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A Decision Support GIS Framework for Establishing Zero-Emission Maritime Networks: The Case of the Greek Coastal Shipping Network

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Abstract

Sustainability of maritime operations is a topic widely considered in recent years, as the shipping industry attempts to limit its environmental impact and meet the decarbonization goals set by the International Maritime Organization (IMO). As alternative fuels and newer ship technologies are gaining interest, the shift to more environmentally friendly fleets is quickly becoming a reality. In this context, potential areas for such shifts need to be determined, to expedite decarbonization efforts and provide passengers with a more sustainable way of travel. Greece is an insular country, with a complex coastal shipping network connecting the mainland with the islands and being of paramount importance for their economic growth. Recognizing accessibility and decarbonization needs, this paper examines whether the Greek coastal shipping network (GCSN) can be restructured, by introducing zero-emission sub-networks operated by electric ferries. The aim is to propose a methodological framework for the spatial analysis and evaluation of coastal networks, with the implementation of exploratory spatial data analysis (ESDA) methods and determination of local indicators of spatial association (LISA) with the help of geographic information systems (GIS). The proposed framework provides insight on whether and where such a restructuring is possible, with the introduction of new transshipment port hubs in the islands from which electric ferries could operate, thus determining potential electrification areas with additionally high renewable resource potential. Final conclusions indicate that a potential electrification of certain parts of the GCSN could be possible, while results for GHG emissions reduced by the introduction of electric ferries are calculated.

Keywords Geographic information systems (GIS) · Exploratory spatial data analysis (ESDA) · Local indicators of spatial association (LISA) · Greek coastal shipping network · Zero-emission routes · Ferry electrification

Introduction

Transportation greenhouse gas (GHG) emissions have doubled since 1970 (Smith et al. 2014; Zisi et al. 2021). Compared to other transport modes, projections for GHG emissions in shipping show an increasing trend (50–250%) until 2050 due to the continuing growth of the sector (Smith et al. 2014; Zisi et al. 2021). Environmental concerns have urged the International Marine Organization (IMO), other marine organizations, and the research community to propose certain solutions for the gradual replacement of fossil fuels in the shipping sector (Zisi et al. 2021) and suggest a shift to decarbonization through the electrification of maritime vessels (Peder Kavli et al. 2017; Koumentakos 2019; Pfeifer et al. 2020; Anwar et al. 2020).

Ferry services connecting the Greek mainland and its 120 islands are of paramount importance for the well-being of island communities (Lekakou et al. 2021). Greece is ranked second in the European Union in terms of ferry traffic, with an average of 35 million passengers and 149 million tons of goods handled annually, over the period between 2015 and 2019. The Greek ferry network (otherwise called the Greek coastal shipping network—GCSN) has an essential role in the country's economy; the GCSN's wider impact is estimated at around 7.4% of the country's GDP (IOBE 2021). However, the GCSN is characterized by geographic

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discontinuity, infrequent connections for smaller islands, poor quality of port infrastructure, and seasonality (Papadaskalopoulos et al. 2015; IOBE 2021); the latter yields highly differentiated ship capacity utilization rates among routes and seasons (Schinas 2009; Lekakou et al. 2021). As of 2021, a fleet of 91 conventional and high-speed Ro-Ro vessels operated the GCSN, with an average age of 26 years; about 60% of them are over 22 years old and a quarter of them are over 30 years old; the GCSN fleet lacks in terms of ship age and environmental footprint, despite the efforts made by shipping companies to comply with the IMO carbon regulations (Papanikolaou and Eliopoulou 2001; Smith et al. 2014).

Despite the extent of the GCSN, no relevant investment in electric ships has so far been implemented even on a trial basis; the closest effort is that of installing a cold ironing system used in the port of Kyllini in Western Greece (Prousalidis et al. 2017). The establishment of zero-emission routes, operated by electric ferries, could contribute toward improving the environmental footprint of the GCSN. However, the introduction of zero-emission vessels should be coupled with improving the structure and services of the GCSN, considering in parallel the possible constraints of electric vessel operations. As such, it is important to consider the operational range and capacity of electric ferries and determine areas where these vessels can operate safely and efficiently. In this context, this paper exploits spatial data analysis techniques for identifying candidate areas of GCSN operations where it is possible to route electric ferries. Based on that, it is possible to restructure the GCSN so that certain areas are then serviced by electric vessels. The remainder of the paper is structured as follows: the next section presents the background of the study. Subsequent sections include the methodology and results. The paper concludes with major study findings.

Literature Review

Currently, slow-steaming, route optimization, and hull fouling management are strategies applied in the shipping sector to abide IMO environmental footprint mandates, although these cannot offer no better than a 10–15% decrease in emissions (Cullinane and Cullinane 2013; Ammar 2018). These strategies focus on improving engine efficiency, often ignoring green technologies and renewable energy sources (Koumentakos 2019). Fossil marine fuels are expected to almost phase out by 2050 (Raucci et al. 2017), which proclaims the IMO's ambition to achieve carbon footprint reduction in line with the initial actions of MEPC 72 that is going to be revised in mid-2023 as a new GHG strategy (MEPC 80).

Ferry electrification has been rapidly gaining interest in recent years in an effort to limit the maritime sector's environmental footprint. There are already several cases where both hybrid-electric and fully electric ferries are operated, with the Scandinavian countries leading the way with respect to policies applied for the subsequent transition to electric fleets (Tarkowski 2021; Sæther and Moe 2021; Tarkowski 2021). However, as reported by Koumentakos (2019), performance and cost efficiency often hinder a successful implementation of ferry electrification and therefore limit the transition to electric ferries only on short-sea maritime routes. Several papers address topics related to ferry electrification technologies, their costs, and environmental impact (Anwar et al. 2020; Bellone et al. 2019; Reddy et al. 2019, Vicenzutti et al. 2020, Kersey et al. 2022). A large part of the literature attempts to assess the potential and feasibility of introducing electric vessels in maritime routes. Among them, Jeong et al. (2020) and Perčić et al. (2020) offer generic lifecycle assessment analyses of ferry fleet electrification, while several other studies attempt case specific evaluations of electric ferry implementation in the context of short-sea maritime routes, inland waterway corridors, and tourist boat cruises (Bianucci et al. 2015; Moe 2016; Palconit and Abundo 2019; Bigerna et al. 2019; Pfeifer et al. 2020; Savard et al. 2020; Wahnschafft and Wolter 2021; Perčić et al. 2021; Maloberti et al. 2022). Finally, part of the literature examines charging infrastructure needs and placement (Zhang et al. 2017; Khan et al. 2022) and integrated route and charging infrastructure planning (Wang et al. 2022). It is becoming evident that recent literature on ferry electrification exhibits several studies focusing on either technology or specific application settings. However, from a planning perspective, to the authors' knowledge, no previous work has attempted to identify service areas of a ferry network that are suitable for electrification, through spatial data analysis. Only a handful of studies have either dealt with charging infrastructure placement or route planning of electric maritime services (Wang et al. 2022). In the transportation sector, the adoption of spatial analysis methods is highly important for the design, planning, and operations decision-making processes, with several studies focusing on the investigation of operational inefficiencies of urban networks through spatial analytics, most notably in bus operations (Iliopoulou et al. 2020; Chioni et al. 2020).

