Sustainable Energy Planning in the Cyclades Islands, Greece: Problems and Perspectives in an Era of Climate Crisis

Yiota Theodora(✉) and Socrates Tsigardas

School of Architectural Engineering, Department of Urban and Regional Planning, National Technical University of Athens (N.T.U.A.), Athens, Greece
ptheodora@arch.ntua.gr

Abstract. In an era of climate crisis and geopolitical realignment, achieving energy neutrality has become a global development priority. Sustainable energy planning requires the responsible use of renewable energy sources, respecting the physiognomy and carrying capacity of places / landscapes. Thus, resource management and the protection of natural, cultural, and man-made ecosystems are essential for a sustainable energy transition that meets local energy needs at the spatial planning level. In this context, the main challenge lies in developing national policies for a sustainable energy transition, as well as using innovative technology to create new methods of producing, storing and distributing energy from renewable sources. In this regard, the dominant global trend is to organize sustainable energy communities at the inter/intra-regional level. Particular interest is held for island regions due to their location, size, energy demand (e.g. shipping, tourism and coastalisation), complexity, vulnerability, seasonality and peripherisation. These characteristics require sustainable resource management and small-scale infrastructure to achieve energy self-sufficiency. This article contributes to the ongoing debate by exploring the potential for inter-island cooperation in creating renewable energy communities in the Cyclades. To this end, the article sets out a methodology for identifying hub islands and defining their roles within these communities. A set of spatial / energy criteria has been proposed to determine favourable and limiting parameters for the energy transition on islands.

Keywords: sustainable energy planning · development policy · spatial planning · renewable energy sources · climate crisis · energy neutrality · renewable energy communities · insular regions

1 The Research Framework

The sustainable transition to energy independence is emerging as a key priority in the spatial planning and development policies of insular countries. At the same time, current experience and practice emphasise the importance of a cooperation strategy that takes everything into account for successful local / interregional implementation. Island regions of all sizes have their own unique characteristics. Thus, it is necessary to systematically and dynamically monitor development options, as well as the spatial changes

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and energy needs that accompany them. This is crucial for island regions, which have incredibly delicate natural, cultural and human ecosystems [1–3].

The diversity of islands in terms of size (i.e. surface area, population density, production base), location (remote/offshore), spatial dispersion and degree of interaction with the mainland (dependence, cooperation), combined with the structure, size, dynamics and specialisation of island economies, exacerbates the phenomena of abandonment and seasonality and reinforces their peripherisation. At the same time, islands' different energy needs result from their development patterns (e.g. shipping, services and tourism), as well as the number of permanent residents and visitors. Therefore, achieving energy autonomy for islands requires innovative methods to produce, store and distribute energy from renewable and marine energy sources (RES/MRE). This is particularly important for non-connected islands (NIIs), which lack the planning, funding or knowledge to utilise RES/MRE effectively [4, 5].

A sustainable energy transition is notably important for island regions that depend on tourism or have a concentration of supra-local infrastructure and activities, such as transportation, education (e.g. universities, research centers), and production. It is also important for small, remote, and inland islands because they have difficulty connecting to the national grid and/or depend on the energy infrastructure of larger neighboring islands. In recent decades, increased urban sprawl on islands due to tourism development and pressure to become trans-regional renewable energy hubs has posed a significant threat to local identity, resilience and sustainability [6–10].

However, gaps remain in the implementation of the institutional framework and the use of spatial planning tools for modernization, spatial planning, and achieving energy neutrality in Greece. Despite its insular nature and the fact that it is made up of many small, isolated and remote islands, Greece still lacks a clearly formulated island policy and a national energy transition plan to achieve energy autonomy for its islands. This gap is reinforced by the lack of an integrated coastal area management strategy and the inability to finalize local, regional and sectoral plans These include the *National Spatial Strategy for the Marine Space* (NSSMS), the *Marine Spatial Framework*, the revised/new *Marine Spatial Strategy Plans* (MSSPs), the *Special Spatial Planning Frameworks for Renewable Energy Sources* (SSPF-RES) and for *Tourism* (SSPF-T), as well as the proposed or in-progress *Local Urban Plans* (LUPs) and *Special Urban Plans* (SUPs) as part of the *Konstantinos Dioxides Urban Planning Programme* (Sect. 3).

In these circumstances, contemporary discussions and practices at the global level highlight the organisation of renewable energy communities at the local, inter/intra-regional levels as a means for countries and their regions to transition to sustainable energy. These communities are particularly significant for insular regions, which are the focus of this article. Such communities are formed through collaboration between islands with the aim of developing the infrastructure needed to produce, store and distribute renewable energy [11]. This development must take into account the positive and limiting environmental, regional, social, economic and spatial factors affecting each island. Therefore, the local scale is important for energy planning, as it prevents the uncritical adoption of energy transition autonomy models that do not align with the specifics of each location. Islands are autonomous entities. However, they also act as nodes in wider networks, forming relationships with each other and with mainland regions. In order

to understand islands, it is necessary to consider two things: what makes them unique and what they require, and the wider spatial context of their activities and interactions. This is a key to creating an effective methodology for identifying sustainable, renewable energy communities (Sects. 2.1, 4, 5).

In the context of the energy transition on islands, the main objective is to promote sustainability and resilience at local and regional levels. This requires optimising the use of modern technology and practices to develop small-scale energy infrastructure, while avoiding the conversion of islands into supra-local energy stations. This is particularly important for islands that have experienced intense tourism development, as well as for abandoned islands that are rich in natural and cultural resources.

In Greece, the favourable factor for establishing renewable energy communities on islands is their potential for generating energy from wind, solar and marine sources. However, limiting factors include the fragmented structure of island spaces and their variety, such as island size and development patterns. Other equally important factors include the characteristics and limitations of marine spaces, such as the exclusive economic zone (EEZ) and continental shelf depths and usage [12]. The richness of terrestrial and marine landscapes, both natural and man-made, is also a critical consideration. Therefore, it is necessary to simultaneously assess the favourable and restrictive conditions for the use of renewable energy sources in relation to the energy planning of the Greek islands (and the country as a whole). This assessment will highlight issues related to selecting renewable energy sources and locating their infrastructure within an island cooperation model. The ultimate goal is to achieve a more balanced spatial distribution of energy infrastructure while taking into account the identity and carrying capacity of operating sites. Thus, Greece could serve as a challenging case study for re-evaluating energy transition and autonomy standards, as well as for trialling new innovative renewable energy sources (Sect. 2.2).

