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# First Steps Towards Structured Energy Planning for Self-Sufficiency: The Island of Sardinia

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**ABSTRACT**

This study addresses the strategic energy planning needs of Sardinia, a Mediterranean island characterized by geographical isolation, energy-intensive industries, and infrastructural gaps. The island's energy system, with a final consumption of 8 TWh for electricity and 20.4 TWh for thermal energy, requires a multidimensional planning approach to ensure energy self-sufficiency, diversification, and sustainability. A rigorous methodological framework was adopted, emphasizing data reliability and non-redundancy, and integrating sources from institutional databases (e.g., ISTAT, Bank of Italy, MISE) and technical literature at urban, national, and European levels. The research incorporates both quantitative and qualitative analyses, focusing on GDP, sectoral energy consumption (industry, residential, transport, services), and sociological trends over the past 15 years. The study also examines the dual pathway of Sardinia's energy transition: a temporary shift to natural gas—still partially unavailable across the region—and the rapid deployment of intermittent renewables, primarily photovoltaic and wind. These developments face infrastructural, economic, and environmental constraints, especially concerning landscape protection.

## 1. INTRODUCTION

In December 2015, with the adoption of the Paris Agreement at COP21 [1], signatory countries committed to "holding the increase in the global average temperature to well below 2℃ above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5℃", recognizing that this would significantly reduce the risks and impacts of climate change. This goal has required national governments to define long-term strategies for the decarbonization of their energy systems, while ensuring energy security, economic sustainability, and climate justice.

At the European level, this commitment materialized in the European Green Deal [2], presented in 2019, which aims to achieve climate neutrality by 2050. A key milestone is the 55% reduction in greenhouse gas emissions by 2030 compared to 1990 levels, a challenging objective especially in countries with energy systems still reliant on coal-fired power plants.

Italy, in line with other EU Member States, implemented the relevant directives through its National Integrated Energy and Climate Plan (PNIEC) [3], which defines sector-specific actions to achieve national targets. For the residential sector, the goal is to reduce energy consumption to 23.2 Mtoe by 2023, supported by Legislative Decree 48/2020 [4], transposing Directive (EU) 2018/844 on building energy efficiency (EPBD) [5]. The industrial sector targets a reduction in primary energy consumption from 140 Mtoe (2022) to 123 Mtoe (2030), governed by Legislative Decree 102/2014 implementing Directive 2012/27/EU [6]. For transport, the national target is to reach 34.2% renewable energy share by 2030, regulated by Legislative Decree 199/2021, which transposes RED II (Directive (EU) 2018/2001) [7]. For agriculture and fisheries, the objective is to reduce greenhouse gas emissions by 43.7% by 2030 compared to 2005 levels, as established in the National Strategic Plan for the CAP 2023–2027 [8].

At the regional level, Sardinia aligns with the PNIEC objectives through the drafting of the Regional Environmental and Energy Plan (PEARS) [9], which aims to pursue energy efficiency and transition goals in accordance with the island's territorial specificities.

This work applies a Top-Down energy balance model [10] for integrated energy planning [11]–thermal and electrical–tailored to the regional scale of Sardinia. Both fossil and renewable energy sources are considered, as per PNIEC guidelines [12]. Given the island's insular nature, the model also accounts for electrical interconnections with mainland Italy through two submarine cables (SAPEI and SACOI), which allow energy exchanges, power balancing, and enhanced energy system security.

The historical LNG development plan [13], currently reconsidered within the energy transition framework, is analyzed in terms of infrastructure cost–benefit ratio and investment payback times. The selection of energy vectors is strongly influenced by the EU Emissions Trading System (ETS), which penalizes high-emission fuels while incentivizing efficiency and cogeneration.