Recent studies have underscored the significance of spatial analysis techniques in facilitating precise assessments and monitoring of emissions in order to highlight the necessity for emission mitigation strategies (Danylo et al. 2019; Uddin and Czajkowski 2022). Regarding the shipping industry, recent studies have highlighted the importance of spatial analytics, especially in emissions monitoring (Johansson et al. 2017; Ding et al. 2018; Russo et al. 2018; Topic et al. 2021), with several others also utilizing spatial analysis methods to assess the benefits of emission mitigation strategies (Okada 2019; Ülker et al. 2020). Unlike

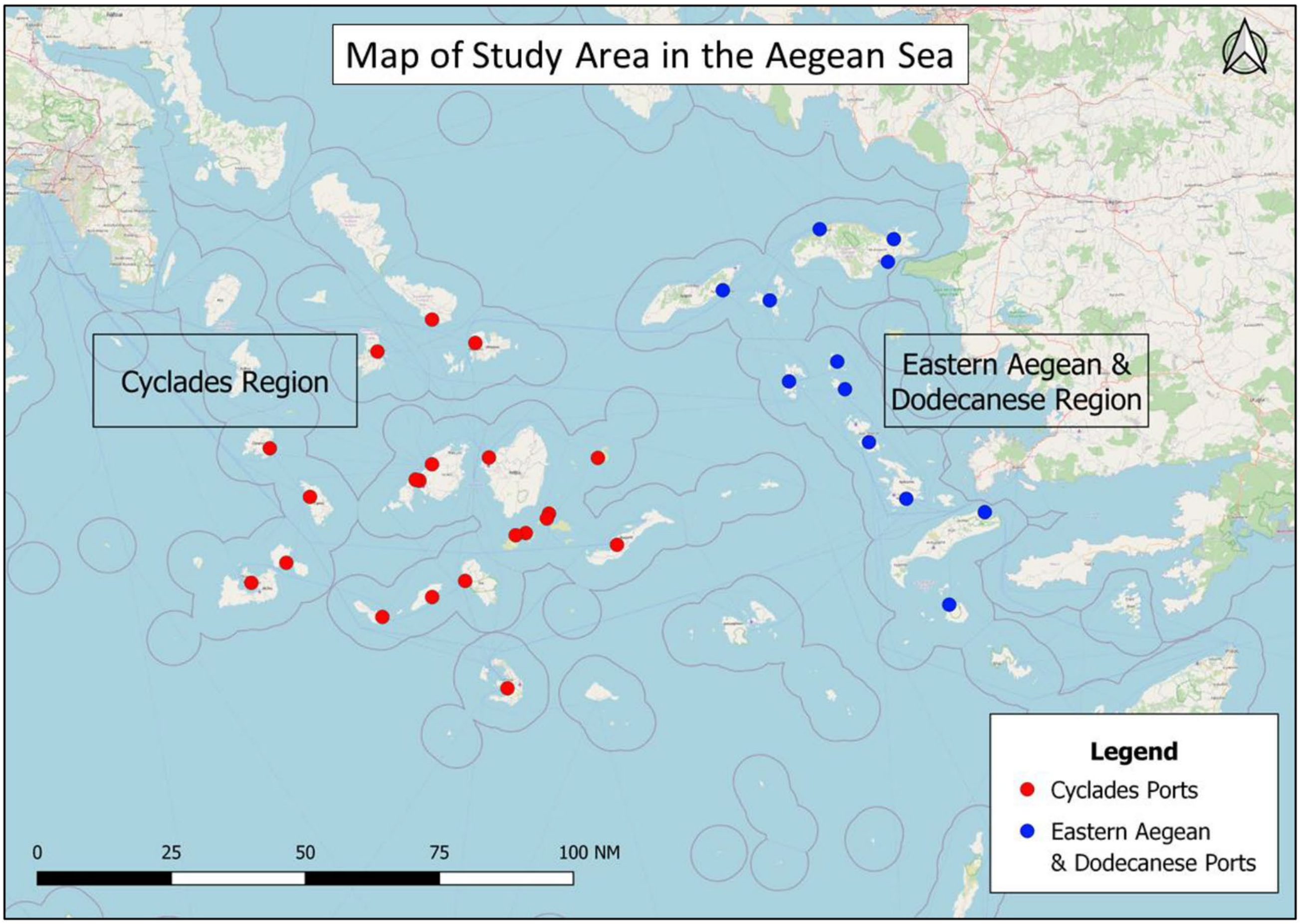


Fig. 1 Case study areas: ports of Cyclades (red) and Eastern Aegean/Dodecanese ports (blue)

overseas shipping, coastal shipping and ferry operations are in most cases occurring between ports within a particular country, which in many cases results in short-sea shipping to be considered as a highly important alternative to reduce GHG emissions from road transport, especially in Europe (Psaraftis and Zis 2020). Nevertheless, research has been limited to short-sea shipping, mainly due to the fact that Ro-Ro and Ro-Pax ships consist of only a small portion of the world fleet, while environmental studies have mostly focused on liner shipping and especially containerships, which are contributing more to GHG emissions (Psaraftis and Kontovas 2009). As decarbonization efforts are continuously increasing in the shipping industry, alternative fuels in short-sea shipping are also gaining interest, although more advances are still necessary for future technological solutions (Zis et al. 2020). As a result, electrification in the shipping industry as a solution for reducing GHG emissions can, for the time being, only be applied to specific areas that facilitate this transition considering topological characteristics and network energy demand, such as northern European countries (Tarkowski 2021), where ferry routes are generally of shorter distances. Considering the available technologies of electrified waterborne transport, range constraints call upon the consideration of spatial and locational aspects when deciding to implement electric ferry services.

In addition to operational constraints due to technological advancements, energy efficiency and supply are also important in zero-emission shipping. Considering the GCSN, energy supply and energy security for the Aegean Islands are both critical, especially in the summer periods as the islands attract large numbers of tourists, thus requiring efficient energy supply planning (Iliopoulou et al. 2018). For the efficient operation of zero-emission systems, energy supply needs to be based on renewable energy sources (RES) so that both operational and energy production emissions are mitigated. Renewable energy has been continuously gaining interest, especially as the cost of various RES systems has rapidly reduced in recent years (Luderer et al. 2021). Electrification of both routes connecting islands and the islands' needs through the application of 100% RES energy systems has gained interest recently, with environmental benefits gained from the transition to fully zero-emission