Against this backdrop, the article contributes to the ongoing debate by exploring the potential for establishing renewable energy communities on islands. The Cyclades archipelago in the Aegean Sea has been chosen as the location for the pilot study. The aim at this stage is to study the developmental dynamics and energy potential of the islands, in order to evaluate the proposed renewable energy communities (hubs and connections) as an autonomous system more effectively. Therefore, the role of the hub islands at the local- regional levels is of great interest. To this end, a methodology based on spatial and energy criteria has been developed to identify favourable and restrictive parameters for energy utilisation on each island. The scope is to determine which islands could form renewable energy networks/communities and what their respective roles would be. The first comprises the largest islands, which have seen growth in infrastructure and an increase in their permanent population. The second includes smaller, less densely populated islands with limited development. However, these islands have experienced significant residential expansion and growing tourism. This attempt to define renewable energy networks in insular regions paves the way for the next stage: an investigation into the role of islands in achieving energy neutrality in Greece based on quantitative indicators (Sects. 2, 4, 5).

The research is organised around two main issues that currently pose significant challenges to energy and spatial planning. The first is of a political nature and relates to the

role of islands in their respective countries' energy transition policies. In other words, it remains to be seen whether and to what extent islands will be treated as supra-local/supra-national poles of renewable energy communities (i.e. small-scale infrastructure), the main goal of which is to achieve energy transition autonomy at the local/regional level. The second is a planning matter concerning the development of expertise in the optimal use of renewable energy sources while respecting natural, cultural, and man-made ecosystems/landscapes. This is a crucial issue for ensuring the sustainability of islands. Therefore, it must be addressed (Sect. 2).

The article is divided into six sections. The first addresses the research framework. The second presents the research methodology and the study area. The third discusses sustainable energy planning in insular areas. The fourth focuses on the Cyclades and attempts to identify islands that could serve as nodes in renewable energy networks. This identification is based primarily on an assessment of the islands' energy profiles and dynamics. In other words, it is based on an analysis of the existing framework and prospects for exploiting renewable energy sources (RES/MRE) through an evaluation of national energy policy, case law from the Council of State, and energy demand and supply indicators. The fifth presents a pilot case study of four islands - Andros, Tinos, Paros and Naxos - that emerged from energy profile research. Using a multifactorial approach incorporating spatial / energy criteria, this section examines the favourable and limiting factors of using these four islands as main nodes in renewable energy networks / communities. At the same time, it identifies smaller, less developed islands within these wider spatio-functional zones. The proposed energy communities could include these islands. The article concludes with a sixth section that highlights key issues that must be addressed in the energy transition of island nations such as Greece.

2 Methodology and Spatial Reference of Research

2.1 Methodology and Sources

The research focuses on organising sustainable renewable energy communities (RES/MRE) to facilitate the energy transition and autonomy. This involves conducting two complementary surveys to identify island hubs and their roles at national, regional and local levels. These surveys provide a basis for understanding current conditions and perspectives. This will enable future studies to examine underlying levels (i.e. islands or island complexes) using quantitative and qualitative indicators to define proposed renewable energy communities. Specifically:

The first survey focuses on assessing the energy profile/ dynamics of the Cyclades. This is based mainly on an analysis of official planning principles and guidelines. The analysis considers the islands' historical connection to the national energy grid, their contribution to national energy production through the use of RES/MRE, their current level of energy autonomy and their potential future role in Greece's energy transition. Attention is given to recent decisions from the Hellenic Council of State, as well as changes in energy indicators, such as production and consumption. The focus is on the north-eastern Cyclades, specifically Andros, Tinos, Paros and Naxos, due to their substantial contribution to national energy production from renewable sources. These islands also support smaller, less developed ones, such as Antiparos, Ios, Sikinos, Folegadros,

Koufonisia, Schoinoussa, Irakleia, Donoussa and Amorgos (Sect. 2.2). The energy relationship observed between the largest islands and their smaller neighbours seems to suggest that through the appropriate planning of infrastructure and networking between these islands, RES energy communities could be formed that are capable of ensuring their own energy transition / autonomy (Sects. 4, 5, 6).

The second survey covers the islands of Andros, Tinos, Paros and Naxos. The first survey identified these islands as having the potential to become key renewable energy hubs due to their development and energy resources. At this stage, the main favourable and limiting factors of using these islands as hubs for renewable energy communities are examined. It also identifies secondary hubs - i.e. neighbouring islands connected (IIs) or not connected (NIIs) to the national energy grid - with which cooperative relations could be established to help achieve energy autonomy at local / intraregional levels. This second survey is based on the assessment criteria for local spatial development and energy demand characteristics. Its purpose is to identify any potential risks posed by renewable energy sources. These criteria have already been tested in previous research into the energy sustainability of small islands [8, 10]. They are as follows: (i) *geographical location*, (ii) *locus* [i.e. settlements, geomorphology, climate], (iii) *nature- culture- landscape* [i.e. natural-cultural heritage sites, and protected areas], (iv) *population* [inhabitants, % population change (2011–2011)], (v) *local economy - production sectors* [i.e. primary, secondary, tertiary (% change by sector 2011–2021)], (vi) *accessibility/networking* (Multimodal Hub (i.e. MH: port and airport)], (vii) *services and infrastructures of supralocal reach* (i.e. administrative, technical and social), (viii) *construction activity* [i.e. building permits, rate of change (2011–2021)], (ix) *tourism* [indicators: ship/ferry passengers (2013–2021), airplane passengers (2011–2021), cruise passengers (2013–2021), overnight stay (2010–2021) and full occupancy (2010- 2021)], και (x) *energy* [i.e. energy demand, energy consumption rate, production rate from conventional and renewable sources (2011–2021)]. This survey revealed the following renewable energy communities: (1) Andros and Tinos, (2) Paros (including Antiparos, Ios, Sikinos and Folegadros), and (3) Naxos (including the Small Cyclades and Amorgos) (Sect. 5).

