

Research paper



Exploring energy scenarios and driving forces of CO₂ emissions of regions: The case of a southern region of Spain through LEAP analysis

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ABSTRACT

Climate change demands urgent action to reduce greenhouse gas (GHG) emissions and transition towards sustainable energy systems. Andalusia, a region with high renewable potential but strong fossil fuel dependence, presents an opportunity to assess regional energy transitions with broader implications for similar contexts. This study employs the Low Emissions Analysis Platform (LEAP) to model Andalusia's energy metabolism and evaluate different energy transition scenarios for 2030 and 2050, focusing on GHG emissions, energy demand, and renewable energy integration.

Three scenarios are analysed: (1) a baseline scenario, reflecting current policies; (2) an efficiency scenario, incorporating ambitious energy-saving measures; and (3) a long-term scenario, targeting climate neutrality. Results show that renewable energy penetration reaches 33.5% by 2030, failing to meet the 42% target, and reductions in primary energy demand and emissions are insufficient to comply with 2050 climate commitments. While energy efficiency and renewables contribute to emission reductions, additional measures such as greater electrification, faster renewable deployment, and enhanced energy storage are required.

These findings highlight the need for stronger policy actions to accelerate decarbonisation, ensuring alignment with the Sustainable Development Goals (SDGs) and the Paris Agreement. This study provides a replicable framework for regional energy planning, offering insights to policymakers to bridge the gap between current trajectories and climate objectives through targeted strategies and infrastructure investments.

1. Introduction

Climate change is currently one of the greatest challenges faced by all countries and regions across the globe. One of the latest reports by the Intergovernmental Panel on Climate Change (IPCC) on the consequences of a global temperature rise of 1.5 °C and the corresponding pathways that global greenhouse gas (GHG) emissions should follow highlights the need for all countries and regions to implement policies to tackle climate change (Masson-Delmotte et al., 2019). Furthermore, the goals of the 2030 Agenda for Sustainable Development (SDGs), particularly those related to climate change, sustainability, and the energy system, emphasise the critical role of regions in their achievement (United Nations, 2015).

Human activity and its high regional and urban concentration act as crucial points of interaction between natural and socio-economic systems. Consequently, unsustainable urban development is contributing

to significant ecological and environmental challenges (Zhang et al., 2015). Since 2008, more than half of the world's population has resided in urban settings, and this proportion is projected to rise to nearly 70% by 2050 (Mehrotra et al., 2011; Carreón and Worrell, 2018). Consequently, energy demand surpasses global energy needs by three-quarters, with 71%–86% of greenhouse gas emissions originating in urban areas (Grubler et al., 2012; Barragán-Escandón et al., 2019). In light of this situation, it is essential to revise energy policies to prevent urban planning from becoming vulnerable to energy shortages. For example, research by Zhang et al. (2011) has explored the relationship between urbanisation, energy consumption, and CO₂ emissions at national and regional levels. Their study concluded that urbanisation increases energy consumption and CO₂ emissions in China, with the impact of urbanisation on CO₂ emissions varying significantly across

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regions. Moreover, by 2050, the expansion of urban areas is expected to significantly increase energy demand, which will result in a substantial rise in greenhouse gas emissions (Fragkos et al., 2017). In this context, regions play a crucial role in the transition towards more sustainable energy systems, mainly due to their reliance on fossil fuels (Conke and Ferreira, 2015). Therefore, forward-looking energy planning becomes an indispensable tool for achieving long-term climate and energy goals.

The main aim of this study arises from this need: to analyse the Andalusian energy system from the perspective of regional energy metabolism, focusing on the relationships between GHG emissions, energy generation, and consumption. The goal is to evaluate its future contribution to the energy transition and the achievement of the Sustainable Development Goals (SDGs), while providing recommendations for decision-making at the regional level. To achieve this, data has been gathered on Andalusia's current energy performance, and its energy model has been processed to develop an energy outlook, estimating future energy consumption and GHG emissions. This approach enables the analysis of Andalusia's decarbonisation pathways and allows its progress to be assessed at any point in relation to the 2030 targets outlined in the SDGs and the Paris Agreement, as well as the 2050 horizon.

This regional-level prospective analysis has been conducted using the Low Emissions Analysis Platform (LEAP) (<https://leap.sei.org/>) software as a modelling tool. Using Andalusia as a case study, three scenarios proposed by the Andalusian Energy Agency have been designed and assessed: a trend scenario that reflects the energy trajectory without the introduction of new policies, an efficiency scenario that incorporates significant improvements in energy efficiency, and a long-term scenario that extends these measures to 2050.

The use of LEAP, widely employed tool in this context, enables the assessment of how regional energy planning can be optimised to achieve the energy targets set for 2030 and 2050. Although this analysis focuses on the Andalusia region, the results and methodology can be extrapolated to other regions facing similar energy challenges. The findings provide a robust foundation for strategic decision-making in regional energy planning, emphasising the importance of long-term policies in achieving an effective energy transition. This study stands out for its innovative approach to energy analysis at the regional level in Spain. While other studies have used LEAP in regional contexts (we will discuss this in more detail in the literature review section), the distinctiveness of this work lies in its detailed approach to energy planning in Andalusia. This analysis addresses a gap in the literature by providing a specific assessment for this region, which has not previously been the subject of case studies using this platform. The application of LEAP in this context allows for an assessment of how different energy policies can influence consumption, production and emissions over time, providing valuable information for strategic decision-making at the regional level.

The application of LEAP in this context enables an assessment of how different energy policies may influence consumption, production, and emissions over time, providing valuable insights for strategic decision-making at the regional level. The study is structured into several sections: first, a literature review is carried out in order to know the current state of research related to our case study; then, the methodology used and the energy data collected for the initial analysis are described; next, the results of the prospective scenarios are presented and evaluated in terms of their alignment with the established energy objectives; finally, the conclusions are discussed, highlighting the importance of the prospective analysis to improve energy planning in Andalusia and its potential applicability to other regions.

2. Literature review

Given the increasing rate of urbanisation and its impact on emissions and energy consumption, innovative approaches to energy planning across diverse territories, including both urban areas and wider regions, are essential. Numerous researchers have developed methodologies aimed at optimising the use of energy resources in these contexts, seeking to mitigate the environmental impact of human development and facilitate the transition towards sustainable energy models.

Studies indicate that regional energy planning can optimise resources and reduce emissions across a variety of contexts (Jacobsson and Lauber, 2006; Bhattacharyya, 2006; Kammen and Sunter, 2016). The challenge for regions lies in advancing towards the implementation of a circular energy metabolism that enhances self-sufficiency and minimises the need for new energy inputs, while simultaneously increasing resilience and the capacity to adapt to the impacts of climate change (Sanz-Alduán and Navazo-Lafuente, 2012; Galán-Cano et al., 2025). In addition, there are authors who have advocated various methodologies for energy studies such as 'Data Envelopment Analysis' (DEA) (Cámara-Aceituno et al., 2023; Yang and Wang, 2013; Yang et al., 2015) to carry out energy-economic studies of demand or the use of the 'Log-Mean Divisia Index Method' (LMDI) (Aceituno et al., 2024; Chong et al., 2017; Ortega-Ruiz et al., 2020, 2022) to decouple GHG emissions from economic activity and to be able to carry out prospective and retrospective studies.

One tool that plays a prominent role in regional energy planning research is LEAP (Low Emissions Analysis Platform). Among the models commonly utilised, LEAP is distinguished by its extensive application, thanks to its robust capacity for detailed record-keeping and its highly adaptable functionality. Additionally, LEAP provides the capability to conduct scenario analyses while offering visual representations of energy flows, from generation to consumption.

At the urban level, Hu et al. conducted an energy foresight study in the city of Shenzhen, proposing a sustainable urban planning model aimed at reducing energy consumption while minimising economic costs (Hu et al., 2019). Similarly, studies utilising LEAP software have been conducted in various Chinese cities to analyse CO₂ emissions and their impacts, with the aim of controlling local air pollution and achieving the targets for CO₂ emission reduction and carbon neutrality in China (Feng and Zhang, 2012; Hu et al., 2019; Zhang et al., 2011; Zhou et al., 2016). Further research includes a city-wide energy analysis by Phdungsilp (2010) which modelled the city of Bangkok to simulate policy interventions and examine how these could influence the trajectory of energy consumption and emissions over the period 2000–2025. Other more recent studies such as the one conducted in the Marun basin (Iran) with a population of 573,000 people in 2016 use LEAP to simulate the energy system in the year 2016–2020 through a scenario based on residential solar panels that manages to reduce CO₂ emissions by 17% (Golfam et al., 2024). The same case study is used to combine LEAP with a neural network to perform a more realistic accuracy of energy and water resources (Golfam and Ashofteh, 2025a,b) and to perform a cost-benefit analysis to study the best alternatives to meet electricity demand (Golfam and Ashofteh, 2024).

At the national level we can highlight the study conducted by Emodi et al. who conducted a LEAP model that applied a scenario-based analysis to explore Nigeria's future energy demand and supply and associated GHG emissions over the period 2010–2040 (Emodi et al., 2017). A longer-term analysis was carried out by El-Sayed et al. (2023) who examined various scenarios of electricity generation and consumption in Egypt over the period 2020–2050.

In the Spanish context, several examples of energy planning can be highlighted. In 2018, García-Gusano et al. (2018) used the LEAP model to project electricity demand in Spain up to 2050. A year later, García-Gusano et al. (2019) conducted another study, this time focusing on energy planning for the city of Madrid, specifically addressing the residential and transport sectors. Their prospective scenarios up to

2050 revealed key insights, such as the potential for decarbonising these sectors to significantly reduce energy demand. Earlier, in 2016, Gómez et al. (2016) examined issues affecting the Spanish electricity generation sector, including excess generation capacity and regulatory instability. Their study developed three scenarios, demonstrating that effective energy planning during the crisis years could have reduced investment needs in the electricity sector without compromising performance.

Energy planning in Andalusia, Spain, has been the subject of extensive research. Carrión et al. (2008) focused on evaluating the electricity generation potential of solar photovoltaic power plants and identifying suitable locations for solar energy sites in the region. Román-Collado et al. (2021) examined the role of energy efficiency in understanding energy consumption patterns in Andalusia. González-Rosell et al. (2020) developed a participatory system dynamics model to assess the water–energy–food nexus in Andalusia, illustrating the interconnectedness of these resources. Prados (2010) explored renewable energy policy and landscape management, providing valuable insights into the strategic adoption of renewable energy in the region. At the XI Andalusian Regional Science Congress, Cardenete et al. (2011) assessed the impact of expanding biomass power generation capacity in cogeneration plants, aligning with the renewable energy development targets of the Andalusian Sustainable Energy Plan.

As mentioned in the introduction, an analysis will be carried out through the LEAP application in order to address this gap in the literature, providing a specific assessment for the Andalusia region in terms of energy consumption, energy production and emissions through a baseline scenario, an energy efficiency scenario and a long-term scenario extending these measures to 2050.

3. Methodology

For this study to be robust and reproducible, a methodological framework that is well-defined and organised is necessary. A flowchart summarising the methodological processes used during this investigation is provided in Fig. 1 to help with a clear understanding of the research process. The study goal and data collection are the first steps in the diagram. Next come model selection, scenario development, and energy demand and supply modelling. The assessment of emissions and transformation processes, the comparison of the findings with previous research, the final conclusions, and the policy implications are also included. By ensuring a methodical and transparent workflow, this organised approach enhances understanding and methodological traceability.

The study starts by establishing its research goal, as shown in the flowchart, and then gathers energy-related data and policy documents. Choosing a suitable modelling technique is the next stage, and the LEAP model was selected because of its flexibility and scenario-based features. Then, using assumptions based on policy, various energy scenarios were created for 2030 and 2050. The LEAP framework is used to analyse energy demand, supply, emissions, and transformation dynamics as part of the core modelling process. The findings are then confirmed by comparison with previous research, leading to conclusions and policy suggestions that further the conversation on regional energy transitions.

3.1. Use of LEAP. Methodological characteristics

Among the methodologies reviewed for energy forecasting and analysing the energy situation in Andalusia, the LEAP (Long-term Energy Alternatives Planning System) software was selected. Developed by the Stockholm Environment Institute (SEI) (Stockholm Environment Institute (SEI), 1980) in the 1980s, the LEAP model has undergone continuous enhancements to enable the analysis of the impacts of economic activity on energy consumption and air pollutant emissions (Zhou et al., 2016). LEAP is a bottom-up simulation model designed for

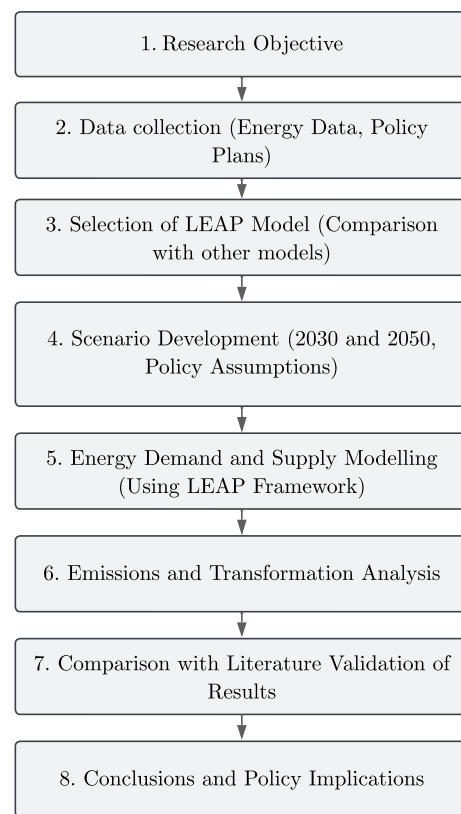


Fig. 1. Flowchart of the research methodology.
Source: Own elaboration.

scenario-oriented energy planning, facilitating the examination of energy consumption, conversion, and production (Zhang et al., 2011). It is an exceptionally versatile tool, suitable for application at global, national, regional, and local scales. Additionally, LEAP provides significant flexibility in energy modelling, making it adaptable to both general analyses and detailed approaches focusing on specific energy uses (El-Sayed et al., 2023).

LEAP is especially well-suited for regional and local energy planning, where data availability is frequently restricted, because it does not necessitate a large amount of data input for calibration, in contrast to other energy modelling methods. Although alternative approaches like TIMES and MARKAL are frequently employed for simulating energy systems, they are typically more intricate and data-intensive, which can present difficulties in certain geographical applications. Because of its ease of use and scenario-based methodology, LEAP is a perfect option for estimating Andalusia's energy metabolism while preserving adaptability for long-term and cross-sectoral planning.