Table 1 Passenger demand between 2015 and 2019 and number of ports in proximity

	Island/port name	Passenger demand						Ports in proximity
		2015	2016	2017	2018	2019	Average	
Cyclades	Aegiale (Amorgos)	17,724	39,848	46,410	58,209	62,990	45,036	2
	Antiparos	472,177	511,785	571,365	652,786	706,252	582,873	2
	Donousa	14,024	27,947	29,900	40,401	41,483	30,751	2
	Folegandros	79,687	80,797	94,156	102,663	102,664	91,993	1
	Ios	232,362	245,641	273,055	312,564	285,136	269,752	3
	Iraklia	20,643	21,174	23,707	26,117	26,255	23,580	4
	Katapola (Amorgos)	99,038	91,781	116,972	127,139	121,057	111,197	2
	Kimolos	70,168	77,937	84,200	91,592	93,998	83,579	2
	Koufonisia	99,276	104,893	122,506	131,912	131,658	118,049	5
	Mikonos	1,186,113	1,194,356	1,410,377	1,571,585	1,667,767	1,406,040	1
	Milos	257,976	281,333	336,936	370,876	423,553	334,135	1
	Naxos	764,323	818,549	947,567	1,035,563	1,087,021	930,605	5
	Paros	1,409,129	1,438,079	1,648,866	1,832,274	1,958,868	1,657,444	2
	Schoinousa	28,511	31,934	34,919	36,663	36,738	33,753	4
	Serifos	116,553	120,350	136,810	152,785	162,859	137,872	1
	Sifnos	195,884	211,494	159,235	264,729	272,068	220,682	2
	Sikinos	15,760	17,298	99,403	23,722	21,975	35,631	2
	Syros	522,479	603,145	631,078	695,731	731,071	636,701	1
	Thira	1,457,004	1,387,560	1,789,519	1,984,999	2,117,940	1,747,405	1
	Thirasia	23,065	25,596	27,319	29,241	25,270	26,099	1
	Tinos	757,105	850,208	941,746	1,000,951	1,001,551	910,312	2
Dodecanese and Eastern Aegean Islands	Agathonísi	802	7604	8394	7154	9025	6596	3
	Agios Kirykos (Ikaria)	59,242	79,021	66,741	47,085	32,273	56,872	2
	Arki	357	4184	5461	4524	6317	4168	4
	Evdilos (Ikaria)	84,987	79,647	106,408	123,494	114,695	101,846	2
	Fournoi	30,651	36,429	39,792	35,683	18,764	32,264	3
	Kalimnos	355,964	320,150	332,428	357,701	384,620	350,173	3
	Kardamaina (Kos)	8124	13,548	6673	5294	6041	7936	3
	Karlovasi (Samos)	88,862	87,331	129,788	115,750	91,638	102,674	2
	Kos	600,854	537,061	528,495	579,027	591,362	567,360	2
	Leipsoi	17,642	28,879	33,082	29,768	36,257	29,125	4
	Leros	89,653	126,321	129,908	134,507	151,987	126,475	3
	Nisiros	53,651	55,444	44,482	40,045	42,020	47,128	1
	Patmos	107,850	155,444	166,622	149,471	166,287	149,135	3
	Pythagoreio (Samos)	11,123	32,044	35,616	30,185	34,074	28,608	3
	Vathy (Samos)	153,604	86,487	71,738	85,261	69,377	93,294	2

islands, albeit with several challenges that must be overcome (Pfeifer et al. 2020). Although there are several criteria to evaluate before selecting an optimal site for the development of RES facilities, studies have always benefited from the use of spatial decision support systems and GIS software in facilitating the decision-making process, especially since offshore RES facilities have also been gaining interest (Sourianos et al. 2017; Taoufik and Fekri 2021). Greece and the GCSN could also benefit from such facilities, as the Aegean Sea is an area with strong winds that would benefit offshore wind farms, extended sunny periods throughout the year that benefit photovoltaic energy output, several inhabited islands, uninhabited islets, and areas where such facilities could be installed (Vagiona and Kamilakis 2018).

In this context, this work contributes to the literature by introducing a methodological framework for the evaluation of potential zero-emission coastal shipping networks, using the GCSN as an application setting.