The implementation of the above two surveys is based on a critical approach to the following: a) Official European and Greek strategic texts on spatial development and energy neutrality; b) Contemporary energy planning policies and practices focusing on island areas; c) The Greek institutional framework, relevant Council of State case law, and existing spatial / energy planning tools (Sect. 3). In order to gain a better understanding, emphasis was placed on studying islands' geomorphological, climatic, natural, cultural, demographic, socio-economic, spatial, and energy features. This was achieved using spatial analysis and assessment methods, as well as GIS mapping. The processing resulted in thematic maps at various spatial scales, such as the Cyclades and individual islands. These maps make it possible to identify specific features, common issues, and favourable, restrictive, or prohibitive factors relating to the energy transition / autonomy of islands. Official databases of international, European, Greek bodies were utilised as sources (Sects. 4, 5, 6).

2.2 The Island Complex of the Cyclades in Greece

The choice of the Cyclades and the four islands on which the research was focused was not made at random (Fig. 1). The key factors were: a) the central location of the complex; the variety of local identities; the development dynamics; the prospects for using renewable energy sources; and the favourable climatic conditions; b) the ever-increasing and diverse energy requirements of the islands due to residential expansion and tourism; and c) the local-level pressures faced by the interconnected islands (IIs) due to their planned role as new providers within the national energy grid (Sect. 4). By spatial reference category, the following were identified:

The Broader Spatial Level of Research: The Cyclades are one of two complexes in the southern Aegean region. The other is the Dodecanese. The 33 inhabited Cycladic islands are close together, with a combined population of 120,989. There are also numerous smaller islands and island groups. Of particular interest are the six small islands between Naxos and Amorgos, collectively known as the Small Cyclades. These are Upper/Lower Koufonisi, Irakleia, Schoinoussa, Donoussa and Keros. The Cyclades are an extremely interesting island group in which to conduct research into natural-cultural resource management, climate and energy crises, coastal urbanisation, tourism and natural disasters (e.g. seismic/ volcanic activity, rising sea levels, heat waves). This is due to the variety of their structures, sizes, natural and cultural wealth, development potential, port networks and relations with Athens and Piraeus. The Cyclades are also a popular tourist destination worldwide. According to the Institute of the Association of Greek Tourism Enterprises (INSETE), the number of overnight stays almost doubled between 2021 and 2022, rising from 3,131,225 to 5,758,194. The growing number of incompatible human activities and infrastructures in territorial and marine areas, along with overtourism and urban sprawl, increases the vulnerability of islands as they put pressure on natural and cultural ecosystems, threatening landscapes and increasing energy demand. Given the multiple pressures they are under, achieving energy neutrality is a priority for the islands' sustainability and resilience.

The Focus Spatial Level of Research: The north-eastern Cyclades islands of Andros, Tinos, Paros and Naxos are exceptional research cases, as confirmed by the results of the evaluation of the proposed spatial, functional and energy criteria (i)–(x), which are included in themes A–C. Theme A refers to the centrality of the islands. Theme B covers the characteristics / peculiarities of the islands' natural, cultural and man-made ecosystems, as well as their developmental dynamics. Finally, theme C focuses on the islands' existing energy profile and the opportunities presented by their level of interconnection to the national grid, namely whether or not they are connected and the extent to which they utilise renewable energy sources. Analysis of the proposed criteria revealed the following:

Themes A and B [criteria (i)-(ix)]: Geographical location and infrastructure are the reasons why all four islands are characterised by high centrality and developmental dynamics. As the largest islands in the Cyclades, they have a high population density and geomorphological variety, as well as a rich natural and cultural heritage. Andros and Naxos have the highest concentrations of Natura 2000 protected areas, at 59.32% and 44.64% respectively. Paros and Tinos islands have significant concentrations of archaeological sites, at 7.6% and 4.4% respectively. Paros and Naxos demonstrate the

strongest signs of tourism development. They have a high concentration of hotels and short-term rentals, as well as airports and cruise ports. Tinos and Andros are close behind, with a large number of holiday homes and a growing tourism sector. Tinos, Paros and Naxos have water infrastructure, including boreholes and desalination plants, as well as sewage and waste management systems. The same islands have a thriving primary and secondary sector, as well as a mining industry. Naxos has many small manufacturing units. The highest population densities are found in Andros, Paros, Naxos and Tinos, in that order. Tinos and Andros boast the most traditional settlements.

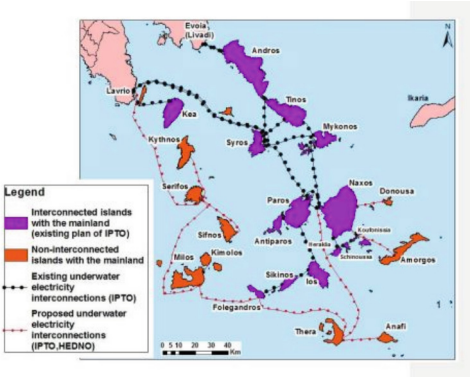


Fig. 1. Cyclades: Interconnected (IIs) and Non-Interconnected islands (NIIs) in the national energy grid [own elaboration] [25, 26]

Theme C [criterion: (x)]: The first phase of the Cyclades Connection Programme involves connecting the four investigated islands to the national energy grid. The four islands currently use renewable energy sources. These include wind and solar farms. Tinos has the greatest potential for wind power. However, Andros has the most wind farms because it is directly connected to the national grid via the Evía - Livadi line. In order to evaluate the pace of the energy transition and the autonomy of the focal islands, it is useful to consider the time at which they were integrated into the grid, as well as the geographical distribution of thermal power stations. This confirms the central role of Andros and Paros. Andros was connected to Syros and Mykonos prior to the addition of Naxos, and subsequently to Paros and Mykonos. Andros and Paros are two of the twelve Cycladic islands with thermal power stations. Syros, Mykonos, Donoussa and Amorgos, on the other hand, have stations located nearby. The Andros and Paros stations supply Tinos and Naxos, respectively. Meanwhile, the Donoussa and Amorgos stations serve local needs as they are not interconnected (Fig. 1).

The research showed that the northeastern islands of the Cyclades are expected to face the greatest pressure as supra-regional hubs for the production, storage, and distribution of renewable energy for two reasons. Firstly, as part of the country's national energy grid, they can supply national needs by exploiting forms of renewable energy in their territorial and maritime areas. Secondly, their favourable climatic and geomorphological characteristics ensure high participation rates in the national production of renewable energy. Andros and Naxos, for example, have the ideal topography for wind turbine

installation. Meanwhile, Tinos, the Small Cyclades and Amorgos are renowned for their strong winds. These features could help the country achieve energy neutrality. However, at a local level, they could affect the resilience and sustainability of the islands. Therefore, a clearly defined island policy is needed to determine their role in the country's tourism development and energy transition (Sect. 6).

