A Comparative Analysis of Energy Transition and Carbon Footprint in the Mediterranean Islands

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Abstract. Energy transition is a global objective. Moving towards cleaner and more sustainable energy sources requires the progressive abandonment of fossil fuels such as coal, oil and gas. The transition also arises from concerns about climate change and national security that require a more secure and resilient energy system.

The European Union aims to be climate neutral by 2050. Key strategies include the European Green Deal, which promotes renewable energy, energy efficiency and sustainable mobility. Significant investments are supporting the transition, including the Just Transition Fund and the InvestEU programme. Italy is actively participating in the energy transition with the National Recovery and Resilience Plan (NRRP) prioritising green initiatives. However, challenges remain, especially for island regions.

The study proposes a method to compare the monthly trend of the carbon footprint in the islands of Sardinia (Italy), Sicily (Italy) and Cyprus, analyzing data for the period 2021–2024, in respect to the following indicators: direct carbon intensity, percentage of low-carbon energy and energy from renewable sources. The results reveal an overall improvement in renewable energy production across the three islands from 2021 to 2024, with a positive trend towards greater adoption of low-carbon and renewable energy sources. The comparison proved to be valuable for informing policy decisions to support energy transitions in the Mediterranean islands.

Keywords: Energy Transition · Carbon Footprint · Mediterranean Islands

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1 Introduction

The energy transition represents a pivotal ongoing transformation posing specific challenges for land governance at the international level. It is a global process with the aim of reshaping the modalities of energy production and consumption. Promoting a shift from a system based on fossil fuels to one centred on renewable and sustainable energy sources [1]. The European Union (EU) is characterized by a significant reliance on energy imports, a factor that impinges upon its global competitiveness, particularly in comparison to China and the self-sufficiency of the United States [2]. In order to address the exigencies of climate change and ensure security of supply, the EU launched the "European Green Deal" in 2019 (European Commission, 2019) [3], an ambitious strategy designed to achieve climate neutrality by 2050, with an interim target of a 55% reduction in greenhouse gas emissions by 2030 (UN, 2015) [4]. This transition is supported by three key principles: security of energy supply, the advancement of a renewable energy sector in order to improve energy efficiency, and the formation of an integrated energy market [5]. The Green Deal is part of an international commitment to sustainability, in line with the United Nations Sustainable Development Goals and the Paris Agreement. The urgency of this transition is underlined by the IPCC reports, which call for the need to limit the increase in global temperature [6]. In addition, a 'just transition' that supports workers and communities affected by change is crucial to ensuring inclusivity [7]. Currently, the EU's energy mix is characterised by an increasing share of renewables, but there is still a significant reliance on fossil fuels to meet overall energy demand and electricity generation. There are also different views among member states on the role of nuclear energy in the transition. Germany, with its 'Energiewende', is a case study illustrating the complexity of this transition [8]. Furthermore, the heterogeneity of EU countries in terms of economic conditions and energy infrastructure has led to the emergence of an "energy gap", which makes the implementation of a coherent energy policy very complex [9]. The energy crisis, exacerbated by the war in Ukraine, has prompted the EU to step up its efforts through the REPowerEU plan [7]. This plan aims to reduce dependence on Russian fossil fuels and accelerate the transition to renewable energy through measures such as demand reduction, diversification of import sources and increased use of clean energy technologies [10]. These plans stipulate that a minimum of 37% of the allocated resources must be directed towards climate objectives, with Italy allocating approximately 40% of its NRRP funds for this purpose [11]. A comparative analysis with the Italian situation reveals both similarities and distinct differences relative to the previously described European context. In Italy, a notable decline in fossil fuel consumption has been observed since 2008, a reduction closely correlated with the decrease in primary energy demand, which is, in turn, linked to GDP per capita [12]. Coal constitutes a limited share (only 3.5% of primary energy demand), but a potential resurgence in its consumption could occur due to the reduction in gas supplies. The demand for oil, following a period of stability between the early 1990s and the early 2000s, has commenced a downward trend. Conversely, the demand for natural gas experienced consistent growth from the 1980s until 2005, subsequently declining from 2008 onwards, a reduction that can be attributed, at least partially, to the decrease in GDP per capita triggered by the economic crisis of 2007–2008. This decline persisted until 2014, whereupon a phase of recovery began. Italy