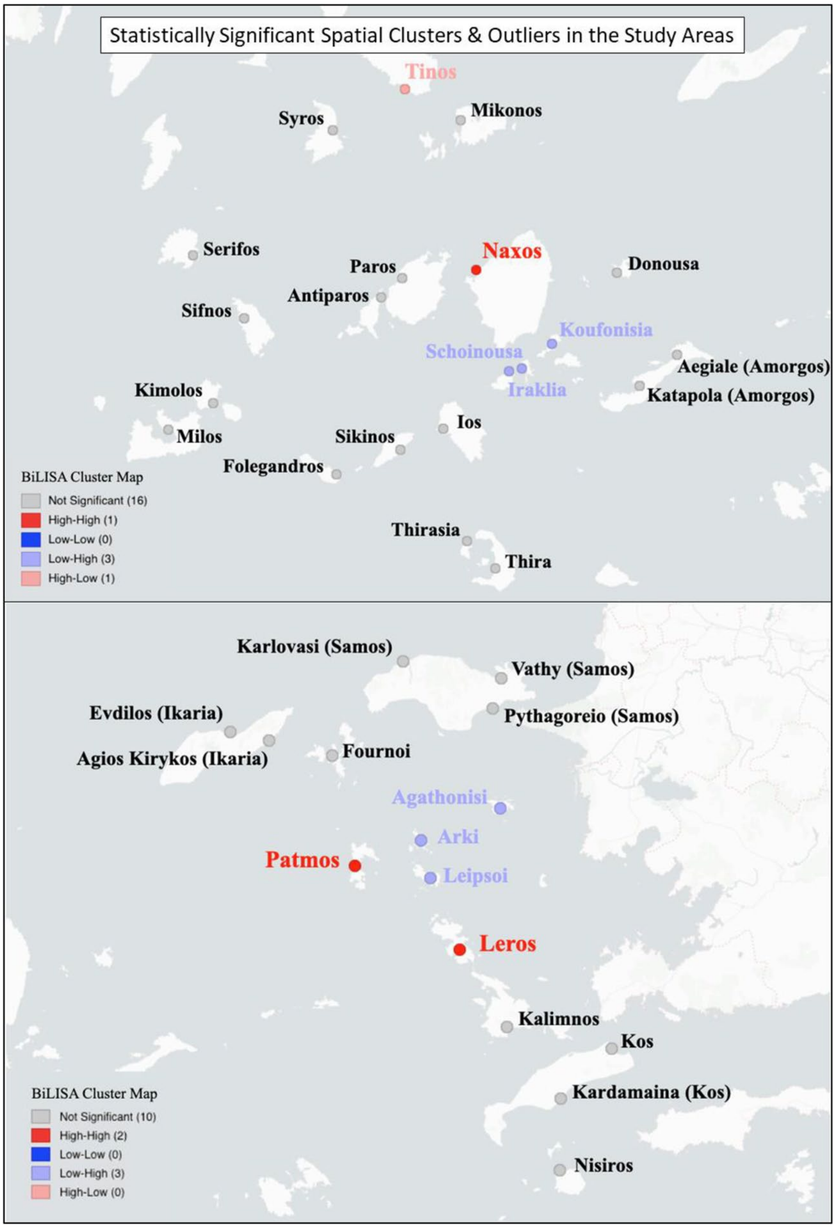


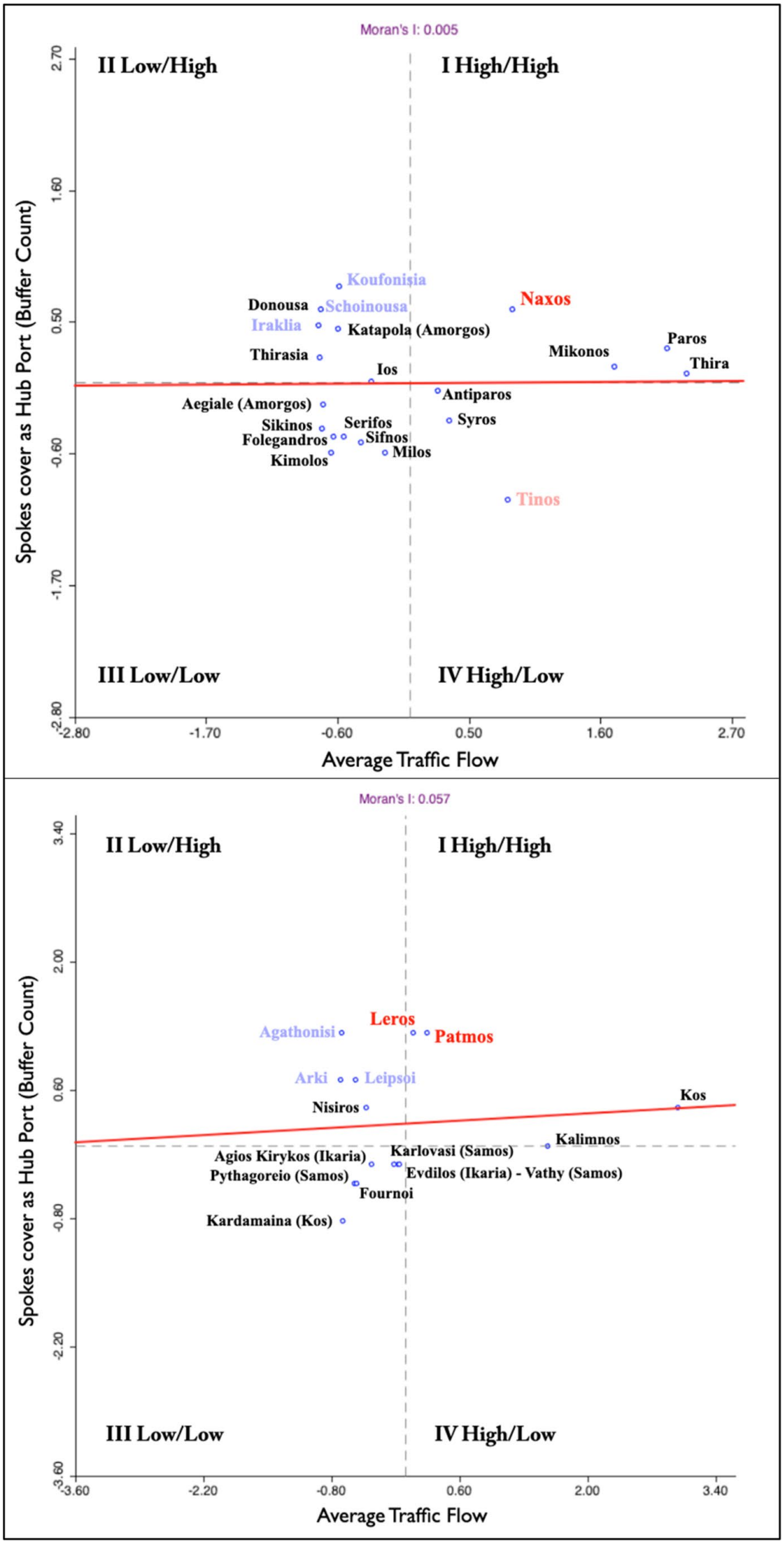
Fig. 2 Cluster maps of potential hubs (High-High features) and spokes (Low–High features)

Methodology

Spatial analysis is widely applied for identifying patterns and assessing trends in space and location-related problems. It can be defined as "a collection of techniques to describe and visualize spatial distributions, identify atypical spatial locations or spatial outliers, discover spatial association patterns, clusters or hotspots, and suggest spatial regimes or other forms of spatial heterogeneity" (Anselin 1998). Spatial analysis methods have been used in shipping for analyzing vessel collision data in hotspots (Rong et al. 2021), NO_2 emissions in the Red Sea (Alahmadi et al. 2019), port traffic forecasting (Zhang et al. 2019), and the identification of possible collision paths in ship routes (Zhao et al. 2019). In a similar context, a methodological framework based on spatial analysis is developed for the identification of areas serviced by the GCSN where there is potential for the electrification of ferry routes with the support of existing and future RES facilities. The objective is to establish suitable locations for island hub ports of the GCSN and then determine which nearby ports could be efficiently serviced by electric ships operating between the said hub ports and smaller islands with lower service requirements, relying on renewable energy, thus resulting in both zero-emission islands and their connecting ferry lines.

The methodology proposed in this study is based on the exploratory spatial data analysis (ESDA) (Anselin et al. 2010). ESDA is based on the collection and analysis of data

Fig. 3 Bivariate Moran's scatterplots of statistically significant clusters and outliers, considering proximity and traffic flow variables



on distances between objects and/or events (Fischer et al. 2019), which allows the investigation of spatial correlations with variables related to socio-economic, environmental, and network characteristics. For that purpose, the concept of "spatial autocorrelation" is exploited, which describes the presence of systematic spatial variation in a variable among different locations, meaning that locations that are close together have attributes of similar values (Getis 2008). Spatial autocorrelation models have the advantage of deriving useful information by detecting deviations from global patterns of spatial association in a given geographic space as well as underlying hotspots for certain variables (Griffith 2005). ESDA methods are increasingly gaining interest among professionals and academics, constituting the need for continuous improvements on existing software and the development of newly introduced ones (Percival et al. 2022) to meet the research community's needs. As a result, ESDA methods are also considered in this study for the development of the methodological framework.

Bivariate Local Indicators of Spatial Association

A bivariate local indicator of spatial association (Bi-LISA) is developed for the purpose of identifying potential areas where spatial autocorrelation exists (Anselin 2010) when taking into consideration two distinct variables and their spatial relationship. The Bi-LISA indicator is derived from a bivariate local Moran's I model (based on Moran metrics). Moran's I statistics are applied in this study for measuring spatial autocorrelation, which is the presence of patterns in geographic data that are not due to chance; these statistics can be calculated at either the global or local level (Getis 2010). Considering global Moran's I statistics in practice, a feature is considered of high value if it has a similar value to the mean one and of low value if it has a dissimilar value compared to the mean (Anselin 2010). For a global spatial autocorrelation statistic, this takes on the general form, as seen in (1), while a generic form for a local indicator of spatial association is seen in (2).

$$\sum_i \sum_j w_{ij} f\left(x_i, x_j\right) \tag{1}$$

$$\sum_j w_{ij} f\left(x_i, x_j\right) \tag{2}$$

where $f\left(x_i, x_j\right)$ is a measure of attribute similarity between a pair of observations x_i and x_j and w_{ij} is an indicator for geographical or locational similarity, in the form of spatial weights.

On the other hand, a local Moran's I statistic measures spatial autocorrelation at the neighborhood level. In this case, the statistic is calculated by comparing the value of a feature to the values of its neighbors, and if its value is similar to the values of its neighbors, then the feature is considered of high value, whereas if the value is dissimilar to the values of its neighbors, then the examined feature is considered of low value (Anselin 2010). The main difference in both statistics is evidently the level at which they are applied, with the global Moran's I statistic focusing on spatial datasets as a whole, thus being utilized when the main focus is to determine whether features show certain spatial patterns (such as clusters or outliers) by measuring overall spatial correlation in a dataset. As for local Moran's I statistics, they are used in cases where there is proof of spatial autocorrelation in order to determine where exactly certain patterns appear, as these measure spatial autocorrelation at the neighborhood (local) level, thus being highly useful when examining sub-regions of a larger area (Guo et al. 2013). Consequently, in most cases, the calculation of a global Moran's I statistic precedes the calculation of a local Moran's I statistic and, therefore, determines whether the latter is necessary.

