily structure, with a secondary morning peak and a dominant evening peak, is characteristic of Italian electricity demand as documented in the ARERA provincial withdrawal profiles that underpin the consumption model.

Figure 4.10 presents the aggregate Abruzzo balance for all four seasons as a four-panel grid, allowing the seasonal evolution of the demand-supply relationship to be read briefly.

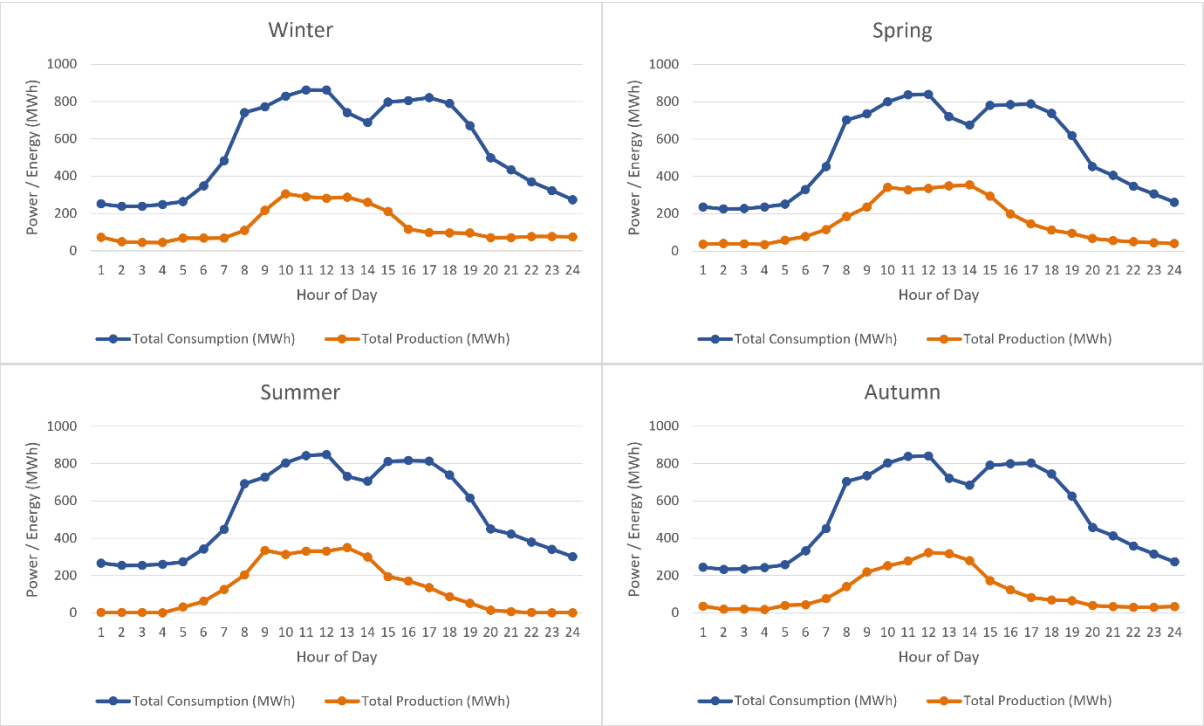


Figure 4.10: Aggregate Hourly Electricity Consumption vs Renewable Production - Abruzzo Region, Working Days by Season (MWh)

In winter, shown in the top left panel of Figure 4.10, the consumption line maintains values between approximately 220 and 870 MWh throughout the day, reaching its daily maximum in the late evening hours. The production line sits near zero from hours 1 through 6, rises only modestly during the central hours of the day to a maximum of roughly 90 to 100 MWh around hours 10 to 12, and returns to near-zero by hour 17. This nearly flat and universally low production profile reflects the combined effect of low solar irradiance, short daylight hours, and the relatively modest wind contribution during winter months identified in the monthly analysis of Section 4.3. The gap between consumption and production is therefore almost perfectly uniform across the 24 hours of the winter working day: there is no hour at which local production comes close to meeting local demand, and the region requires substantial grid imports throughout the entire day.

Spring, shown in the top right panel, marks the first appearance of a meaningful midday production window. The production line rises more substantially during the central hours of the day, reaching approximately 300 to 325 MWh between hours 10 and 14, as increasing solar irradiance begins to generate a visible contribution to the regional supply. The result is a partial narrowing of the demand-supply gap during the midday hours, though the gap remains substantial even at its narrowest point.

The best time of year for Abruzzo's local renewable supply is summer, as seen in the bottom left panel. The production line exhibits a prominent bell-shaped curve that peaks at about 340 MWh at hour 12 and is centered on hours 11 to 14. The demand-supply difference at the crucial evening peak hours is not significantly less than in winter, even though summer has the largest

production of any season. This is because summer consumption is also increased by cooling demand. The noon window, which lasts roughly four to five hours and does not stretch into the morning or evening hours when the greatest amounts of energy are consumed, is when local output most closely matches local demand.

As solar irradiance decreases and heating demand starts to rise again, autumn, depicted in the bottom right panel, shows a shift back toward the winter trend. The fall profile, which is essentially halfway between spring and winter, attests to the directionality and consistency of the seasonal dynamic.

The provincial-level analysis that follows disaggregates these regional patterns into the four individual provinces, where differences in renewable energy mix create meaningfully different daily profiles.

L'Aquila

L'Aquila's hourly profiles, shown in Figure 4.11, reflect its balanced solar-wind generation mix in a way that distinguishes it clearly from the other three provinces.

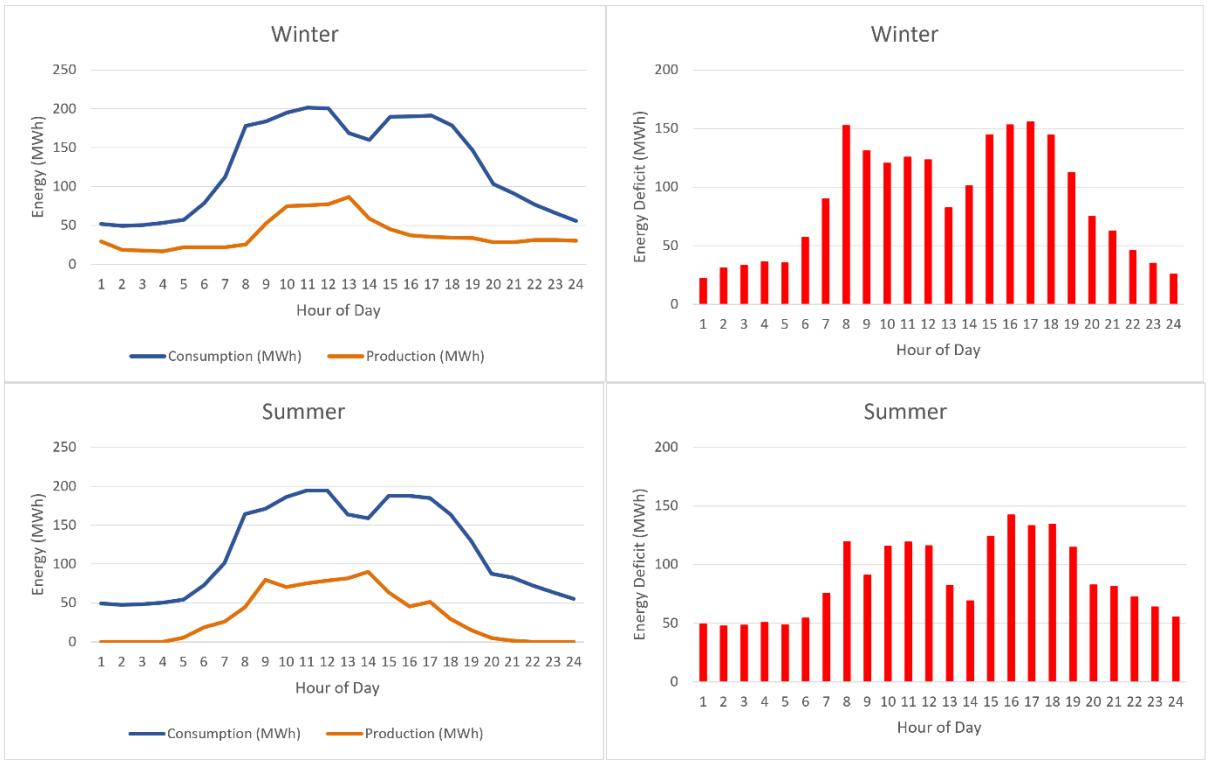


Figure 4.11: Hourly Electricity Consumption, Renewable Production, and Energy Deficit - L'Aquila Province, Winter and Summer Working Days (MWh)

In winter, shown in the top panels of Figure 4.11, the production line for L'Aquila does not fall to near-zero in the early morning and evening hours as one would expect from a purely solar-dependent province. Instead, it maintains a meaningful baseline of approximately 25 to 45

MWh throughout the overnight and early morning hours, reflecting the wind component of provincial production that operates independently of sunlight and time of day. The midday solar contribution adds a visible bump to this baseline between hours 9 and 15. The winter deficit bars confirm that L'Aquila's deficit is relatively uniform across hours, ranging between approximately 20 and 155 MWh per hour, with the largest deficits concentrated in the evening peak hours when consumption is highest and production has returned to its wind-only baseline.

In summer, shown in the bottom panels of Figure 4.11, L'Aquila's production reaches its annual maximum during the midday hours, with the solar contribution layered on top of the wind baseline to create a production peak of approximately 70 to 90 MWh between hours 10 and 14. Even at hour 12, the summer deficit chart shows a deficit of about 100 MWh, indicating that at the highest production period, local production accounts for about 40% of simultaneous consumption. The deficit is greater outside of the midday window, especially in the early morning before solar production starts and in the evening after it has stopped.

Chieti

Chieti's profiles, shown in Figure 4.12, share the balanced solar-wind character of L'Aquila but at higher absolute consumption and production values, reflecting the province's larger total energy flows.

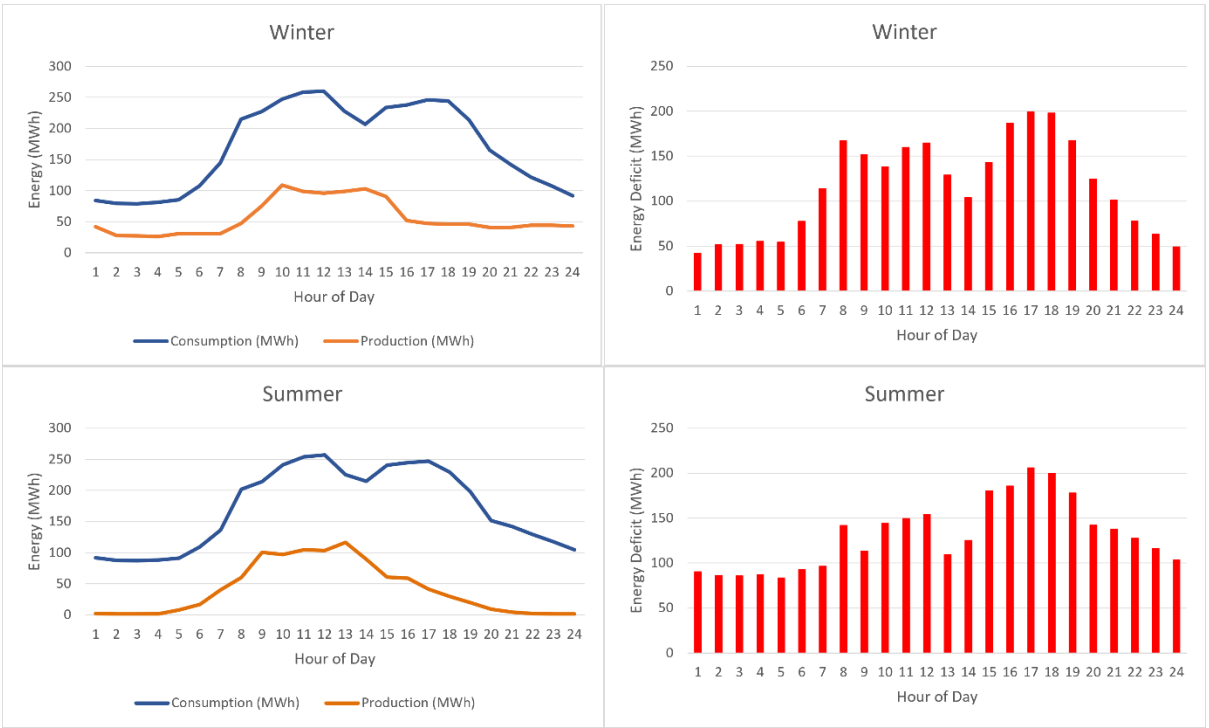


Figure 4.12: Hourly Electricity Consumption, Renewable Production, and Energy Deficit - Chieti Province, Winter and Summer Working Days (MWh)