holds the leading position within the EU for electricity generation via natural gas. The Italian decision to diversify its supply through the construction of the TAP (Trans Adriatic Pipeline), which transports gas from Azerbaijan and initially faced opposition, is now considered a crucial solution in response to the reduction in gas supplies from Russia. Regarding renewable energies, they represent a substantial portion of Italian energy demand (11.5% in 2020), but after a growth phase until 2013, they have experienced a deceleration and even a decline. This shift in trend is attributable to several factors, including the reduction of subsidies for renewables under the "conto energia" scheme, the sluggish post-crisis economic recovery, and protracted administrative procedures for project approval [13]. In this context, the development of the National Recovery and Resilience Plan (NRRP) assumes a role of considerable importance in establishing concrete pathways towards a just ecological transition. The NRRP represents a fundamental instrument for overcoming the economic and social crisis precipitated by the pandemic and offers a significant opportunity to expedite the transition towards an economic development model based on circularity and energy-environmental sustainability. The National Recovery and Resilience Plan (NRRP) defines the allocation criteria for the European funds from Next Generation EU (NGEU) for the post-Covid recovery. Italy submitted its proposal, which was approved by the EU in July 2021. Mission 2 of the NRRP, with a budget of 59.33 billion euros, is dedicated to the "green revolution and ecological transition" and is structured into four components: Circular economy and sustainable agriculture (M2C1), Renewable energy, hydrogen, network and sustainable mobility (M2C2), Energy efficiency and building renovation (M2C3), and Protection of the territory and water resources (M2C4) [14]. Mission M2C2, with a planned investment of 23.78 billion euros, focuses on five key areas: increasing the share of renewable energy, enhancing and digitizing networks, promoting hydrogen, developing sustainable local transport, and fostering industrial and research leadership in the transition. A total of 5.9 billion euros are allocated to augmenting production from RES, with anticipated investments in utility-scale plants (unlocking potential through regulatory and market reforms and valorizing agrivoltaics), energy communities and small-scale distributed systems (particularly pertinent in Italy due to the limited availability of large land areas), innovative solutions (including integrated and offshore technologies), and the strengthening of biomethane [15]. The government intends to operate at two levels: incentivizing large-scale RES plants and promoting energy communities, with a focus on municipalities with populations under 5,000 inhabitants. Despite the substantial allocation for energy communities (2.2 billion euros), a contrast remains with large-scale plants in terms of localization strategies and resource utilization. The plan allocates significant funding to "*agrivoltaics*", aiming to integrate sustainable agricultural and energy production, although its actual innovative scope requires careful evaluation regarding its impact on the territory and biodiversity. Substantial investments are directed towards long-term energy vectors such as green hydrogen, while some argue for greater investment in energy efficiency and RES. Furthermore, reference is made to PITESAI for hydrocarbon exploration, indicating a continued anticipated role for fossil fuel sources. The government's rationale is to facilitate private investments in renewables by streamlining procedures, but this could potentially lead to a relaxation of territorial protections [16]. The diffusion of renewable energy sources in Italy, supported by various national

regulations and strategies (including the Bersani Decree, Burden Sharing, SEN 2017, PNIEC 2018, the "Mille Proroghe" Decree, and Legislative Decree 199/2021), exhibits substantial stagnation, with slow and insufficient growth to meet the 2030 targets. This growth has been primarily driven by photovoltaics and wind power. At the international level, Italy ranks behind China and other European countries in terms of new RES installations, despite a total installed capacity that places it in a more favorable position [13, 14]. However, it is essential that the National Recovery and Resilience Plan (NRRP) supports the crucial role of just transition policies to ensure an inclusive ecological transformation [15]. Following the pandemic emergency, trade unions presented a unified document on energy policy, anticipating their positions on the Recovery Fund and the priorities for the utilization of European funds at the national level. Key concerns include the historical institutional and administrative inability to spend, the slowness of bureaucratic procedures, the limited valorization of synergies between projects, an insufficient assessment of the socio-economic impact (particularly on employment), and the necessity for a more defined governance system and greater involvement of social partners and territorial institutions, all of which are crucial elements for the implementation of just transition policies [16].

1.1 The Mediterranean Scenario

The Mediterranean area presents a notable potential for the development of renewable energies, owing to the abundance of solar irradiance and wind resources, as well as the declining costs of relevant technologies, within a context of robust growth in energy demand, particularly for electricity. The International Energy Agency projects that renewable capacity in the Middle East and North Africa region will double within the next five years, propelled by solar photovoltaics and incentivized by private investments [17]. This potential is geographically dispersed throughout the area, spanning from Morocco to Turkey and the Balkans. Southeastern Europe alone boasts an estimated technical capacity of 740 GW [18], with recent studies by IRENA indicating that 127 GW could already be cost-competitive. North Africa follows this trend, exhibiting solar irradiation three times greater than that of Europe and significant wind potential [19].

Regarding natural gas, in addition to the established reserves of North Africa, the Eastern Mediterranean is reassessing its own resources, estimated at 3,500 billion cubic meters [20], as corroborated by recent offshore explorations, including the discovery of the Zohr field by Eni in Egypt. Despite the substantial potential, the Mediterranean region has exhibited a slow rate of renewable energy adoption, with coal and oil dominating (especially in Turkey and the Western Balkans), leading to elevated CO2 emissions. It is crucial to harness the potential of both renewable energy and gas for a rapid energy transition. The political, economic, and social transformations in the Southeastern Mediterranean are intrinsically linked to regional energy dynamics, influenced by crises and instability that impede the sustainable development of the sector. Political uncertainty and reduced investments, coupled with geopolitical tensions and territorial disputes, constrain the exploitation of resources, despite demographic and economic growth that augment energy demand. A significant increase in energy consumption is