The use of LISAs has been discussed in various studies (Fotheringham 1997; Boots 2002, 2003; Bivand and Wong 2018). In most cases, LISAs are used to measure the spatial autocorrelation of a single variable in a dataset at the neighborhood level. In recent years, though, LISAs that account for more than one variable are gaining popularity (Bivand and Wong 2018; Oxoli et al. 2020; Eckardt and Mateu 2021), with their use being facilitated with the help of GIS software (Anselin et al. 2010). Bivariate LISAs are the most common ones regarding cases of more than one variable, as they take into account two distinct variables and measure their spatial autocorrelation in a dataset. They are considered an extension of the univariate LISAs while having certain advantages over them, mainly due to the fact that they can identify spatial patterns that may not be apparent when analyzing each variable separately. As a result, when analyzing two distinct variables where not only their respective importance to the dataset should be considered but also the spatial relationships between them, the use of bivariate LISAs is necessary.

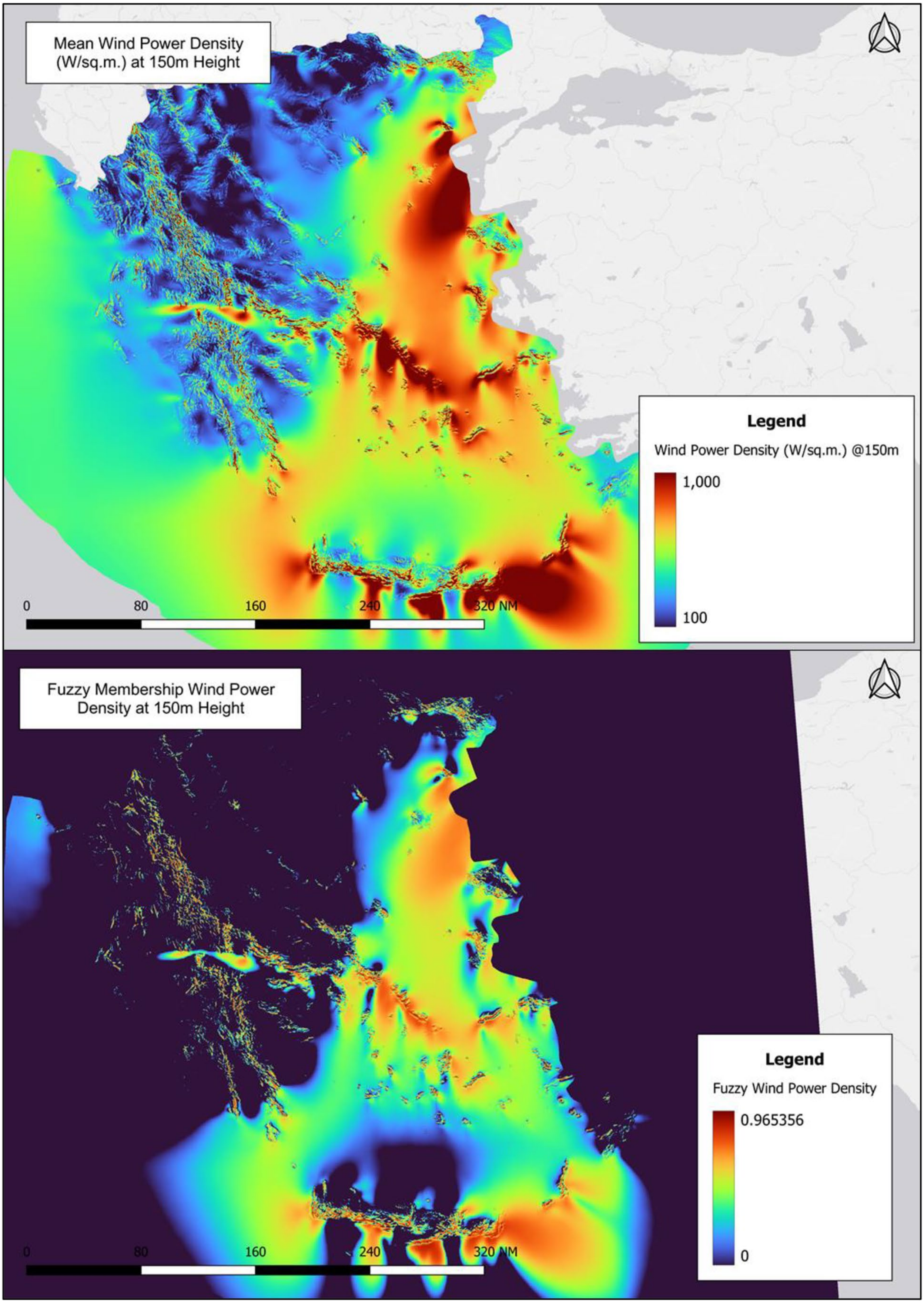
The approach of the bivariate local Moran's I model closely follows that of its global counterpart (Anselin et al. 2002) and can be defined as shown in (3) for the calculation of its statistics and determination of statistically significant areas:

$$I_{kl} = z_k^i \sum_{j=1}^{n} w_{ij} z_l^j \tag{3}$$

where

$$z_k^i = \left[x_k^i - \overline{x_k}\right] / \sigma_k \tag{4}$$

$$z_l^j = \left[x_l^j - \overline{x_l}\right] / \sigma_l \tag{5}$$


Mean Wind Power Density (W/sq.m.) at 150m Height
Legend
Wind Power Density (W/sq.m.) @150m
1,000
100
0
80
160
240
320 NM
Fuzzy Membership Wind Power Density at 150m Height
Legend
Fuzzy Wind Power Density
0.965356
0
0
80
160
240
320 NM

◂**Fig. 4** Potential wind resources for wind farm facilities at areas under study. Initial data accessed from World Bank Group's Global Wind Atlas (https://globalwindatlas.info/en)

where x_k^i is the value of variable k at location I; x_l^j is the value of variable l at locator j; $\overline{x_k}$ and $\overline{x_l}$ are the mean values of the variables k and l, respectively; σ_k and σ_l are the variance of X for variables k and l, respectively; and w_{ij} is the elements of the spatial weights matrix (Anselin et al. 2002).

Spatial weights are key factors in most spatial models where the representation of spatial structure and typology is necessary (Getis and Aldstadt 2004; Getis 2009; Zhang and Yu 2018), as they provide the way to create spatially explicit variables, such as spatially lagged variables and spatially smoothed rates. In essence, weights express the neighbor structure, which denotes the spatial relationships between the observations, as a $n \times n$ matrix W in which the elements w_{ij} of the matrix are the spatial weights. Such a matrix can then be used in order to encode a variety of spatial relationships, including contiguity, distance, and network connectivity (Anselin 2022), so that spatial dependence is easily incorporated into statistical models, such as LISA statistics.