In winter, shown in the top panels of Figure 4.12, Chieti shows a production profile broadly similar to L'Aquila, with a wind-maintained overnight baseline and a solar-boosted midday

contribution. The deficit bars show higher absolute values than L'Aquila in every hour, consistent with Chieti's larger total consumption, but the relative pattern across the day is similar. Because of its larger installed solar and wind capacity, Chieti's production in the summer reaches higher midday values than L'Aquila, as seen in the bottom panels. However, its consumption in the summer is also significantly higher due to the industrial activity of the Val di Sangro corridor, which operates during the day and adds a significant non-residential load to the residential cooling demand. The afternoon and evening hours have the biggest deficits, according to the summer deficit bars. The production peak at noon only partially and momentarily closes the gap before it grows again as solar output decreases.

Pescara

Pescara's hourly profiles, shown in Figure 4.13, tell a distinctly different story from L'Aquila and Chieti, reflecting its almost complete absence of wind generation.

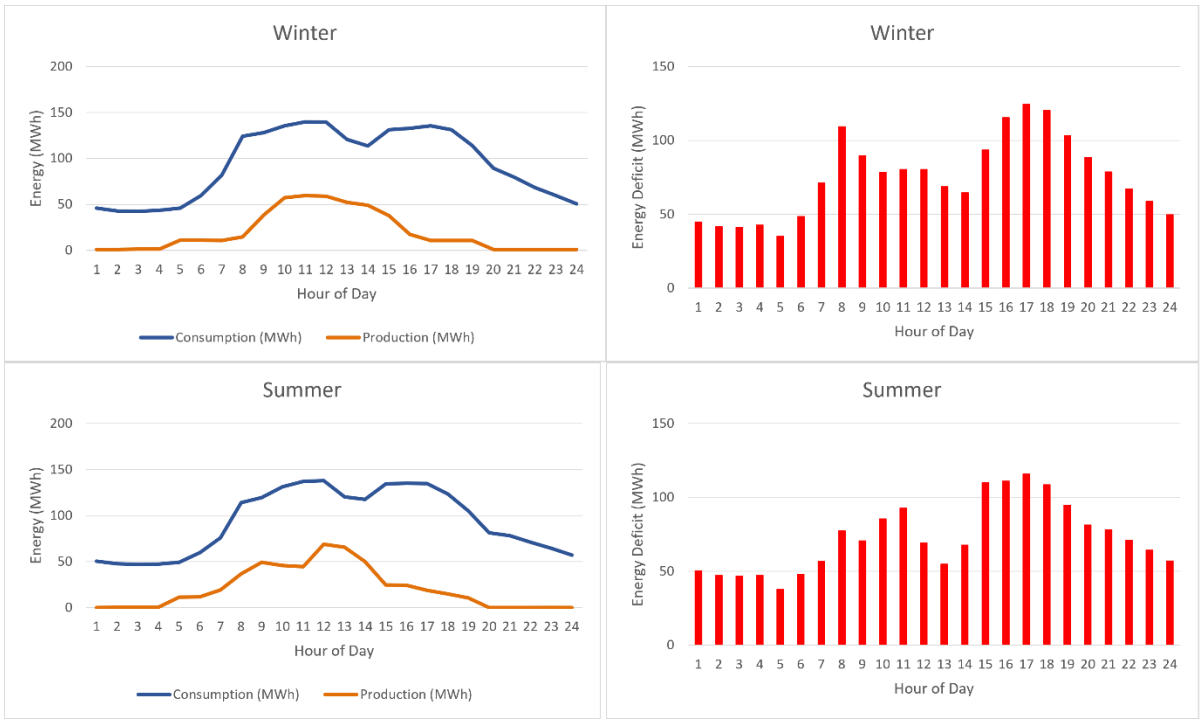


Figure 4.13: Hourly Electricity Consumption, Renewable Production, and Energy Deficit - Pescara Province, Winter and Summer Working Days (MWh)

In winter, shown in the top panels of Figure 4.13, Pescara's production line sits very close to zero throughout the early morning and evening hours, with only a shallow midday contribution from solar reaching approximately 15 to 20 MWh at its peak. During the early morning, the production line is kept from reaching absolute zero by the small but steady contributions from the hydroelectric and biomass components. The winter deficit bars demonstrate that there is no hour of significant production-demand convergence and that the shortfall is almost constant throughout the whole day. Pescara's solar production increases to a more noticeable midday

high of roughly 55 to 65 MWh around hours 11 to 13 throughout the summer, as seen in the bottom panels. Even at the peak production hour, the summer deficit remains around 60 to 75 MWh, meaning local production covers only about 45% of simultaneous consumption during the best hour of the best season.

Teramo

Teramo's hourly profiles, shown in Figure 4.14, are the most extreme expression of solar dependence in the dataset and illustrate most clearly the limitations of a single-source renewable portfolio for territorial self-sufficiency.

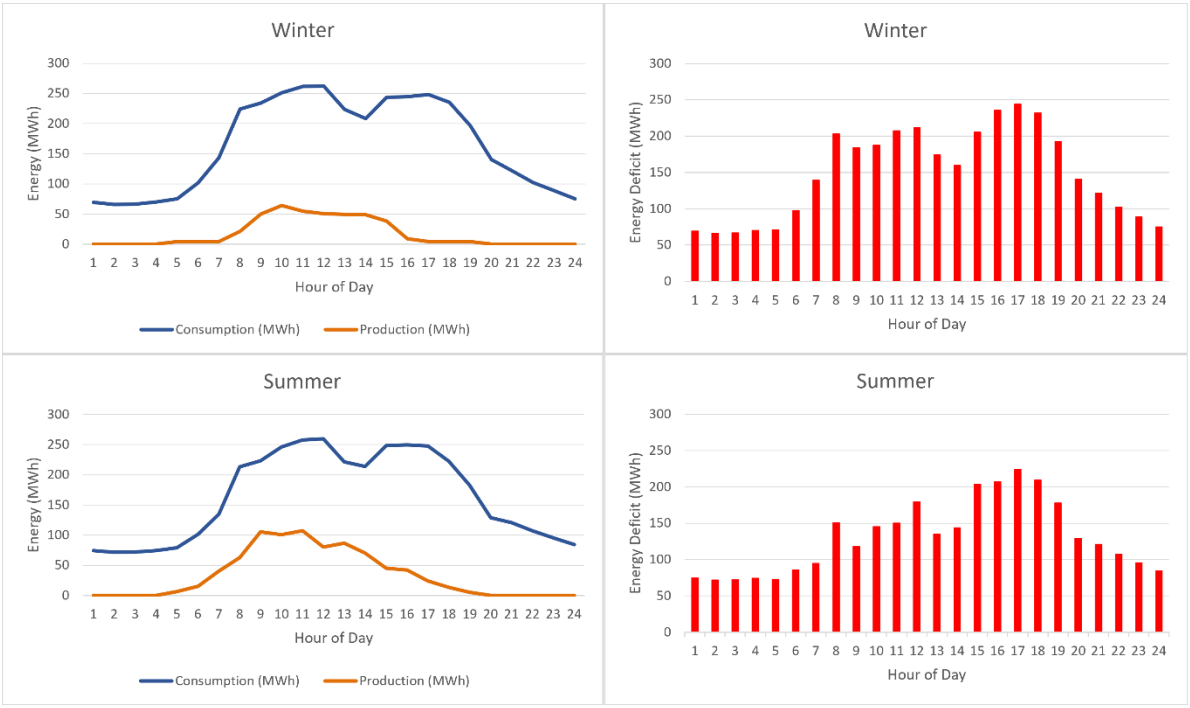


Figure 4.14: Hourly Electricity Consumption, Renewable Production, and Energy Deficit - Teramo Province, Winter and Summer Working Days (MWh)

In winter, shown in the top panels of Figure 4.14, Teramo's production line is essentially flat at zero for the entire 24-hour period, with only a faint midday trace of 5 to 10 MWh visible in the central hours. The combination of the lowest solar irradiation, the shortest daylight hours, and the minimal wind capacity results in this nearly complete lack of production throughout the winter. Because local output contributes relatively little, the deficit at each hour is about equal to consumption, making the winter deficit bars nearly a mirror copy of the consumption profile. This is the most severe demand-supply mismatch of any province in any season in the dataset.

In summer, shown in the bottom panels of Figure 4.14, Teramo's production rises to a visible and meaningful midday peak, reaching approximately 100 to 115 MWh between hours 10 and 14. The summer deficit bars show that this midday solar window creates a genuine, if partial, convergence between production and consumption in the central hours of the day. At hour 12,

the deficit narrows to approximately 115 to 130 MWh, suggesting that local production covers roughly 40 to 45% of simultaneous consumption at the peak summer hour. However, outside this four to five hour window, the deficit returns to near-consumption levels: before hour 7 and after hour 18, Teramo's production falls back to near-zero and the province must source virtually all of its electricity from the national grid.

The contrast between Teramo's summer midday window and its winter near-zero profile represents the widest seasonal range of any province in the study and underscores the vulnerability of a solar-only generation portfolio to seasonal variation. A key problem for a REC built for Teramo would be that the hours with the greatest potential for energy sharing also happen to be the times when residential cooling demand is at its lowest, while the hours with the highest demand are exactly those when solar production is either nonexistent or very low. Either battery storage that can move the midday solar surplus into the evening peak or the addition of wind capacity to supply power beyond the solar window would be necessary to address this mismatch. The scenario analysis in Section 4.5 explores the scale of additional renewable capacity that would be needed to close the provincial gap, and Section 4.5.3 reflects on the implications of Teramo's solar dependence for the type of additional investment that would be most effective.

Spring and autumn profiles for all four provinces, which show transitional patterns broadly consistent with the trends identified in the winter and summer analysis above, are provided in Appendix C.

4.5 Self-Sufficiency Scenario Analysis

4.5.1 Scenario Definition and Baseline Conditions

The temporal and spatial analysis presented in Sections 4.3 and 4.4 established that all four Abruzzo provinces are in persistent electrical energy deficit, that the severity and structure of this deficit differ substantially across provinces depending on their renewable energy mix, and that the temporal mismatch between local production and local demand is most acute in the evening hours and in the winter months. The scenario analysis presented in this section builds on these findings by asking a forward-looking question: how much additional renewable generation capacity would each province need to reach a defined level of electrical self-sufficiency, and where would that additional capacity need to come from given each province's current resource orientation?

Three scenarios are evaluated, corresponding to the SSI thresholds defined in Section 3.4.1. Scenario A targets an SSI of 40%, representing the minimum threshold above which a territory can be considered to have achieved a meaningful degree of electrical self-reliance and corresponding approximately to the current best-performing province in the region. The target of Scenario B is for an SSI of 75%, which is in line with the High sufficiency class and roughly in line with the amount of renewable capacity increase suggested by Italy's national PNIEC 2030 plans (Ministero dell'Ambiente e della Sicurezza Energetica, 2023). An annual SSI of 100%, or complete electrical self-sufficiency, is the goal of Scenario C. When taken as a whole,

the three scenarios outline a path from a short-term, attainable improvement to a medium-term, policy-aligned goal to a long-term, aspirational standard.