To make the model more accessible to macroeconomists and regional planners who assess investments from a financial standpoint, the authors present 2020 energy data as an energy balance aligned with the latest available regional energy plan. These data are benchmarked against national datasets. After verifying data consistency, the analysis incorporates the region's socioeconomic indicators, drawing from Kuznets' economic development theory [14, 15] and the modified IPAT equation including energy consumption [16]. The three variables—Population, Energy Intensity, and GDP per capita—are used to assess sensitivity to energy demand variations [17].

To achieve the highest possible resolution of the region's economic and energy dynamics, data collection spans a 15-year period (2009–2023). This time horizon enables temporal comparisons and the development of graphical trends, supporting interpretation of energy usage evolution, population quality of life, and the progress made in decarbonization.

## 2. DATA COLLECTION AND RELIABILITY

The adoption of rigorous methodologies for data collection and analysis enables a comprehensive understanding of resource management, thereby supporting strategic decision-making in the context of energy transition initiatives [18]. An integrated and up-to-date energy information system forms the foundation for the development of effective and sustainable policy measures. The methodological rigor and interdisciplinary nature of the approach adopted in this study have enabled a precise characterization of both energy uses and the availability of energy vectors—whether fossil-based or renewable—within the territory under investigation.

Data collection for the energy analysis of Sardinia was based on a broad spectrum of institutional sources, including:

- Energy reports issued by the GSE (Gestore dei Servizi Energetici) and TERNA for electricity and thermal renewable energy sources (RES);
- TERNA, for electricity consumption across different economic sectors;
- The Regulatory Authority for Energy, Networks and Environment (ARERA) and MEDEA, for data on gaseous energy carriers;
- The Regional Energy and Environmental Plan of Sardinia (PEARS) and the region's internal energy monitoring systems;
- Fossil energy statistics (oil, coal, gas) from the Ministry of Environment and Energy Security (MASE);
- Data from regional chambers of commerce and trade associations;
- Socioeconomic indicators from the Bank of Italy, related to household and sector-specific economic conditions;
- Annual monitoring reports by the CRENoS Economic Research Center for the North-South regions;
- National statistical data from ISTAT, particularly those regarding demographic and social trends;
- Technical data from energy service companies involved in industrial conversion processes, which fall under final energy uses [19].

The dataset spans a 15-year period (2009–2023), enabling the construction of a coherent and verifiable framework of production, transformation, and energy use patterns in Sardinia, contextualized within its socioeconomic evolution. All data, regardless of source, were harmonized using the Ton of Oil Equivalent (TOE) metric.

The TOE represents the amount of energy released by the combustion of one ton of oil, based on the Lower Heating Value (LHV) as defined by official sources, including the Intergovernmental Panel on Climate Change (IPCC) [20].

Regarding thermal fossil energy consumption, official sources were consulted—including national oil and coal statistics and historical series for liquefied natural gas (LNG) usage—published by MASE [21]. These data were extracted with regional disaggregation to enable a geographically specific analysis.

For electric energy uses, digitalized statistics from the TERNA web portal [22] were utilized, allowing extraction of data disaggregated by region and economic sector. Data on renewable energy sources (RES), both electrical and thermal, were retrieved from the open databases of GSE and ARERA.

Once all inputs were standardized to the TOE unit, a cross-comparison was performed with the PEARS dataset and its corresponding energy balance reports, to assess the internal consistency and identify any significant discrepancies.

The international competitiveness of regions and states is generally measured using indicators such as GDP per capita, Energy Intensity (EI), and the Baseline Emissions Inventory (BEI). The regional socio-demographic data analysis aimed to correlate energy consumption trends with key structural variables, including population dynamics and economic conditions, thus allowing the definition of meaningful synthetic indicators. Historical population data from 2009 to 2023 were collected for this purpose.

## 3. DESCRIPTION OF THE CURRENT REGIONAL ENERGY SYSTEM

Unlike other regions, Sardinia must meet its energy demand within the constraints of an island-based system, making self-sufficiency, self-production, and a diversified energy mix essential energy planning objectives.