By creating scenarios, LEAP enables the investigation of the temporal evolution of both global and detailed final fuel consumption across all sectors, as well as energy production and the economic variables associated with energy consumption and production. In the case of Andalusia, demand across various economic sectors—including residential, industrial, transport, services, and primary sectors—was analysed, disaggregated by activity and energy source (e.g., oil derivatives, natural gas, electricity, and renewable energies). In addition to demand analysis, the modelling also incorporated an examination of energy production, transport, and transformation within the region. This comprehensive approach provides a clear understanding of energy flows, from generation to consumption.

A comparative examination of energy transition routes is made possible by the study's methodological contribution, which also consists of integrating various policy initiatives into a unified framework. This

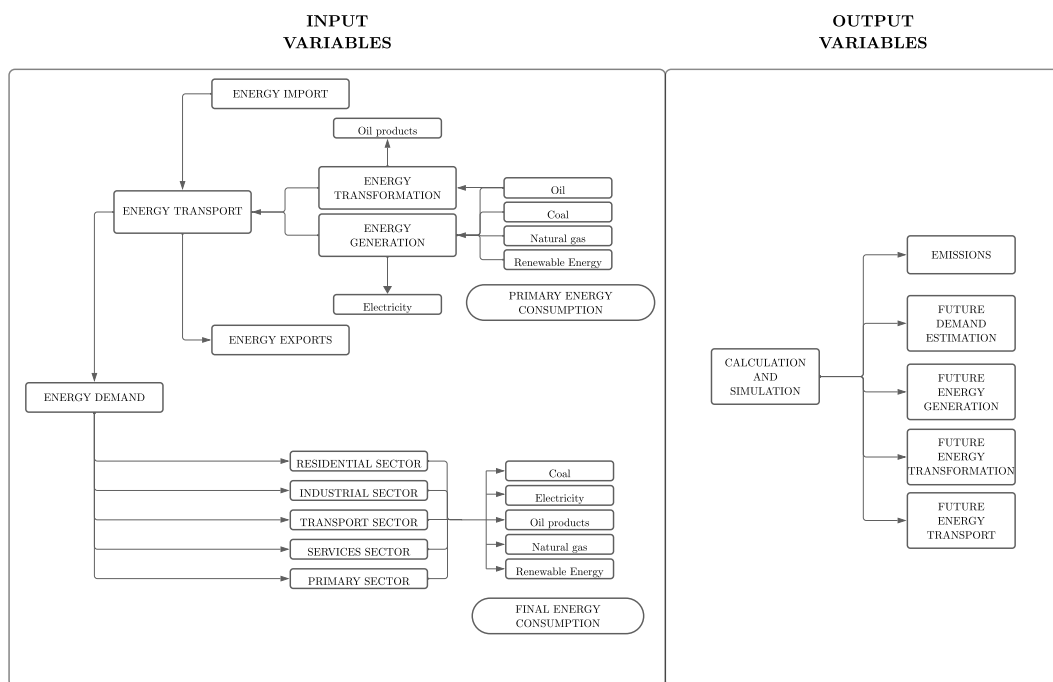


Fig. 2. Outline of the energy modelling of the Andalusia Region.
Source: Own Elaboration.

fills in the gaps left by earlier research, which frequently concentrated on discrete policy effects rather than a whole regional shift. This study offers important insights into the combined consequences of energy efficiency, renewable integration, and electrification at the regional level by integrating policy-driven scenarios.

The methodology used in this study is adaptable to other regions with varying energy mixes and policy contexts. By modifying baseline energy data and policy assumptions, it can be applied to regions with different levels of renewable energy potential and socio-economic conditions, making it a flexible tool for cross-regional comparisons and policy planning.

Fig. 2 shows a schematic of the modelling representing the input and output variables. First, a base year (referred to in LEAP as a current account year) was modelled, serving as the foundation for making the necessary estimates for each proposed scenario. Once the base year was modelled, several scenarios were developed, incorporating different considerations to evaluate varying degrees of compliance with the objectives set by official institutions, such as the Andalusian Energy Agency (AAE) (Andalusian Energy Agency, 2021) and the National Integrated Energy and Climate Plan (PNIEC) (Instituto para la Diversificación y Ahorro de la Energía (IDAE), 2021).

The 2030 and 2050 scenario selection adheres to global energy planning best practises. Although there are other long-term forecasting techniques, including hybrid energy-economy models or backcasting, the use of LEAP offers a clear, policy-driven strategy for scenario analysis. In this instance, LEAP's primary benefit is its capacity to incorporate mandated energy policy goals into a bottom-up framework, enabling a thorough sectoral analysis in line with regional and national goals.

3.2. Demand modelling

For LEAP to effectively model energy demand, it is crucial to provide detailed information (input variables) on the proportion of each energy source relative to the total within each sector, along with their respective energy consumption. Final energy consumption was modelled by considering the key sectors that act as the main energy sinks in a city: transport, residential, industrial, services, and

primary. Within each sector, the most common energy sources—such as electricity, oil derivatives, natural gas, and renewable energies—were analysed, along with the processes of production, transport, and transformation of primary energy sources.

LEAP enables a bottom-up approach to energy demand estimation, taking into account policy-driven behavioural shifts, technological adoption rates, and energy efficiency advancements, in contrast to strictly econometric forecasting models. This makes it possible to depict future trends in energy use in the Andalusian region with more accuracy.

The total final energy consumption is calculated with the following equation (Zhou et al., 2016; Terry Heaps, 2016):

$$TC = \sum_m \sum_n AA_{w,n,m} \cdot EI_{w,n,m} \quad (1)$$

where: – TC is the total energy consumption of a sector (measured in GWh). – AA (Activity Amount) is the magnitude of demand or the usage of services, goods, and resources associated with energy over a specific period. – EI (Energy Intensity) is the amount of energy used per unit of economic or social activity. – w represents the type of energy source meeting the energy demand. – m refers to broader societal divisions used to organise and analyse energy consumption (e.g., industrial, residential, or commercial). – n represents subcategories or specific divisions within sectors, allowing for a more granular analysis.

To see it in a more schematic way, Fig. 3 shows how Andalusia's energy demand is modelled:

3.3. Transformation modelling

To accurately model the transmission and distribution of energy, it is essential to account for the losses inherent in these processes. In this context, the average annual percentage of electricity losses during transmission and distribution has been incorporated into the analysis (Red Eléctrica de España (REE), 2021).

With respect to power generation, it is essential to start by modelling the reserve margin and then proceed with a number of important parameters. These include installed power (MW), annual power generation (GWh), efficiency and dispatch rules. Once LEAP has all the

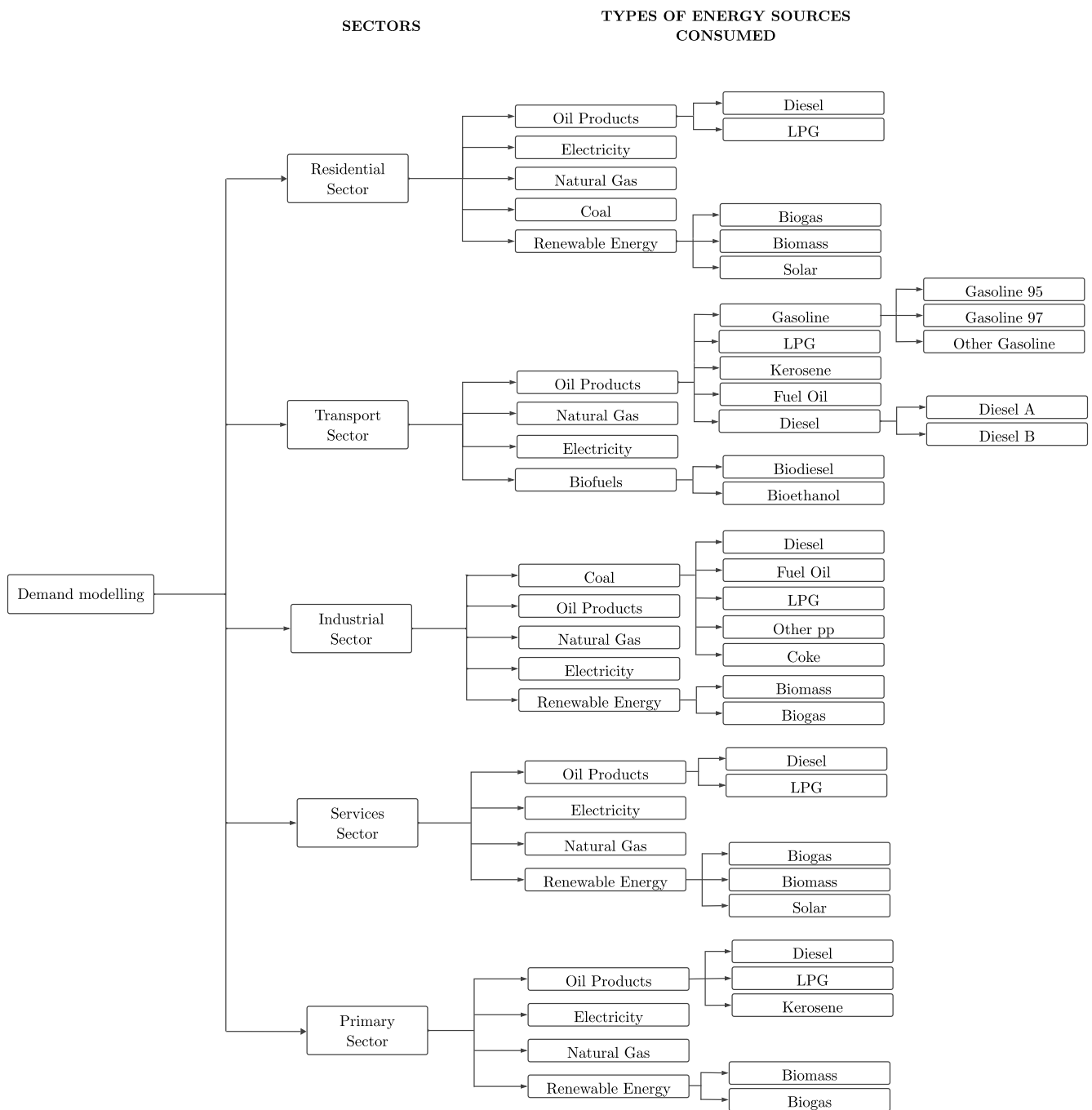


Fig. 3. Schematic of base year energy modelling.
Source: Own elaboration.

required information, it performs a comprehensive resource analysis, covering data on the availability of primary resources, both fossil and renewable, as well as imports and exports of primary resources and secondary fuels (El-Sayed et al., 2023).

The incorporation of anticipated technological developments is a crucial component of this study’s transformation models. This includes anticipated cost savings and efficiency gains in renewable energy technology, both of which have an impact on the financial feasibility of various energy transformation strategies. The study offers a longer-term perspective on the evolution of the energy system that is more realistic by taking these dynamics into account.

In the context of energy transformation, power plants, heating plants, or refineries can be considered as energy producers. Energy losses from transformation to demand can be modelled (Zhou et al.,

2016). Fig. 4 illustrates the processes involved in energy generation, transportation, and transformation. It categorises the flow of energy through three main paths: electricity production, transport and distribution losses, and the refining process. Electricity production is further divided into renewable and non-renewable sources. The renewable energy sources include solar photovoltaic, solar thermal, ocean thermal, hydraulics, wind, biomass, and pumping. The non-renewable sources include coal thermal, combined cycle, and cogeneration. If the city lacks these facilities, the energy balance will indicate that the needs are imported (Barragán-Escandón et al., 2019).

For the energy consumption associated with the transformation processes of the ET, the following equation is applied (Zhou et al., 2016;

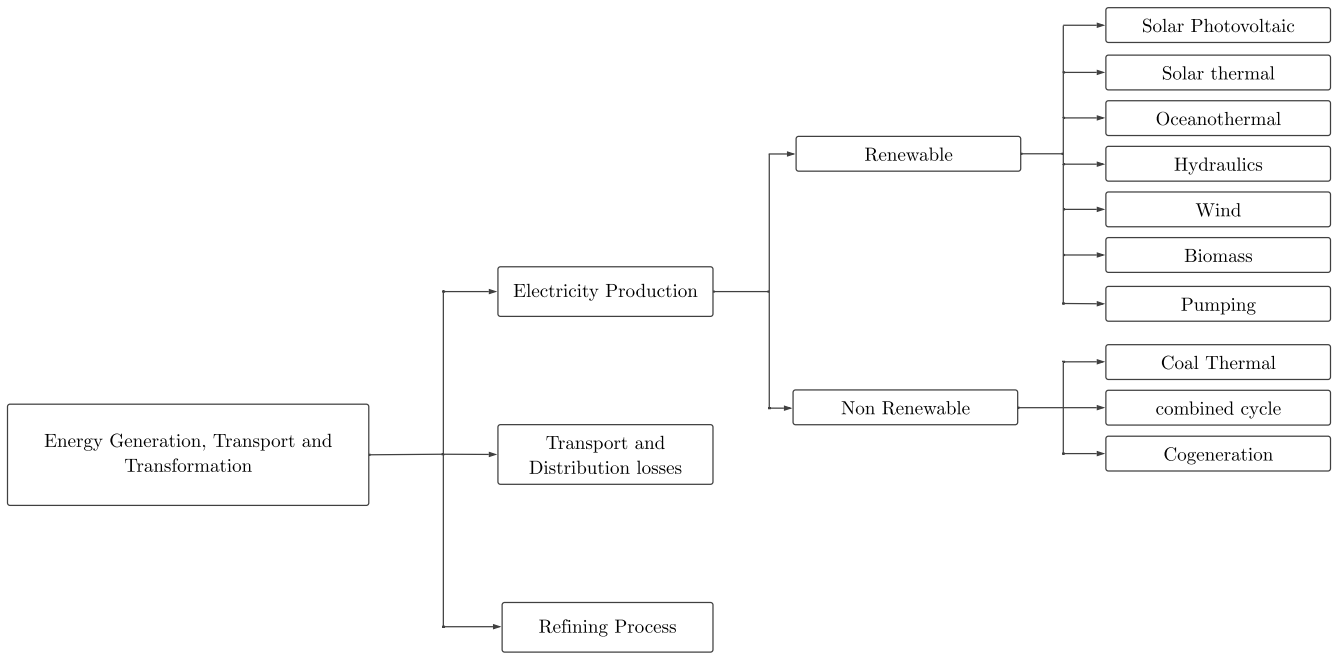


Fig. 4. Schematic of energy transformation modelling. Source: Own elaboration.

Terry Heaps, 2016):

$$TE_u = \sum_k \sum_v AET_v \cdot \left(\frac{1}{\eta_{u,v,k}} - 1 \right) \quad (2)$$

where: TE_u is the total energy after transformation. AET_v (After Energy Transformation) is the energy amount after transformation. $\eta_{u,v,k}$ (Transformation Efficiency) is the efficiency of the transformation process. u is the type of primary energy. k is the type of equipment. v is the type of secondary energy.