anticipated, accompanied by macroeconomic risks and environmental impacts associated with the extensive utilization of fossil fuels. The transition towards cleaner sources, energy efficiency, the integration of energy markets, and infrastructural development are paramount, also considering the potential of biogas and green hydrogen. The Mediterranean region necessitates substantial investments, particularly within the renewable energy sector. In this regard, private investment is crucial for bridging the financial gap, enhancing technologies, and generating commercial opportunities within the energy sector, as such synergies foster political dialogue and sustainable economic development. In this context, Italy, alongside Germany and France, is a prominent actor, with major companies such as Eni, Enel, Snam, Terna, and Edison, and international players like TAP AG, constituting key drivers of the energy transition in the Mediterranean, encompassing both the gas and renewable energy sectors. The paucity of infrastructure represents a constraint on the development of gas and renewable energy sources in the Mediterranean. The Italian private sector is actively involved in various energy infrastructure projects in the Mediterranean: Snam participates in the TAP gas pipeline to diversify European supply and support the decarbonization of the Balkans, and explores collaborations in Egypt (Snam, 2018); Edison contributes to the EastMed gas pipeline to bolster the EU's energy security; Terna plays a fundamental role in electricity interconnections, such as Sicily-Tunisia and Pescara-Kotor; Enel invests in wind power projects in Morocco, Spain, the Balkans, and Greece. Islands represent ideal sites for the study of the socio-spatial dimensions of the energy transition, owing to their isolation and the necessity to ensure energy security, in addition to their aspirations for political autonomy [21, 22]. The central objective of this paper is to examine the evolution of the carbon footprint within the context of the energy transition, with a specific focus on the Mediterranean islands, particularly those large and geographically isolated from the mainland: Sardinia, Sicily, and Cyprus. Through a comparative analysis of data pertaining to carbon intensity, the percentage of low-emission energy, and the proportion derived from renewable sources, for the period 2021–2024, the intention is to evaluate the monthly trend of this footprint. Concurrently, the study aims to elucidate the specificities of island contexts in their energy transition pathway, considering both the vulnerabilities and the opportunities arising from local renewable resources. Consequently, the investigation intends to provide a detailed and comparative analysis of the impact of the energy transition on the carbon footprint in the Mediterranean islands, with the aim of identifying sustainable strategies and models for the future.

2 Method

This study proposes a method to compare the monthly trend of carbon footprint in Mediterranean islands. The employment of a comparative method offers numerous substantial advantages [23], enabling the examination of multiple cases to identify both similarities and differences in the trends of the indicators analysed. This methodological approach facilitates the identification of both commonalities and distinctions between the indicators, thereby enabling the discernment of specificities and shared characteristics. A crucial strength of this approach is its enhanced ability to understand the causes of these trends. By comparing islands with different characteristics and energy policies, it is possible to identify the factors that most influence carbon intensity, the share

of low-carbon energy and the use of renewables. Furthermore, the comparison of different islands enables the identification of best practices and areas for improvement. The analysis of multiple case studies, especially over a temporal comparison between years, constitutes an ongoing assessment, allowing to distinguish significant trends from temporary fluctuations. Finally, the findings from comparative studies are invaluable in guiding policy decisions, thereby providing a foundation for the development of more effective strategies for the energy transition. The comparison method proposed by the present study analyzes the following indicators over the year 2021–2024: Carbon Intensity (direct) [gCO_2eq/kWh], Percentage of Low-Carbon Energy, and Percentage of Energy from Renewable Sources. Specifically, the first indicator, termed "Carbon Intensity (direct)", measures the quantity of greenhouse gases directly emitted for each unit of electricity produced and consumed. It is expressed in grams of CO_2 equivalent per kilowatt-hour (gCO_2eq/kWh) and illustrates the direct contribution of electricity generation to emissions. The second indicator, labeled "Percentage of Low-Carbon Energy", indicates the percentage share of electricity generated from sources that produce low carbon emissions. This category includes renewable energies (biomass, geothermal, hydroelectric, solar, and wind) and nuclear energy, excluding fossil fuels. Lastly, the final indicator analyzed, namely the "Percentage of Energy from Renewable Sources", indicates the percentage share of electricity generated from renewable sources [24]. To better understand consumption patterns, the method stipulates that each indicator expressed in absolute value be related to the annual population within the reference territorial context, described according to the following socio-geographic and economic elements that exert a significant influence on energy consumption models: Area, Density, Population, Average Age, GDP, and Climate Zone according to the Köppen Climate Classification (KCC). The Köppen climate classification, a widely used system for defining climate classes [25], proves to be a relevant element in studies focused on analyzing the performance of the energy transition.

3 Case Studies

This study analyses the trend of the carbon footprint taking the Mediterranean islands as a case study, particularly those large and geographically isolated from the mainland: Sardinia and Sicily (Italy), and Cyprus. As a matter of fact, Islands represent ideal sites for the study of the socio-spatial dimensions of the energy transition, owing to their isolation and the necessity to ensure energy security, in addition to their aspirations for political autonomy.

Sardinia has been selected as a case study due to its complex energy situation. Its insularity, supply challenges, political relationships with the central State, and economic vulnerabilities render it a particularly interesting territory. Despite the notable potential of natural resources, such as wind and solar, the island's energy transition is progressing with difficulty. The island has made some progress, exceeding European targets in terms of renewable energy, reaching 24% of total consumption, and reducing CO2 emissions. Photovoltaics, particularly in greenhouses, have experienced significant expansion. However, important challenges persist. Dependence on fossil fuels, especially in transportation, remains high [26], and the development of RES (Renewable Energy Sources) in the electricity sector is limited (Fig. 1).