Interconnections

The electrical interconnection between Sardinia and mainland Italy began in 1968 with the SA.CO.I. (Sardinia–Corsica–Italy), an alternating current (AC) transmission line linking Sardinia, Corsica, and Tuscany. It was upgraded in 1992 with SA.CO.I.2 and further modernized under the SA.CO.I.3 project, aimed at reinforcing the network to ensure both regional and national grid stability [23].

A second interconnection, the SA.PE.I. submarine cable, was inaugurated in 2011 with an investment of €750 million. This high-voltage direct current (HVDC) line connects Sardinia and Lazio with a transmission capacity of 1,000 MW [24].

Future developments include the Tyrrhenian Link, a submarine HVDC cable connecting Sardinia, Sicily, and Campania. It addresses the need to reinforce the interconnection of the two largest Italian islands with the mainland, especially in light of the phase-out of coal and other high-emission thermal power plants, and the surge in connection requests for new renewable energy (RES) plants [25]. Sardinia, Sicily, and Campania currently exhibit high RES penetration, particularly from non-dispatchable sources such as solar PV and wind energy [26].

**Final Energy Uses**

Final energy consumption is categorized into electric and thermal forms. The industrial sector is the most electricity-intensive, accounting for 44% of total final electricity consumption. The residential sector follows with 28%, while the tertiary sector contributes approximately 24%. The agricultural sector and transportation represent 3% and 1%, respectively.

In terms of thermal energy consumption (excluding energy transformation), transport emerges as the dominant sector, accounting for 60%, underscoring its reliance on fossil-based liquid and gaseous fuels. The residential sector is the second-largest consumer, with approximately 21%, sourced 58% from fossil fuels and 42% from renewable sources.

The primary regional energy transformations involve:

- Thermal-to-electricity conversion (19%),
- Refined product-to-mechanical energy conversion in transport (about 60%),
- Oil product refining for thermal use in residential and industrial sectors (around 30%).

The latter two rely heavily on coal and petroleum, targeted for replacement since the Kyoto Protocol due to their high $CO_2$ emissions [27].

The integration of lower-emission fossil fuels, such as LNG (a priority in Sardinian planning since the late 1990s), is a key development strategy. LNG offers high gravimetric and volumetric energy density (liquid methane has 600 times the density of its gaseous form), making it advantageous for storage and transport. However, LNG also involves higher costs and energy demands for storage: current prices are approximately €36/MWh for LNG, €16/MWh for coal, and €244/MWh for LPG [28]. LNG must be stored cryogenically at –162°C and ~3 bar, leading to boil-off gas (BOG) losses due to partial evaporation [29]. Storage tanks are therefore vacuum-insulated and double-walled, which increases system complexity and cost.

**Renewable Energy Sources**

Sardinia's climatic conditions are highly favorable for the development of non-dispatchable renewable energy sources, particularly solar PV and wind (Figures 1 and 2). The average annual solar irradiance is approximately 1,580 kWh/m² (UNI 10349). Wind speeds range from 4 to 6 m/s, particularly along coastal areas and the island's western regions exposed to prevailing Mistral winds. As a result, Sardinia ranks among the most wind-rich regions in Italy, alongside Sicily and Apulia.

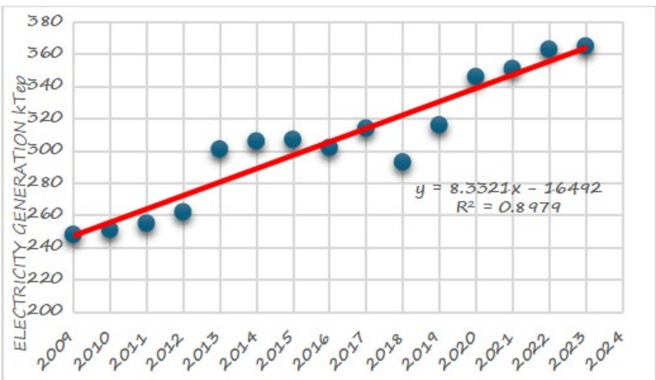


**Figure 1.** Generation electricity energy from F.E.R.

Current installed capacity includes:

- 1,140 MW of photovoltaic power,
- 1,100 MW of wind power,

which representing 6.2% of Italy's total installed capacity.