The model also takes into account how energy storage technologies, including pumped hydro and battery storage, might help reduce the unpredictability of renewable energy sources. In situations with a high penetration of renewable energy sources, the integration of storage enhances grid stability and the dependability of the energy transformation process.

The resources needed could include primary energy such as biomass, wind, solar, natural gas and others, secondary energy such as electricity or energy derived from refining processes. Fig. 5 provides a visual representation of these energy resources, categorising them into primary and final energy types. Primary energy sources include crude oil, coal, biomass, wind, solar, hydro, geothermal, and natural gas, which are used as the initial inputs in the energy system. Final energy refers to processed energy forms, such as gasoline, diesel, fuel oil, LPG, electricity, biofuels (biodiesel and bioethanol), argon, residual fuel oil, kerosene, and lubricants, that are directly consumed by end-users. This distinction is critical for understanding the energy supply chain and ensuring efficient energy planning and management.

3.4. Emissions analysis

LEAP also addresses the analysis of emissions related to final and primary energy consumption. To do this, a fossil fuel emissions factor is introduced and assigned to each type. This feature allows LEAP to carry out a comprehensive environmental impact analysis and provide detailed information on the emissions associated with each energy source. A more thorough evaluation of emissions by industrial, transportation, and residential activities is made possible by LEAP's ability to sectorally disaggregate emissions, in contrast to traditional emission estimation

models. This makes it easier to pinpoint the main sources of emissions and helps with the development of focused decarbonisation plans.

Demand-related emissions (CEC) and transformation (CET) can be calculated using the following equation (Terry Heaps, 2016; Zhang et al., 2011):

$$CEC = \sum_p \sum_q \sum_r AL_{r,q,p} \cdot EI_{r,q,p} \cdot EF_{r,q,p} \quad (3)$$

where: CEC is the cumulative energy consumption. $AL_{r,q,p}$ (Activity Amount) is the magnitude of demand or the use of services, goods, and resources associated with energy over a specific period. $EI_{r,q,p}$ (Energy Intensity) is the amount of energy used per unit of economic or social activity. $EF_{r,q,p}$ (Emission Factor) is the emission factor related to the fuel type r , equipment q , and sector p . r represents the fuel type. q represents the equipment type. p represents the sector.

$$CET = \sum_u \sum_v \sum_w AET_{w,v} \cdot \frac{1}{\eta_{w,v,u}} \cdot ETF_{w,v,u} \quad (4)$$

where: CET is the cumulative emission transformation. $AET_{w,v}$ (After Energy Transformation) is the energy amount after transformation. $\eta_{w,v,u}$ (Transformation Efficiency) is the efficiency of the transformation process. $ETF_{w,v,u}$ (Emission Transformation Factor) is the emission factor related to the primary fuel type u , secondary energy type w , and equipment type v . u represents the primary fuel type. v represents the equipment type. w represents the secondary energy type.

To further ensure a more realistic representation of local energy system features, this analysis also applies region-specific emission factors based on revised IPCC recommendations. Indirect emissions from energy transition losses and grid inefficiencies are included in emission calculations in addition to direct emissions from fuel burning.

The emission factors applied in this analysis are those recommended by the Intergovernmental Panel on Climate Change (IPCC). It is important to highlight that emissions associated with electricity consumption are excluded from this stage of the process, as they are accounted for at an earlier stage.

As shown in Fig. 2, the output variables generated by LEAP form part of an optimisation process in which future energy demand for each sector during the study period is calculated based on the input variables. Additionally, this process includes the calculation of

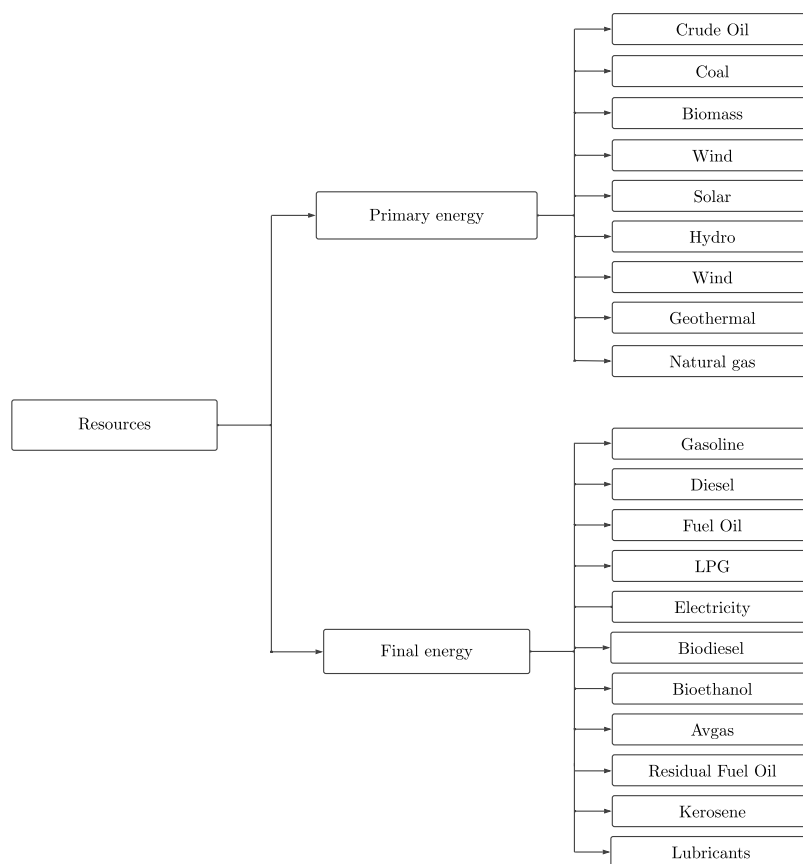


Fig. 5. Diagram of the resources needed for energy modelling.
Source: Own elaboration.

environmental loads, such as the emissions associated with these energy demands. While LEAP is also capable of conducting integrated cost–benefit analyses, this functionality has not been utilised in this study.

4. Case study: Andalusia

In the first instance, the energy situation of the Autonomous Community of Andalusia was analysed by studying all energy aspects referring to the selected base year, which is 2021. For this year, all available energy information on demand and production in Andalusia was compiled from the annual report ‘Energy data for Andalusia 2021’ (Andalusian Energy Agency, 2021).

Andalusia, a region in southern Spain (as shown in Fig. 6), has a diversified energy profile shaped by its natural resources, which significantly influence its energy matrix. The region is renowned for its abundant renewable energy potential, particularly its intense solar radiation, making it an ideal location for solar energy generation. Furthermore, several of its eight provinces experience favourable wind conditions, which have facilitated the development of wind farms across the territory.

Even though other parts of Spain and the Mediterranean region, including Extremadura, Murcia, or parts of southern Italy and Greece, may have been used as case studies, Andalusia has a special set of characteristics that make it worthy of being chosen.

First, Andalusia is ideally situated for photovoltaic and solar thermal energy since it has some of the highest amounts of sun radiation in Europe. With several wind farms already operational, it also has significant wind potential. These circumstances offer a strong basis for researching the extensive integration of renewable energy sources.

Second, the area has taken the lead in putting energy policies into action that are in line with national and European goals, making it

easier to evaluate policy-driven energy transitions. The implementation of energy efficiency initiatives and renewable energy projects is encouraged by Andalusia’s clearly defined regional energy policy.

Third, a thorough examination of diverse energy consumption patterns is made possible by Andalusia’s economic structure, which consists of industry, agriculture, and tourism. It is a representative example for wider applications in Mediterranean regions because of its diversity, which allows for a more thorough assessment of energy consumption across many industries.

Finally, Andalusia is an intriguing case study for researching energy independence and grid stability in high-renewable penetration scenarios because of its particular problems with regard to energy interconnections and energy storage requirements brought about by its location at the southernmost tip of Europe.

Furthermore, Andalusia’s contribution to the advancement of hydrogen-based energy solutions enhances its standing as a leader in the integration of renewable energy. In order to create a cross-border hydrogen economy that lessens reliance on fossil fuels, the region has actively participated in hydrogen valley activities, working with Portugal on projects like Sinte. This is in line with the larger European plan to promote energy self-sufficiency and create green hydrogen corridors. Andalusia’s strategic importance in spearheading low-carbon energy transitions is further supported by the imperative need to find alternative energy sources to replace carbon sources derived from fossil fuels.

Beyond its technical and financial elements, the climate vulnerability of Andalusia emphasises how urgent it is to accelerate the deployment of renewable energy. The need for robust energy infrastructures is highlighted by the region’s growing climate hazards, which include excessive heat and protracted droughts. Furthermore, global uncertainty and worries about energy dependency highlight how crucial it is to have a secure, self-sufficient energy infrastructure that can



Fig. 6. Location of the Andalusia region in Europe.
Source: Own Elaboration.

endure market swings. Andalusia is a prime example of how energy transitions can be planned to promote long-term sustainability and regional stability because of these elements as well as the socioeconomic dynamics of migration.

Andalusia's energy profile is distinguished by its rich biomass resources, primarily derived from agricultural origins and related industries. These resources serve as a substitute for fossil fuels, enhancing self-sufficiency and promoting energy diversification. To further illustrate the region's energy potential, Andalusia is home to 94 hydroelectric power plants with a combined capacity of 650 MW, accounting for nearly 15% of the national total. All these characteristics will be incorporated into the modelling of the region.

To summarise, the combination of Andalusia's strong regional energy regulations, varied economic activity, great potential for renewable energy, and advantageous geographic location justifies the region's selection as a case study. With conclusions that can be applied to other Mediterranean and southern European regions, these variables make it a perfect place to study the viability and ramifications of a large-scale energy shift.

4.1. Demand

To understand the energy demand behaviour in Andalusia, its evolution over a period prior to the base year has been analysed to estimate its future trend for scenario design. Data from 2011 to 2021 have been examined. Regarding primary energy consumption, a significant reduction of 8.18% is observed compared to 2011. Of particular note is the virtual absence of coal use and the notable increase in renewable energy consumption, which has grown by 45% since 2011. In 2021, renewable energy accounted for 22.26% of total consumption, in contrast to 14.1% in 2011.

Regarding fossil fuels such as oil, there is no significant change in primary energy consumption; instead, it remains constant, having shifted from 45.87% in 2011 to 45.96% in 2021. As for natural gas, its consumption has decreased by 19.24% since 2011. In both scenarios, it is proposed that the region of Andalusia will continue to prioritise increasing its consumption of renewable primary energy, with the main objective of replacing fossil fuels.

Final energy consumption decreased by 3.73% compared to 2011. The sectors with the largest increases in consumption are transportation and services, while the industrial, primary, and residential sectors have seen reductions in their consumption, although not all of these

Table 1

Average annual variation in energy consumption by sector and by fuel.

Final energy consumption	Average annual variation in energy consumption (%/year)	
Residential sector	-0.58%	Decrease
Industrial sector	-0.21%	Decrease
Transportation sector	+0.72%	Increase
Service sector	+0.27%	Increase
Primary sector	+1.71%	Increase
Primary energy consumption	Average annual variation in energy consumption (%/year)	
Coal	-11.13%	Decrease
Natural Gas	-1.22%	Decrease
Oil	-0.49%	Decrease
Renewable	+4.30%	Increase

reductions are significant. The main objective for 2030 is not only to reduce energy consumption but also to achieve a high percentage share of renewable energy within that consumption. All scenarios envisage an increase in the share of renewable energy in final energy consumption.

Table 1 presents the average annual percentage change in primary and final energy consumption during the study period, providing an overview of the situation in Andalusia by sectors and fuel types.

Figs. 7 and 8 illustrate the evolution of energy consumption in Andalusia during the period 2011–2021, showing the trends in final and primary consumption of the different energy sources. These graphs allow us to visualise the structural and sectoral transformations in the energy system, supporting the quantitative analysis presented previously.

Fig. 7 details the changes in final consumption, broken down by energy source, while Fig. 8 complements this analysis by presenting the evolution of primary energy consumption, providing a comprehensive perspective of the regional energy system

4.2. Energy production

The analysis of energy production in Andalusia during the 10-year period prior to the base year has been essential for understanding regional energy dynamics. This study not only provides vital information for modelling future scenarios, but also underpins proposed energy strategies and policies. Table 2 summarises the average annual variation in energy consumption by electricity production technologies, distinguishing between non-renewable and renewable sources.

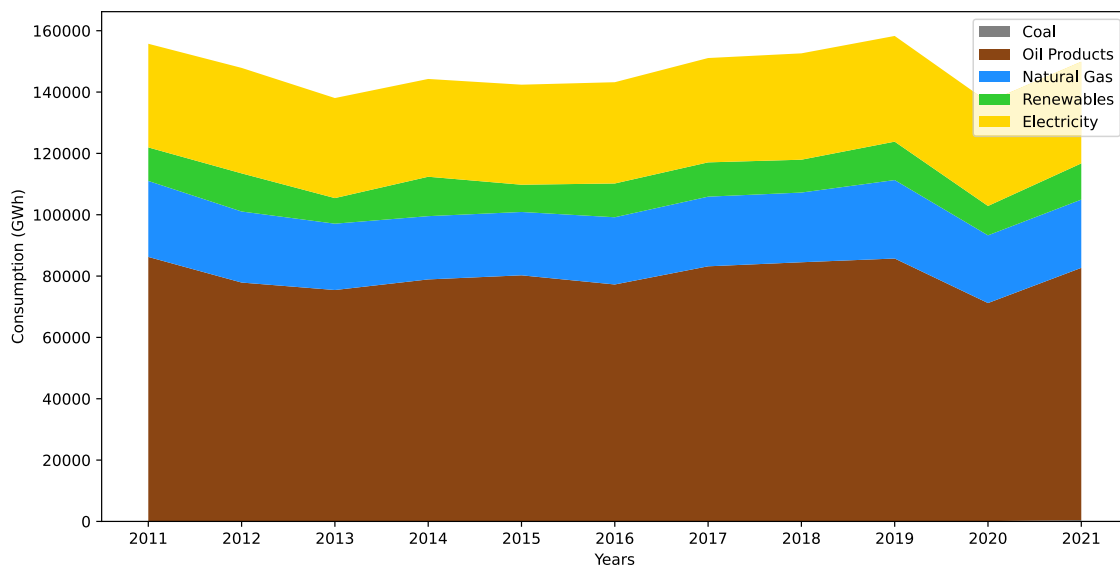


Fig. 7. Evolution of final energy consumption in Andalusia in the period 2011–2021.
Source: AAE and own elaboration.