Table 4.2 summarizes the baseline conditions and the total additional generation capacity required under each scenario for each of the four provinces.

Table 4.2: Self-Sufficiency Scenario Analysis - Baseline Conditions and Additional Renewable Generation Capacity Required for Each Target Threshold, Abruzzo Provinces

Province	L'Aquila	Chieti	Pescara	Teramo
Current SSI (%)	40.4	38.7	24.8	20.7
Current Production (GWh)	429.03	605.00	210.98	296.39
Consumption (GWh)	1,062.5	1,562.7	850.67	1,428.93
Scen A Extra (GWh)	0.0	20.1	129.3	275.2
Scen A New SSI (%)	40.4	40.0	40.0	40.0
Scen B Extra (GWh)	367.9	567.0	427.0	775.3
Scen B New SSI (%)	75.0	75.0	75.0	75.0
Scen C Extra (GWh)	633.5	957.7	639.7	1,132.5
Scen C New SSI (%)	100.0	100.0	100.0	100.0

Note: Scenario A targets SSI = 40%; Scenario B targets SSI = 75%; Scenario C targets SSI = 100%. Additional capacity values represent the additional annual renewable electricity production required to reach each target, calculated following the proportional expansion methodology described in Section 3.4.2. L'Aquila already meets the Scenario A threshold under current conditions and requires no additional capacity at that level.

Source: Author's own elaboration.

The baseline conditions visible in Table 4.2 confirm the ranking established throughout the preceding analysis. L'Aquila is the only province that already meets the Scenario A threshold at its current SSI of 40.4%, meaning no additional capacity is required for it to reach that level. Chieti comes closest among the remaining three provinces, requiring only 20.1 GWh of additional production to cross the 40% threshold, a comparatively modest increment relative to its current production of 605.00 GWh. To reach Scenario A, Pescara needs to increase production by 129.3 GWh, whereas Teramo needs to increase production by 275.2 GWh, which is the biggest absolute increment at this threshold while having the smallest existing production base of the four provinces.

Teramo would need 1,132.5 GWh of renewable production to reach full self-sufficiency under Scenario C, nearly four times its current production of 296.39 GWh. This figure shows how difficult it is for solar-dependent provinces to close the demand-supply gap by proportionally expanding a single intermittent source. This requires investment that strains physical feasibility, given finite rooftop area and available land, and financial viability within plausible planning horizons.

4.5.2 Additional Capacity Requirements by Province and Source Type

The total additional capacity figures in Table 4.2 become analytically more informative when disaggregated by renewable source type, since the source composition of additional investment determines not only the technical feasibility of each scenario but also its implications for the

temporal demand-supply matching problem identified in Section 4.4. Table 4.3 presents this disaggregation for all four provinces and all three scenarios, distributing the required additional production across solar, wind, hydroelectricity, and biomass in proportion to each province's current generation mix.

Table 4.3: Additional Renewable Generation Capacity Required by Province and Source Type under Three Self-Sufficiency Scenarios - Abruzzo

Province	Scenario	Additional Solar (GWh)	Additional Wind (GWh)	Additional Hydro (GWh)	Additional Biomass (GWh)	Total Additional (GWh)	New SSI (%)
L'Aquila	A: Target 40%	0	0	0	0	0	40.4
	B: Target 75%	171.4	162.3	12.9	21.3	367.9	75.0
	C: Target 100%	295.1	279.5	22.2	36.7	633.5	100.0
Chieti	A: Target 40%	8.3	9.0	1.9	0.9	20.1	40.0
	B: Target 75%	234.2	255.2	53.6	24.0	567.0	75.0
	C: Target 100%	395.5	430.9	90.4	40.8	957.7	100.0
Pescara	A: Target 40%	63.6	4.8	30.9	30.0	129.3	40.0
	B: Target 75%	210.1	15.8	102.2	98.9	427.0	75.0
	C: Target 100%	314.7	23.7	153.1	148.2	639.7	100.0
Teramo	A: Target 40%	243.3	0.0	11.5	20.4	275.2	40.0
	B: Target 75%	685.4	0.1	32.4	57.4	775.3	75.0
	C: Target 100%	1,001.3	0.1	47.3	83.8	1,132.5	100.0

Note: Additional capacity distributed proportionally to the current renewable energy mix of each province following the methodology described in Section 3.4.2. Geothermal is excluded as no geothermal capacity is registered in any Abruzzo province. L'Aquila already meets the Scenario A threshold and requires no additional capacity at that level. Values rounded to one decimal place.

Source: Author's own elaboration.

The source-type breakdown in Table 4.3 reveals meaningful differences across the four provinces that the total figures in Table 4.2 alone cannot convey. These differences reflect the varying renewable energy mix of each province and have direct implications for both investment strategy and temporal demand-supply matching. Figure 4.15 summarizes the total additional capacity requirements across all three scenarios for each province, providing a visual complement to the detailed source-type breakdown in Table 4.3.

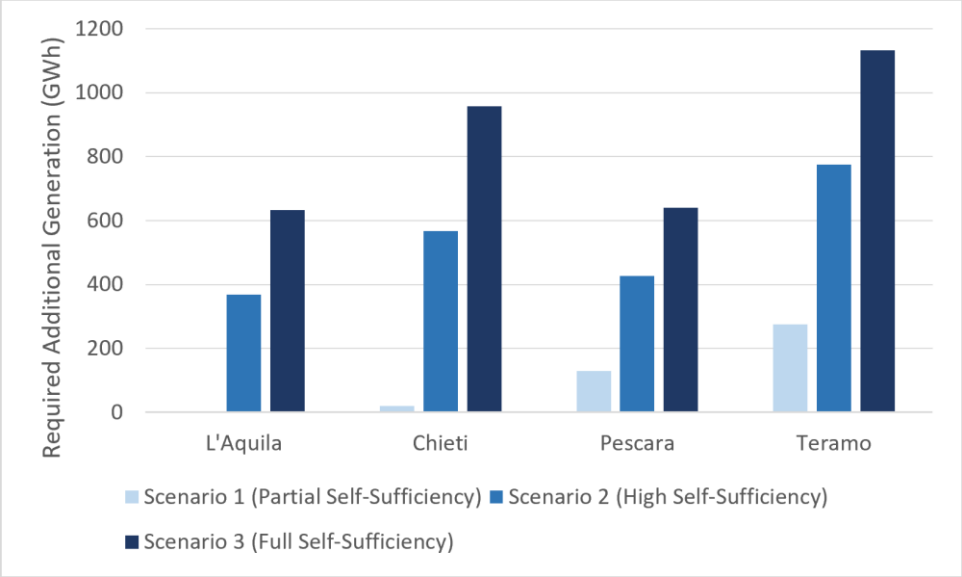


Figure 4.15: Additional Renewable Generation Capacity Required per Province under Three Self-Sufficiency Scenarios (GWh)

According to the source-type breakdown under Scenario B, L'Aquila would need to add roughly 171.4 GWh of additional solar and 162.3 GWh of additional wind, along with lesser additions of hydro and biomass, to attain 75% SSI. The increased investment would maintain and strengthen the province's current solar-wind equilibrium because of this generally balanced distribution, which reflects L'Aquila's current mixed generation portfolio. Given the province's vast Apennine terrain with proven wind resources and its sizable areas of south-facing mountain slopes suitable for ground-mounted photovoltaic, the necessary increments under Scenario C increase to 295.1 GWh of additional solar and 279.5 GWh of additional wind. This scale represents a significant but not implausible expansion of existing capacity.

Chieti's scenario breakdown under Scenario B shows a requirement for 234.2 GWh of additional solar and 255.2 GWh of additional wind, with a notable hydroelectric component of 53.6 GWh reflecting the province's existing river-based generation capacity. The wind component is proportionally the largest of any province at the Scenario B level, which has a favorable implication for temporal matching: as demonstrated in Section 4.4, wind generation provides production outside the solar window, including in the early morning and overnight hours when residential and industrial demand persists but solar output is zero. Adding wind capacity in Chieti would enhance annual production and improve its distribution throughout the day, thereby eliminating the nighttime deficit in all four provinces.

Pescara's scenario analysis differs from the other three provinces. The proportional expansion assumption allocates new investment heavily toward solar and hydro rather than wind since its generation mix is almost equal between solar (49.2%), hydroelectricity (23.6%), and biomass (23.4%), with wind providing only 3.7%. Under Scenario C, the required additional solar is 314.7 GWh and additional hydro is 153.1 GWh, while additional wind is only 23.7 GWh. This source composition has an important implication for temporal matching that Table 4.3 cannot

by itself convey: additional solar and hydro capacity in Pescara would reinforce an already solar-dominated and hydro-supplemented production profile without introducing the overnight and early-morning wind contribution that would be most effective at closing the evening deficit. The proportional expansion assumption, by holding the generation mix constant, preserves a source composition that the temporal analysis of Section 4.4 identified as insufficient to address the province's most severe deficit hours.

Teramo's breakdown is the most concentrated of the four. At every scenario level, the proportional expansion of its near-entirely solar portfolio means that almost all additional capacity takes the form of new photovoltaic installations. Under Scenario B, this amounts to 685.4 GWh of additional solar, and under Scenario C, it rises to 1,001.3 GWh. The near absence of additional wind, hydro, or biomass in Teramo's scenario figures reflects the arithmetic of proportional expansion: with wind currently contributing only 0.05 GWh annually, 0.03% of total production, proportional expansion assigns virtually no share of the additional requirement regardless of which scenario level is targeted.

This concentration of additional solar in Teramo's scenarios deserves specific discussion because it highlights the most significant limitation of the proportional expansion assumption when applied to a province with a highly unbalanced generation mix. The temporal analysis in Section 4.4 showed that Teramo's summer midday solar window is the only period of the year in which local production approaches a meaningful fraction of local demand. Adding 685 or 1,001 GWh of additional solar capacity would widen this midday window, increase the peak production values, and potentially extend the productive hours slightly into the morning and afternoon. But it would do nothing to address the near-zero winter production that leaves the province entirely dependent on grid imports for five to six months of the year, and it would not extend production into the evening hours when residential and commercial demand reaches its daily peak in every season. A diversified expansion that introduced significant wind capacity alongside solar would be more effective at temporal matching, even if it achieved the same annual SSI target, because wind generation fills precisely the hours and seasons that solar cannot.

The finding provides a qualitative note on proportionate expansion planning boundaries. It is transparent, replicable, and based on existing facts without assumptions about future technology costs or regulatory frameworks, making it an appropriate analytical baseline. However, proportional expansion worsens the temporal mismatch in provinces like Teramo, where the current mix reflects previous investment patterns rather than an efficient resource strategy. A more advanced planning exercise would maximize future investment source composition versus annual SSI targets and hourly temporal matching objectives. This would be a natural extension of the present work, drawing on the hourly demand-supply profiles documented in Section 4.4 as the optimization target rather than the annual SSI alone.

4.5.3 Comparative Discussion and Planning Implications

Comparing the four provinces across the three scenario levels shows a clear and consistent pattern: provinces closer to self-sufficiency require less investment to reach any given target, and provinces with more diversified generation mixes have a more manageable path to self-

sufficiency than those dependent on a single source. L'Aquila is best positioned to increase SSI due to its low consumption and balanced solar-wind portfolio. Teramo's high consumption and near-total solar dependency make it the most difficult, requiring investment at a scale that the research has proven to be technically hard and potentially insufficient to meet the province's temporal demand-supply mismatch.