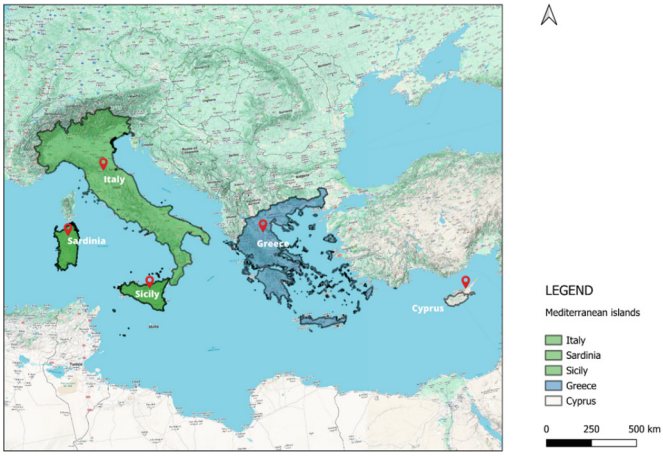

Fig. 1. Case studies: Sardinia, Sicily and Cyprus.

The region is at a crossroads, with a mix of progress and obstacles. On one hand, the expansion of photovoltaics in greenhouses is a positive development. On the other hand, resistance to large-scale renewable plants, such as CSP (Concentrated Solar Power), and the scarcity of storage systems hinder change. Regional policies, which promote smart grids and small local energy systems, clash with the strong lobbies of the fossil fuel industry, which impede a more rapid transition. The role of Terna, the operator of the national electricity grid, is crucial, with investments in power lines and storage. However, the lack of incentives and political uncertainty regarding storage make the island's energy future uncertain [27]. Sardinia, therefore, despite having significant renewable resource potential, finds itself in an intermediate position within the Italian energy landscape, with latent potential and the need to overcome resistance to fully embrace the transition towards a sustainable future.

Sicily, another Italian island taken as a case study, is establishing itself as a strategic hub in the European energy landscape, thanks to its privileged geographical position and rich potential for renewable resources. The Environmental Energy Plan of the Sicilian Region (PEARS) serves as a compass for this change, promoting the adoption of clean energy sources and cutting-edge technologies [28]. A pillar of this strategy is the incentivization of the installation of photovoltaic plants (which reached a capacity of 2637 MW in November 2024) and wind farms (2462 MW), with the aim of fostering energy self-production and self-consumption. Simultaneously, the installation of lithium battery storage systems (47,940 units) is supported, which are fundamental for stabilizing the electricity grid and strengthening the technological skills of local businesses [29]. For large-scale plants (over 1 MW), the PEARS has identified suitable areas through an inter-institutional mapping process involving various regional departments, in order to protect the island's environmental and cultural heritage. The plan also includes the development of wind power (with revamping, repowering, and offshore plants), concentrated solar power, and tidal energy in the Strait of Messina, aiming for a flexible and decentralized energy system, with particular attention to the smaller islands. The

expected positive repercussions are both environmental and socio-economic: the PEARS estimates the creation of 14,000 new jobs and an impact of over 1 billion euros on the regional GDP by 2030. Sicilian ports, such as Augusta and Milazzo, are undergoing a transformation, becoming hubs of the energy transition, ready to host LNG (Liquefied Natural Gas) terminals and green hydrogen plants. Sicily's proximity to North Africa makes it a crucial point for energy interconnection between the two shores of the Mediterranean. The collaboration between the Sicilian Region and Terna translates into investments of 3.2 billion euros to strengthen electricity infrastructure, with key projects such as the Caracoli – Ciminna power line, the Fulgatore – Partinico connection, and the Priolo – Rossano submarine cable [30]. Sicily, therefore, through the PEARS 2030 and a series of infrastructural initiatives, proposes itself as a protagonist of the energy transition in the Mediterranean, promoting sustainable development, technological innovation, and the creation of new opportunities for the territory. Similar to the islands of Sardinia and Sicily, Cyprus is also making significant strides in the energy transition. The European program CITyFiED (2014–2019) promoted the transformation of cities into smart cities, creating a "Community of Interest" with 44 cities from 19 countries, including Cyprus. The primary objective was to reduce energy demand and emissions, increasing the use of renewable energies and developing replicable energy retrofitting models. Cyprus, as a member of the "Community of Interest", benefited from the sharing of retrofitting methodologies, with the aim of disseminating the project's solutions [31]. In the Mediterranean context, Cyprus, despite tensions with Turkey, is a potential energy player thanks to offshore natural gas reserves, such as the "Aphrodite" field. The EastMed project, which aims to connect the Eastern Mediterranean gas reserves to Europe, is hindered by territorial disputes with Turkey [32]. Despite the challenges, Cyprus explores options for exploiting its gas resources and invests in renewable energies. Geopolitical tensions, particularly with Turkey, influence energy cooperation projects, such as the EastMed pipeline [33].

4 Results

In accordance with the proposed methodology, the key geographic data have been collected for each case study (Fig. 2 and Fig. 3): Area, Density, Population, Average Age, GDP, and Climate Zone (according to the Köppen climate classification KCC). Specifically, for insular contexts, the Köppen climate classification served as a significant element in the analysis of energy transition, with regard to energy consumption and the associated carbon intensity.