Annual renewable energy statistics from GSE [26] provide detailed insights into resource types and volumes (Figure 3). For thermal renewables, solid biomass dominates with 235 kTOE in the residential sector and 4.4 kTOE in non-residential sectors. Heat pumps contribute 45 kTOE, followed by solar thermal systems at 9.7 kTOE, and geothermal systems with approximately 1.4 kTOE.

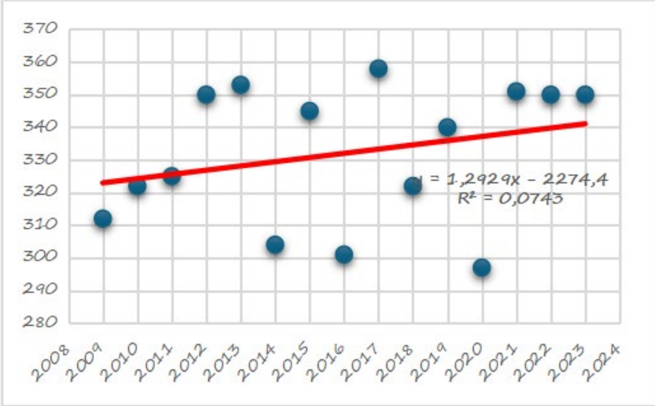


**Figure 2.** Generation thermal energy from F.E.R.

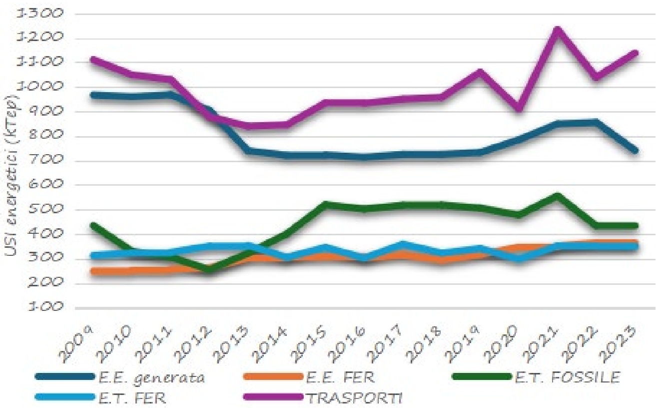


**Figure 3.** The energy analysis of Sardinia from 2009 to 2023

**Storage**

According to Legislative Decree 249/2012, Sardinia currently holds 74 kTOE in regulatory petroleum reserves.

## 4. CONSIDERATIONS ON THE REGIONAL ENERGY SYSTEM GENERAL REMARKS

The most significant contributor to regional GDP and industrial output in Sardinia is Saras S.p.A., which employs approximately 6,000 people, directly and indirectly. Its substantial energy demand plays a major role in the regional energy balance [9]. A by-product of its petroleum refining processes, TAR (Thermal Asphalt Residue), is used as a gaseous fuel by Sarlux, powering steam turbines for electricity generation in one of the island's two main thermoelectric power plants.

**Electricity Consumption**

Analysis of electricity consumption data reveals a significant drop–approximately 210 kTOE–in industrial electricity use between 2011 and 2013, which can be seen in Figure 4, attributed to the closure of major energy-intensive industries (e.g., EuroAllumina, Alcoa, Glencore, Ottana Polimeri).