Scenario B at 75% SSI is the most balanced Abruzzo planning aim of the three. Three factors underpin this advice. First, L'Aquila outperforms Scenario A and would achieve Scenario B with a mild 367.9 GWh investment, a suitable medium-term development of its wind and solar base. Second, Scenario B's 75% criterion matches Italy's PNIEC 2030 national targets for renewable expansion (Ministero dell'Ambiente e della Sicurezza Energetica, 2023), providing a regulatory grounding that the 40% and 100% thresholds lack. Third, and most practically, Scenario C at 100% SSI requires Teramo to invest volumes that exceed what is physically and financially realistic within a decade-long planning horizon due to finite rooftop area, land availability constraints, and grid absorption capacity.

Figure 4.16 presents the spatial distribution of the additional renewable generation capacity required under Scenario B across the four Abruzzo provinces, illustrating the geographic concentration of investment effort that the scenario implies.

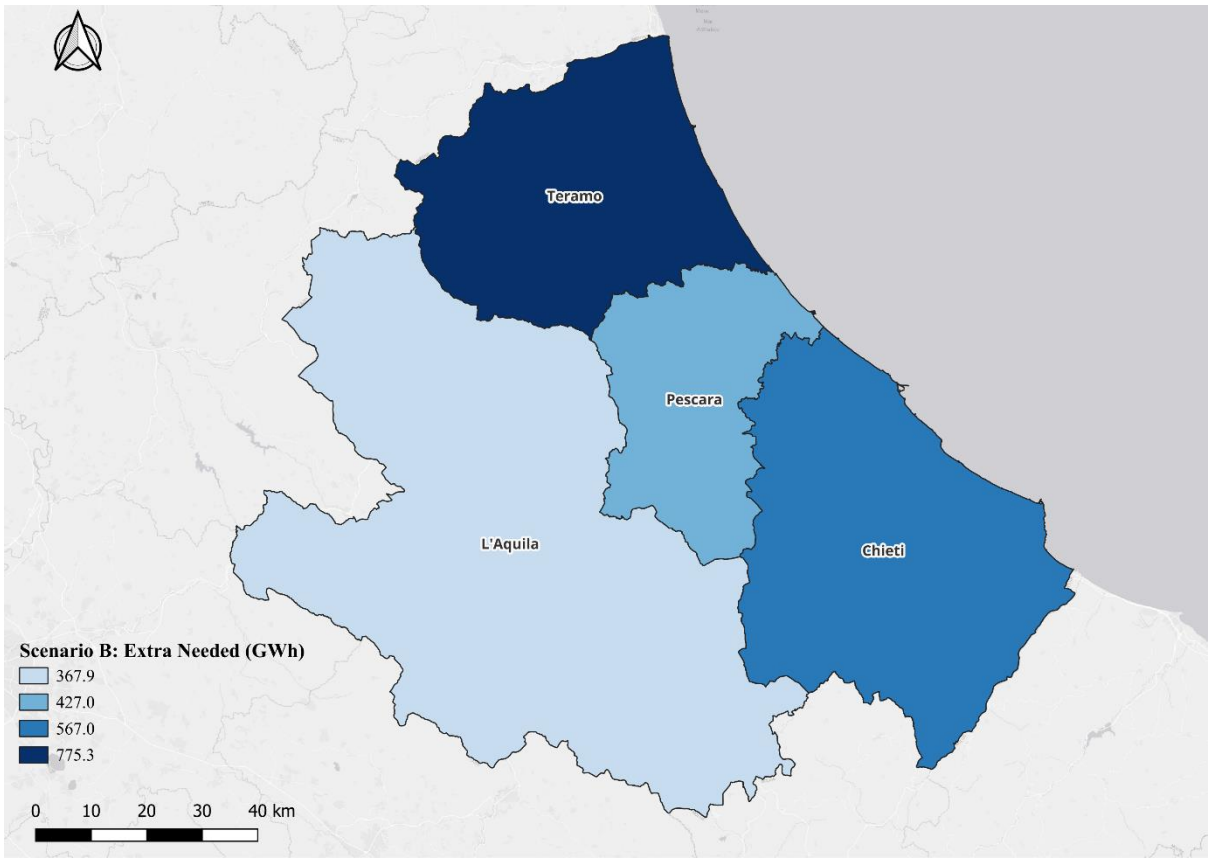


Figure 4.16: Additional Renewable Generation Capacity Required to Achieve 75% Self-Sufficiency - Scenario B, Abruzzo Provinces (GWh)

Basemap: OpenStreetMap contributors.

Under Scenario B, Teramo would need the most production, 775.3 GWh, followed by Chieti, 567.0 GWh, Pescara, and L'Aquila, 427.0 and 367.9 GWh, respectively. This spatial trend has planning implications beyond the provincial level: provinces with the largest investment requirement may not have the most renewable resources. Teramo, which needs the most production, has the most limited generation mix due to its near-total solar dependence and lack of wind resource in its accessible topography. Chieti, which needs the second-largest boost, has a greater wind resource and a more diverse portfolio, making its Scenario B aim more realistic. The geographic mismatch between investment need and resource availability across the four provinces supports treating Abruzzo as an integrated territorial system in REC planning rather than as four isolated energy balances.

An integrated territorial approach links this research to Legislative Decree 199/2021's Renewable Energy Communities (Italian Republic, 2021). As discussed in Section 2.3, the REC mechanism allows producers and consumers in the same major substation service region to share energy. A REC configured across multiple primary cabin areas in Abruzzo could combine the wind-rich production of western L'Aquila and Chieti with the coastal provinces' high residential and industrial consumption to improve collective self-consumption without requiring each province to achieve self-sufficiency. The data infrastructure developed in this thesis, which provides annual and hourly consumption and production estimates at the primary cabin level and the provincial level, is designed to support sub-provincial REC configuration analysis and is the most direct link between the territorial energy baseline established here and the operational REC planning tools reviewed in Chapter 2.

When considered collectively, the scenario findings provide Abruzzo with a logical planning narrative. The area has significant renewable resources, especially in its western Apennine terrain, and a building stock whose energy consumption is not exceptionally high when compared to similar Italian regions. Even Scenario B, the suggested medium-term target, calls for investment volumes that are within the range of what Italian renewable policy has shown it can mobilize at the regional scale over a decade, so the gap between current production and the levels necessary for meaningful self-sufficiency is significant but not insurmountable. However, the study also reveals that narrowing the annual production gap is a prerequisite for territorial energy resilience, but not a sufficient one. Investing in production capacity alone, without accompanying storage or demand flexibility, will only partially address the structural problem of the temporal mismatch between the production and use of renewable energy. Future research, building on the hourly framework developed in this thesis, will need to delve more into this aspect of the issue.

Chapter 5: Conclusions and Planning Implications

5.1 Summary of Principal Findings

The purpose of this thesis was to determine how much of the electricity needs of the four provinces of Abruzzo can be met by local renewable generation, at a temporal resolution fine enough to identify discrepancies hidden by annual balances, and to determine how much more generation capacity would be needed to close that gap under alternative self-sufficiency targets. Three research questions structured the analysis. The findings that emerge from Chapters 3 and 4 in response to each are summarized below.

In response to RQ1, concerning the annual electricity consumption and renewable production of each Abruzzo province and the implications for current self-sufficiency, the analysis established that all four provinces are in persistent electrical energy deficit. Total annual electricity consumption across the region amounts to approximately 4,905 GWh, against a total actual renewable production of approximately 1,541 GWh, yielding a regional self-sufficiency ratio of roughly 31%. L'Aquila has the highest Self-Sufficiency Index at the provincial level, at 40.4%, thanks to its balanced solar-wind generation mix and relatively lower demand. Due to its extremely high consumption in the industrial and service sectors as well as its power portfolio's 88.4% reliance on solar PV, Teramo registers the lowest at 20.7%. At 38.7% and 24.8%, respectively, Chieti and Pescara hold intermediate places. Every province has a Self-Consumption Index of 100%, indicating that there is no annual overproduction and that all locally generated renewable electricity is fully consumed by local demand. The amount of power that each province currently imports from the national grid is represented by the structural gap between production and consumption, which ranges from 633 GWh in L'Aquila to 1,133 GWh in Teramo. Given Abruzzo's geographic endowment, this deficit position is not inevitable, according to the comparative overview across the five study regions. Neighboring Basilicata, sharing comparable Apennine terrain and latitude, already exports electricity thanks to intensive wind energy development over the past two decades, while the alpine regions of Valle d'Aosta and Trentino-Alto Adige achieve large surpluses through hydroelectric dominance.

In response to RQ2, concerning the temporal structure of the demand-supply mismatch and its seasonal and monthly variation, the analysis revealed that the energy deficit in Abruzzo is persistent across all hours of the day and all months of the year, with no province achieving a sustained surplus at any temporal resolution examined. Due to the combination of wind output and moderate sun irradiation in the early spring, L'Aquila and Chieti exhibit their optimum self-sufficiency conditions monthly in February and March, attaining monthly SSI values of almost 50%. In contrast to Teramo, whose monthly SSI closely follows the solar irradiance cycle and never rises over 24% in any month, falling to 8.2% in January when solar production is at its lowest, this winter-to-spring SSI peak is a wind-driven occurrence. The analysis revealed a consistent structural pattern at the hourly scale in all four provinces: a midday production window of roughly four to five hours in the summer, when local demand is partially

offset by solar generation, surrounded by deficit periods in the morning and evening when local production makes little to no contribution. While wind-bearing regions like L'Aquila and Chieti maintain a modest overnight production baseline that somewhat mitigates the nocturnal shortfall, this noon window narrows to almost nil in winter for solar-dependent provinces like Teramo and Pescara. The evening consumption peak, which represents the highest demand period of the day in every season, is never covered by local renewable production in any province, since it occurs after solar output has declined and wind alone is insufficient to bridge the gap. This temporal mismatch between midday solar production and evening demand constitutes the central structural challenge for REC planning in Abruzzo.

In response to RQ3, concerning the additional renewable generation capacity required to reach 40%, 75%, and 100% self-sufficiency, the scenario analysis quantified the production gap for each province under three progressively ambitious targets. In Scenario A, which aims for 40% SSI, Chieti only needs 20.1 GWh of new production, Pescara 129.3 GWh, and Teramo 275.2 GWh, whereas L'Aquila already fulfills the requirement and needs no additional capacity. With increased needs of 367.9 GWh for L'Aquila, 567.0 GWh for Chieti, 427.0 GWh for Pescara, and 775.3 GWh for Teramo, the requirements significantly increased under Scenario B, which aims for 75% SSI. Teramo alone would need an extra 1,132.5 GWh of renewable energy under Scenario C, which aims for complete self-sufficiency. This is a roughly four-fold increase over its existing total output and suggests a very significant expansion of solar capacity under the proportional expansion assumption. In contrast to Teramo, whose near-total reliance on solar energy concentrates nearly all additional capacity requirements in a single intermittent source that is unable to address the province's structural evening deficit, provinces with diverse generation mixes, especially L'Aquila and Chieti, face a more manageable and technologically diverse investment path toward higher self-sufficiency, according to the source-type disaggregation of these requirements. Based on these findings, Scenario B at 75% SSI is identified as the most balanced planning target for the region, offering meaningful progress toward energy independence while remaining within a scale of additional capacity broadly consistent with Italy's PNIEC 2030 renewable expansion trajectory.

5.2 Planning Recommendations for Renewable Energy Communities in Abruzzo

5.2.1 Provincial Investment Priorities by Renewable Source Type

The scenario analysis presented in Section 4.5 established how much additional renewable generation capacity each Abruzzo province would need to reach meaningful self-sufficiency targets, and the source-type disaggregation in Table 4.3 identified where that capacity should come from given each province's current generation mix. Translating these quantitative findings into investment priorities requires connecting the production gap figures to the territorial characteristics and resource endowments documented in Section 4.4, since not all additional capacity is equally feasible or equally effective at addressing the temporal mismatch problem identified in Section 4.4.5.