Italy, including Sardinia and Sicily, is predominantly characterized by a Hot-summer Mediterranean climate (Csa), typical of latitudes between 30° and 45°, featuring mild, wet winters and hot, dry summers dominated by subtropical high pressure. Coastal areas may experience cooler summers and fog phenomena due to cold ocean currents. The majority of precipitation is concentrated in the winter and spring months, with generally arid summers. Local variations in rainfall may exist. The island of Cyprus also falls under the Csa climate classification. However, in specific areas such as the Alps and the Po Valley, a Monsoon-influenced humid subtropical climate (Cwa) is found, typical of lower latitudes (25°-40°). This climate features hot, humid summers and mild or

Region		*Sardinia*	*Sicily*	*Italy*
Area [km²]		24.090	25.711	302.073
Density [ab/km²]		64.8	185.12	195.4
Population [inhabitants]		1.578.146	4.814.016	58.997.201
Average age of population		48,4	45,2	46,6
GDP per capita [€]	2021	22.300	17.110	30.118
	2022	25.042	18.078	33.000
	2023	26.315,80	22.891	36.077
Climate Zone [Köppen climate classification (KCC)]		Csa	Csa	Csa, Cwa

Fig. 2. The key geographic data for each case study (Sardinia, Sicily and Italy).

Region		*Cyprus*	*Greece*
Area [km²]		9.251	131.957
Density [ab/km²]		132	84
Population [inhabitants]		1.260.138	10.413.982
Average age of population		38,4	46,5
GDP per capita [€]	2021	25.940	17.610
	2022	30.430	19.888
	2023	32.150	19.460
Climate Zone [Köppen climate classification (KCC)]		Csa	Csa

Fig. 3. The key geographic data for each case study (Cyprus and Greece).

cold winters, with abundant precipitation distributed throughout the year, peaking in the summer. Inland Cwa zones exhibit greater seasonal temperature variations, with potentially cold and foggy winters.

The comparative method has been applied to evolute the carbon footprint in each island and relative country, considering the following indicators: Direct Carbon Intensity, Low-Carbon Energy Percentage, and Renewable Energy Percentage, available on the Electricity Maps platform [34]. This study compares the three islands (Sardinia – Sicily – Cyprus) for the period 2021–2024, as this timeframe is representative of the post-COVID-19 phase and the subsequent acceleration towards the energy transition.

Carbon Intensity

The monthly trend of carbon intensity (gCO_2eq/kWh) for Sardinia, Sicily, and Cyprus over the period 2021 – 2024 is described both in absolute and normalized values (normalized by population: per capita values multiplied by 100000) in Fig. 4 and Fig. 5. Cyprus records the highest rank of emission intensity in both years. In 2021, absolute values consistently exceed 600.00 gCO_2eq/kWh, peaking in August (626.76 gCO_2eq/kWh) and remaining high until December (625.71 gCO_2eq/kWh). In 2024, an improvement is observed, ranging from a minimum in May (437.12 gCO_2eq/kWh) to a maximum in December (536.74 gCO_2eq/kWh). The normalized value as well, shows Cyprus leads with per capita values ranging from 41.14 to 50.35 gCO_2eq/kWh in 2021, and between 34.46 and 42.31 gCO_2eq/kWh in 2024, indicating a persistent strong reliance on fossil fuels in its energy system.

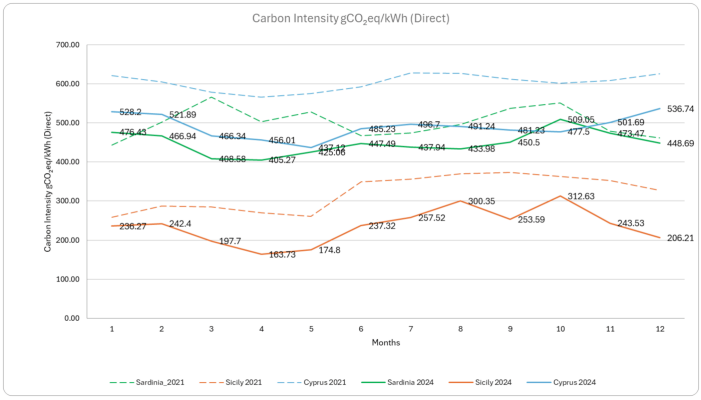

Fig. 4. Direct Carbon Intensity (gCO_2eq/kWh) for the three islands. Data source: [34].

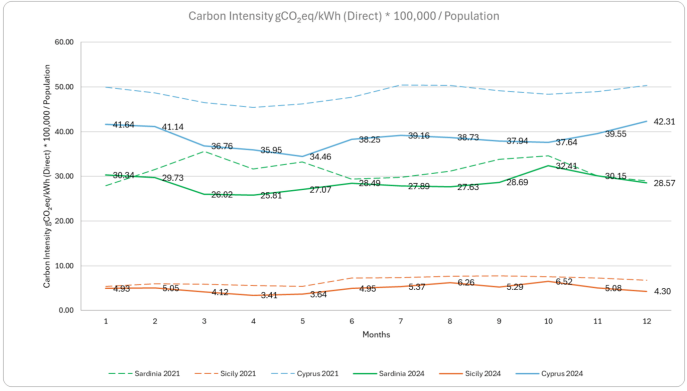

Fig. 5. Direct Carbon Intensity (gCO_2eq/kWh) *100000 / Population for the three islands. Data source: [34].

Sardinia records a high carbon intensity, albeit lower than Cyprus, with pronounced seasonal changes. In 2021, absolute values vary significantly between a peak in March (565.73 gCO_2eq/kWh) and a minimum in January (443.10 gCO_2eq/kWh). The phenomena appears more stable in 2024, fluctuating between a minimum in April (405.27 gCO_2eq/kWh) and an autumn peak in October (509.05 gCO_2eq/kWh). As regard the normalized value, Sardinia records a maximum of 35.58 gCO_2eq/kWh in March and a minimum around 27.87 gCO_2eq/kWh in January 2021, but a clear spring reduction in 2024 (minimum 25.81 gCO_2eq/kWh in April), with a slight autumn increase culminating in October (32.41 gCO_2eq/kWh). This evolution reflects a slight but significant rationalization in the use of energy sources.