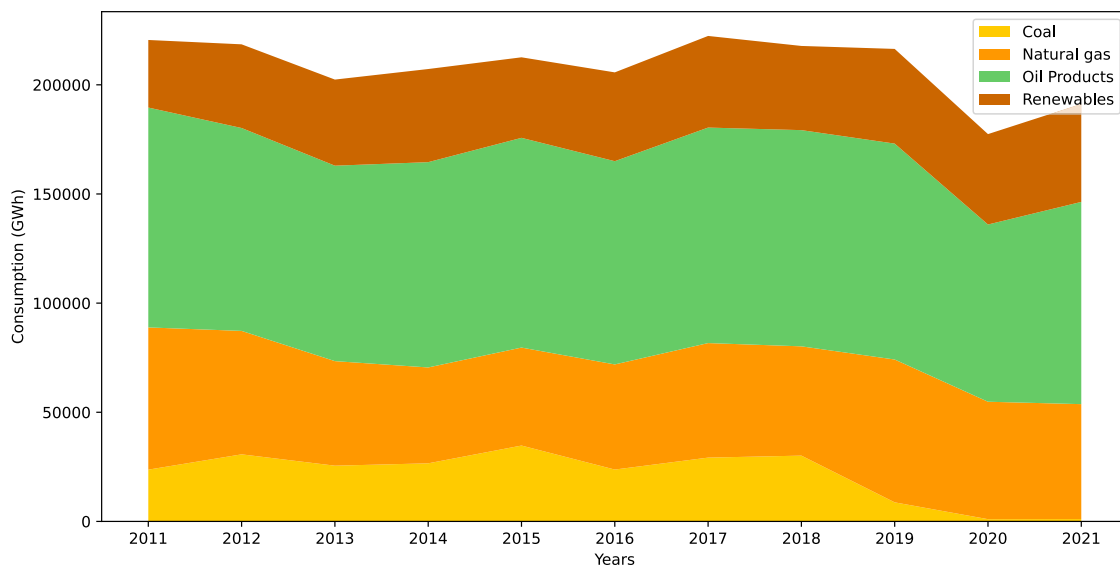


Fig. 8. Evolution of primary energy consumption in Andalusia in the period 2011–2021.
Source: AAE and own elaboration.

During this period, electricity generation in Andalusia has seen a significant decline, with a reduction of 21.88% compared to 2011. This decrease has been particularly pronounced in non-renewable technologies, such as conventional thermal power plants and combined heat and power plants, which have experienced substantial drops in production. By contrast, cogeneration has maintained relatively stable output, though with a slight decrease. In contrast, renewable technologies have experienced a notable increase in their production. Of particular note is the significant growth of photovoltaic energy, which has increased its production by almost 4000 GWh since 2011. Likewise, solar thermal energy has experienced substantial growth, as have other renewable sources, although to a lesser extent. Hydroelectric power is the exception, having halved its generation compared to 2011.

Fig. 9 details the evolution of electricity production broken down by technology, allowing us to identify the specific changes in the energy sources used in Andalusia during the analysis period. On the other hand, Fig. 10 summarises the energy transition by illustrating the overall trends in renewable and non-renewable technologies. Together,

Table 2

Average annual change in energy consumption.

Source: AAE and own elaboration.

Electricity production	Average annual variation in energy consumption (%/year)	
Non-renewable		
Pumping	+5.59%	Increase
Coal thermal power plant	-12.96%	Decrease
Combined-cycle power plant	+2.11%	Increase
Cogeneration	-1.31%	Decrease
Renewable		
Biomass	+2.63%	Increase
Wind energy	+1.98%	Increase
Hydroelectric	-1.90%	Decrease
Solar PV	+17.42%	Increase
Solar thermal	+13.37%	Increase

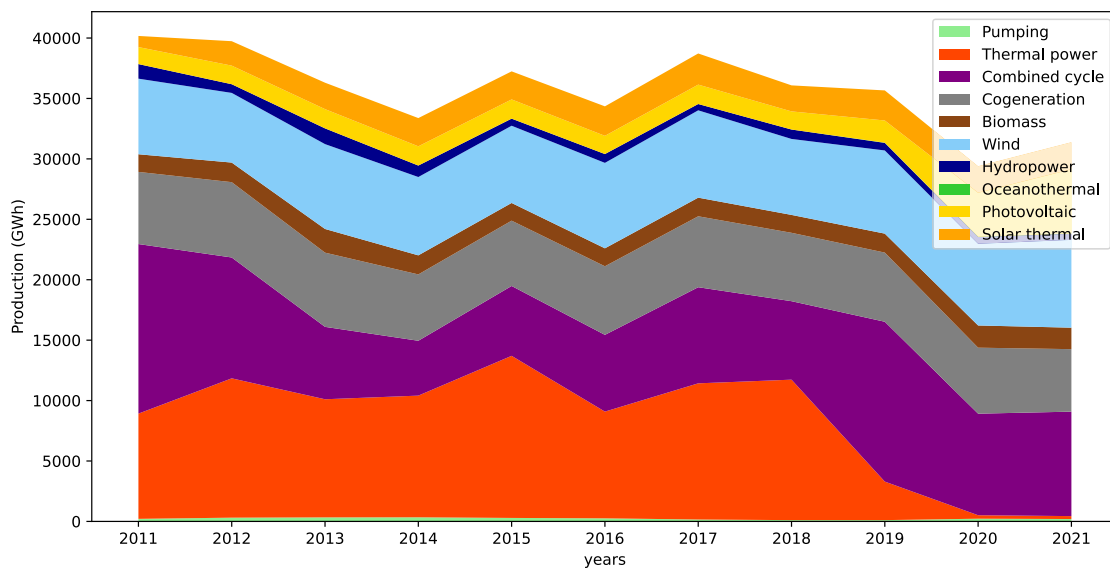


Fig. 9. Evolution of energy production in the period 2011–2021.
Source: AAE and own elaboration.

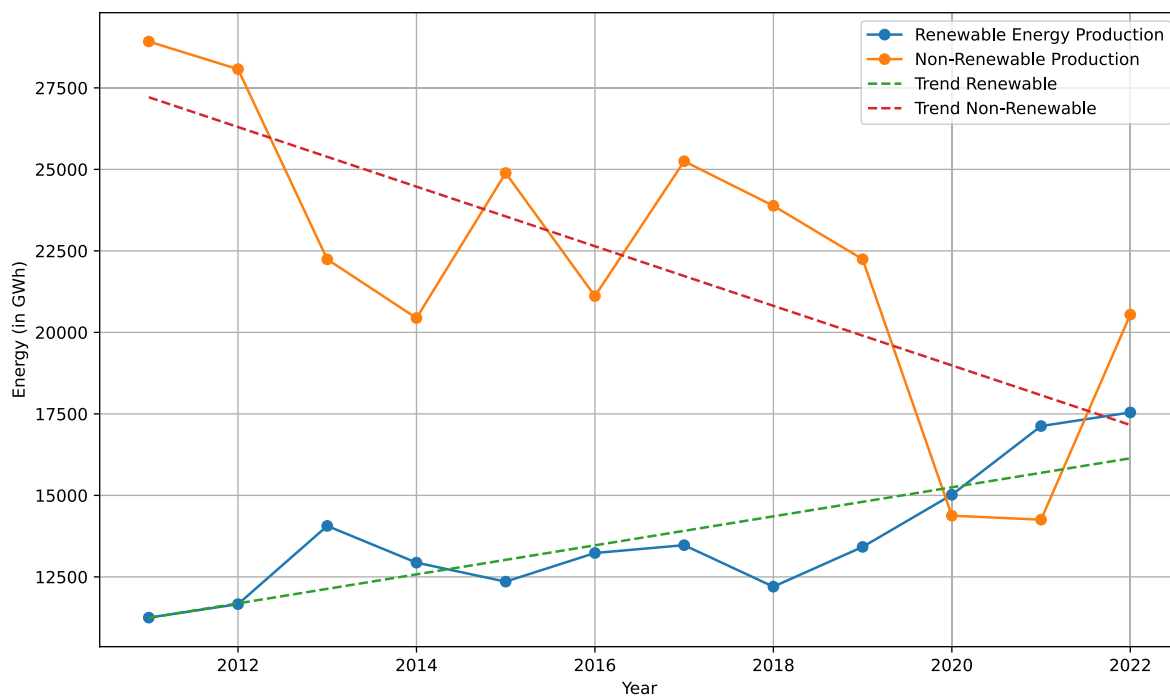


Fig. 10. Evolution of energy production in the period 2011–2021.
Source: AAE and own elaboration.

these figures offer a comprehensive perspective, blending technical detail with an overarching view of structural changes in the regional energy matrix.

Andalusia is projected to continue to prioritise renewable energy as part of its strategy to replace fossil fuels. The main objective is to significantly increase the share of renewable energy in its energy matrix. For the base year, the following data (Table 3) have been taken into account for the different electricity production technologies:

4.3. Losses in electricity transmission

As mentioned before, the transformation module, LEAP also gives the possibility to consider the transmission losses of any energy source.

In this case, Fig. 11 illustrates the monthly variation, adjusted monthly variation, and trend line of electricity transmission losses, using data provided by Red Eléctrica de España (REE). For 2021, a total average loss of 5% was considered. The figure highlights the significant seasonal variability in losses, with peak values occurring in spring and minimum losses during the autumn months.

4.4. Energy transformation processes

In the context of transformation processes, it is important to consider the two most significant refineries in the country, located in Cádiz and Huelva. At these facilities, crude oil is received and processed through refining to produce a variety of derivatives, including petrol, diesel, paraffin, and liquefied petroleum gas (LPG), among others.

Table 3
Energy data considered for modelling the energy production of the Andalusia region.
Source: AAE and own elaboration.

Type of technology	Annual electricity production (GWh)	Installed capacity (MW)	Efficiency (LEAP) ^a	Maximum availability (%) (LEAP) ^b
FV	5364.2	3455.8	100	17.72
Wind	7266.7	3515.2	100	23.59
Thermal power plant	241.6	870	33	3.17
Pumping plants	198.4	570	70	3.97
Thermosolar	2239.9	997	100	25.64
Hydraulics	507.3	650	100	8.90
Biomass	1776.2	274	22	74.01
Cogeneration	5171.3	893.3	80	66.08
Combined Cycle	8643.9	5953	52.5	16.57

^a The LEAP software considers 100% efficiency of renewable technologies to simplify comparisons with other technologies because there are no significant energy losses in the direct conversion process. In the case of non-renewable technologies such as thermal and biomass plants, efficiencies are lower due to inherent losses in the conversion of fuels to electricity. Efficiencies for non-renewable technologies have been obtained from the International Energy Agency (IEA).

^b The LEAP software has calculated the maximum availability through annual generation (GWh/year) and installed power, which are data entered by the user.

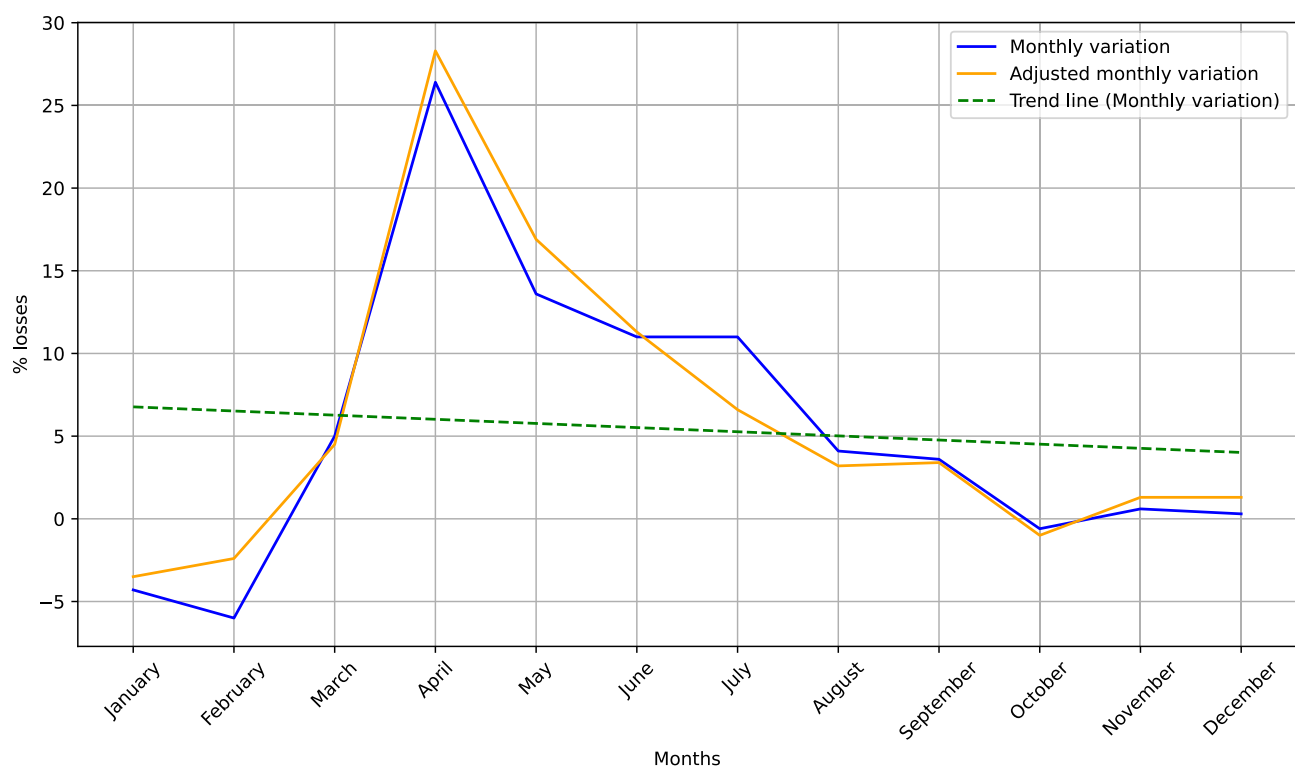


Fig. 11. Losses in electricity transmission.
Source: REE and own elaboration.

To enable LEAP to model the crude oil transformation process and associated emissions at the La Rábida (Huelva) and San Roque (Cádiz) refineries, several key parameters have been incorporated. These include the refining capacity of the facilities, process efficiency, refinery availability, and other relevant factors for analysing emissions and the production of oil derivatives.

Once the base year has been modelled using data provided by the Junta de Andalucía and the Andalusian Energy Agency various scenarios are designed to project the energy evolution for 2030 and 2050. These scenarios represent potential trajectories of the energy system, taking into account variables such as technological advancements, energy policies, and social trends. Each scenario provides insight into how energy demand and emissions might evolve in the future.

Fig. 12 shows the Sankey diagram for the base year. This diagram shows the energy flows from their origin to their final destination, which would be the different sectors that make up demand.

5. Definition of prospectives scenarios

Three scenarios were created in order to investigate Andalusia’s energy future: (1) a baseline scenario that reflected the policies in place at the time, (2) an efficiency scenario that included aggressive energy-saving efforts, and (3) a long-term scenario that was in line with climate neutrality goals. These scenarios were chosen because they ensured viability within the geographical context while representing a range of possible energy transitions.