There are two basic strategies for creating the weight's values in order to quantify the relationships among features in a dataset: binary and variable weighting. In the case of this study, a binary strategy is applied for the spatial weights w_{ij}, with a value of 1 when i and j are neighbors and zero otherwise. By convention, the self-neighbor relation is excluded, so that the diagonal elements of W where $i = j$ are zero. Row standardization is applied, meaning that given weights w_{ij} are divided by the row sum as shown in (6).

$$w_{ij(s)} = {}^{w_{ij}}\Big/_{\sum_j w_{ij}} \tag{6}$$

With row-standardized weights applied, each row sum of the weights is equal to 1, while the sum of all weights S_0, as shown in (7), will equal n, which is the total number of observations.

$$S_0 = \sum_i \sum_j w_{ij} \tag{7}$$

In this study, spatial weights emphasize in contiguity with a queen's criterion, which leads to all eight neighbors of each cell in all directions equaling 1, while others equaling 0. In the proposed framework, a limitation is applied to the neighborhood distance set, which is given by the operating range of the electric ship, resulting in a maximum neighborhood distance threshold equal to the maximum operating range of the electric ship considered. Consequently, i and j are neighbors ($w_{ij} = 1$) when $d_{ij} \leq \delta$, where

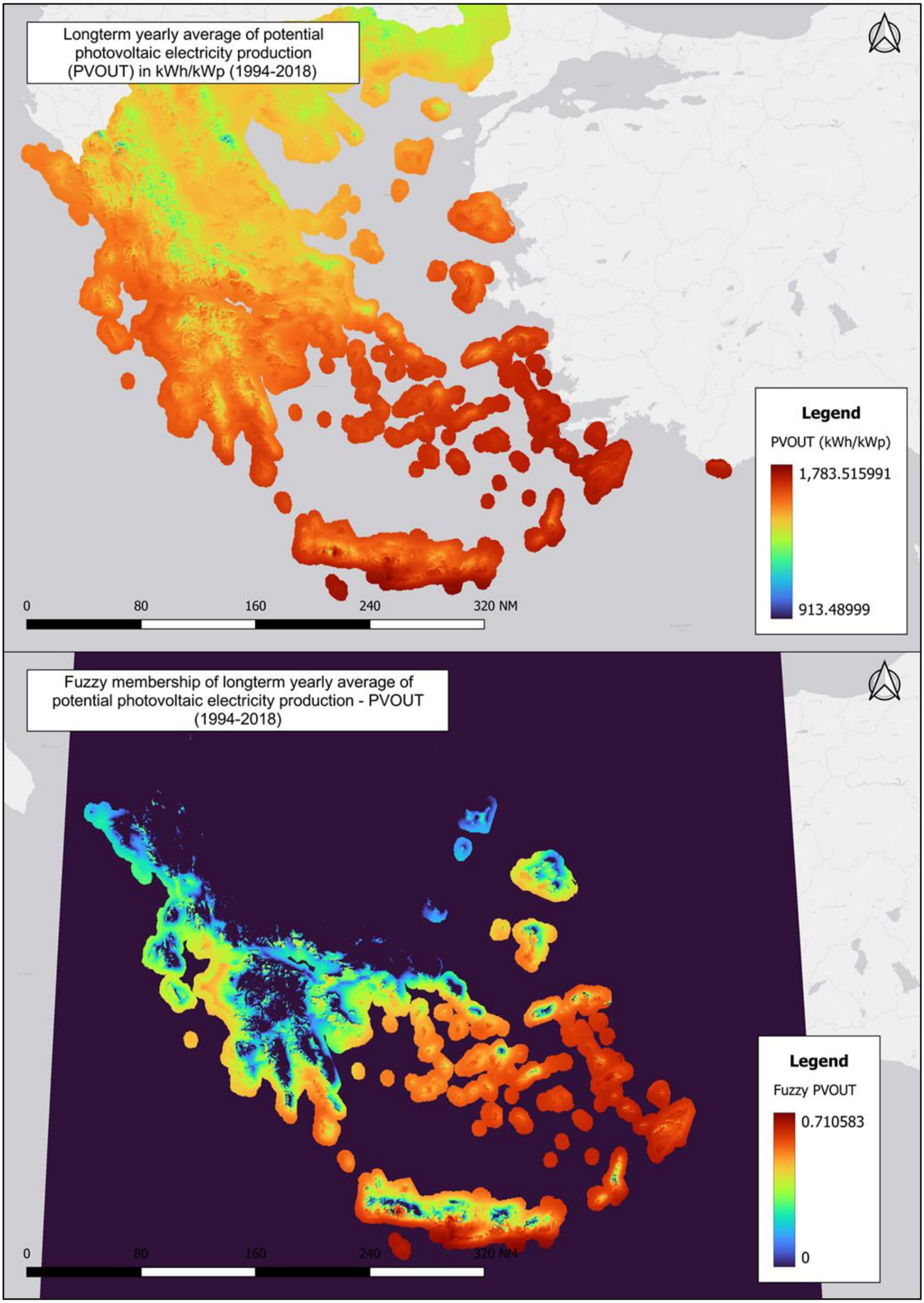
$$d_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \tag{8}$$

with d_{ij} being the Euclidean distance for two points i and j with coordinates $\left(x_i, y_i\right)$ and $\left(x_j, y_j\right)$ respectively, while δ denotes the preset critical distance cutoff. After that combination, the final spatial weights matrix can be derived. In this study, the two variables selected for the spatial analysis are the total passenger flow of each island/port and each port's proximity to other ports in the study with respect to the given operating range of an electric ship.

For the purposes of the study, two popular and complex island groups in the Aegean are taken into consideration for the implementation of the Bi-LISA model. The first group consists of the islands of the Cyclades, and the second comprises islands from the Dodecanese and Eastern Aegean regions, as these islands show the highest passenger demand, especially in peak summer periods, while also being highly complex regarding topological characteristics. As this study focuses on the feasibility of introducing zero-emission electric ships to certain routes of the GCSN, topology is highly important as such ships can only operate over short-sea distances. For this purpose, proximity between islands is considered the most important topological characteristic for the determination of island hub ports, and therefore, it is used as the first variable of the proposed framework.

For the framework to generate reasonable results, proximity as a variable should be quantified for each port of the study. As such, features of the variable are designed for each potential hub port to show the number of islands that can be reached within a given operating range of an electric vessel. Those other ports that are within that operating range are identified using a proximity analysis method by determining the number of ports in a range of 16.5 nautical miles, which is the maximum operating range of an e-ferry (Gagatsi et al. 2016), reduced by 25% in favor of operational safety. As a result, as more ports are reached from a potential hub port by an electric ferry, it is more likely for the examined port to be determined as a hub port from which zero-emission routes to other island spokes can be introduced.

Overall passenger demand is also a variable considered for the selection of hub ports, with total embarking and disembarking passengers calculated for each port to describe that variable. The proposed framework takes into consideration the fact that for zero-emission routes to be applied, certain islands serviced by electric ferries will be reached with an added time delay due to the transfer of passengers from larger ships to smaller electric ferries. To compensate for that time loss and the fact that electric ferries have limited capacity capabilities compared to larger vessels, it is proposed that more popular islands, in terms of total passenger demand, are more suitable to be selected as hub ports. This


Longterm yearly average of potential photovoltaic electricity production (PVOUT) in kWh/kWp (1994-2018)
Legend
PVOUT (kWh/kWp)
1,783.515991
913.48999
0
80
160
240
320 NM
Fuzzy membership of longterm yearly average of potential photovoltaic electricity production - PVOUT (1994-2018)
Legend
Fuzzy PVOUT
0.710583
0
0
80
160
240
320 NM

◂**Fig. 5** Potential photovoltaic electricity production at areas under study. Initial data accessed from World Bank Group's Global Solar Atlas (https://globalsolaratlas.info) and SOLARGIS (https://solargis.com/)

assumption is made for two reasons: first, as more popular islands operate as hub ports and less popular ones as spoke islands to be serviced by electric ferries, fewer passengers will be affected by time delays from passenger transfer at hub ports. In addition, as less popular islands will be operated by electric ferries, there is less chance for the electric ferries to reach their maximum capacity of passengers due to reduced passenger demand for such islands. With the proposed framework, while passengers to less popular spoke ports will have to endure increased total travel times due to transfers, their overall environmental footprint will be reduced as part of their route will be electrified, with certain island destinations being serviced by zero-emission routes.