Sicily ranks as the region with the lowest and most stable emission intensity in both years. In 2021, absolute values fluctuate between a minimum in January (258.73 gCO_2eq/kWh) and a maximum in October (373.39 gCO_2eq/kWh). A clear improvement is observed in 2024, particularly in the spring months, with values dropping to 163.73

gCO_2eq/kWh in April, before rising to 312.63 gCO_2eq/kWh in October. The normalized value highlights that Sicily records values between 5.35 and 7.72 gCO_2eq/kWh in 2021, while further improving in 2024, with a minimum of 3.41 gCO_2eq/kWh in April and a maximum of 6.52 gCO_2eq/kWh in October. This trend indicates increasing energy efficiency and a reduced reliance on fossil fuels.

The described comparison highlights Cyprus as the island with the highest carbon intensity, despite an improvement in 2024. Sardinia shows significant progress in terms of stability and emission reduction, although remaining at average levels higher than Sicily. The latter stands out positively, confirming itself as the most virtuous region in terms of carbon intensity, with a consolidated trend towards a more sustainable and less emissive energy system.

Low-Carbon Energy

The comparison of the monthly trends in the share of electricity generated from low-carbon sources (%) in Sardinia, Sicily, and Cyprus during the period 2021–2024, including both absolute and normalized values (normalized by population: multiplied by 100000) is represented in Fig. 6 and 7.

Regarding absolute values, Sicily dominated in terms of the quantity of energy produced from low-carbon sources in 2021, with an initial peak in January (49.01%), a second in May (48.13%), and a subsequent progressive decline in the following months. Sardinia recorded lower but stable levels, with values ranging from 24.25% (October) to 38.38% (January), showing continuity with a slight recovery at the end of the year. Cyprus registered more modest levels at the beginning of the year (12.47% in January), followed by a significant increase until April (20.31%), and then a progressive decrease in the second half of the year.

The analysis of population-normalized values reveals that Sardinia emerged as the leader in per capita terms, with values exceeding 1.50% for most of the year and a maximum of 2.53% in February. Cyprus ranked second, with an increase up to 1.63% in April, maintaining values around 1.00% in the following months, while Sicily fell to third place, showing more moderate values (between 0.58% and 1.00%) and less seasonal variability.

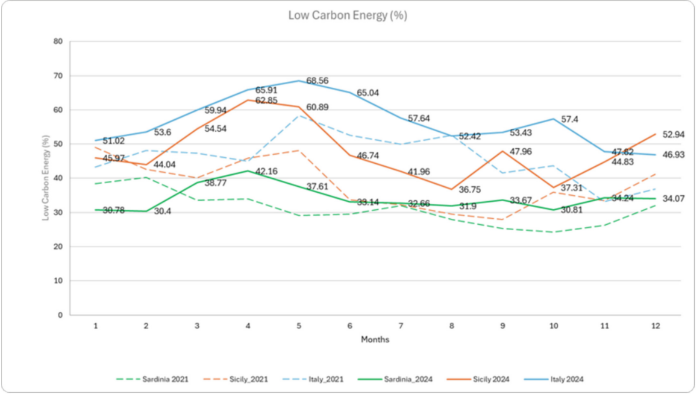

Fig. 6. Low-Carbon Energy Percentage for the three islands. Data source: [34].

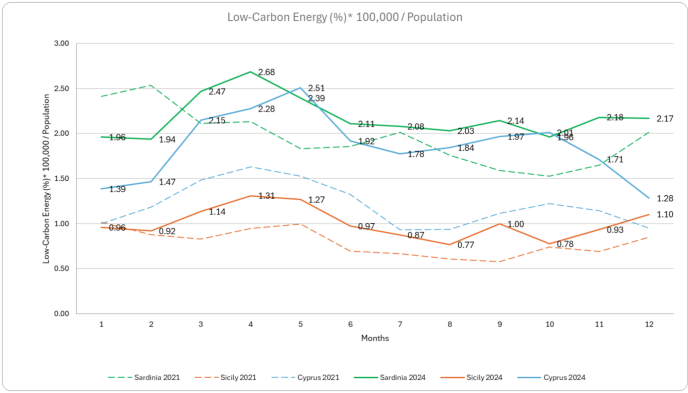

Fig. 7. Low-Carbon Energy Percentage *100000 / Population for the three islands. Data source: [34].

A general strengthening of low-carbon energy production was recorded in the three islands in 2024. Regarding absolute values, Sicily confirmed and reinforced its leading position, maintaining levels above 40.00% for most of the year, with the maximum reached in April (62.85%). Sardinia showed a more moderate but stable performance, ranging from a minimum in January (30.78%) to a maximum in April (42.16%). Cyprus remained the region with the lowest absolute share, reaching its maximum in May (31.82%) and its minimum in December (16.28%), indicating a slower decarbonization process compared to the other regions.

The normalized value confirms Sardinia as the most effective region in per capita terms also in 2024, with values close to or above 2.00% and a peak of 2.68% in April. Significant was the improvement in Cyprus during the first part of the year, which exceeded Sardinia between March and May (maximum of 2.51% in May), followed, however, by a decrease in the second half of the year (closing at 1.28% in December). Sicily also showed a positive trend compared to 2021, consistently exceeding 1.00% in the first months of the year with a maximum of 1.31% in April, then decreasing in the summer and recovering slightly at the end of the year (December: 1.10%).