The 2030 and 2050 time ranges were chosen in accordance with the Andalusian Energy Agency’s energy planning, which aligns with the goals of the Andalusian Climate Action Plan and the National Integrated Energy and Climate Plan (PNIEC). To ensure a sustainable energy transition in the region, the Andalusian Energy Strategy 2030, in particular, offers a framework in line with national and European energy policy. This method guarantees the viability and applicability

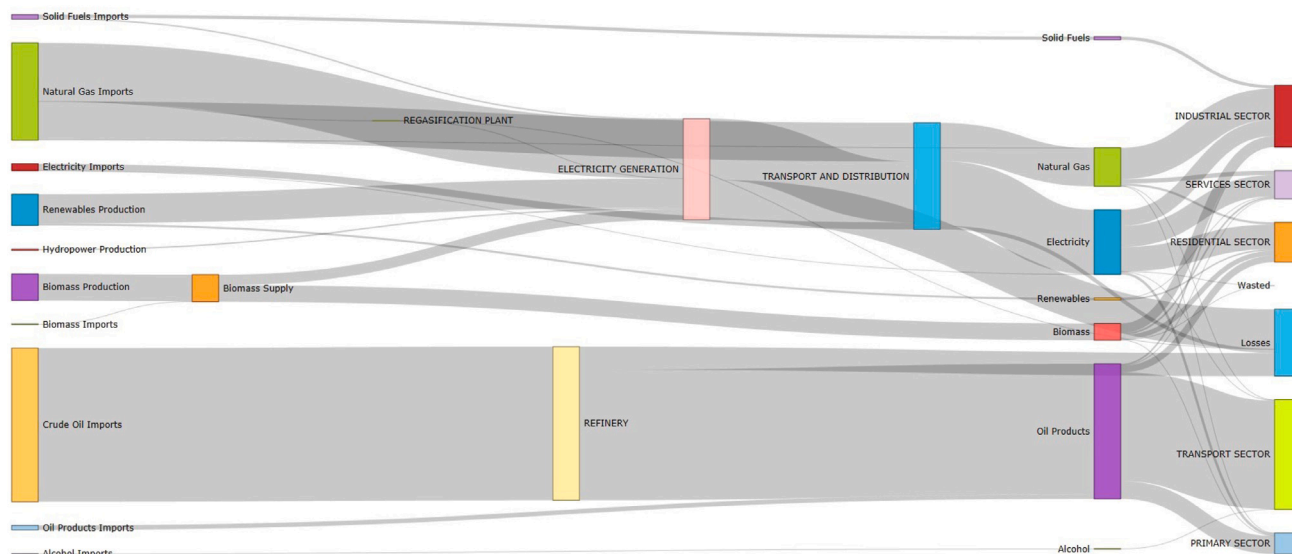


Fig. 12. Sankey diagram of the base year 2021.
Source: Own elaboration.

of decarbonisation policies in the Andalusian context by enabling the evaluation of energy demand evolution, renewable energy integration, and greenhouse gas (GHG) mitigation strategies within a framework in line with European commitments, such as the European Green Deal and the Fit for 55 initiative.

Furthermore, in order to fully assess the possible paths of the energy system, the two scenarios that were taken into consideration—efficiency and trend—represent extreme situations. We can determine whether the anticipated energy transition is in line with the suggested goals or whether more policy interventions are needed to reach regional, national, and European climate targets by contrasting these scenarios. Furthermore, by extending the efficiency scenario, a third scenario for 2050 has been created, enabling us to evaluate if the short-term actions taken will be adequate to meet the 2050 climate neutrality and decarbonisation goals. Policymakers can make well-informed decisions based on thorough scenario planning thanks to this methodological approach, which guarantees that the analysis covers a broad variety of potential energy futures.

Other modelling strategies might have included hybrid models that combined top-down and bottom-up techniques, high-renewable penetration scenarios, or backcasting techniques. Nonetheless, the scenario framework that was chosen makes it possible to clearly and methodically assess the effects of policies and technology advancements.

Additionally, energy markets are inherently volatile, and global political dynamics—especially policy shifts in major economies like the USA and China—can have profound effects on energy transitions. Given the current geopolitical instability, unexpected changes in energy policies could lead to extreme scenarios that significantly impact regional energy planning. To address this uncertainty, it is essential to consider an intermediate scenario that accounts for potential disruptions while maintaining feasible projections. This approach allows us to evaluate the resilience of Andalusia's energy strategy under different geopolitical and economic conditions, ensuring a more adaptable and robust transition framework.

This strategy has the benefit of being directly in line with national and regional policies, guaranteeing that the model represents practical transition routes. A thorough evaluation of Andalusia's capacity for decarbonisation is also made possible by the inclusion of a long-term climate neutrality scenario, which connects short-term policy planning with long-term sustainability objectives.

The different scenarios considered in the energy analysis of the Andalusia region are detailed in Tables 4 and 5:

Historical patterns, technology forecasts, and policy pledges were all incorporated to increase the scenarios' plausibility. This guarantees that every scenario is supported by practical evidence and reasonable expectations in addition to being conceptually sound.

6. Results

Once the base year has been analysed using the energy data provided by the Andalusian Energy Agency (AAE) and the scenarios have been modelled based on the characteristics outlined in the Andalusia Energy Strategy 2030 document, the software's results for the various cases are interpreted. Firstly, a divergent trend in energy demand emerges between the two scenarios. In the baseline scenario, demand shows a notable increase, reflecting the absence of sustainable measures to control it. By contrast, the efficient scenario demonstrates a significant reduction in demand, attributed to the implementation of more stringent and effective measures. This contrast highlights the direct impact of adopted measures on shaping energy demand in each scenario.

According to Riahi et al. (2017), “The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview”, which examines the effects of various socioeconomic trajectories on energy demand and emissions, these results are consistent with earlier research on regional energy transitions. This study offers a sector-specific analysis, highlighting significant variations in demand reduction across industry, transportation, and residential sectors in a regional context, in contrast to earlier work that mostly concentrates on national and worldwide estimates.

In both scenarios, the increasing share of renewable energies in the final consumption matrix is a key feature. This shift has contributed to a reduction in emissions in both cases, as the use of fossil fuels gradually decreases in favour of cleaner energy sources.

6.1. Trend scenario (TS01)

In the baseline scenario, energy demand increases by 15% compared to the base year, reaching a total of 154,046.3 GWh. All sectors experience an increase in energy consumption, except for the services sector, which shows a slight decrease relative to the base year. The primary sector and transport are the most affected, with increases of 35% and 22%, respectively, followed by the residential and industrial sectors, which record increases of 19.6% and 1.7%.

Table 4
Characteristics of demand modelling in the scenarios proposed through LEAP.
Source: Own elaboration.

Scenario name		Trend scenario 2030		Efficient scenario 2030	
Abbreviation	TS01	ES01		ES02	
Sector	Total consumption	(Energy sources)	Total consumption	(Energy sources)	Total consumption and energy sources
Residential	19% increase	Greater use of electronic devices, higher comfort demands for climate control, higher per capita consumption due to population growth.	10% reduction	65% electricity, 10% natural gas, 20% renewables (geothermal, solar, thermal biomass). Increased use of solar thermal, geothermal, biomass, and self-consumption technologies to reduce losses and optimise consumption.	Pro-rata implementation of the efficiency scenario up to 2050
Industrial	0.4% decrease	Improvements in energy efficiency, structural changes in production, and greater electrification with reduced fossil fuels.	8% reduction	30% electricity, 50% natural gas, 17% renewables. The sector will see stable natural gas use, reduced oil derivatives, and increased electrification and renewable thermal energy use. The reduction in electricity costs driven by renewables will promote sector electrification.	
Transport	22% increase	Increase in the number of vehicles (cars, trucks, vans), although lower growth than collective transport and motorcycles.	25% reduction	80% electricity, 12% natural gas, 7% renewables. The sector will adopt nearly zero-energy buildings and retrofit older ones, improving energy efficiency in thermal insulation, lighting, and HVAC systems.	
Services	3% reduction	Greater electrification, higher energy efficiency, slight reduction in natural gas consumption.	8% reduction	80% electricity, 12% natural gas, 7% renewables.	
Primary	35% increase	Mechanisation of the sector.	2% reduction	60% oil derivatives, 18% electricity, 16% natural gas, 6% renewables. Fossil fuel consumption will remain significant, but electricity, natural gas, and renewables (like biomass) will increase.	

Table 5
Features in the modelling of energy transport, transformation and production.
Source: Own elaboration.

Scenario name		Trend scenario 2030		Efficient scenario 2030	
Abbreviation	TS01	ES01		ES01	
Electricity production	24% increase in electricity production compared to 2019, accounting for 26% of final energy consumption in 2030.	Renewable energy will account for 75% of electricity production. Fossil fuel-based production (combined cycles, cogeneration, etc.) will cover the remaining 25%.		Renewable energy will account for 75% of electricity production. Fossil fuel-based production (combined cycles, cogeneration, etc.) will cover the remaining 25%.	
Renewable energy capacity	Significant growth in solar, wind, and biomass generation, leveraging Andalusia's high renewable potential.	Renewable capacity is projected to grow by 340% by 2030, reaching 31 GW and representing 81% of total installed capacity.		Renewable capacity is projected to grow by 340% by 2030, reaching 31 GW and representing 81% of total installed capacity.	
Fossil fuel share	Oil derivatives will increase slightly from 37% to 43% of total energy consumption. Natural gas will rise by 6%, reaching 26%.	The share of fossil fuels will continue decreasing. Oil derivatives will drop, coal will be phased out, and natural gas will stabilise at around 26% of primary energy consumption.		The share of fossil fuels will continue decreasing. Oil derivatives will drop, coal will be phased out, and natural gas will stabilise at around 26% of primary energy consumption.	
Coal use	Coal consumption will decrease, representing only 4% of total primary energy by 2030.	The use of coal will be phased out completely, contributing to reduced greenhouse gas emissions.		The use of coal will be phased out completely, contributing to reduced greenhouse gas emissions.	
Installed capacity (2030)	Total installed renewable capacity will rise significantly, but coal-fired power plants will remain part of the energy mix.	By the end of 2030, renewable installed capacity will reach 31 GW, and coal-fired plants will be fully decommissioned. Renewable energy will dominate the energy landscape in Andalusia.		By the end of 2030, renewable installed capacity will reach 31 GW, and coal-fired plants will be fully decommissioned. Renewable energy will dominate the energy landscape in Andalusia.	

With regard to energy source consumption, there is a notable increase in renewable energies (such as solar energy, biomass, and bio-fuels) and electricity, achieving an increase of nearly 50% compared to 2021. Conversely, a clear decline in the consumption of fossil fuels derived from oil and coal is anticipated. Coal experiences the largest reduction in consumption (57.9% compared to the base year), followed by liquefied petroleum gas (LPG) and fuel oil, with reductions of 24.4%.

Diesel consumption also decreases by 7%, although petrol consumption rises significantly by 38.2%. Natural gas shows a considerable reduction of 31% compared to the base year.

This pattern is consistent with the International Energy Agency's "World Energy Outlook 2023", [Iea - International Energy Agency \(2023\)](#) which projects that the rate at which fossil fuels are replaced varies by sectoral electrification. According to [Creutzig et al. \(2015\)](#) in

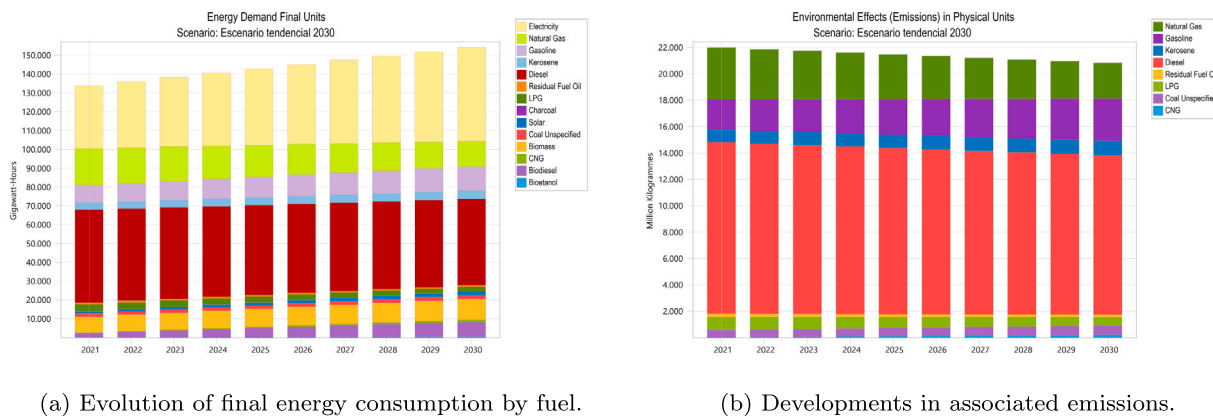


Fig. 13. Results obtained in scenario TS01. Source: Own elaboration.

“Urban Transport and Energy Demand”, which highlights the necessity of complementary infrastructure investment in public transport and EV incentives, the observed 38.2% increase in petrol consumption shows that transportation remains a challenge for decarbonisation.

This overall decline in fossil fuel consumption results in a reduction of emissions associated with energy demand. Among the various sectors, the residential sector achieves the greatest reduction in associated emissions, with a decrease of 43.13% compared to the base year, followed by the services sector, which reduces its emissions by 37.1% due to greater electrification. The industrial sector also achieves a 22.1% reduction in emissions, while the transport sector sees a smaller reduction of 2.9%. The only sector that increases its emissions is the primary sector, which, due to the mechanisation of its activities, records a 33% increase in emissions compared to the base year.

Fig. 13 presents the results obtained. Subfigure (a) illustrates the evolution of final energy consumption by fuel, showing the significant increase in renewable energy sources and electricity, alongside the decline in fossil fuels such as coal and natural gas. Subfigure (b) depicts the corresponding developments in emissions, highlighting reductions across most sectors, with the residential and services sectors achieving the greatest decreases, while the primary sector is the only one to exhibit an increase in emissions.

With regard to the production of electrical energy, an increase in production through renewable energy can be seen. The greatest increase is seen in photovoltaic energy due to the ever-increasing commitment to it, reaching an installed power of 3 times more than that contemplated in the base year. Wind energy is followed by solar energy, which will increase its installed capacity by 50%, as it is estimated that wind farms will be installed in some provinces to make this installation efficient. Other renewable energy sources are also increasing their share of the energy matrix, but to a lesser extent. Other energy facilities that have seen their activity increase are combined cycle facilities, which increased their production by 30%. Both thermal power plants and cogeneration are estimated to reduce their output by 50% each compared to the base year. This is combined with a reduction in emissions since, as they are less involved in the matrix, the effects of these fuels are smaller.

Fig. 14 shows the Sankey diagram for the baseline scenario 2030 (T01), illustrating the energy flows and the contribution of various sources to the energy matrix.