3 Sustainable Energy Planning in Insular Regions: The Debate

This section summarises the key time periods that have shaped perceptions of energy neutrality in the context of the climate crisis. It also emphasises the main impact these periods have had on relevant European and Greek policies, particularly in island regions, and their effect on the energy autonomy of the Greek islands. Specifically:

The debate on the use of renewable energy sources in Europe began after 1997 with the publication of the White Paper for a Community Strategy and Action Plan [13]. Over the past 27 years, two distinct periods have emerged in the transition to clean energy. The first period began in 1997 with the formulation of EU-level energy transition laws and directives. Of particular interest is the second period, which began in 2008 and is still ongoing, as significant progress has been made in the energy transition during this time and interest in blue energy has grown. The years 1997, 2006 and 2009, along with the period after 2015, are seen as significant milestones in the shift towards renewable energy sources. The period after 2007, and especially after 2012, was pivotal for Greece as it sought to align itself with the broader objectives of the *Paris Agreement*, the *European Green Deal*, the *European Climate Law*, the *Climate-Neutral & Smart Cities EU Mission*, and the revised Renew*able Energy Directive*[1] [14–17].

In terms of the sustainable energy transition, and the autonomy of island regions in particular, the European Commission's Clean Energy for EU Islands initiative is of interest [5]. This initiative promotes long-term energy planning for the 2,200 inhabited islands in Europe. In this context, each island prepares a *Clean Energy Transition Agenda* (CETA) by taking the following steps: a) assembling a transition team, b) mapping the island dynamics, c) developing an island clean energy vision and island transition paths, and d) disseminating results and arranging follow-up. To date, more than 38 Community Energy Transition Agreements (CETAs) have been drawn up, seven of which concern Greek islands, including Halki, Chios, Kasos, Symi, Sifnos, Kos and Samos. Several other Greek islands, including Andros, Syros and Spetses, have also received technical support relating to the energy transition. These plans emphasise the importance of

[1] COM(97)599 Energy for the Future; COM(2006)105 Green Paper; COM(2007)575 Blue Paper; 2008/56/EC Marine Strategy Framework Directive; 2009/28/EC Renewable Energy Directive; COM(2012)494 Blue Growth; COM(2014) 8 Blue Energy; EUCO/169/14 2030 Climate and Energy Policy Framework; 2018/1999/EU European Climate Law; 2018/2001/EU Revised Renewable Energy Directive; COM(2019)640 The European Green Deal; COM(2020)80 European Climate Law; COM(2020)741 An EU Strategy to harness the potential of offshore renewable energy for a climate neutral future; (2021) European Council (2021) Fit for 55: EC proposal to revise the directive and raise the target for 2030 to 40%; European Commission (2022) REPowerEU Plan at a glance: new EC proposal to further raise the renewable energy target; EU/2023/2413 Revised Renewable Energy Directive.

taking local geomorphological and climatic conditions into account, as well as local identity. This includes natural and cultural heritage, the landscape, infrastructure, and aspects such as production, technology, transport and society. The focus is on the development model, which influences the energy supply, demand, and dynamics of the islands. This includes determining whether the islands are interconnected and how they utilise renewable energy sources in terrestrial and marine areas. The diversity of the islands means that innovative methods are required for the production, storage and distribution of sustainable energy.

In 2006, Greece set a binding target for the proportion of electricity produced from renewable sources [18]. In 2008, Greece adopted the Special Framework for Spatial Planning and Sustainable Development for Renewable Energy Sources (SFSPSD-RES) [19] which is under review. Aligning the Greek institutional framework with that of the EU will transform how the energy transition is perceived. Examples include Law 4513/2018 on energy communities [12] and the National Energy and Climate Plans (NECPs) [20]. The latter document serves as Greece's foundational strategic roadmap for energy and climate policy up to the year 2030. Both the Special Framework for Renewable Energy Sources (SFSPSD-RES) and the National Energy and Climate Plans (NECPs) state that any islands selected for the utilisation of renewable energy must be connected to the mainland network in order to contribute to the national balance. Additionally, two decisions by the Hellenic Council of State (1421/2013 and 1429/2022) have played a key role in promoting the use of renewable energy sources in island regions, particularly the Cyclades. These decisions recognise the need to consider the unique characteristics of the islands during their energy transition, emphasising the importance of protecting and sustainably managing their natural and cultural resources [21]. Finally, the text of Approval of Stage B1 of the Study *Evaluation, Revision and Specification of the Regional Framework for Spatial Planning and Sustainable Development of the South Aegean Region*, outlines considerations regarding the energy transition of the Cyclades [22]. In conclusion, the Greek institutional framework sets national targets in line with European directives. However, these targets do not consider the country's unique geological, natural, cultural and economic features or its distinct spatial and social units. At a local level, this has consequences, as renewable energy developments are carried out in terrestrial and marine areas without considering how to distribute them more evenly in terms of resilience, sustainability, and social justice.

4 Identifying Dynamic Renewable Energy Hubs in the Cyclades

4.1 Current Context and Dynamics

The energy profile of the Cyclades complex was evaluated using an ArcGIS analysis of official strategic energy planning documents and geoinformatics data [24–27]. The analysis was based on the following four parameters: (1) the climate characteristics of the islands; (2) their integration into the national energy network [i.e. whether they are interconnected (IIs) or non-interconnected (NIIs)], and their contribution to the national energy balance through renewable energy sources (RES/ MRE); (3) their local energy demands; and (4) their potential for renewable energy development within the framework of the national energy transition. Specifically:

Climatic - Geomorphological Advantages: The South Aegean region (the Cyclades and the Dodecanese) has favourable climatic - geomorphological characteristics. Its extensive maritime space makes it ideal for exploiting renewable energy sources. Due to their mountainous terrain and high wind potential, the islands of Andros, Tinos and Naxos are particularly well-suited to the development of wind farms. All islands are ideal locations thanks to their exceptional solar potential.