For L'Aquila, the recommended investment priority is the continued and balanced expansion of both solar and wind capacity, following the province's existing generation mix. The Apennine terrain of L'Aquila provides demonstrated wind resource on exposed ridgelines and plateaus, and large areas of south-facing mountain slopes and open valley floors are suitable for ground-mounted photovoltaic installations. The province's balanced solar-wind profile and 40.4% SSI make it the best place in the four provinces for REC development, and targeted expansion of both source types would strengthen this advantage and improve production timing. Scenario B requires L'Aquila to add 171 GWh of solar and 162 GWh of wind, a large but possible growth considering the province's geographical resource base.

Chieti's most strategic investment is wind capacity. At 272.33 GWh, Chieti has the largest absolute wind production of the four provinces, and the temporal analysis showed that wind generation occurs in the early morning and overnight when solar output is zero and residential and industrial demand is high. Thus, adding wind capacity in Chieti would eliminate the annual output gap and enhance the province's hourly demand-supply matching, eliminating the evening shortfall in all four provinces. The Val di Sangro industrial corridor, which drives much of Chieti's high electricity demand, operates during daytime hours and could benefit from the daytime solar component of a diversified investment strategy, while the overnight wind component would serve the residential and service loads that persist after industrial activity ceases.

For Pescara, the investment challenge is more constrained. The province's almost complete absence of wind resource limits diversification options, and its generation mix of solar, hydro, and biomass already reflects what the local resource endowment can realistically support. The expansion of distributed rooftop solar across the dense coastal urban fabric is suggested as the top priority within these limitations, along with modest increases in small hydropower capacity on the Pescara River where both technically and environmentally possible. Because Pescara cannot rely on wind to extend its productive hours beyond the solar window, battery storage would be especially beneficial. By shifting the midday solar surplus into the evening peak, storage would address the temporal mismatch that more solar capacity alone cannot.

Moving away from solar homogeneity rather than simply expanding present capacity proportionately is the most important planning recommendation for Teramo. The temporal analysis shows that Teramo's near-total solar dependence causes the most severe and structurally intractable demand-supply mismatch of any province in the dataset, with nearly zero production in winter and a narrow midday window in summer that leaves the evening peak completely uncovered in every season. Increasing solar capacity would enhance the summer midday window but have no influence on the year-round evening deficit or winter near-zero production, according to Scenario B's proportionate expansion assumption. Teramo's primary strategic objective should therefore be to identify and harness wind resources in the province's western Apennine areas, whose terrain may permit turbine installations despite the area's historically poor wind development. This recommendation goes beyond what the proportional expansion scenarios can quantify but is directly motivated by the hourly temporal analysis of Section 4.4.5, which showed that a wind component is what Teramo's generation profile most fundamentally lacks.

5.2.2 REC Configuration Strategies for Demand-Supply Temporal Matching

The self-sufficiency scenarios defined in Section 3.4 and evaluated in Section 4.5 treat each province as an independent energy unit, measuring how much additional capacity would be needed for each province to meet its own demand from its own production. Since the Italian REC framework under Legislative Decree 199/2021 is intended to facilitate energy sharing between producers and consumers within the same primary substation service area, this province-level framing is analytically helpful for identifying spatial investment priorities.

The core geographic unit of the Italian REC regulatory system is the major substation boundary. Every member of REC must be connected to the same low-voltage or medium-voltage transformer substation. The Collective Self-Consumption benefit is determined on an hourly basis by taking the minimum of the energy taken out of the grid and the energy provided into the grid within each substation region. Because the calculation is done hourly rather than on a daily or monthly aggregate, a producer who feeds energy into the grid at hour 12 benefits members who withdraw energy at hour 12 but not members who withdraw at hour 20. This means that the temporal matching of production and consumption profiles within a substation area is just as important as the absolute volume of production.

This regulatory structure has a direct implication for REC design in Abruzzo that the provincial-scale analysis of this thesis illuminates clearly. The provinces with the best temporal production profiles, namely L'Aquila and Chieti with their wind-enhanced overnight baselines, are also the provinces with the largest industrial consumption concentrated in daytime hours. A REC configured within a substation area in western L'Aquila or western Chieti, aggregating wind producers with industrial consumers whose demand is highest during working hours, would achieve a more favorable collective self-consumption ratio than a REC composed entirely of solar producers and residential consumers, since the wind production baseline aligns better with the continuous industrial load than the intermittent solar peak does.

The most effective REC design method for coastal provinces like Pescara and Teramo, where solar dominates output and residential consumption dominates demand, is to aggregate users with complementary temporal demand profiles rather than similar ones. A REC that combines residential prosumers, whose solar production peaks at midday but whose consumption peaks in the evening, with commercial or service users, whose consumption is concentrated in daytime hours, can achieve higher collective self-consumption than a purely residential REC because the commercial daytime demand absorbs the midday solar surplus that would otherwise be fed back into the grid at zero collective benefit. The data infrastructure developed in this thesis, which provides hourly consumption and production profiles at the primary cabin level, is designed to support exactly this kind of substation-scale REC configuration analysis.

Storage systems represent the most direct technical tool for improving temporal matching within a REC regardless of generation mix. As demonstrated by the scenario analysis in the Villar Pellice case study by Mutani et al. (2021), battery storage sized to shift midday solar surplus into the evening demand peak can substantially improve both the Self-Sufficiency Index and the Self-Consumption Index of a REC without requiring additional generation capacity. For Abruzzo provinces, particularly Teramo and Pescara where the solar-only

generation profile creates a systematic afternoon surplus and evening deficit pattern, storage integration should be considered a complementary component of any REC design rather than an optional upgrade.

5.2.3 Policy and Governance Implications

The findings of this thesis have implications not only for the technical design of individual RECs but also for the regulatory and governance framework within which REC development in Abruzzo is organized. Three governance recommendations emerge directly from the analysis.

The first relates to how the self-sufficiency scenario structure created in this thesis aligns with provincial energy planning. The proper institutional level to convert the provincial SSI gap statistics reported in Chapter 4 into legally binding or suggestive renewable capacity targets is the region of Abruzzo through its Piano Energetico Ambientale Regionale. In accordance with the PNIEC national framework, adopting Scenario B as the regional planning horizon for 2030 would provide municipalities and energy communities with a precise and measurable benchmark by which to assess their respective contributions. A distinct provincial renewable development strategy within the regional energy plan might be based on the provincial breakdown given in Table 4.3, which provides a ready-made spatial allocation of this regional target throughout the four provinces.

Prioritizing public buildings and municipal assets as anchor prosumers in REC development is the subject of the second recommendation. The strategic role of public buildings as founding members of RECs is already acknowledged by the Italian regulatory framework, especially through the provisions of Ministerial Decree 414/2023 (Ministero dell'Ambiente e della Sicurezza Energetica, 2023b), which introduced specific incentives for municipalities with fewer than 5,000 residents. The building stock database developed in this project, which identifies and classifies all public-sector buildings including schools, healthcare facilities, municipal offices, and public lighting infrastructure across Abruzzo, provides the spatial and volumetric foundation for a systematic identification of which public buildings in each primary cabin area have the greatest potential to contribute to REC formation as prosumers. Integrating this building-level information with the hourly consumption profiles documented in Chapter 4 would allow municipal energy planners to identify the substation areas where a single public building retrofit with photovoltaic installation could provide the most significant boost to collective self-consumption for surrounding residential members.

The third recommendation concerns the governance of cross-provincial energy flows within the Abruzzo territorial system. The provincial-scale analysis of this thesis showed that L'Aquila and Chieti together produce more renewable electricity per unit of consumption than Teramo and Pescara, and that the production mix of the western mountain provinces is temporally more diverse than that of the eastern coastal provinces. While the current REC regulatory framework limits energy sharing to the primary substation scale and does not permit cross-provincial virtual sharing, the evolution of Italian energy community legislation, particularly through the ongoing implementation of RED III under Directive 2023/2413/EU (European Parliament and Council of the European Union, 2023), may progressively expand the geographic scope of

eligible energy sharing arrangements. In anticipation of this regulatory evolution, it would be valuable for the Abruzzo regional authority to map the primary cabin areas in L'Aquila and Chieti with the highest surplus production potential under Scenario B and to assess their proximity to high-demand cabin areas in Pescara and Teramo, establishing the groundwork for a territorial energy solidarity framework that goes beyond the current substation-scale limitation.

5.3 Contributions and Limitations of the Research

Contributions

This thesis makes three distinct contributions to the field of urban and regional energy planning, operating at different scales of generality.

The creation of a standardized, building-level energy database for five Italian regions as part of the Urban Energy Atlas project is the first and most obvious contribution. In order to support energy analysis at scales ranging from the individual building to the provincial aggregate, the database combines regional building geometry, ISTAT census data, ARERA electricity consumption profiles, and the GSE renewable plant registry into a single spatially referenced infrastructure. The development of a unified ten-category building use classification system that addresses the terminological heterogeneity of Italian regional building datasets, a four-level hierarchical height estimation procedure that assigns plausible building heights across a stock of more than 600,000 records by combining regional attributes, ISTAT floor-count indicators, and DSM-derived measurements, and a multi-sector consumption estimation pipeline that distributes non-residential demand through volumetric allocation weighted by ISTAT employee counts. These methodological components are documented in sufficient detail in Chapter 3 to be reproduced and adapted for other Italian regions, and they represent a practical contribution to the ongoing construction of the national Urban Energy Atlas beyond the five regions directly processed in this project.

The second contribution is the temporal extension of the annual energy balance analysis into hourly and monthly resolution for the four Abruzzo provinces. Current regional energy evaluations in Italy are based on annual and, at most, monthly aggregates, such as the ENEA annual efficiency reports that were used as a calibration reference for the consumption model. This thesis shows that resolving the energy balance to the hourly scale reveals a structural temporal mismatch between electricity demand and renewable production that is not captured by annual statistics and that directly affects the viability and design of Renewable Energy Communities. The finding that the evening consumption peak is systematically uncovered by local renewable production in every province and every season, regardless of how high annual self-sufficiency rises, is a result that emerges only from hourly analysis and that fundamentally shapes the planning recommendations offered in Section 5.2. This temporal dimension of territorial energy assessment represents a methodological advance relative to the existing Italian atlas literature reviewed in Section 2.6.

The third contribution is the scenario framework developed in Section 3.4 and applied in Section 4.5, which translates the abstract concept of self-sufficiency into concrete, province-

specific capacity targets disaggregated by renewable source type. While self-sufficiency scenarios are not new in the REC literature, their application at the provincial scale with source-type disaggregation grounded in actual registered plant data is less common, and the connection between the scenario results and the hourly temporal analysis provides a richer planning basis than annual SSI targets alone. The identification of Scenario B at 75% SSI as the recommended planning target for Abruzzo, justified through its alignment with PNIEC 2030 national trajectories and its compatibility with the territorial resource base of each province, represents a concrete policy output that the regional energy planning authority could directly adopt as a spatial planning reference.

Limitations

Several limitations of the methodology and data used in this thesis should be acknowledged explicitly, complementing the technical discussion already provided in Section 3.5.

The most significant boundary condition of the entire analysis is the restriction to electricity only. Space heating and cooling delivered through natural gas, district heating, or other thermal carriers is not captured by the consumption model, and renewable heat production from solar thermal, geothermal, or biomass combustion is not included in the production model. In Abruzzo, where the mountain provinces experience cold winters with high heating degree-day counts, thermal energy represents a substantial share of total building energy demand. The SSI values reported in Chapter 4 therefore overestimate the true degree of territorial energy independence relative to total energy needs. Extending the analysis to include thermal energy would require a fundamentally different data infrastructure and lies outside the scope of this project, but it is an important caveat that the reader should bear in mind when interpreting the self-sufficiency results.