6.2. Efficiency scenario (ES01)

Secondly, in the efficient scenario, energy demand decreases rather than increases, due to the adoption of measures that enhance energy efficiency. In this case, demand reduces by 14.6% compared to the base year, with electricity accounting for 32.3% of total final energy

consumption. Following electricity, diesel and natural gas have the next highest shares, contributing 25.8% and 16.7%, respectively. Although renewable energies are projected to have a smaller share in 2030 than these sources, their consumption is expected to grow significantly, with photovoltaic solar energy increasing by 50% and biomass by 7%. Additionally, the consumption of biofuels, such as biodiesel, is anticipated to rise by 25%.

With regard to energy consumption by sector, it can be concluded that, with the exception of the primary sector, which increases its consumption by 2%, all other sectors experience a reduction, with the transport sector seeing the largest decrease of up to 25%. The residential sector also shows a decrease of nearly 10%, followed by the industrial and services sectors, which experience reductions of 8.6% and 8.2%, respectively.

As expected, emissions associated with demand are significantly lower in this scenario compared to the baseline scenario. This is due not only to a reduced share of fossil fuels but also to an overall decrease in energy demand across all sources, leading to a corresponding reduction in emissions. The total reduction is 30% compared to the base year, with the most notable decreases observed in the residential and service sectors. These are followed by the transport sector, which achieves a 33% reduction in emissions, and the industrial sector, with a reduction of 21.7%.

These results are consistent with those of Barrett et al. (2022) in “Energy Demand Reduction Options for Meeting Zero-Emission Targets”, which highlights how aggressive efficiency initiatives affect patterns of energy use. This report offers a more thorough sectoral analysis of Andalusia than more general national assessments, highlighting particular issues such the noted 2% increase in the primary sector’s energy use. This pattern is in line with Yang et al.’s (2022) “Dynamic Linkage Between Mechanisation and Carbon Emissions”, which posits that, even in the face of overall efficiency gains, agricultural mechanisation may increase localised energy demand.

In the projected scenario, the region of Andalusia is expected to significantly enhance its commitment to renewable energy for electricity generation, achieving a substantially larger share than in the baseline scenario, with an estimated total installed capacity of 36,500 MW. The majority of this capacity will be derived from photovoltaic solar energy, which sees a decisive expansion, with an increase of nearly fivefold compared to 2021 levels. Fig. 15 presents the results obtained in the efficient scenario, showing the change in final energy consumption per fuel in subfigure (a) and the associated changes in emissions in subfigure (b).

This approach aims not only to integrate solar PV and other renewable energy sources into the energy mix but also to partially replace fossil fuel-fired combined cycle, cogeneration, and thermal power plants. As these technologies are inherently unstable due to their

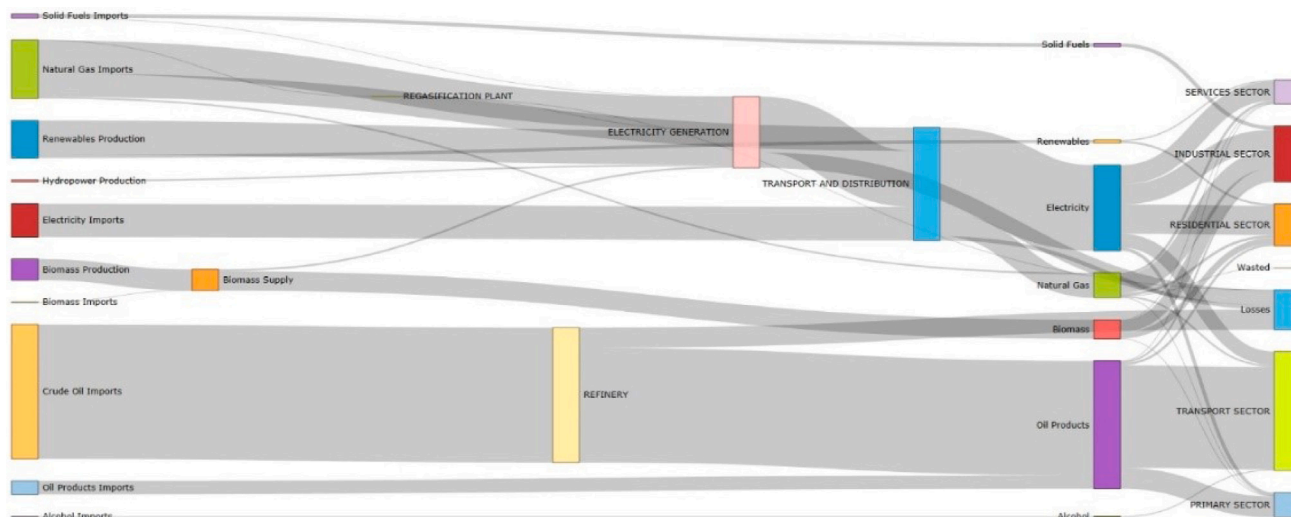
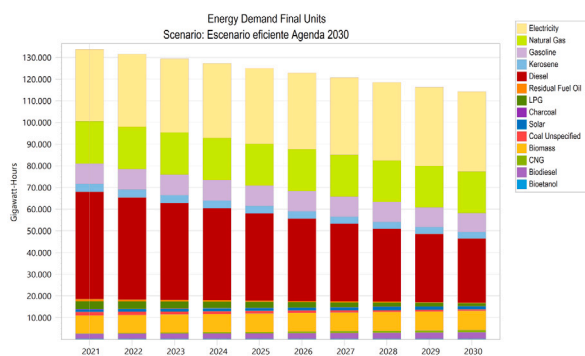
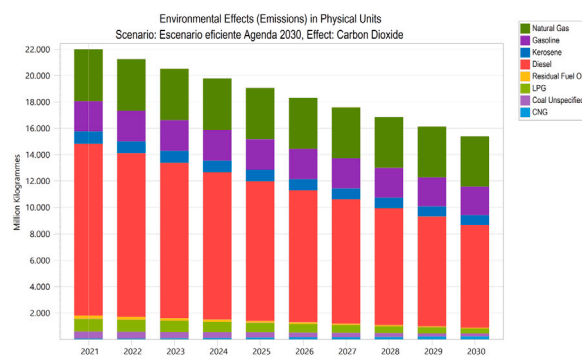


Fig. 14. Sankey diagram for the baseline scenario 2030 (T01).
Source: Own elaboration.



(a) Change in final energy consumption per fuel.



(b) Change in associated emissions.

Fig. 15. Results obtained in scenario ES01.
Source: Own elaboration.

reliance on external factors and lack of energy storage capacity, it is projected that by 2030 significant investments will have been made in energy storage systems to enhance overall system stability. Fig. 16 illustrates the Sankey diagram for the efficient scenario 2030 (ES01), showcasing the energy flows and the reduced reliance on fossil fuels while highlighting the greater integration of renewable energy sources into the energy system.

Decarbonisation scenarios are placing a greater emphasis on the importance of energy storage and grid flexibility, as IRENA (2023) (Iea - International Energy Agency, 2023) points out in “Renewable Energy Benefits: Measuring the Economics”. This analysis supports these conclusions by showing that, as the proportion of variable renewables rises, a significant investment in storage devices will be necessary to preserve system reliability and avoid intermittency problems. To maximise Andalusia’s energy transition, future studies should concentrate on evaluating the viability of various storage systems.

6.3. Comparison of trend scenario (TS01) and efficient scenario (ES01)

Comparing the two scenarios reveals the final energy consumption and associated emissions that could be avoided. On the demand side, the efficient scenario would save a total of 39,844 GWh, with corresponding emissions savings of 5429 tonnes of CO₂. In environmental terms, this reduction in CO₂ emissions represents a significant step

towards mitigating climate change and improving air quality. Additionally, these savings would contribute to global efforts to meet international emission reduction targets, which are essential to addressing today’s climate challenges.

These emissions reductions are consistent with the estimates from IRENA (2023) (Irena, 2016), “Renewable Energy Benefits: Measuring the Economics”, which quantifies the role of energy efficiency in reducing CO₂ emissions at the regional level. This study expands upon such findings by providing a sector-specific assessment of Andalusia, identifying that the transport sector remains a key contributor to emissions even in an efficiency-driven transition. The results suggest that while energy savings are substantial, further policy interventions targeting transportation are required to maximise decarbonisation potential, a challenge also highlighted by Creutzig et al. (2015) in “Urban Transport and Energy Demand”.

From an economic perspective, the savings of 39,844 GWh could translate into substantial financial benefits. These savings would not only reduce consumers’ energy bills but also positively impact the competitiveness of businesses by lowering their operating costs.

Economic assessments from IEA (2022) (Iea - International Energy Agency, 2023), “Net Zero by 2050: A Roadmap for the Global Energy Sector”, indicate that energy efficiency policies provide long-term cost reductions, reinforcing the financial benefits observed in this study. However, unlike global estimates, this research provides a more

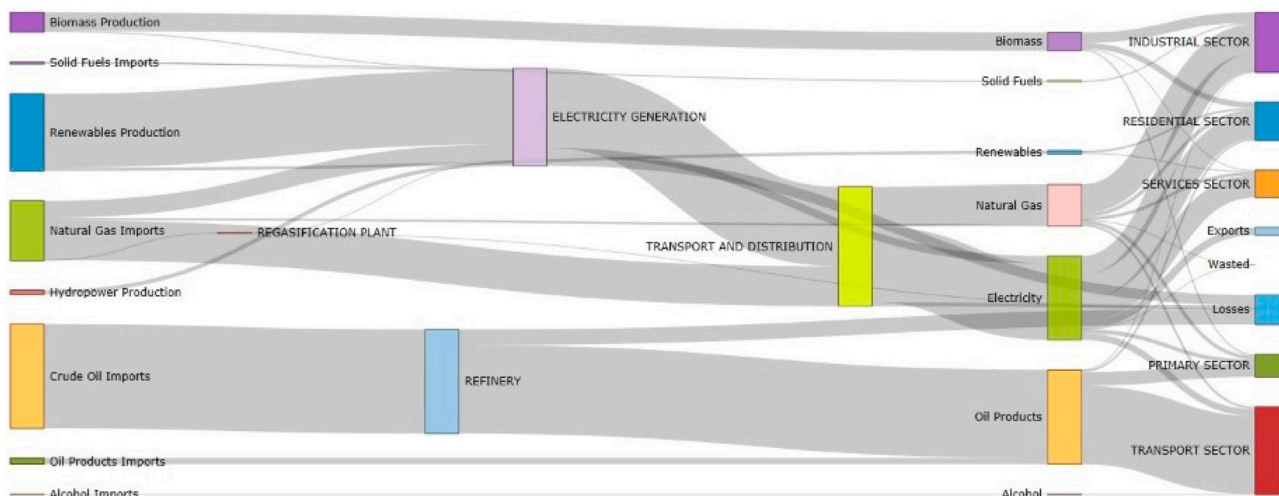
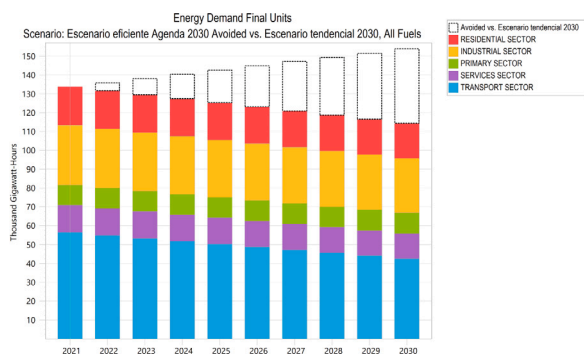
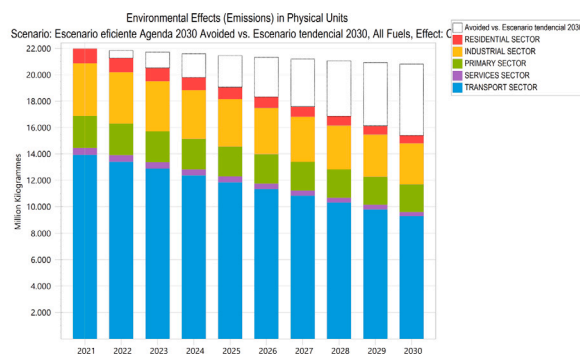


Fig. 16. Sankey diagram for the efficient scenario 2030 (ES01).
Source: Own elaboration.



(a) Change in final energy consumption per fuel.



(b) Change in associated emissions.

Fig. 17. Results obtained in scenario TS01 vs. ES01.
Source: Own elaboration.

localised perspective, demonstrating how Andalusian businesses and households could experience cost savings in response to the transition. Such findings could be instrumental for policymakers in designing incentives and financial mechanisms to accelerate energy efficiency investments.

Fig. 17 summarises these results, showing the change in final energy consumption per fuel in subfigure (a) and the change in associated emissions in subfigure (b).

6.4. Andalusia 2050 scenario (ES02)

In this scenario, as previously mentioned, the measures adopted for the efficient scenario have been extended to 2050. The purpose of modelling this scenario is to assess whether Andalusia could fully comply with the objectives set at the national level by the National Integrated Energy and Climate Plan (PNIEC) for 2050.

A significant decrease in energy demand of 31.78% is projected compared to the base year. The transport sector drives this trend, with a reduction of 54.6%, followed by the residential and services sectors, which decrease their demand by 25.7% and 21.5%, respectively. Furthermore, the residential sector shows a 12.5% reduction in demand compared to 2021. However, the primary sector is the only area where demand is expected to increase, with a projected rise of 5.7% compared to the base year.

In terms of energy sources consumed, this scenario is expected to achieve neutrality in fossil fuels such as coal and fuel oil. Significant reductions are projected in the use of fuels such as diesel and petrol, with decreases of 78% and 18%, respectively. A 13% reduction in natural gas consumption is also anticipated. Conversely, electricity consumption is expected to increase by 12.3%, alongside a substantial rise in solar energy demand, which is projected to double compared to the base year. Growth is also observed in other renewable energy sources, such as biomass, with a 27% increase, and biodiesel or bioethanol, with increases of up to 25%.

These results are consistent with “Mitigation Pathways Compatible with 1.5 °C”, by Gasser and Luderer (2018), which highlights that systemic changes beyond energy efficiency and renewable integration are necessary to achieve deep decarbonisation by 2050. Although the anticipated rise in solar energy demand is consistent with global trends noted by IRENA (2023) (World Energy, 2023), the persistence of fossil fuel consumption in certain industries indicates that further structural policies, like investments in energy storage and flexible grid management, will be necessary for complete decarbonisation. In this scenario, the focus has been exclusively on modelling energy demand, as forecasting long-term energy production is considerably more complex. The interaction of multiple factors, such as technological developments, energy policies, and economic conditions, introduces substantial uncertainty to long-term production projections. Consequently, this analysis prioritises demand as the key reference point for understanding future trends in energy consumption.