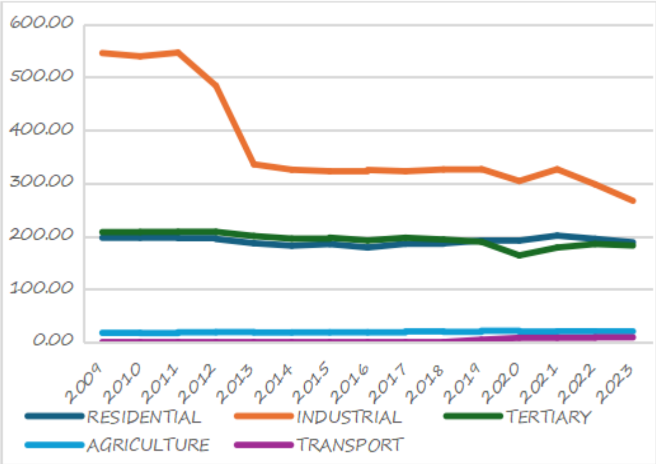


**Figure 4.** Electricity consumption in kTOE divided by sectors

In the same period, regional per capita GDP declined by around 5%, from €20,237 in 2012 to €19,328 in 2013. A second variation occurred during the COVID-19 pandemic (2020), with a drop in electricity demand followed by a recovery of approximately 40 kTOE, distributed across sectors.

**Thermal Energy Use**

The transport sector remains the dominant consumer of thermal energy, accounting for 60% of fossil fuel use, reflecting the sector's reliance on liquid fuels. A gradual increase in transport-related thermal energy consumption is observed post-2014, continuing through 2023 (see Figure 5). The residential sector saw a 23% decrease in thermal consumption during the Russia–Ukraine conflict, likely due to volatile fossil fuel prices. Industrial thermal use, mainly for internal energy transformation, accounts for only 6% of total fossil thermal consumption, with fuel oils comprising about 30 kTOE per year. This trend highlights the limited industrial base of the region.

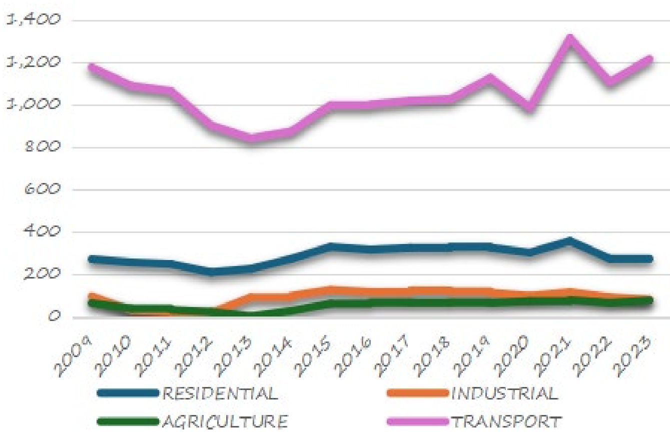


**Figure 5.** Thermal consumption in kTOE divided by sectors

**Renewable Energy Considerations**

Despite being strategic for decarbonization and energy security, the ongoing expansion of RES in Sardinia faces notable challenges. The shift from centralized production (often in isolated industrial hubs) to decentralized generation across larger territorial areas has introduced significant visual and spatial impacts. This evolution lacks sufficient planning frameworks to ensure coherent development. Therefore, the deployment of non-dispatchable RES requires clear regulatory instruments aligned with energy, environmental, and spatial planning objectives (Figure 6).