The Islands' Connection to the National Energy Grid and Intra-regional Networks: Andros and Tinos (Evía, 2003) and Kea (Lavrio, 2003) were the first Cycladic islands to be connected to the mainland grid by an underwater cable. The interconnection of the islands is an ongoing process taking place in phases. Currently, there are two groups of islands: the Interconnected Islands (IIs) and the Non-Interconnected Islands (NIIs). The former includes the northeastern Cyclades (excluding Donoussa and Amorgos, which form part of the Naxos Prefecture), and the latter comprises the southeastern Cyclades (Thira and Milos, with a planned connection), as well as the western Cyclades (Kythnos, Serifos, Sifnos, Milos and Kimolos). The existing connections between the north-eastern Cyclades islands meet most of the region's local electricity needs, forming two energy networks with a local - regional scope: (a) Andros–Tinos; (b) Paros–Antiparos–Ios–Sikinos–Folegandros–Naxos–Schoinoussa–Koufonisi–Irakleia. The main nodes of these networks are the islands of Andros, Tinos, Paros and Naxos (Fig. 5).

Islands	Existing projects in operation (MW)			Recommended projects (MW)		
	Wind farms	Photovoltaic stations (PV)	Total	Wind farms with production licenses and AEPO	Permitted wind farm installations	Total
The focus spatial level of research (Andros, Naxos, Paros, Tinos)						
Andros	20	1,3	21,3	234,6	0	234,6
Naxos	8,76	2,1	10,86	73,6	0	73,6
Paros	3,6	2,5	6,1	73,6	0	73,6
Tinos	2,7	0,8	3,5	23	0	23
Mykonos	3	1,1	4,1	1,8	0	1,8
Milos	2,65	0,7	3,35	0	0	0
Syros	2,64	1,9	4,54	1,7	0	1,7
Sifnos	1,8	0	1,8	0	0	0
Thira / Santorini	1,2	0,7	1,9	0	1,32	1,32
Ios	1,2	0	1,2	0	1	1
Kea	0	0	0	0	4,8	4,8
Kythnos	0,9	0	0,9	0	0	0
TOTAL	**48,45**	**11,1**	**59,55**	**408,3**	**7,12**	**415,42**

Fig. 2. Cyclades: Electricity generated from renewable energy sources: existing and projected following the completion of energy transition projects [own elaboration] (2011–2021) [23–26]

Thermal Power Plants Produce Electricity Using Conventional Sources: Oil-fuelled thermal power stations still largely meet the energy needs of the Cyclades islands. The thermal power stations on Sifnos, Kythnos, Anafi, Donoussa and Amorgos will remain operational until they are connected to the mainland grid. The following island energy networks continue to support energy needs by operating active thermal power plants within their territories and/or on nearby islands: (a) Andros and Tinos, (b) Paros, Antiparos, Ios, Sikinos, Folegadros, Naxos, Schoinoussa, Koufonisi and Irakleia, (c) Milos and Kimolos, and (d) Mykonos and Delos [23–25].

Utilization of Renewable Energy Sources: Fig. 2 provides an overview of energy production in the Cyclades. It illustrates current power production alongside the projected

output of the recommended renewable energy projects, both expressed in megawatts. Compared to Paros and Tinos, Andros and Naxos generate the most energy from renewable sources, primarily from wind farms. Andros's superiority is clear. Conversely, although Paros and Tinos currently show no notable potential, they are expected to play a crucial role in the future [23–26] (Fig. 2).

The data shows that Andros, Paros, Naxos and Tinos stand out among the Cyclades islands in terms of the use of renewable energy sources. These islands have seen the most activity and investment interest in proposed renewable energy projects, particularly wind farms. This is no coincidence. They all have favourable climatic conditions and were among the first islands to be connected to the national power grid. This means that local sources have the capacity to meet not only the energy needs of the Cyclades, but also those of the rest of the country. However, their role in the national energy transition must be considered during the planning process to prevent degradation of the landscape and local identity (Sects. 5, 6).

4.2 Emerging Renewable Energy Hubs: Andros, Tinos, Paros and Naxos

A multifaceted research study was conducted to better understand the role of the four islands in the development of sustainable energy communities. The study evaluated the *seasonality* and *peripherisation* of these islands in the context of an investigation into the various factors that could influence the role of the four islands in establishing sustainable energy communities in the Aegean. This approach enables us to evaluate the energy demands of the islands and neighbouring smaller islands, and determine the feasibility of meeting them using renewable energy sources. The key factors in achieving this are: a) the *development dynamics of the four islands* (i.e. settlement structure, urban density, construction activity, demographic data, production sectors, tourism and infrastructure); b) the *local identity* (i.e., the natural-cultural environment, the landscape, and the memory); and c) the *energy profile*, (i.e. energy sources, consumption and needs). Evaluating the above factors enables us to identify islands that could play a key role in establishing sustainable energy communities, confirming the superiority of Andros, Tinos, Paros and Naxos. Particular attention was paid to assessing the demographic and socio-economic characteristics of the specific islands. To this end, quantitative indicators were used to measure the development dynamics of the islands during critical periods (Fig. 3), while the infrastructure table takes the form of a checklist stating what is available and in what quantity (Fig. 4).

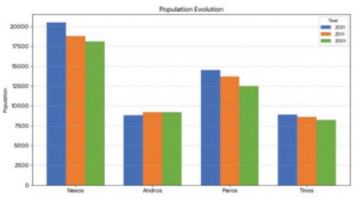
In brief, the findings regarding population change, the local economy, production sectors, tourism development, construction activity and the urban and traditional settlement networks are as follows (22, 25, 26, 27):

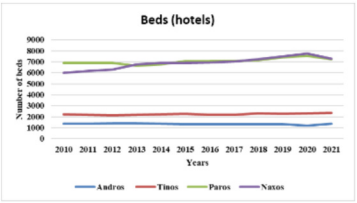
Population change (2011–2021): Naxos experienced the highest population growth (8.86%), followed by Paros and Tinos, while Andros recorded a decline of 4.28%.