For a better visualization of the results of the proposed framework, Moran's scatterplots are generated. An effective interpretation of a Moran scatterplot centers on the extent to which the linear regression line reflects the overall pattern of association between W_y and y (Anselin 1996). The purpose is to find observations that do not follow the overall trend and thus tend to exhibit, to some extent or completely, local instability or non-stationarity. Therefore, with the help of a Moran scatterplot, it is possible to identify clusters of positive and/or negative associations, outliers, leverage points, and spatial regimes (Anselin et al. 2007; Anselin 1996).

Evaluation of Renewable Energy Source Capabilities

Numerous studies have applied spatial data analysis methods for the assessment of renewable energy sources' (RES) potential in different areas. Most of them have utilized GIS-based spatial decision support systems and multi-criteria analyses for the siting of renewable energy source facilities by combining several criteria with spatial variables, such as different stakeholder interests (Hanssen et al. 2018), land use, and geological constraints, in addition to economic benefits (Van Haaren and Fthenakis 2011). While multi-criteria site evaluation studies have generally focused on onshore renewable energy source facilities, recent studies have also investigated offshore RES sites for efficient energy supply and decarbonization (Doorga et al. 2022; Vanegas-Cantarero et al. 2022). To this extent, an additional step proposed in this methodology is the evaluation of existing and future RES capabilities for the resulting areas under study to better assess the potential of the facilities supporting electricity-based shipping for zero-emission operations. To do this, open data for renewable energy source facilities were collected by the Greek Regulatory Authority for Energy for the resulted areas, consisting of existing wind and solar farms, either already in operation or under construction, to better assess the existing RES infrastructure. In addition, in order to evaluate the potential for future RES infrastructures, wind and solar data were collected from the World Bank Group's Global Wind Atlas and Global Solar Atlas, respectively. In order to gain better insights on the combined data for existing facilities and potential RES capabilities for the islands under study, fuzzy membership functions are applied to existing data and fuzzy overlays for their combination to provide a better understanding of whether the resulted areas can support the electrification of shipping routes by existing or future RES infrastructures.

Evaluation of Emission Mitigation Strategy

Determining potential areas of electrification will yield zero-emission networks, thus resulting in certain routes of the network under study being replaced by electric battery-powered ferries. This replacement will lead to operational emission nullification with the introduction of e-ferries. In order to provide better insight on the environmental benefits of the proposed methodology, it is necessary to determine the amount of GHG emissions saved because of electrification. To do so, an emissions analysis is conducted for 80 routes of the GCSN, servicing the islands under study, by utilizing reported maritime CO_2 emissions data from the THETIS EU-MRV platform for the European Union Monitoring, Reporting, and Verification system (European Maritime Safety Agency 2019). Although several recent studies have focused on the estimation of maritime CO_2 emissions through mathematical models (Deniz et al. 2010; Song and Xu 2012; Song and Shon 2014; Uyanık et al. 2020; Tarelko and Rudzki 2020), reported CO_2 emissions are used in this study to avoid statistical variances of model-based estimations, resulting in more accurate results through measured data that are in accordance with the EU Regulation 2015/757. However, one of the major drawbacks of EU-MRV data is the fact that, based on EU Regulation 2015/757, CO_2 emission reports only apply to vessels of over 5000 gross tonnage. In the case of this study, not all vessels operating in the Aegean Sea are above 5000 GT in size, and their respective operators and shipping companies are not obligated to report either CO_2 emissions or fuel consumption. In such a case and for the purposes of this study, when a route is operated by a ship that has not reported its CO_2 emissions, this route is assumed to be operated by an existing ship of the same type, similar capacity, and engine characteristics, for which such data exists. All available emission data are then added to a GIS database and incorporated into the respective main routes of the GCSN.

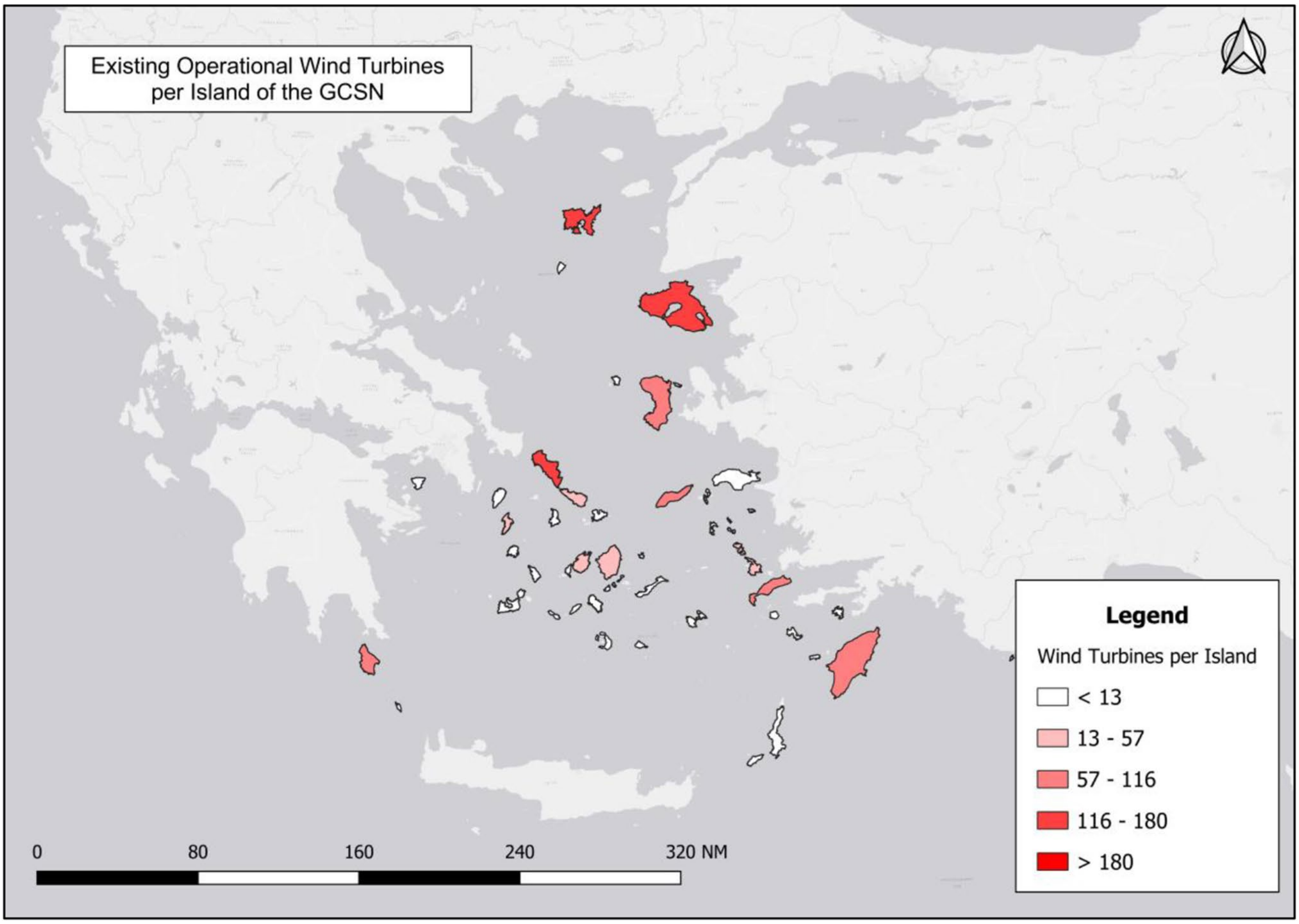


Fig. 6 Existing operational wind turbines per islands on the islands under study. Initial data accessed from the Greek Regulatory Authority for Energy (https://www.rae.gr/)