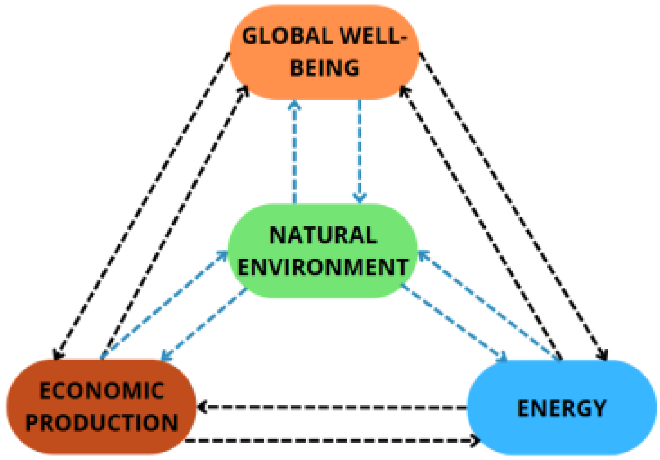


**Figure 6.** Sustainability system interactions

**Final Energy Use Considerations**

Assuming LNG as the main energy vector for regional industrial conversion processes, the Kuznets curve [30] is used to explore the relationship between per capita GDP and $CO_2$ emissions. The Kuznets model evolves into a multidimensional framework where well-being ($CO_2$ emissions vs. GDP), economic production (GDP vs. consumption), and energy consumption (consumption vs. emissions) are enclosed within a control surface representing the environmental carrying capacity (average number of inhabitants). This conceptual framework is mathematically formalized by the IPAT equation [16].

$$E_{\text{cons}} = N_p \cdot E.I. \cdot GDP_{\text{proc}} \quad (1)$$

Through this formulation, it becomes possible to estimate energy demand and forecast short-term system dynamics.

The Final Energy Consumption (FEC) in 2020 was approximately 2,800 kTOE (electric + thermal). When correlated with GDP, this yields the Energy Intensity (EI) index [31]:

$$\text{Energy Intensity} = \text{GEC/GDP} \quad (2)$$

Energy intensity is a proxy for macroeconomic energy efficiency. Lower values of E.I. reflect more efficient economies [32].

Applying IPAT, one can estimate territorial energy demand as a function of population, energy intensity, and per capita wealth. In this context, replacing high-emission fuels (e.g., coal, TAR) with LNG is an effective decarbonization strategy, keeping total energy consumption constant while significantly reducing $CO_2$ emissions. Moreover, LNG-based plants offer higher conversion efficiency [33], further reducing energy intensity and enhancing system sustainability.

For Sardinia, the EI index is approximately 1.016 kWh/€GDP, indicating high energy consumption relative to a low regional GDP. This reflects a resource-intensive economic structure heavily dependent on internal energy transformations. Comparative EI values at different territorial scales show:

- EU average: 98.3 TOE/Million €
- Italy: 83.5 TOE/Million €
- Sardinia: 87.2 TOE/Million € [34]

## 5. GEOGRAPHICAL, INFRASTRUCTURAL, SOCIAL, AND ECONOMIC ASPECTS OF SARDINIA

Sardinia covers an area of 24,000 km², characterized predominantly by mountainous and hilly terrain, with an average elevation of approximately 400 meters above sea level. The presence of lowland areas is limited to regions such as Campidano and the Otzieri plain. The combination of a low population density and a vast territorial extension give the Sardinian system a polycentric structure, marked by significant disparities between dynamic coastal areas and marginalized inland zones.

The energy infrastructure of the island includes electrical interconnections with mainland Italy, which are essential for maintaining grid stability. However, in terms of thermal energy, Sardinia currently lacks a dedicated distribution network for heating fuels.

For several years, Sardinia has experienced a gradual demographic and economic decline, directly impacting its development prospects and long-term energy planning. Recent demographic data (2023–2024) confirm a negative population trend, with a resident population of approximately 1.58 million, representing 2.8% of the national total. The majority of inhabitants are concentrated in coastal and urban areas (63%), whereas rural and mountainous municipalities have suffered the greatest population losses and highest aging rates, underscoring the broader issue of depopulation in the inland regions of southern Italy.

Economically, the region's GDP in 2023 grew by only 0.7%, significantly below the national average, hindered by weak consumption, high inflation, and a contraction in foreign demand. A notable disparity in per capita GDP is observed: approximately €27,000 per year in coastal areas compared to €17,000 per year in inland municipalities. While NRRP (National Recovery and Resilience Plan) funds have provided partial stimulus, agriculture and industry sectors have shown signs of contraction, with value-added losses of - 4.5% and - 2.1%, respectively.