The comparison highlights a general increase in low-carbon energy production from 2021 to 2024. Sicily leads in absolute terms, Sardinia leads in the energy-to-population ratio, while Cyprus shows initial improvements, particularly in the first part of 2024.

Renewable Energy

The comparison of the monthly trend of electricity produced from renewable sources (%) in Sardinia, Sicily, and Cyprus during the period 2021–2024, including both absolute and normalized values (normalized by population: multiplied by 100,000) is shown in Fig. 8 and 9.

Regarding the absolute values, Sicily emerges as the region with the highest renewable energy production in 2021, recording a peak in May (48.03%) and a marked decrease during the summer months, reaching a minimum in August (27.86%). Sardinia shows a lower but more stable production compared to Sicily, fluctuating between 38.77% and 40.26% with peaks in the winter months (February) and a slight decrease in summer. Cyprus presents lower absolute values compared to the other two islands, starting

from low levels in January (12.47%), progressively increasing until April with a peak of 20.31%, but experiencing a significant drop during the summer months down to July (11.59%).

The scenario changes significantly when considering the population-normalized data in 2021. Sardinia leads in terms of per capita production, with values generally above 2.0%, reaching a maximum of 2.53% in February, followed by a minimum in October (1.52%), with a final recovery in December (2.01%). Cyprus, despite its low absolute values, ranks second in per capita share, growing to a maximum of 1.63% in April before decreasing in the second half of the year. Sicily ranks third in per capita terms, with lower and more stable values between 0.58% and 1.00%, while dominating in absolute values. Moreover, Sicily confirms and strengthens its leading position in absolute values in 2024, showing a significant increase compared to 2021, with values above 40.00% for most of the year and reaching a peak in April (62.75%), maintaining high levels also in May (60.80%), followed by a summer decrease and a new increase in December (52.87%). However, it remains the region with the lowest values in per capita terms, although improved compared to the past, ranging between 0.76% and a maximum of 1.31% recorded in April, showing greater continuity throughout the year.

Sardinia remains the leading region for per capita renewable energy also in 2024, with a share close to or above 2.0%, and a maximum of 2.68% in April, while maintaining lower absolute values than Sicily (annual maximum of 42.10% in April). The monthly trend is more stable compared to 2021, indicating greater regularity and robustness of renewable energy production throughout the year, with a slight summer decrease and a final recovery (2.16% in December).

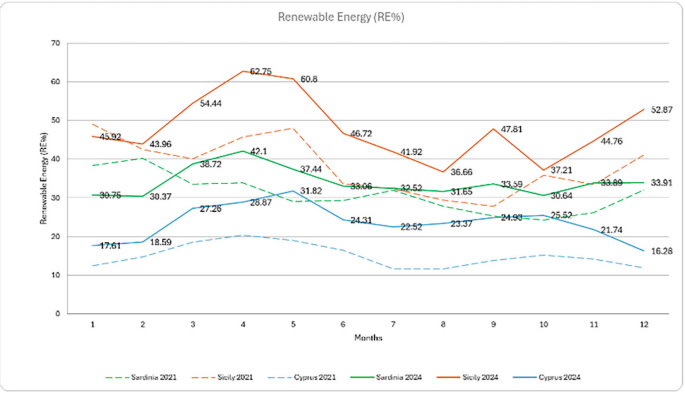

Fig. 8. Renewable Energy Percentage for the three islands. Data source: [34].

Cyprus shows an interesting evolution in 2024: in absolute terms, it reaches a maximum in May (31.82%), followed by a gradual decrease to the annual minimum in December (16.28%). Regarding the population-normalized values, it records a significant increase in the first months of 2024, surpassing Sardinia in April and May, reaching a peak of 2.51% in May. However, this positive dynamic is not maintained throughout

the year, and the share progressively decreases in the second half, ending the year in December at 1.28%.

The comparison shows an overall improvement from 2021 to 2024 in renewable energy production: Sicily consolidates its absolute leadership; Sardinia confirms a position of per capita excellence; Cyprus shows significant signs of progress in the first half of the year, although remaining at lower values.

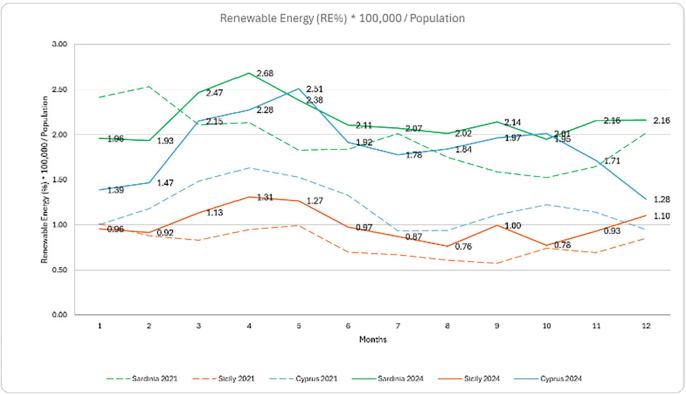

Fig. 9. Renewable Energy Percentage *100,000 / Population for the three islands. Data source: [34].