Local Economy - Production Sectors (2011–2019): There are significant cultivated areas on all four islands, and beekeeping is also a key activity. The most important livestock areas are found on the islands of Andros, Naxos and Tinos. The main fishing areas are located between Paros and Naxos, and between Koufonisia islands and Amorgos. Hence, fishing activity is mainly concentrated around Paros and the smaller islands of the Naxos archipelago, particularly Amorgos, Irakleia and Schoinoussa. Mining is also an

important industry. The marbles of Paros, Naxos and Tinos are renowned for their quality. Most manufacturing and craft enterprises produce goods related to local traditions and the primary sector. They operate within a limited market. However, some products from Paros, Naxos and Tinos have a wider market (e.g. cheese, wine, local sweets). These islands have facilities for producing, preserving and processing fruit/vegetables (Naxos), meat (Naxos and Tinos) and dairy products (Paros, Naxos, and Tinos). There are also olive mills on the islands of Andros, Naxos and Paros. Between 2011 and 2021, a significant increase in the primary sector (comprising agriculture, livestock and fisheries) was observed in Paros (94.44%) and Andros (31.90%), while Tinos experienced a decline (−4.93%). Tinos experienced the largest decrease in industrial activity, at −21.29%. There was also a decline in construction activity in Andros (−34.19%), Tinos (−31.62%) and Naxos (−26.18%). These decreases may have been affected by the economic crisis. Therefore, the period after 2019, particularly the post-Covid era, will be an interesting time to examine.

	Andros		Tinos		Paros		Naxos	
Island Area (km²)_ Population (2011-2021)								
(km²)	377.69		194.73		196.23		428.4	
	2011	2021	2011	2021	2011	2021	2011	2021
	9221	8826	8636	8934	13715	14520	18904	20578
% change	-4,28%		3,45%		5,87%		8,86%	
Production and Entrepreneurial (2014-2019)								
A_ Primary Sector : Agriculture, Live-stock, Fishery (2014-2019)								
	2014	2019	2014	2019	2014	2019	2014	2019
total units	442	583	365	347	198	385	949	1.026
% change	31,90%		-4,93%		94,44%		8,11%	
B_ Secondary Sector : Craft / Industry (2011-2019)								
	2011	2019	2011	2019	2011	2019	2011	2019
total units	69	60	108	85	139	118	181	163
% change	-13,04%		-21,29%		-15,10%		-9,94%	
C_ Tertiary Sector : Construction (2011-2019)								
	2011	2019	2011	2019	2011	2019	2011	2019
total units	272	179	253	173	498	389	527	389
% change	-34,19%		-31,62%		-21,88%		-26,18%	
C_ Tertiary Sector : Trade (2011-2019)								
	2011	2019	2011	2019	2011	2019	2011	2019
total units	268	210	328	271	673	646	710	626
% change	-0,21%		-0,17%		-0,04%		-0,11%	
C_ Tertiary sector : Recreation/ Leisure (2011-2019)								
	2011	2019	2011	2019	2011	2019	2011	2019
total units	334	286	367	354	958	973	1.059	1.163
% change	-14,37%		-3,54%		1,56%		9,82%	
D_ Tourism Development (2010-2021)								
Hotel beds								
	2010	2021	2010	2021	2010	2021	2010	2021
total	1381	1354	2237	2336	6893	7255	6003	7277
% change	-1,95%		4,42%		5,25%		21,22%	
Overnight stays								
	2010	2021	2010	2021	2010	2021	2010	2021
total	58711	55623	114874	76041	324818	354859	70191	252703
% change	-5,25%		-33,80%		9,24%		260,02%	
E_ Built Surface with Building Permit (2011-2021)								
	2011	2021	2011	2021	2011	2021	2011	2021
total (sqm)	16422	2096	11.342	6739	47.556	62692	32.762	31094
% change	-87,23%		-40,58%		31,82%		-5,09%	
Decade total (sqm)	56.044		63.815		343.358		286.813	
F_ Urban Network TOTAL (traditional settlements) (2021)								
	2021		2021		2021		2021	
total	88 (35) - [40%]		60 (36) – [60%]		75 (10) – [13%]		65 (19) – [29%]	





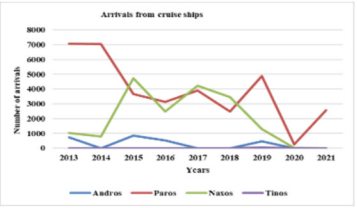
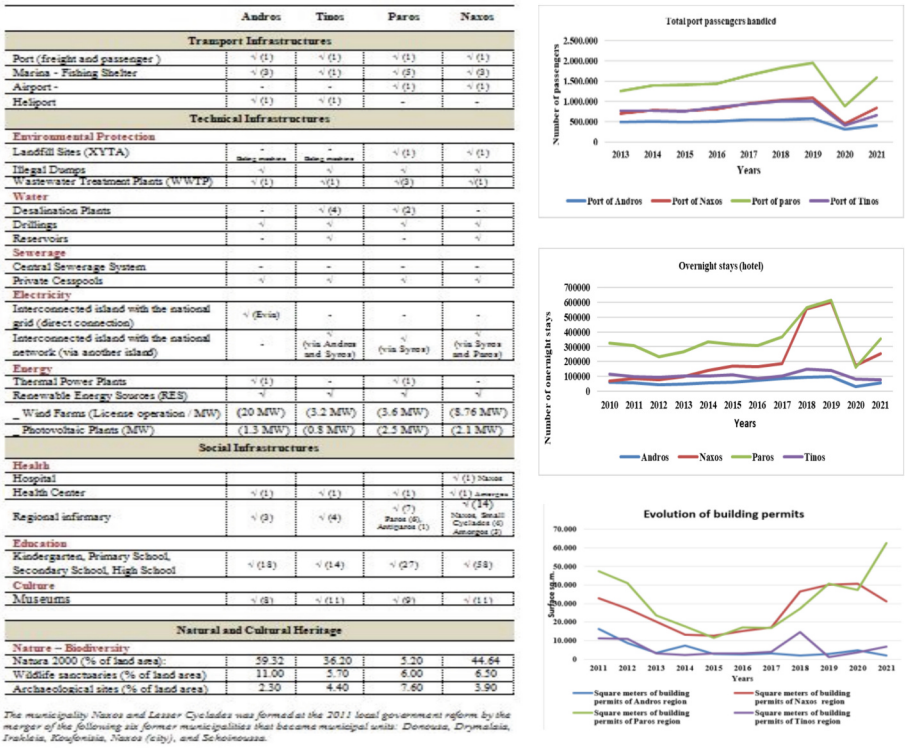


Fig. 3. Demographic and socio-economic characteristics [own elaboration] [23–25]

Tourism Development (2010–2021): In addition to the coastal areas, the inland urban network and traditional settlements are under intense pressure due to the impact of tourism. Thus, alongside areas of intense tourist development, primarily in Paros and Naxos, the mountainous regions of the islands are also witnessing a trend of converting abandoned settlements into holiday homes or short-term rental properties, (Airbnb) particularly in Andros and Tinos. Based on the number of hotel beds, the islands of

Paros, Naxos and Tinos excel as tourist destinations. Although Paros and Tinos are much smaller than Naxos, they have a similar number of hotel beds. At the same time, the 21.22% increase in the number of beds on Naxos threatens the island's sustainability and resilience. Paros, on the other hand, had the most overnight stays, while Naxos had the highest percentage increase (260.02%), establishing itself as a new tourist hotspot. In contrast, Tinos saw a decline of 33.8%. This is an interesting trend to analyse. There is relatively little cruise traffic, primarily due to a lack of infrastructure in Andros and Tinos. Undoubtedly, increased tourism leads to more built-up areas and a higher demand for energy [6, 8–10].