Overall, Sardinia emerges as a region marked by demographic aging, a sluggish service-based economy, and pronounced territorial inequalities. These structural characteristics must be integrated into any sustainable and differentiated energy planning strategy, to ensure effective and context-sensitive policy implementation.

## 6. DEVELOPMENT OF THE PLANNING METHODOLOGY

Recognizing that collective economic well-being is deeply connected to the availability and accessibility of secure energy sources—defined as reliable, sustainable, and stable both politically and technically—this study emphasizes the biunivocal relationship between energy, economic production, and quality of life, which must be interpreted in interaction with the natural environment, as framed by the IPAT equation.

Within this environmental perspective, the analysis focuses on the uses of energy vectors for the production of energy and final energy products, integrating the objectives of decarbonization and energy efficiency. The conversion of energy vectors employed in industrial cycles represents a critical node in the transition toward a low-carbon economy.

To date, a significant portion of production processes in Europe and Italy still rely on high-emission fossil fuels, such as coal and diesel. Although historically cost-effective, these fuels generate very high specific emissions: approximately 94 kg $CO_2$ per GJ for coal, compared to about 56 kg $CO_2$ per GJ for liquefied natural gas (LNG), indicating a reduction of over 50% in emissions for equivalent useful energy produced [20].

However, transitioning to more sustainable energy vectors entails substantial upfront investment in technological upgrades of industrial systems. This includes the replacement of thermal generators, adaptation of process lines, and installation of new fueling and storage systems. Despite their initial financial burden, these investments are economically justified in the medium-to-long term, due to lower $CO_2$ emission certificate purchase costs under the EU Emissions Trading System (EU ETS). The current price of such certificates is approximately €65 per ton of $CO_2$, and projections by the European Commission estimate a rise to over €80/t$CO_2$ by 2026 [35], rendering the continued use of high-emission fuels increasingly unsustainable.

The benefits are multifold: avoiding the purchase of large volumes of certificates, improving industrial energy efficiency, and gaining access to subsidized financing mechanisms established under EU directives [36]. In particular, Regulation (EU) 2021/1119 (European Climate Law), the Fit for 55 Package, and Directive (EU) 2023/2419 promote the phasing out of fossil fuels in industry through the provision of structural funds, capacity-building instruments, and sector-specific incentives.

At the national level, initiatives such as the NRRP (National Recovery and Resilience Plan), the Energy Transition Fund administered by the Ministry for Enterprises and Made in Italy (MIMIT), and regional development programs (POR FESR) further support the implementation of such interventions.

This initial planning approach seeks to combine environmental sustainability, economic return, and reduced dependence on increasingly expensive carbon markets. The shift in energy vectors is not merely a technological adaptation, but a systemic tool for enhancing industrial competitiveness and improving quality of life.

## 7. POSSIBLE METHODOLOGICAL APPROACHES

A methodological approach increasingly adopted in energy transition planning involves the use of multi-scenario optimization models capable of systematically integrating the energy, economic, and environmental dimensions. Among these, the TIMES model (The Integrated MARKAL-EFOM System) [37, 38], developed under the IEA-ETSAP (Energy Technology Systems Analysis Programme) of the International Energy Agency, has become one of the leading tools for developing medium- and long-term energy scenarios. TIMES enables the optimization of energy system configurations by identifying the most technologically and economically efficient pathways to achieve predefined targets (e.g., emission reductions, energy independence, cost minimization), while linking the evolution of energy vectors, primary sources, and infrastructure to the projected energy demand.