5 Discussions

The present study provides a comparative analysis of carbon intensity, low-carbon energy production, and renewable energy trends across Cyprus, Sardinia, and Sicily between 2021 and 2024. The findings reveal distinct energy profiles for each island, highlighting their progress and challenges in transitioning towards more sustainable energy systems.

As regards the carbon intensity, Cyprus consistently registered the highest levels in both absolute and per capita terms throughout the study period. While there was an improvement observed in 2024, this still indicates a significant and persistent reliance on fossil fuels within its energy mix. Sardinia exhibited a high carbon intensity as well, albeit lower than Cyprus, with noticeable seasonal fluctuations in 2021 that became more stable with a slight reduction by 2024. This suggests a gradual optimization in the utilization of energy sources. In contrast, Sicily demonstrated the lowest and most stable carbon intensity in both absolute and per capita values. It showed further improvement in 2024, particularly during the spring months, signifying increasing energy efficiency and a decreasing dependence on fossil fuels. This positions Sicily as the most environmentally sustainable of the three islands in terms of carbon intensity, demonstrating a clear trajectory towards a less emissive energy system.

In 2021, Sicily led in absolute low-carbon energy production with peaks early in the year, while Sardinia maintained lower but stable levels, and Cyprus recorded the lowest

initial production with mid-year growth. Regarding population-normalized values in 2021, Sardinia was the per capita leader, followed by Cyprus, and then Sicily. By 2024, all three islands showed increased low-carbon energy production. Sicily strengthened its absolute lead, Sardinia maintained a stable performance, but Cyprus still had the lowest absolute share, indicating a slower decarbonization. In normalized terms for 2024, Sardinia remained the per capita leader. Cyprus showed significant improvement in the first half of the year, temporarily surpassing Sardinia, before a subsequent decrease. Sicily also demonstrated a positive trend compared to 2021. Overall, low-carbon energy production increased across the islands from 2021 to 2024. Sicily led in absolute terms, Sardinia in per capita ratio, and Cyprus showed initial progress, particularly in early 2024.

The trends in renewable energy production from 2021 to 2024 indicate that Sicily had the highest absolute production in 2021, peaking in May. Sardinia presented lower but more stable production, and Cyprus recorded the lowest absolute values with a peak in April. Considering population-normalized data in 2021, Sardinia led in per capita renewable energy, followed by Cyprus, with Sicily ranking third despite its absolute dominance. In 2024, Sicily solidified its absolute leadership with a significant increase in renewable energy production. Sardinia remained the per capita leader with a stable monthly trend, and Cyprus showed an interesting evolution with an absolute peak in May followed by a decrease. Focusing on per capita renewable energy in 2024, Sardinia continued to lead, while Cyprus demonstrated a notable increase in the first half of the year, temporarily surpassing Sardinia, before a decline in the latter half. Sicily, despite its absolute leadership in production volume, remained the region with the lowest per capita renewable energy, although showing improvement compared to 2021.

6 Conclusions

The study proposed a comparative analysis of the trend of the energy transition in the Mediterranean islands considering significant factors such as Carbon Intensity [gCO_2eq/kWh], Low-Carbon Energy [%] and Energy from Renewable Sources [%]. Three large islands have been selected as a case study - Sardinia and Sicily (Italy), and Cyprus - understood as ideal sites for the analysis of the socio-spatial dimensions of the energy transition, owing to their isolation and the necessity to ensure energy security, in addition to their aspirations for political autonomy.

The analysis of multiple case studies, particularly over an extended period (temporal comparison across years 2021–2024), highlighted different trends and temporary fluctuations. Moreover, each indicator has been expressed in absolute value and normalized value (related to the annual population), within a specific context well described by socio-geographic and economic characteristics to better understand consumption patterns.

Sicily, Sardinia, and Cyprus show distinct characteristics and varying paces of transition towards sustainability between 2021 and 2024. Sicily emerges as a leader in mitigating climate impact, consistently demonstrating the lowest carbon intensity and a strong absolute production of both low-carbon and renewable energy, showcasing a clear trajectory towards a less emissive energy system. Sardinia excels in per capita renewable

and low-carbon energy production, indicating a strong commitment to cleaner energy sources relative to its population, despite having a moderate carbon intensity. Cyprus, while showing improvements in reducing carbon intensity and increasing low-carbon and renewable energy production, particularly in the first half of 2024, still lags behind the other two islands, showing the highest carbon intensity and the lowest absolute share of low-carbon energy, suggesting a slower decarbonization process and a persistent reliance on fossil fuels.

In conclusion, the study reveals an overall improvement in renewable energy production across the three islands from 2021 to 2024, with a positive trend towards greater adoption of low-carbon and renewable energy sources, demonstrating unique strengths for further development in energy transitions. In this sense, the results are valuable for informing policy decisions, providing a basis for developing more effective strategies for the energy transition in the Mediterranean islands.

More precisely, Sardinia faces a crucial stage regarding the energy transition. The increase in the utilization of renewable sources is essential to guarantee a sustainable energy future, but it requires necessary interventions to adapt the existing electricity grid. This is fundamental also to integrate renewable energy communities (RECs) as a tool to overcome geographical barriers and bring clean energy to the most remote areas. Therefore, the challenge for Sardinia and for other countries with low population density is to strengthen and implement new infrastructure to ensure that renewable resources are effectively used to meet local energy demands, thus contributing to face climate change in the Mediterranean region.

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