	Andros	Tinos	Paros	Naxos
Transport Infrastructures				
Port (freight and passenger)	√ (1)	√ (1)	√ (1)	√ (1)
Marina - Fishing Shelter	√ (2)	√ (1)	√ (5)	√ (2)
Airport -	-	-	√ (1)	√ (1)
Heliport	√ (1)	√ (1)	-	-
Technical Infrastructures				
Environmental Protection				
Landfill Sites (XYTA)	- Being realized	- Being realized	√ (1)	√ (1)
Illegal Dumps	√	√	√	√
Wastewater Treatment Plants (WWTP)	√ (1)	√(1)	√(2)	√(1)
Water				
Desalination Plants	-	√ (4)	√ (2)	-
Drillings	√	√	√	√
Reservoirs	-	√	-	√
Sewerage				
Central Sewerage System	-	-	-	-
Private Cesspools	√	√	√	√
Electricity				
Interconnected island with the national grid (direct connection)	√ (Evia)	-	-	-
Interconnected island with the national network (via another island)	-	√ (via Andros and Syros)	√ (via Syros)	√ (via Syros and Paros)
Energy				
Thermal Power Plants	√ (1)	-	√ (1)	-
Renewable Energy Sources (RES)	√	√	√	√
_ Wind Farms (License operation / MW)	(20 MW)	(3.2 MW)	(3.6 MW)	(8.76 MW)
_ Photovoltaic Plants (MW)	(1.3 MW)	(0.8 MW)	(2.5 MW)	(2.1 MW)
Social Infrastructures				
Health				
Hospital				√ (1) Naxos
Health Center	√ (1)	√ (1)	√ (1)	√ (1) Amorgos
Regional infirmary	√ (3)	√ (4)	√ (7) Paros (6), Antiparos (1)	√ (14) Naxos, Small Cyclades (4) Amorgos (2)
Education				
Kindergarten, Primary School, Secondary School, High School	√ (18)	√ (14)	√ (27)	√ (58)
Culture				
Museums	√ (8)	√ (11)	√ (9)	√ (11)
Natural and Cultural Heritage				
Nature – Biodiversity				
Natura 2000 (% of land area):	59.32	36.20	5.20	44.64
Wildlife sanctuaries (% of land area)	11.00	5.70	6.00	6.50
Archaeological sites (% of land area)	2.30	4.40	7.60	3.90

The municipality Naxos and Lesser Cyclades was formed at the 2011 local government reform by the merger of the following six former municipalities that became municipal units: Donousa, Drymalaia, Irakleia, Koufonisia, Naxos (city), and Schoinoussa.

Fig. 4. Infrastructures and Natural-Cultural Heritage [own elaboration] [23–25]

Construction Activity (2011–2021): Paros and Naxos have seen the greatest increase in built-up area, followed by Tinos and Andros. However, the data shows that Paros saw a significant increase of 31.82% in the number of new building permits issued, while Andros and Tinos experienced dramatic decreases, namely 87.23% and 40.58% respectively. These new permits are probably intended for large hotels.

Urban Network and Traditional Settlements (2011–2021): Andros and Naxos are similar in size, but Andros has more settlements. Similarly, despite their similar size, Tinos has fewer settlements than Paros. Tinos has the largest percentage of traditional settlements in its urban network by far, followed by Andros. In contrast, Naxos and

Paros have much smaller percentages, giving Tinos and Andros a distinctive traditional character. Therefore, their energy transition must be approached with the utmost respect for their cultural heritage and landscape.

With regard to infrastructure (i.e. transportation, technical and social), as well as elements of natural and cultural heritage, the following is noted [25, 26] (Fig. 4):

Infrastructures: In addition to their main port, which caters for commercial - tourist needs, the four islands have marinas and fishing shelters. Paros Port has the highest passenger traffic index (2013–2021), followed by Naxos and Tinos, with Andros in last place. Paros and Naxos have airports with direct international connections, making them important tourist gateways. Paros has the highest number of arrivals. All the islands face significant technical infrastructure challenges, particularly with regard to water, waste management and energy. These issues are exacerbated during the tourist season. The lack of healthcare and educational facilities is also a cause for concern. However, it is worth noting that there are a significant number of museums and other cultural facilities across the four islands.

Natural and Cultural Heritage: Only 5.2% of Paros is designated as a protected area, whereas 59.32% of Andros falls within protected areas. There are also marine protected areas on both islands. Overall, approximately 11% of Andros is covered by wildlife sanctuaries, compared to 6.5% for Naxos, 6% for Paros, and 5.7% for Tinos. Paros has the largest percentage of land occupied by archaeological sites (7.6%), followed by Tinos (4.4%), Naxos (3.9%) and Andros (2.3%). Meanwhile, Andros has the greatest number of underwater archaeological sites. It should be noted that some archaeological sites and wildlife refuges are located within Natura 2000 areas. In any case, the intense spatial dispersion of archaeological sites and traditional settlements across the islands poses significant challenges to the planning of their energy transition, particularly with regard to the location and size of renewable energy facilities.

In summary, all four islands boast significant natural and cultural heritage, as well as diverse landscapes. At the same time, some are strengthening their local economies by developing the primary sector. However, all the islands have problems with their technical and social infrastructure. Paros and Naxos are the most dynamic in terms of economic growth. However, both islands are under significant pressure due to intense urban development, particularly along the coast, as well as overtourism. These factors have led to a substantial increase in energy demand. Unfortunately, meeting these requirements remains challenging in Paros and Naxos, despite there being sufficient renewable energy potential. The situation in Andros is better, but remains weak in Tinos. The reason for this is that Greece has no overall plan for its energy transition.