The consumption estimates at the building level carry uncertainty from two principal sources. The first is the volumetric proportionality assumption, which treats volume as a proxy for occupancy in a way that ignores actual variation in household size, occupancy rate, or per-capita consumption within a census section. This assumption is used to allocate census-section dwelling counts and employee counts among individual buildings. The second is the non-residential sectors' use of 2011 ISTAT employee data, which is over ten years old and might not fairly represent the distribution of economic activity today, especially in provinces that have undergone substantial industrial restructuring since the census reference year.

Instead of using plant-specific measured generation values, the production estimates rely on province-level usage hours generated from GSE data reports, which provide averages across source types. A consistent provincial utilization hour cannot account for the variations in individual plant productivity caused by local wind speed, shading circumstances, plant age, and maintenance status. Plants installed or decommissioned after October 2021 are not included in the analysis due to the plant registration reference date, which causes a rising disparity between the modeled and actual production base over time.

Finally, the scenario analysis rests on the proportional expansion assumption, which holds the current renewable energy mix of each province constant as total capacity scales upward. As

discussed in Section 4.5.2, this assumption is methodologically transparent and reproducible but reproduces existing technological imbalances rather than correcting them. For Teramo in particular, proportional expansion amplifies solar dependence rather than addressing it, which means the scenario results for that province understate the planning effort that would actually be required to achieve the target SSI in a way that also improves temporal matching.

5.4 Directions for Future Work

The analysis presented in this thesis establishes a provincial-scale electrical energy baseline for Abruzzo and four other Italian regions, identifies the temporal structure of the demand-supply mismatch, and quantifies the additional renewable capacity required to reach defined self-sufficiency targets. Several directions for future work emerge naturally from these findings, each of which would extend the analytical reach of the present contribution in a meaningful and practically relevant way.

The most immediate and impactful extension would be the integration of the energy balance results produced in this thesis with the spatial suitability and restriction mapping being developed in parallel by other members of the Urban Energy Atlas project group. The scenario analysis in Section 4.5 identified how much additional renewable production each Abruzzo province needs and what source types should provide it, but it cannot answer the question of where within each province that capacity could actually be installed. Renewable energy installations in Italy are subject to a complex and layered set of spatial constraints: national parks and protected natural areas, landscape heritage designations under the Codice dei Beni Culturali, agricultural land protection regulations, minimum distance requirements from residential buildings for wind turbines, and local urban planning restrictions (Italian Republic, 2004). The restriction map being produced within the Urban Energy Atlas project will identify, for each area of the study territory, which categories of renewable installation are permitted, which are subject to authorization, and which are excluded entirely. The scenario results would be transformed from indicative targets into spatially actionable planning guidance by overlaying the provincial capacity gap figures from Table 4.3 with this spatial suitability layer. This would enable the identification of primary cabin service areas where the necessary additional solar or wind capacity could realistically be installed within regulatory constraints. The most straightforward step in transforming the Urban Energy Atlas from an analytical reference into an operational planning tool is this integration.

A second important direction is the disaggregation of the provincial-scale analysis to the primary cabin service area level, which is the spatial unit that actually governs REC membership eligibility under Legislative Decree 199/2021. The database infrastructure developed in this thesis already contains the spatial mapping of each building and each renewable plant to its containing primary cabin area, through the primarycabins_2025 layer described in Section 3.1.1. The consumption and production estimation pipelines could therefore be run at the cabin level rather than the provincial level with relatively modest additional effort, producing self-sufficiency indicators and hourly demand-supply profiles for each of the hundreds of primary cabin areas within Abruzzo. This sub-provincial resolution would allow energy planners and municipal administrators to identify which specific cabin

areas already have favorable conditions for REC formation, where the production-to-consumption ratio is highest, where the temporal matching between local solar production and local demand is most favorable, and where public building prosumers could anchor a new community energy initiative. Moving from the provincial to the cabin scale is the analytical step that connects the territorial energy baseline of this thesis most directly to the operational design of specific RECs on the ground.

A third direction concerns the extension of the analysis to thermal energy. As acknowledged in Section 5.3, the restriction of the consumption model to electricity means that the self-sufficiency indicators reported in this thesis capture only part of the total building energy picture. Space heating is the dominant energy use in the colder mountain provinces of Abruzzo, and its decarbonization through heat pumps, solar thermal collectors, or district heating fed by biomass or geothermal sources is a planning challenge of comparable importance to the electricity self-sufficiency question addressed here. Extending the Urban Energy Atlas framework to include thermal energy carriers would require additional data sources, most importantly gas distribution records and heating plant registries that are not currently integrated into the project database, but the building-level volumetric and classification infrastructure developed in this thesis provides a ready-made geometric foundation on which a thermal energy layer could be built. Given the growing importance of heat pump electrification as a decarbonization pathway, a combined electricity and thermal model would also allow the project to address the interaction between the two sectors: as heating is progressively electrified through heat pumps, electricity demand will increase and its seasonal and daily profile will shift in ways that the current electricity-only model cannot anticipate.

A fourth direction is the extension of the methodology to the remaining Italian regions not yet covered by the Urban Energy Atlas project. Since they only cover a small portion of the country's building stock, the five districts examined in this thesis constitute a varied sampling of Italian territorial circumstances, from the wind-rich Apennine south and the Mediterranean islands to the Alpine hydropower north. Resolving the data harmonization issues outlined in Chapter 3 for each additional regional building dataset would be necessary to scale the methodology to all twenty Italian regions. The unified classification system and hierarchical height estimation procedure documented in this thesis are designed to be replicable and adaptable, and they provide the methodological foundation for this national scaling effort. A fully national Urban Energy Atlas, combining provincial-scale energy balance results with the spatial suitability mapping and primary cabin disaggregation described above, would represent a significant contribution to the Italian energy planning infrastructure and a resource of direct value to the national and regional authorities responsible for implementing the PNIEC 2030 targets at territorial scale.

Finally, the scenario framework developed in Section 3.4 could be extended to incorporate economic dimensions that the present analysis deliberately set aside. The proportional expansion scenarios quantify the additional generation capacity required to reach each self-sufficiency target but say nothing about the investment costs, the available incentive structures, or the payback times associated with reaching those targets. A cost-optimal extension of the scenario analysis, following the approach developed by Mutani et al. (2021) for the Villar

Pellice REC and adapting it to the provincial scale, would allow the comparison of alternative pathways to Scenario B not only in terms of the capacity mix but also in terms of economic return for different categories of investors, including municipalities, residential prosumers, and industrial actors. This economic layer would transform the scenario results from a statement of what is physically required into a statement of what is financially viable under current Italian incentive frameworks, providing the final link between the territorial energy baseline established in this thesis and the investment decisions that will ultimately determine whether Abruzzo's self-sufficiency gap closes in the years ahead.

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Appendix A: Building Use Classification Dictionaries for the Five Study Regions

This appendix presents the building use classification dictionaries applied to each of the five regional building datasets processed within the Urban Energy Atlas project. For each region, the table maps every original use label present in the regional dataset to the corresponding unified classification code described in Section 3.2.1. The dictionaries were constructed through a systematic review of regional metadata documentation and applied exhaustively to all building records before any energy calculation was performed. Labels are reproduced in their original Italian form as they appear in the source datasets.

Table A.1: Building Use Classification Dictionary - Abruzzo (D.B.T.R. Regione Abruzzo)

Original Label (Regional Dataset)	Unified Classification Code
Edificio agro-forestale, stalla, rimessa attrezzi agricoli	PA
Edificio civile	RL
Edificio di culto / Sede comunale	TC
Edificio in costruzione / Stabilimento, opificio	SP
Torre, campanile, faro	Others

Source: Developed by the Urban Energy Atlas project group, Politecnico di Torino, in collaboration with ENEA (2025).

Table A.2: Building Use Classification Dictionary - Basilicata (CTR vettoriale per Comune)

Original Label (Regional Dataset)	Unified Classification Code
Agricoltura / agricoltura – allevamento / agricoltura – fienile / agricoltura – stalla	PA
Residenziale	RL
Amministrativo / amministrativo – municipio / amministrativo - sede provincia / amministrativo - sede regione / commerciale / commerciale – mercato / commerciale - sede di centro commerciale / luogo di culto / ricreativo - sede di attività culturali – cinema / ricreativo - sede di attività culturali – museo / servizio pubblico	TC
Industriale / industriale - impianto di produzione energia / industriale - impianto di produzione energia - stazione di trazione / industriale – inceneritore / industriale - stabilimento industriale / servizi di trasporto - ferroviario - deposito ferroviario per vagoni, rimessa locomotive	SP
carcere, istituto di pena / militare / ricreativo - sede di attività culturali / ricreativo - sede di attività culturali – biblioteca / ricreativo - sede di attività culturali – pinacoteca / ricreativo - sede di attività sportive - piscina coperta / servizi di trasporto / servizi di trasporto - aereo – eliporto / servizi di trasporto – ferroviario / servizi di trasporto - ferroviario - casello ferroviario / servizi di trasporto - ferroviario - fermata ferroviaria / servizi di trasporto - ferroviario - stazione passeggeri ferroviaria / servizi di trasporto – stradale / servizi di trasporto - stradale - parcheggio multipiano o coperto / servizi di trasporto - stradale - stazione autolinee / servizio pubblico – sanità / servizio pubblico - sanità - sede clinica / servizio pubblico - sanità - sede di Ospedale / servizio pubblico - sanità - sede servizi sanitari asl / servizio pubblico - sede di forze dell'ordine / servizio pubblico - sede di tribunale / servizio pubblico - sede di vigili del fuoco / strutture ricettive / strutture ricettive - rifugio montano / strutture ricettive - struttura alberghiera	TH

Original Label (Regional Dataset)	Unified Classification Code
Ricreativo / ricreativo - sede di attività culturali - teatro, auditorium / ricreativo - sede di attività sportive / ricreativo - sede di attività sportive – palestra	TI
servizio pubblico – istruzione / servizio pubblico - istruzione - sede di scuola / servizio pubblico - istruzione – università	TS
altro	Others

Source: Developed by the Urban Energy Atlas project group, Politecnico di Torino, in collaboration with ENEA (2025).

Table A.3: Building Use Classification Dictionary - Sardegna (DBGT 1:10,000)

Original Label (Regional Dataset)	Unified Classification Code
Agricolturale / stalla	PA
Residenziale	RL
Amministrativo / cinema / commerciale / convento / luogo di culto / mercato / municipio / museo / oratorio / sede di centro commerciale / sede di poste-telegrafi / sede di supermercato, ipermercato / sede provincia / sede regione / servizio pubblico	TC
deposito ferroviario per vagoni, rimessa locomotive / impianto di produzione energia / industriale / stabilimento industriale	SP
Aereo / altro impianto di trasporto / biblioteca / carcere, istituto di pena / caserma / centrale elettrica / centrale idroelettrica / centrale termoelettrica / fermata ferroviaria / ferroviario / militare / parcheggio multipiano o coperto / pinacoteca / piscina coperta / sanità / sede di attività culturali / sede di forze dell'ordine / sede di Ospedale / sede di tribunale / sede di vigili del fuoco / sede servizi sanitari asl / servizi di trasporto / stazione autolinee / stazione di telecomunicazioni / stazione marittima / stazione passeggeri aeroportuale / stazione passeggeri ferroviaria / struttura alberghiera / strutture ricettive	TH
Palaghiaccio / palestra / ricreativo / sede di attività sportive / teatro, auditorium	TI
Istruzione / sede di scuola	TS
Altro / casa cantoniera / casello ferroviario / casello forestale	Others

Source: Developed by the Urban Energy Atlas project group, Politecnico di Torino, in collaboration with ENEA (2025).