In the context of the ongoing energy transition, Sardinia is moving along two main strategic directions:

1. Adoption of Natural Gas (Methane)

Until 2020, natural gas was completely absent from Sardinia's energy mix and remains unavailable in several areas [39]. Infrastructure investments and end-user price competitiveness remain uncertain. The main weaknesses associated with LNG conversion include:

- Lack of an interconnected methane network
  Sardinia is the only Italian region not connected to the national methane grid. LNG was therefore assessed as an alternative vector.
- Fragile demographic and economic context
  The region suffers from internal depopulation, low industrial demand, and a generally weak economic structure.
- Widespread use of propane-air and LPG
  In many cities, methane is neither technically nor economically advantageous compared to existing systems using LPG or propane-air mixtures.
- High initial investment costs
  LNG logistics require cryogenic infrastructure, local depots, and isolated distribution networks, involving significant capital expenditure.

Strengths of LNG Conversion:

- Energy efficiency gains
  Replacing high-emission fuels with less carbon-intensive ones (LNG) in power generation and transformation processes would lead to significant $CO_2$ emission reductions, lowering the cost of emission allowance purchases.
- Opportunities in the residential sector
  LNG presents a realistic development path in urban areas such as Cagliari, Sassari, Oristano, and Nuoro, enabling shifts in inefficient end-use behaviors.
- Opportunities in the industrial sector
  Industrial transformation plants could be converted to more efficient and cleaner systems, significantly reducing their environmental impact.
- Potential maritime applications
  LNG could serve marine refueling in the port of Olbia, particularly for cruise traffic, representing a strategic niche market.

**Expansion of Renewable Energy Sources**

- Sardinia exhibits excellent conditions for the deployment of non-dispatchable renewable energy sources, especially photovoltaic and wind power due to its favorable climate.
- However, the delocalization of power plants and their landscape impact have become points of contention among national, regional authorities, and the local population.

After conducting a multidisciplinary analysis of Sardinia's energy system, the objective is to apply the TIMES optimization methodology to the island's case. This aims to identify decarbonization pathways compatible with Sardinia's specific characteristics, ensuring both energy security and the economic viability of the selected strategies.

## 8. CONCLUSIONS

Sardinia faces significant challenges related to the energy transition and energy use, compounded by ongoing demographic decline and population outmigration.

The region's current structural weaknesses, which hinder its regional development, stem from several interconnected factors. The volatile international context, which influences the use of specific transitional energy vectors, also affects national and regional dynamics. The absence of large-scale energy-intensive industrial clusters has resulted in a substantial decline in energy consumption and associated $CO_2$ emissions (due to the shutdown of major industrial sites). However, this also contributed to a weakened industrial base and a contraction of economic growth.

On the other hand, one of the main strengths for Sardinia's energy transition is the potential use of liquefied natural gas (LNG). Replacing current energy carriers with LNG could lead to a more efficient system, thanks to the deployment of new types of infrastructure, ensuring equal energy output and greater system stability. This would result in a substantial reduction of $CO_2$ emissions, translating into lower expenses for emission allowance purchases. Although the initial investments are considerable, they are justified over the medium-to-long term by the expected economic returns from emission cost savings.

Moreover, LNG could be deployed in the residential sector, facilitating a shift in energy use habits, which are currently shaped by the high costs of existing carriers, such as LPG. The comparatively lower cost of LNG would render certain uses more economically viable.

Thanks to its favorable climatic conditions and the growing availability of non-dispatchable renewable energy systems, Sardinia holds strategic potential to evolve into an energy self-sufficient system, with the ability to export electricity, the highest-value form of energy. However, this model of energy generation currently faces challenges related to the geographic dispersion of installations, which require significant land use and raise concerns regarding land availability, social acceptance, and the preservation and enhancement of local landscapes.

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## NOMENCLATURE

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|---|---|
| TOE | ton of oil equivalent |
| $N_p$ | present population |
| E.I. | Energy Intensity |
| G.D.P.$_{proc}$ | Gross domestic product per capita |
| G.E.C. | Gross energy consumption |