5 Proposed Sustainable Renewable Energy Communities: A Multifactorial Typological Approach Through Networking

This section introduces the proposed sustainable, renewable energy communities in the Cyclades. The primary and secondary nodes of these communities were identified through an assessment of the energy potential of the islands and their capacity to utilise renewable energy sources (1st survey), combined with an investigation into development models that could establish the islands as main hubs in these communities (2nd survey).

Focusing on the development model of the hub islands using demographic and economic indicators provides insight into their energy demands, as well as those of neighbouring smaller islands that depend on them, either directly or indirectly, for development or energy. This is due to the nature and frequency of the energy production required to meet their needs, as well as the degree of interconnection (i.e. whether the islands are connected to the national grid or local grids).

Proposed sustainable energy communities in the Cyclades

Main Nodes	Natural and Cultural Resources	Built-up areas	Tourism development			Energy	Secondary Nodes
			Hotels	Hotel beds	Overnight hotel stays		
	% land area	building permits (sq m) (2011-2021	% change (2011-2019)	% change (2010-2021)	% change (2010-2021)	% coverage by RES/MRE (2011-2021)	
(1) ANDROS - TINOS							
ANDROS	70%	56,044	-14.37%	-1.95%	-5.25%	135.23%	-
TINOS	45%	63,815	-3.54%	4.42%	-33.80%	28.57%	-
(2) PAROS- Antiparos – Ios - Sikinos - Folegadros							
PAROS	13%	343,358	1.56%	5.25%	9.24%	10.16%	Antiparos, Ios, Sikinos, Folegadros
(3) NAXOS – Koufonisia – Schoinoussa – Irakleia - Donoussa – Amorgos							
NAXOS	49%	286,813	9.82%	21.22%	260.02%	31.02%	Koufonisia, Schoinoussa, Irakleia, Donoussa, Amorgos

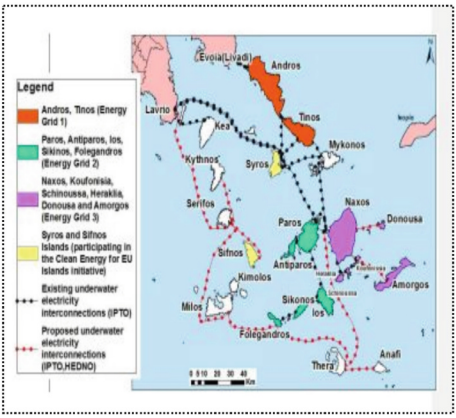


Fig. 5. Proposed sustainable renewable energy communities in the Cyclades [own elaboration]

In principle, the study identifies three communities that could play a significant role in the Cyclades' energy transition, as well as that of the country as a whole, by using sustainable renewable energy. From north to south, these are: (1) Andros and Tinos, (2) Paros, Antiparos, Ios, Sikinos and Folegadros, and (3) Naxos, Koufonisia, Schoinoussa, Irakleia, Donoussa and Amorgos. All three proposed communities are of particular interest in terms of sustainable energy planning. Specifically, the first energy community could serve as a case study due to the key role its islands play in the country's energy transition and the local-level challenges this role poses, particularly with regard to protecting and managing natural and cultural resources while respecting the islands' vulnerability. Similarly, the second and third renewable energy communities are of equal research interest due to the increased need for connectivity between the main hub islands (Paros and Naxos) and neighbouring smaller islands. This requires the development of smaller-scale energy infrastructure on land and at sea, which is particularly important in vulnerable areas such as island regions, given their fragmented and complex geography (Fig. 5).

The three proposed renewable communities represent an initial identification approach that will require further investigation through pilot studies in a subsequent phase. The aim of these studies should be to identify and measure the developmental and energy demands of the islands within the proposed communities. Thus, the communities will be analysed using quantitative indicators at two basic levels. The first level will focus on identifying how the proposed renewable energy communities could achieve energy neutrality and self-sufficiency. The second will examine how renewable resources on the

islands could be used to generate nationwide energy. The focus will be on developing innovative infrastructure for the production, storage and distribution of energy that takes into account the carrying capacity and local identity of the islands.

6 Open Issues for Building Sustainable Island Communities

In the context of the climate and energy crises, utilising renewable energy sources presents both a challenge and an opportunity to promote sustainability and resilience Research in the Cyclades revealed the need for an integrated island policy to determine the islands' developmental role and their position in the energy sector. Given their size, fragility and characteristics (i.e. *insularity*, *peripheralisation* and *seasonality*), the islands must ensure energy autonomy and protect their natural and cultural resources and landscapes from reckless exploitation within their territories.

Against the backdrop of the ongoing debate on the energy transition, insular countries must seek answers in the form of sustainable energy communities that are ready to utilise available resources while respecting the identity and carrying capacity of the islands. The aim should be for these island communities to generate renewable energy to meet their own needs throughout the year while preserving their unique character. In this context, achieving energy autonomy for the islands must be the main objective. It is also crucial to prevent islands from becoming supra-local hubs for the production, storage and distribution of energy intended for national consumption or export. This is because it could have a negative impact on their territories [8, 10, 28].

In line with this, the research on the Cyclades seeks to highlight the significance of islands and insular regions as research sites. The objective is to highlight the role of islands in the energy transition, paving the way for the identification of sustainable methods of utilising renewable resources through novel practices that honor human scale, local identity and resilience in the next phase. Insular regions can present challenges when it comes to planning renewable energy communities due to their complexity. This is mainly because small-scale installations are required to enable flexibility in energy production and consumption. This is particularly important in the current era, when energy autonomy is a key factor in a country's development policies, given the recent impact of military conflicts on countries that dominate the global energy scenery.

It is clear from the above that a sustainable energy transition and energy self-sufficiency are vital for the resilience and competitiveness of vulnerable island regions. To this end, it is proposed that achieving energy neutrality requires the classification of island development dynamics by type, alongside an evaluation of local energy needs and the challenges presented by each island. Such challenges include factors such as size, the natural and man-made environment, and landscape quality. Therefore, to ensure a successful energy transition, a multifactorial research approach is strongly recommended, assessing geographical, environmental, spatial, socio-economic and energy criteria simultaneously. Issues that need to be investigated at the next stage, with particular attention paid to the local level, include organising new, innovative planning tools for location selection, and developing production, storage, and distribution units [5, 8, 9, 11].

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