Unlike prior studies that focus on broad regional and national estimates, this study presents a more localised and sector-specific assessment, highlighting that despite ambitious demand reductions, residual emissions remain a challenge in certain industries. These findings support the need for targeted sectoral policies, as suggested by Grubler et al. (2018) in “A Low Energy Demand Scenario for Meeting the 1.5 °C Target”, where regionalised planning is highlighted as a key enabler of sustainable transitions.

7. Discussion of the results in relation to the objectives

7.1. Energy consumption

The analysis conducted using LEAP reveals that, in this study, energy demand exhibits completely divergent trends between the two proposed scenarios, reflecting the impact of sustainable measures implemented in one of them. The baseline scenario presents a much less favourable outcome in terms of meeting the established targets, one of which is to achieve a 39.5% reduction in primary energy consumption compared to the 2007 baseline (equivalent to 148,004 GWh). In this scenario, primary energy consumption is projected to increase to 229,111 GWh. Comparing this figure with the target for 2030 shows a reduction of only 6.3%, leaving 84% of the target unmet.

Conversely, in the efficient scenario, the set of adopted measures leads to a reduction in final energy consumption and, consequently, in primary energy consumption. In this case, primary energy consumption is estimated at 184,917 GWh, representing a 24.41% reduction. While this marks significant progress, it still falls short of the 39.5% target, leaving 38% of the target yet to be achieved.

These findings suggest that even if the efficiency scenario results in notable decreases, further technical developments and legislative changes would be necessary to reach the 2030 goal. Stricter building regulations, a quicker rollout of energy-efficient equipment, and demand-side management techniques are some actions that could help close the gap. Additionally, comparisons with comparable research conducted in Germany indicate that the energy network's stability and efficiency can be improved by including smart grid technologies and efficient energy storage systems. Recent studies highlight the significance of incorporating distributed photovoltaic (PV) systems into smart grids, emphasising German-specific technical and regulatory considerations (Chen and Heilscher, 2024). Furthermore, studies on the long-term power storage needs for large renewable energy shares highlight the need for adaptable storage options to maintain grid stability and promote the integration of renewable energy (Zerrahn and Schill, 2017) (see Fig. 18).

7.2. Emissions

Another key target is the reduction of greenhouse gas emissions. The objective is to achieve a 39% reduction compared to 2005 levels, with total emissions in 2005 amounting to 67,679.6 kt of CO₂ (Livestock and of Agriculture, 2020). By 2021, emissions had already fallen to 30,223.9 kt, representing a reduction of 55%, which not only signifies substantial progress but also surpasses the target set (Andalusian Energy Agency, 2021). In the trend scenario, emissions continue to decrease slightly, reaching 29,295 kt, which corresponds to a reduction of 56.7%, further exceeding the target. The efficient scenario presents an even more positive outcome, with the measures implemented leading to an estimated 18,334 kt of emissions, representing a 73% reduction compared to 2005.

The efficient scenario highlights the importance of aggressive mitigation strategies, even though both scenarios surpass the 39% emissions reduction objective. The notable reduction in emissions implies that electrification of end users, energy efficiency enhancements, and the deployment of renewable energy should continue to be important policy initiatives. Furthermore, the outcomes are consistent with national energy transition studies' conclusions (Gobierno, 2021; Nacional, 2024), which highlight the necessity of ongoing investment in low-carbon technologies (see Fig. 19).

7.3. Renewable energy participation

The third indicator analysed is the share of renewable energy in final energy consumption, with a target of 42% set for 2030. In 2021, the share of renewables in final energy consumption was approximately 19%, considering the proportion of electricity consumption generated exclusively from renewable sources. In the baseline scenario, the share of renewable energy is projected to reach 25.7% by 2030, while in the efficient scenario it is estimated to increase to 33.48%. Although the efficient scenario comes closer to the 42% target, it still falls short of full compliance.

These findings underscore the difficulty in achieving the 42% target, even with advancements in the integration of renewable energy. The shift might be sped up with the support of more incentives for self-consumption, system modernisation to manage variable renewable generation, and more energy storage capacity. In addition, regulatory tools like feed-in tariffs or renewable energy capacity auctions must be taken into account in order to stimulate additional investment. Recent research has highlighted the significance of smart grid control and dependability when renewable energy sources are present, highlighting major issues and possible fixes (Ourahou et al., 2020). Furthermore, studies on Portugal's photovoltaic mini-generation demonstrate how financial incentives and policy frameworks influence the growth of decentralised renewable energy systems (Carvalho et al., 2011) (see Fig. 20).

7.4. Long-term objectives

The region of Andalusia is also committed to the long-term goal of achieving carbon neutrality by 2050. Spain and its 17 regions have pledged to develop a unified and coordinated response to the climate crisis, aiming to leverage opportunities to modernise and enhance the competitiveness of the economy, while ensuring that the transition is socially fair and inclusive.

Large-scale renewable energy deployment, sophisticated energy storage technologies, and the creation of green hydrogen infrastructure will all be necessary to reach carbon neutrality. To support efforts to reduce emissions, the function of natural carbon sinks, such as afforestation initiatives and wetland restoration, should also be increased. Furthermore, extensive electrification throughout all economic sectors is crucial, according to lessons learnt from international carbon neutrality roadmaps. According to recent study, integrating hydrogen energy storage into hybrid renewable systems is a crucial tactic to improve grid sustainability and stability (Arsad et al., 2022). Furthermore, techno-economic evaluations highlight the potential for decarbonisation by proving the feasibility of standalone renewable energy systems with hydrogen generation and storage (Kalinci et al., 2015). The relevance of hydrogen in reaching carbon neutrality is further supported by the potential for green hydrogen generation from hybrid renewable energy sources (Sarker et al., 2023) (see Fig. 21).

8. Conclusions and policy implications

As outlined in the previous sections, the region of Andalusia, even if adhering to the assumptions made to achieve the energy efficiency scenario in the efficient case, would still fail to meet all the objectives set by national and regional institutions. This highlights the need to reconsider strategies and policies that not only address energy efficiency but also focus on diversifying energy sources and promoting sustainable technologies. Modelling of the base year already revealed Andalusia's ongoing dependence on non-renewable resources, which must be imported, underscoring the urgency of reducing this reliance.

In this regard, policy alignment with broader European strategies, such as the REPowerEU plan and the Fit for 55 package, could accelerate the transition by ensuring regulatory coherence and facilitating access to EU funding mechanisms. These initiatives provide valuable

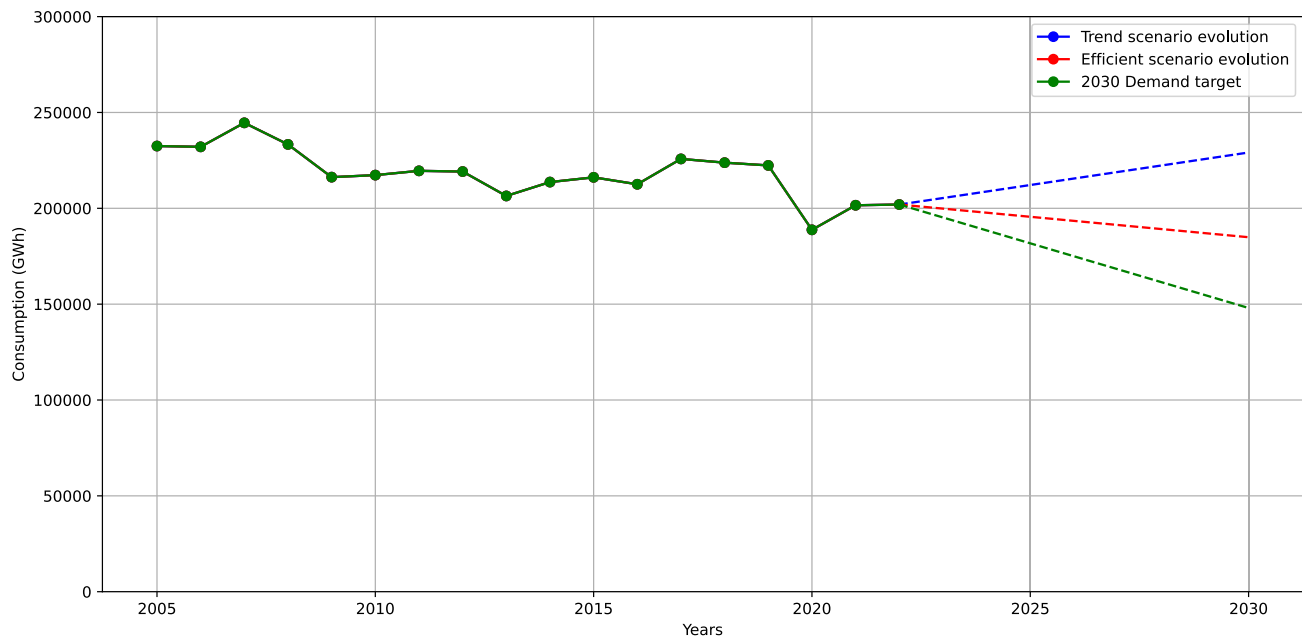


Fig. 18. Estimated evolution of primary energy consumption for the proposed scenarios. Source: Own elaboration.

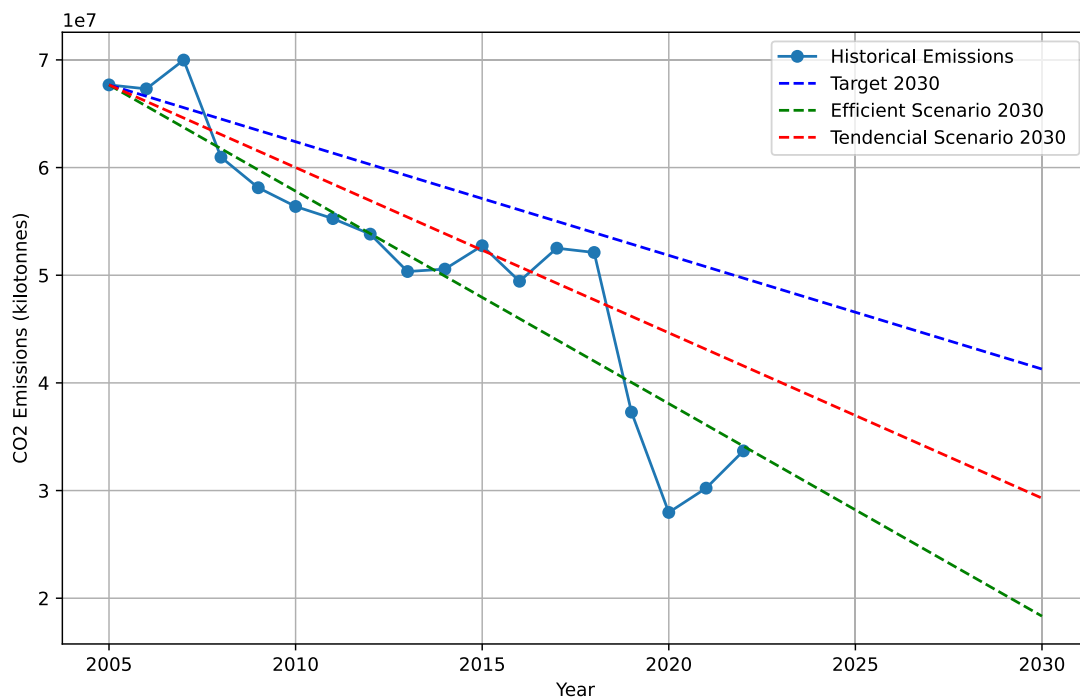


Fig. 19. Estimated evolution of primary energy consumption for the proposed scenarios. Source: Own elaboration.

frameworks for integrating renewable energy sources at a faster pace while addressing energy security concerns (see Table 6).

The incorporation of offshore wind energy, a tactic effectively employed in Scandinavian nations, ought to be taken into consideration for Andalusia’s coastal regions in addition to sector-specific regulations. This could play a major role in reaching the targets for renewable energy.

Furthermore, implementing financial incentives for industrial sector energy efficiency improvements may hasten the decrease of emissions. Similar initiatives have been successful in reducing energy use in

heavy industry and manufacturing in Germany, including subsidies for efficiency upgrades and subsidised energy audits.

From a governance standpoint, creating a specific regional task force to supervise energy policy implementation and guarantee adherence to national and European goals could improve accountability and progress monitoring. The effectiveness of comparable institutions in France and Denmark emphasises how crucial a methodical approach to enforcing policies is.

Seeking the full achievement of medium- and long-term objectives, a series of future measures are proposed. Regarding the reduction of primary energy demand, policies could be implemented focusing

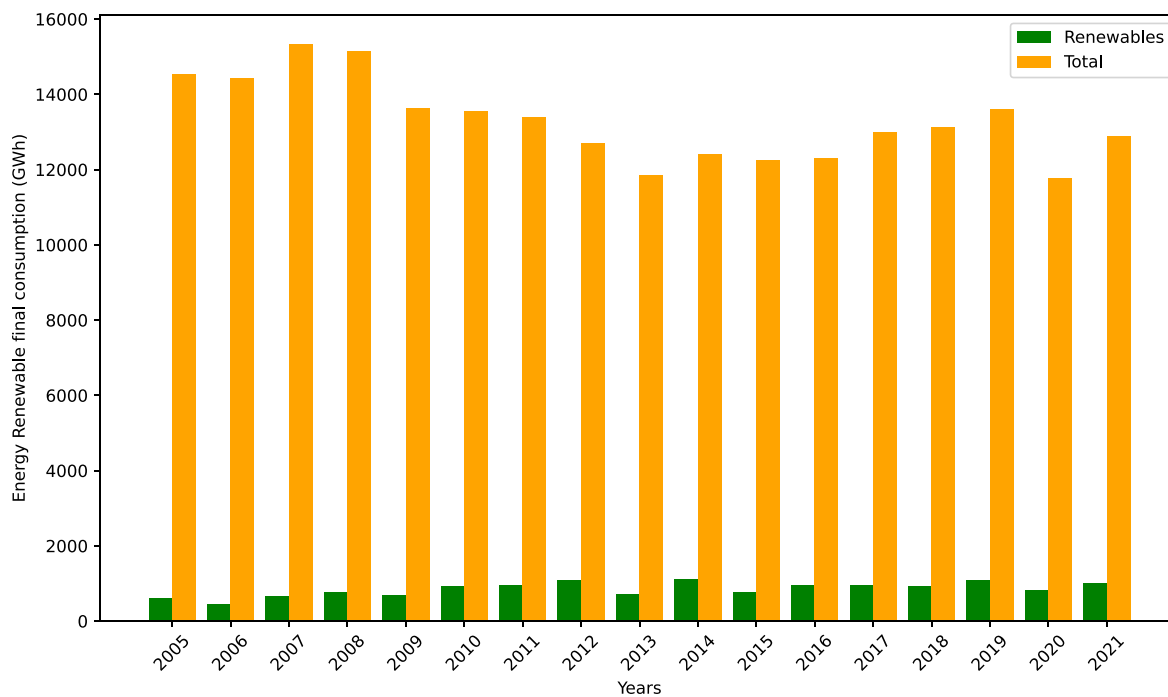
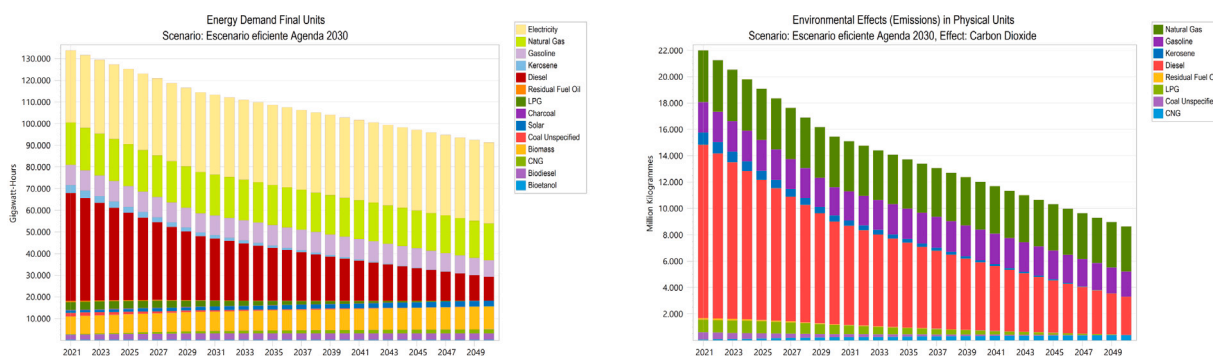


Fig. 20. Share of renewable energy in Andalusia for the period 2011–2021 (without taking into account electricity consumed from renewable sources). Source: Own elaboration.