Table A.4: Building Use Classification Dictionary - Trentino-Alto Adige (Carta Tecnica Provinciale)

Original Label (Regional Dataset)	Unified Classification Code
Agriculture / Capannone vivai / Serra / Stalla- Fienile /	PA
Residential / Civile	RL
commerceAndServices / Baracca / Edificio Culto / Luoghi di culto	TC
Industriale	SP
Casello- Staz / Centrale-Cabina	TH
Portico loggia	Others

Source: Developed by the Urban Energy Atlas project group, Politecnico di Torino, in collaboration with ENEA (2025).

Table A.5: Building Use Classification Dictionary - Valle d'Aosta (Edifici e Viabilità da Ortofoto)

Original Label (Regional Dataset)	Unified Classification Code
Infrastrutture Agricole	PA
Residenziale	RL
Castelli e palazzi di eminenti pregi artistici o storici / Servizi commerciali / Servizi finanziari e assicurativi / Servizi religiosi / Uffici e studi privati	TC

Original Label (Regional Dataset)	Unified Classification Code
Industrie dei prodotti finali leggeri / Magazzini e locali di deposito	SP
Pubblica amministrazione, difesa militare e sicurezza / Servizi culturali interni / Servizi di alloggio e ristorazione / Servizi sanitari e sociali	TH
Infrastrutture sportive	TI
Scienza, ricerca ed educazione	TS
Altri usi / Non classificato / Stalle, scuderie, rimesse e autorimesse	Others

Source: Developed by the Urban Energy Atlas project group, Politecnico di Torino, in collaboration with ENEA (2025).

Appendix B: SQL Implementation of Electricity Consumption and Renewable Production Estimation Pipelines

This appendix presents selected SQL queries from the generalized pipelines used to implement the building-level electricity consumption and actual renewable production estimation described in Chapter 3. The code was developed and executed within a PostgreSQL database extended with the PostGIS spatial extension, using DBeaver as the client interface, and was applied to all five study regions processed within the Urban Energy Atlas project: Abruzzo, Basilicata, Sardegna, Trentino-Alto Adige, and Valle d'Aosta. All tables follow the naming convention [region_schema]_[table_name], where [region_schema] is the lowercase schema name of the target region. Administrative boundary layers (prov_2024, primarycabins_2025) and energy reference tables (prelievo_medio_dei_clienti_domestici, rapporto_annuale_sull_efficienza_energetica) are stored in the public schema and shared across all regional schemas. The coordinate reference system used throughout is EPSG:32632 (ETRS89 / UTM zone 32N). Complete pipeline scripts are available from the author upon request.

B.1 Electricity Consumption Estimation Pipeline

This section presents selected SQL queries illustrating the core analytical steps of the electricity consumption estimation pipeline described in Section 3.3.1, implemented in PostgreSQL with the PostGIS spatial extension. Six queries are shown, covering the spatial assignment of buildings to administrative boundaries via ST_Intersects operations, the downscaling of census dwelling counts and sectoral employee counts to individual buildings using volumetric shares, the annual consumption calculation for each of the four sectors (residential, services, industry, and agriculture), and the hourly temporal disaggregation using lookup table coefficients. Each query is implemented as a PostgreSQL UPDATE, INSERT, or DO block operation. The queries are presented in generalized form using placeholder notation: replace [region_schema] with the schema name of the target region and [region_code] with the corresponding ISTAT region code as used in the ENEA energy balance reference table. Complete pipeline scripts including geometry preparation, spatial indexing, volumetric allocation, and denominator aggregation steps are available from the author upon request.

```
-- ============================================================
-- QUERY 1: SPATIAL MAPPING
-- Each building assigned to province, census sections,
-- and primary substation area via spatial intersection
-- ============================================================

INSERT INTO [region_schema].[region_schema]_building_spatial_mapping
    (building_fid, year)
SELECT fid::text, 2024
FROM [region_schema].[region_schema]_buildings;

UPDATE [region_schema].[region_schema]_building_spatial_mapping m
SET cod_prov = p.cod_prov::text
FROM [region_schema].[region_schema]_buildings b,
     public.prov_2024 p
WHERE m.building_fid = b.fid::text
```

```
  AND ST_Intersects(b.geom_cnt, p.geom);

-- Same pattern repeated for sez2011, sez2021, and cod_ac

-- ============================================================
-- QUERY 2: DWELLING DOWNSCALING
-- Dwellings distributed from census section to buildings
-- using residential volume share and vacancy rate
-- active_dwellings = (res_v / total_res_v) x A8 x (1 - r_empty)
-- ============================================================

UPDATE [region_schema].[region_schema]_buildings_integrated AS b
SET
    dw_a8_21 = CASE
        WHEN b.total_res_v_sez > 0
        THEN (b.res_v / b.total_res_v_sez)
             * COALESCE(i21.a8::float, 0)
        ELSE 0 END,
    active_dwellings_21 = CASE
        WHEN b.total_res_v_sez > 0
        THEN ((b.res_v / b.total_res_v_sez)
             * COALESCE(i21.a8::float, 0))
             * (1 - b.ratio_empty_11)
        ELSE 0 END
FROM [region_schema].r13_indicatori_2021_sezioni AS i21
WHERE b.sez2021::text = i21.sez21_id::text
  AND b.is_energy_relevant = TRUE;

-- ============================================================
-- QUERY 3: RESIDENTIAL CONSUMPTION
-- C_res = active_dwellings x ARERA average kWh per dwelling
-- Reference year 2024, matched by province code
-- ============================================================

UPDATE [region_schema].[region_schema]_buildings_integrated AS b
SET cons_res_kwh_yr = b.active_dwellings_21 * a.yearly_kwh
FROM [region_schema].[region_schema]_building_spatial_mapping AS m
JOIN public.prelievo_medio_dei_clienti_domestici AS a
    ON m.cod_prov::text = a.cod_prov::text
WHERE b.fid::text = m.building_fid::text
  AND a.year = 2024
  AND b.is_energy_relevant = TRUE;

-- ============================================================
-- QUERY 4: SERVICE SECTOR CONSUMPTION (RESIDUAL METHOD)
-- k_ser = (civil_total - residential_total) / service_employees
-- C_ser = work_ser x k_ser
-- Replace [region_code] with ISTAT region code
-- ============================================================

WITH regional_metrics AS (
    SELECT civile_gWh * 1000000.0 AS total_civil_kwh
    FROM public.rapporto_annuale_sull_efficienza_energetica
    WHERE report_year = 2025
      AND cod_reg = [region_code]
    LIMIT 1
),
assigned_totals AS (
    SELECT
        SUM(COALESCE(cons_res_kwh_yr, 0)) AS total_res_assigned,
        SUM(work_ser_11) AS total_emp_relevant
    FROM [region_schema].[region_schema]_buildings_integrated
    WHERE is_energy_relevant = TRUE
),
factor_calc AS (
    SELECT (rm.total_civil_kwh - att.total_res_assigned)
           / NULLIF(att.total_emp_relevant, 0) AS kwh_per_emp
    FROM regional_metrics rm, assigned_totals att
```

```
)
UPDATE [region_schema].[region_schema]_buildings_integrated AS b
SET cons_ser_kwh_yr =
    COALESCE(b.work_ser_11, 0) * fc.kwh_per_emp
FROM factor_calc fc
WHERE b.is_energy_relevant = TRUE;

-- ============================================================
-- QUERY 5: INDUSTRY AND AGRICULTURE CONSUMPTION
-- Proportional downscaling from ENEA regional sectoral totals
-- C_ind = (work_ind / sum_ind) x ENEA_ind_total
-- C_agr = (work_agr / sum_agr) x ENEA_agr_total
-- Replace [region_code] with ISTAT region code
-- ============================================================

WITH regional_source AS (
    SELECT industria_gWh AS total_ind_gwh,
           "agricoltura e pesca_gwh" AS total_agr_gwh
    FROM public.rapporto_annuale_sull_efficienza_energetica
    WHERE report_year = 2025
      AND cod_reg = [region_code]
    LIMIT 1
),
global_drivers AS (
    SELECT SUM(work_ind_11) AS sum_ind,
           SUM(work_agr_11) AS sum_agr
    FROM [region_schema].[region_schema]_buildings_integrated
    WHERE is_energy_relevant = TRUE
)
UPDATE [region_schema].[region_schema]_buildings_integrated AS b
SET
    cons_ind_kwh_yr = CASE
        WHEN gd.sum_ind > 0
        THEN (b.work_ind_11 / gd.sum_ind)
             * src.total_ind_gwh * 1000000.0
        ELSE 0 END,
    cons_agr_kwh_yr = CASE
        WHEN gd.sum_agr > 0
        THEN (b.work_agr_11 / gd.sum_agr)
             * src.total_agr_gwh * 1000000.0
        ELSE 0 END
FROM regional_source src, global_drivers gd
WHERE b.is_energy_relevant = TRUE;

-- ============================================================
-- QUERY 6: HOURLY TEMPORAL DISAGGREGATION
-- Annual consumption disaggregated into 24-element arrays
-- for each month and day type using lookup table coefficients
-- C_sector[h,m,d] = C_annual x coeff[h,m,d,sector,province]
-- ============================================================

DO $$
DECLARE m integer;
BEGIN
    FOR m IN 1..12 LOOP
        CREATE TEMP TABLE temp_monthly_lookup AS
        SELECT cod_prov::text AS cod_prov, hour, fr_fs,
            MAX(CASE WHEN sector = 'res'
                THEN coefficient ELSE 0 END) AS res_coeff,
            MAX(CASE WHEN sector = 'ind'
                THEN coefficient ELSE 0 END) AS ind_coeff,
            MAX(CASE WHEN sector = 'ser'
                THEN coefficient ELSE 0 END) AS ser_coeff,
            MAX(CASE WHEN sector = 'agr'
                THEN coefficient ELSE 0 END) AS agr_coeff
        FROM
[region_schema].[region_schema]_consumption_hourly_profile_lookup
        WHERE month::integer = m
```

```
        GROUP BY cod_prov, hour, fr_fs;

        INSERT INTO
        [region_schema].[region_schema]_building_hourly_consumption
        SELECT fid, 2024, m, fr_fs,
            array_agg(r_k::numeric(10,3) ORDER BY hour),
            array_agg(i_k::numeric(10,3) ORDER BY hour),
            array_agg(s_k::numeric(10,3) ORDER BY hour),
            array_agg(a_k::numeric(10,3) ORDER BY hour),
            array_agg((r_k+i_k+s_k+a_k)::numeric(10,3)
                ORDER BY hour)
        FROM (
            SELECT b.fid, p.hour, p.fr_fs,
                (COALESCE(b.cons_res_kwh_yr,0)*p.res_coeff) AS r_k,
                (COALESCE(b.cons_ind_kwh_yr,0)*p.ind_coeff) AS i_k,
                (COALESCE(b.cons_ser_kwh_yr,0)*p.ser_coeff) AS s_k,
                (COALESCE(b.cons_agr_kwh_yr,0)*p.agr_coeff) AS a_k
            FROM [region_schema].[region_schema]_buildings_integrated b
            JOIN temp_monthly_lookup p
                ON b.cod_prov::text = p.cod_prov
            WHERE b.is_energy_relevant = TRUE
              AND (COALESCE(b.cons_res_kwh_yr,0)
                  + COALESCE(b.cons_ind_kwh_yr,0)
                  + COALESCE(b.cons_ser_kwh_yr,0)
                  + COALESCE(b.cons_agr_kwh_yr,0)) > 0
        ) sub
        GROUP BY fid, fr_fs;

        DROP TABLE temp_monthly_lookup;
    END LOOP;
END $$;
```