(a) Change in final energy consumption per fuel

(b) Change in associated emissions.

Fig. 21. Long-term estimates 2050. Source: Own elaboration.

on improving energy efficiency, promoting electrification, and encouraging the use of renewable energy sources in the residential and service sectors. This includes tax incentives and subsidies to implement renewable technologies, replacing fossil fuel-dependent technologies with sustainable alternatives aimed at designing a self-consumption or nearly zero-energy system, in line with EU proposals. Measures such as installing LED lighting, replacing boilers with heat pumps or solar water heating (ACS) or athermal systems with more efficient performance (SEER and SCOP) coefficients (thermal efficiency coefficients for cooling and heating) above 2.5, efficient appliances, thermal insulation, and utilising rooftops and spaces oriented for incorporating photovoltaic self-consumption installations and energy storage systems (batteries). The integration of industrial thermal and energy surpluses into residential networks via public transport networks for effluents nearby would also contribute to this objective. Additionally, home automation using programmable devices would enable greater control and reduction of energy consumption.

Fig. 22 compares the established objectives with the estimates in the different designed scenarios, highlighting the degree of fulfilment for

emissions reductions, primary energy reductions, and renewable energy increases in 2030 and 2050.

The industrial sector can implement measures such as energy audits to identify areas for improvement in efficiency and modernising equipment to achieve more sustainable processes. The installation of renewable generation systems, such as solar panels, and the use of cogeneration and trigeneration technologies will contribute to reducing non-renewable energy consumption and improving overall efficiency. The implementation of energy management systems (EMS) will enable real-time monitoring and optimisation of energy consumption. Additionally, the transition to LED lighting and the installation of energy storage systems will reduce dependence on non-renewable sources, fostering a more sustainable industry.

In transportation, it is essential to encourage the adoption of electric and hybrid vehicles through fiscal incentives and the development of charging infrastructure in urban areas and on motorways. Investing in clean public transport, such as electric buses, trams, and sustainable trains, will be key to reducing dependence on fossil fuels. Other

Table 6
Summary table of the results obtained.
Source: Own elaboration.

Objective	Trend scenario 2030	Efficient scenario 2030	Institution proposing the objectives
To reduce Andalusia's diffuse greenhouse gas emissions by 39% compared to 2005.	A reduction of 56.7% is achieved with respect to the reference year (2005), which means that, even in the most negative scenario, this objective would be met.	A 73% decrease is achieved compared to 2005, so that the target is not only fully achieved, but even exceeded, reaching almost double the target.	AAE (regional)
Reduce trend primary energy consumption by at least 39.5% compared to 2007.	Instead of decreasing as projected since the base year, energy demand has increased, and compared to the base year (2007), the reduction was only 6.3%, much lower than the 39.5% initially estimated.	In this scenario, the target is not achieved either. Demand is reduced by 8.28% with respect to the base year and by 24.4% with respect to 2007, coming close to compliance, but not achieving it in its entirety.	AAE (regional)
To provide at least 42% of gross final energy consumption from renewable energy sources.	The share of renewable energy in final energy consumption in this scenario is projected at 25.7%, falling short of the proposed target of 42%.	In this case, a turnout of 33.48% was achieved, which, although close to 42%, still falls short of the target.	AAE (regional)
Efficiency scenario extrapolated to 2050			
97% renewable energy by 2050	Considering that all electricity produced is of renewable origin, in 2050 the share of renewable energy in final energy consumption would reach a total of 58.66% representation, reaching the 2030 target, but still far below the 97% share of renewables estimated for 2050.		PNIEC (national)
90% reduction in emissions compared to 1990	By 2050, a total of 8622.1 tonnes of CO ₂ is expected, which represents a reduction of 77.56% compared to 1990, without reaching the 90% target for carbon neutrality.		PNIEC (national)

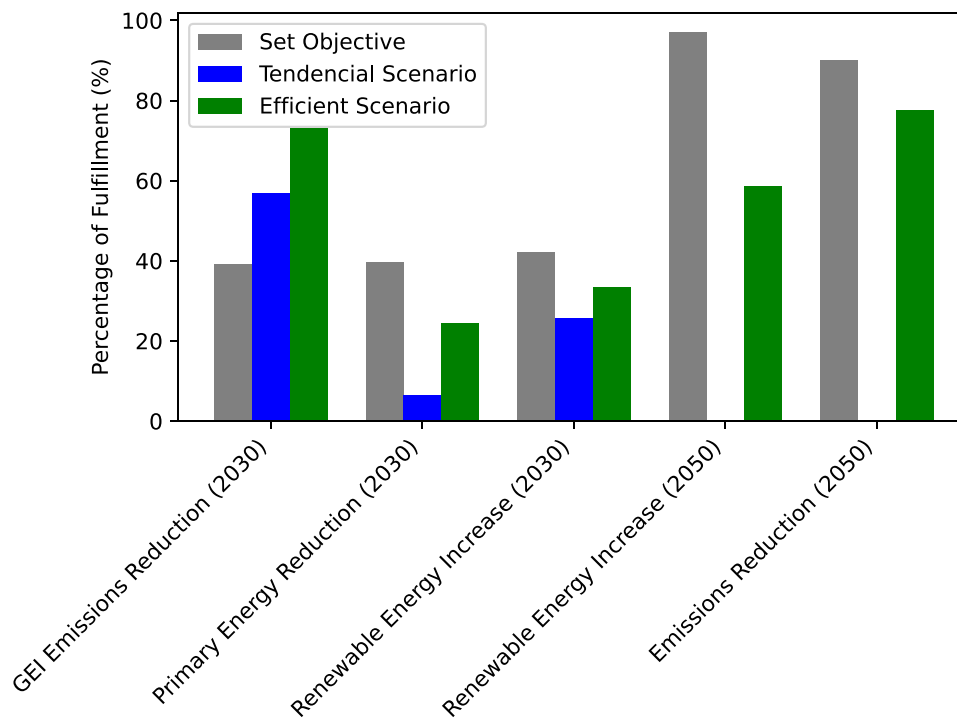


Fig. 22. Comparison between the established objectives and the estimates in the different designed scenarios.
Source: Own Elaboration.

measures include car-sharing and sustainable mobility services, such as bicycle rentals, improving the efficiency of conventional fuels through advanced technologies, and optimising routes using intelligent traffic management systems. Research into biofuels and synthetic fuels will also complement these actions towards a more sustainable transport system.

In the primary sector, the installation of renewable energy systems, such as solar panels and wind turbines, will reduce the need for fossil fuels. The use of biodigesters to generate biogas from organic waste will

promote more efficient waste management and renewable energy generation. Updating agricultural machinery to more sustainable models, as well as using agricultural and forestry waste to produce biofuels, will be essential to achieving an energy transition in this sector. Efficient irrigation systems that reduce both water and energy consumption are also suggested.

This study not only provides insights for Andalusia but also offers a replicable framework for regions seeking to reduce emissions through data-driven energy planning strategies. All these measures

Measures by Sector and Connection to Goals

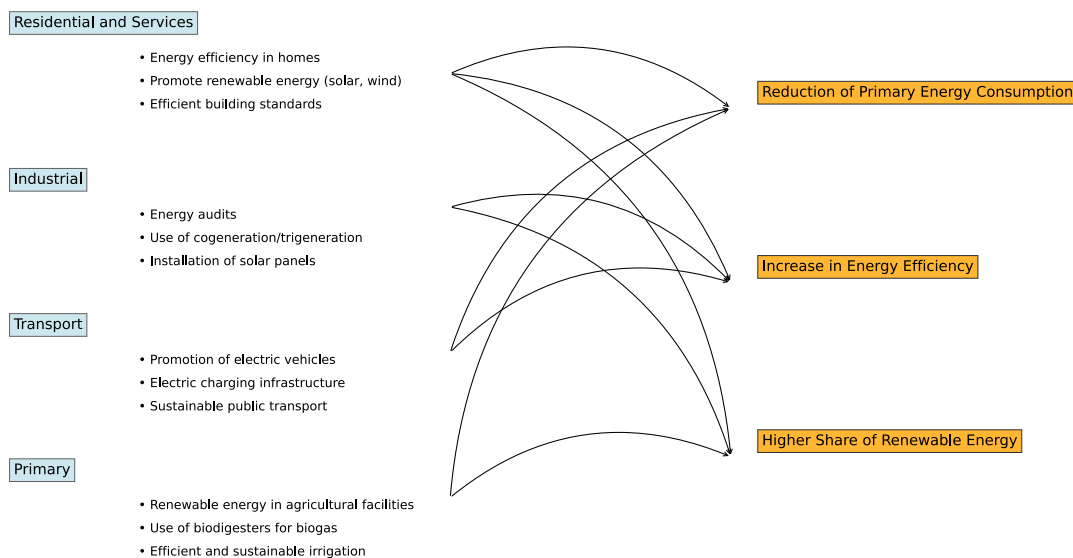


Fig. 23. Connection between sector-specific lines of action and goals.
Source: Own Elaboration.

could directly contribute to meeting national and regional objectives, promoting energy efficiency, reducing primary and final energy consumption, and minimising associated emissions. Furthermore, the aim is to achieve nearly 100% renewable energy participation in final consumption, consolidating a comprehensive energy transition across all sectors.

Fig. 23 summarises the connection between sector-specific lines of action and their corresponding goals, highlighting how measures in residential, industrial, transport, and primary sectors can contribute to reducing primary energy consumption, increasing energy efficiency, and achieving a higher share of renewable energy.

8.1. Limitations and future research

This study uses the LEAP model to examine many potential scenarios while providing a thorough energy analysis of the Andalusia region. Nevertheless, several limitations must be recognised in spite of its all-encompassing approach. First, the conclusions' accuracy is dependent on the assumptions made about the evolution of energy demand, policy implementation, and technical advancements. The forecasts may be greatly impacted by unforeseen socioeconomic or technological upheavals, such as shifts in the world's energy markets or unanticipated developments in renewable energy storage. Furthermore, because the model oversimplifies sectoral relationships, indirect effects are not completely captured, such as how household energy consumption patterns may be impacted by growing electrification in the industrial sector.

The study's emphasis on environmental and energy-related issues rather than a thorough analysis of the social and economic ramifications of the scenarios that were suggested is another significant drawback. A more thorough examination of economic viability, job creation, and public acceptance would offer a more comprehensive viewpoint, even as the technical feasibility of various energy transitions is investigated. Furthermore, assuming that planned and existing policies do not change until 2050, the policy framework is seen as static. Different transition pathways than those described in this paper may result from the dynamic evolution of energy policies in response to geopolitical, economic, and technical advancements.

In order to overcome these constraints, future studies should include a more thorough sensitivity analysis of important input factors, quantifying the effects of uncertainties in population growth, technological costs, and energy efficiency advancements using techniques like Monte Carlo simulations. Furthermore, combining LEAP with macroeconomic models—like Computable General Equilibrium (CGE) models—may shed light on the employment effects and economic viability of various energy routes. The evaluation of grid flexibility initiatives and energy storage technology is another crucial area that has to be improved. Demand-side management, green hydrogen, and battery storage will play an increasingly important role in maintaining grid stability and dependability as the proportion of renewable energy sources rises. Future research could examine the effects of various flexibility and storage options on the viability of decarbonisation goals.

Additionally, current research efforts are focusing on exploring correlations between new socio-economic and energy indicators to enhance existing energy analysis methodologies. Future research could increase the robustness of scenario modelling and energy policy evaluations by incorporating these correlations into decomposition analysis methods like Data Envelopment Analysis (DEA), LEAP, and Logarithmic Mean Divisia Index (LMDI). This would enable a more thorough validation of findings, offering a greater degree of accuracy and dependability for evaluating the efficacy of energy transition plans.

In addition to tackling these constraints, there are a number of encouraging avenues for further investigation. Examining long-term decarbonisation plans after 2050 with an emphasis on net-negative emissions using technologies like carbon capture and storage, nature-based solutions, and synthetic fuels is one crucial direction. Studies that compare Andalusia to other parts of Europe with comparable climates and economies may also provide insightful information that will assist policymakers in identifying potential obstacles as well as best practises. Moreover, additional sector-specific studies might be carried out to assess the viability of complete electrification or the incorporation of hydrogen-based solutions, especially in energy-intensive sectors and the transportation sector.

Finally, given the speed at which digitalisation and artificial intelligence are developing, future studies may examine how smart grids,

digital twins, and AI-driven energy management systems might maximise energy efficiency and enhance grid stability. While lowering costs and guaranteeing system resilience, the integration of these technologies may be crucial in hastening Andalusia's energy transition. Future study could further solidify the groundwork for a sustainable and financially feasible energy transition in the area by filling in these research gaps.

CRedit authorship contribution statement

Lucía Galán-Cano: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Juan Cámara-Aceituno:** Writing – original draft, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Julio Terrados-Cepeda:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition. **Manuel Jesús Hermoso-Orzáez:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Methodology, Investigation. **Edgar Antonio Barragán-Escandón:** Validation, Supervision, Conceptualization. **Ángel Mena-Nieto:** Writing – review & editing, Validation, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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