B.2 Actual Renewable Production Estimation Pipeline

This section presents selected SQL queries illustrating the core analytical steps of the actual renewable electricity production estimation pipeline described in Section 3.3.2, implemented in PostgreSQL with the PostGIS spatial extension. Three queries are shown, covering the spatial assignment of registered renewable plants to province and primary substation service areas, the annual production calculation using province-specific equivalent full-load utilization hours by source type, and the hourly temporal disaggregation using lookup table coefficients. Italian source type labels from the GSE plant registry (ai_fonte field) are normalized to standard English labels during the annual production calculation. Each query is implemented as a PostgreSQL INSERT or DO block operation. Replace [region_schema] with the schema name of the target region. Complete pipeline scripts including geometry preparation and data type alignment steps are available from the author upon request.

```
-- ============================================================
-- QUERY 1: ANNUAL PRODUCTION CALCULATION
-- E_annual = P_installed (kW) x utilization_hours (h/yr)
-- Italian source type labels (ai_fonte) normalized to English.
-- Utilization hours are province-specific for solar and
-- uniform regional benchmarks for wind, hydro, and biomass.
-- Geothermal utilization hours are zero for all provinces.
-- ============================================================

INSERT INTO
[region_schema].[region_schema]_actual_plants_annual_production
SELECT
```

```
    a.fid,
    CASE
        WHEN UPPER(a.ai_fonte) = 'SOLARE'    THEN 'solar'
        WHEN UPPER(a.ai_fonte) = 'EOLICA'    THEN 'wind'
        WHEN UPPER(a.ai_fonte) = 'IDRAULICA' THEN 'hydroelectricity'
        WHEN UPPER(a.ai_fonte) IN (
            'BIOGAS','BIOMASSE LIQUIDE',
            'BIOMASSE SOLIDE','RIFIUTI')      THEN 'biomass'
        WHEN UPPER(a.ai_fonte) = 'GEOTERMICA' THEN 'geothermal'
        ELSE 'other'
    END AS type_res,
    m.cod_prov,
    a.potenza AS potenza_kw,
    CASE
        WHEN UPPER(a.ai_fonte) = 'SOLARE'
            THEN a.potenza * COALESCE(u.solar, 0)
        WHEN UPPER(a.ai_fonte) = 'EOLICA'
            THEN a.potenza * COALESCE(u.wind, 0)
        WHEN UPPER(a.ai_fonte) = 'IDRAULICA'
            THEN a.potenza * COALESCE(u.hydroelectry, 0)
        WHEN UPPER(a.ai_fonte) IN (
            'BIOGAS','BIOMASSE LIQUIDE',
            'BIOMASSE SOLIDE','RIFIUTI')
            THEN a.potenza * COALESCE(u.biomass, 0)
        WHEN UPPER(a.ai_fonte) = 'GEOTERMICA'
            THEN a.potenza * COALESCE(u.geothermal, 0)
        ELSE 0
    END AS yearly_production_kwh
FROM [region_schema].[region_schema]_actual_plants a
JOIN [region_schema].[region_schema]_actual_plants_spatial_mapping m
    ON a.fid = m.plant_fid
JOIN [region_schema].[region_schema]_actual_plants_utilization_hour u
    ON m.cod_prov = u.cod_prov;

-- ============================================================
-- QUERY 2: HOURLY PRODUCTION DISAGGREGATION
-- Annual production disaggregated into 24-element arrays
-- for each month and day type using lookup table coefficients
-- E_plant[h,m,d] = E_annual x coeff[h,m,d,type_res,province]
-- ============================================================

CREATE UNLOGGED TABLE
[region_schema].[region_schema]_actual_plants_hourly_production (
    plant_fid int8,
    month int2,
    fr_fs char(2),
    type_res text,
    production_kwh_arr real[]
);

DO $$
DECLARE m integer;
BEGIN
    FOR m IN 1..12 LOOP

        CREATE TEMP TABLE temp_prod_lookup AS
        SELECT cod_prov::text AS cod_prov,
            type_res, fr_fs, hour,
            coefficient::real
        FROM
[region_schema].[region_schema]_actual_production_hourly_profile_lookup
        WHERE month::integer = m;

        CREATE INDEX idx_temp_prod
        ON temp_prod_lookup(cod_prov, type_res, fr_fs);

        INSERT INTO
        [region_schema].[region_schema]_actual_plants_hourly_production
```

```
        SELECT
            sub.plant_fid, m, sub.fr_fs, sub.type_res,
            array_agg(sub.p_k ORDER BY sub.hour)
                AS production_kwh_arr
        FROM (
            SELECT s.plant_fid, l.fr_fs, l.hour, s.type_res,
                (COALESCE(s.yearly_production_kwh, 0)
                 * l.coefficient)::real AS p_k
            FROM
[region_schema].[region_schema]_actual_plants_annual_production s
            JOIN temp_prod_lookup l
                ON s.cod_prov::text = l.cod_prov
               AND s.type_res = l.type_res
        ) sub
        GROUP BY sub.plant_fid, sub.fr_fs, sub.type_res;

        DROP TABLE temp_prod_lookup;

    END LOOP;
END $$;

ALTER TABLE
[region_schema].[region_schema]_actual_plants_hourly_production
SET LOGGED;

CREATE INDEX IF NOT EXISTS idx_plant_final_fid
ON [region_schema].[region_schema]_actual_plants_hourly_production
(plant_fid);
```

Appendix C: Supplementary Hourly Energy Balance Profiles: Spring and Autumn Working Days

This appendix presents the spring and autumn hourly electricity consumption and production profiles for the four Abruzzo provinces, complementing the winter and summer analysis presented in Section 4.4.5. The profiles are computed from working-day (FR) hourly distribution coefficients following the methodology described in Section 3.3.3. As discussed in Section 4.4.5, spring and autumn patterns are broadly transitional between the winter and summer extremes, showing a midday solar production window of intermediate magnitude and demand levels that fall between the heating-driven winter peak and the cooling-driven summer peak. These profiles confirm the trends identified in the main text without altering the principal findings.

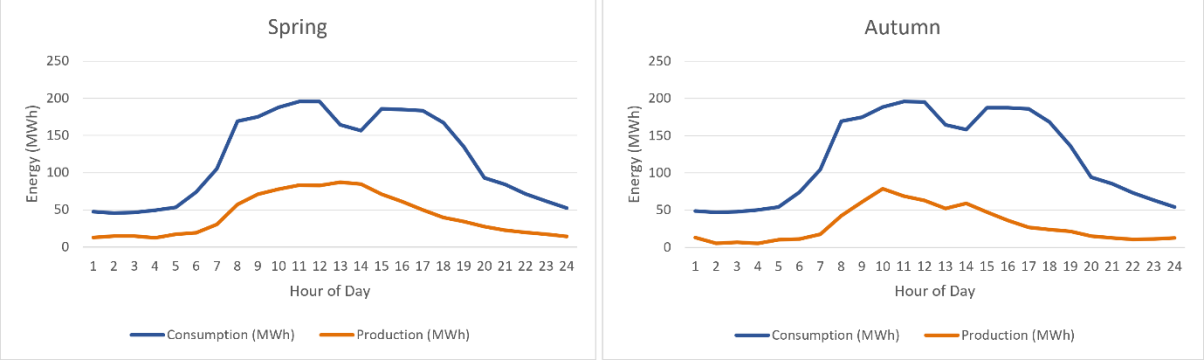


Figure C.1: Hourly Electricity Consumption vs Renewable Production - L'Aquila Province, Spring and Autumn Working Days (MWh).

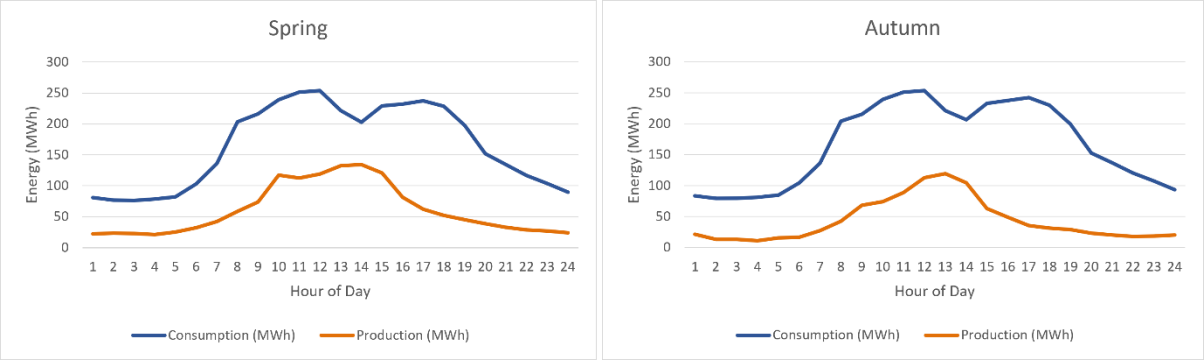


Figure C.2: Hourly Electricity Consumption vs Renewable Production - Chieti Province, Spring and Autumn Working Days (MWh).

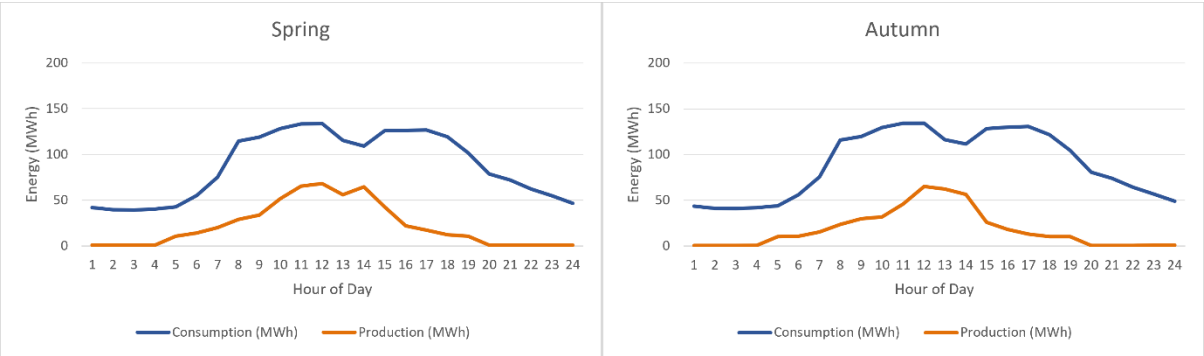


Figure C.3: Hourly Electricity Consumption vs Renewable Production - Pescara Province, Spring and Autumn Working Days (MWh).

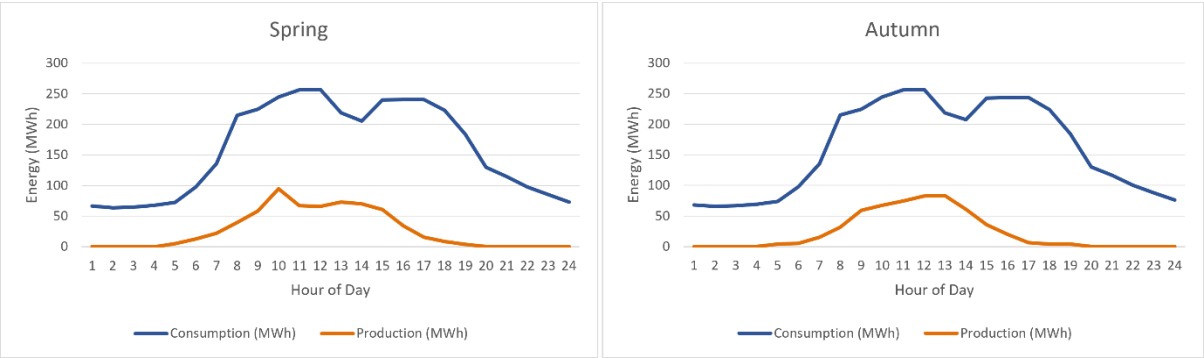


Figure C.4: Hourly Electricity Consumption vs Renewable Production - Teramo Province, Spring and Autumn Working Days (MWh).