Application

The methodology is applied to the GCSN routes to and from islands belonging to two Aegean Sea insular groups: the first group is that of the Cyclades island chain and the second island group comprises some islands from both the Dodecanese and the Eastern Aegean island chains, as shown in Fig. 1. As the Aegean Sea is the focus of this study, these specific island groups (Cyclades and Dodecanese—Eastern Aegean) were selected due to the fact that they are separately treated in the GCSN. In total, 20 islands with 21 ports are selected from the first group and 12 islands with 15 ports from the second group, as shown in Table 1. Passenger flow data are derived from the Hellenic Statistical Authority (ELSTAT) (2022): for each island, passenger traffic (passengers embarking and disembarking) is presented on a yearly basis, from 2015 to 2019. For the purposes of the study, average traffic flow is the first variable of the bivariate local Moran's I model, with the second one being the number of ports in proximity that each port can service if it operates as a hub port. As mentioned, the distance used for the proximity analysis is 16.5 nautical miles, which is, as mentioned earlier, the maximum e-ferry operating range, reduced by 25%, considering operational safety. Even though data on passenger flow between islands is not available as it is proprietary, in this case, where the GCSN mainly connects the Aegean Islands to the mainland, demand for each island is considered sufficient for characterizing the importance of each island in the network. In addition, in this particular case, island grouping is straightforward due to the established practice in the GCSN (Cyclades and Eastern Aegean—Dodecanese). In other cases, a density-based clustering method such as DBSCAN (CITE) can be used as a first step to determine island groups. In this case, we applied DBSCAN with a search distance of 26.4 nautical miles and a minimum of 6 elements per cluster and obtained the same grouping; therefore, we omit this step herein.

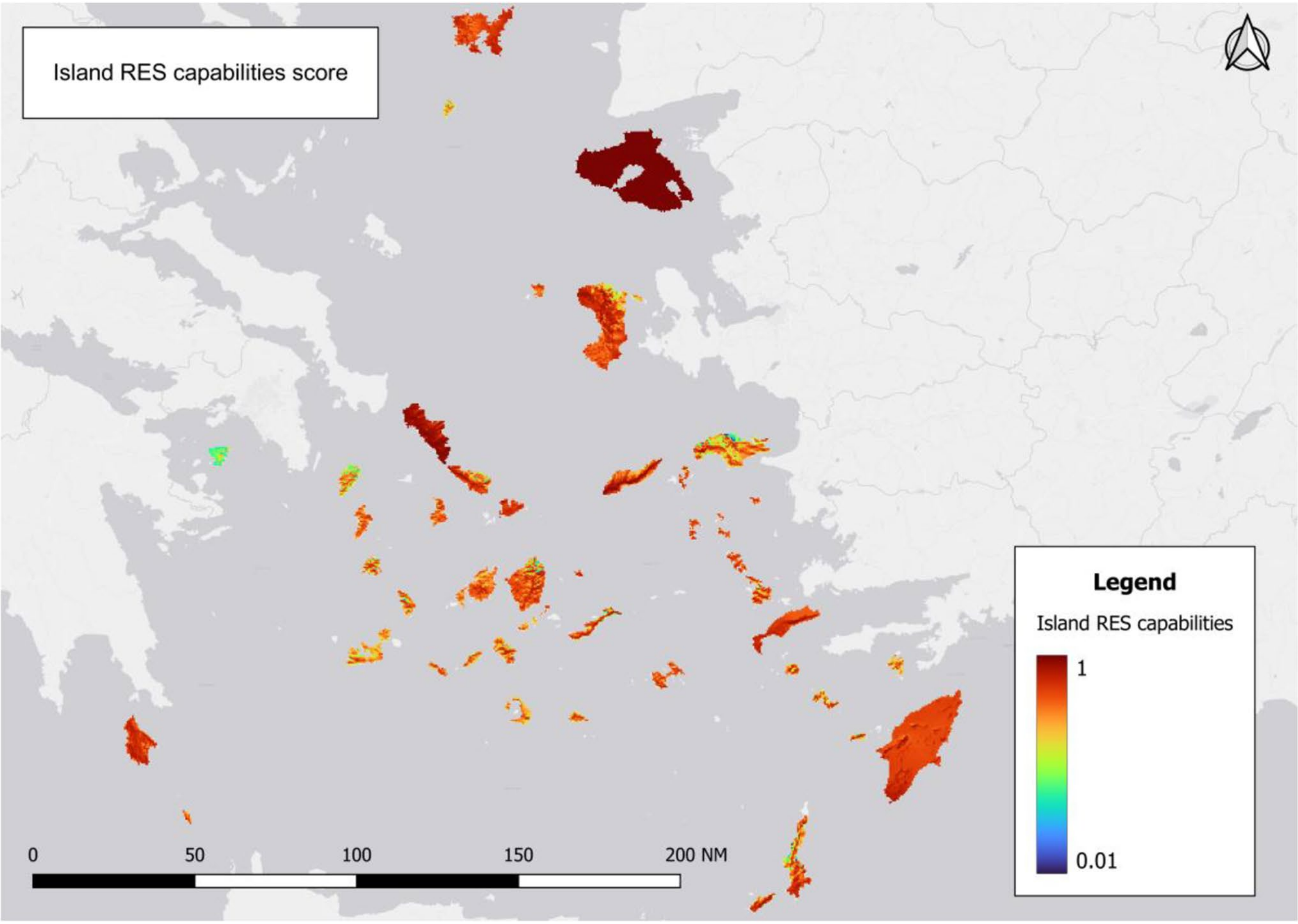


Fig. 7 Overall island potential for RES facilities, as a combination of existing infrastructure and available resources for future investments

Results and Discussion

Spatial analysis results are shown in Figs. 2 and 3. Figure 2 presents the results of the existing spatial autocorrelation of the examined ports with Bi-LISA outputs regarding statistically significant clusters, categorized into five distinct classes. Clustering results are based on the combination of the value pairs with respect to the normalized value of the variable (*z*-score) and the normalized value of the sum of the values of the neighbors weighted by the corresponding weights. These five categories are the following:

i) High-High: spatial entities with high values of both variables under study
ii) Low-Low: spatial entities with low values of both variables under study
iii) Low–High: spatial entities of low value for the first variable and high value for the second variable under study
iv) High-Low: spatial entities of high value for the first variable and low value for the second variable under study
v) Statistically non-significant areas

Taking into consideration the above categories, it becomes clear which categories present the optimal solutions for hub ports and for spoke ports. Cases denoted as High-High are considered the optimal candidates to operate as hub ports, as they show high passenger flows while also

Table 2 RES capabilities and existing RES infrastructure on islands under study

Region	Island	Potential RES capabilities score	Existing RES infrastructure (wind turbines)
Cyclades	Naxos	0.82	57
	Schoinousa	0.67	0
	Iraklia	0.72	0
	Koufonisia	0.84	0
Eastern Aegean-Dodecanese	Patmos	0.84	2
	Agathonisi	0.85	0
	Arki	0.81	0
	Leipsoi	0.81	1
	Leros	0.84	29

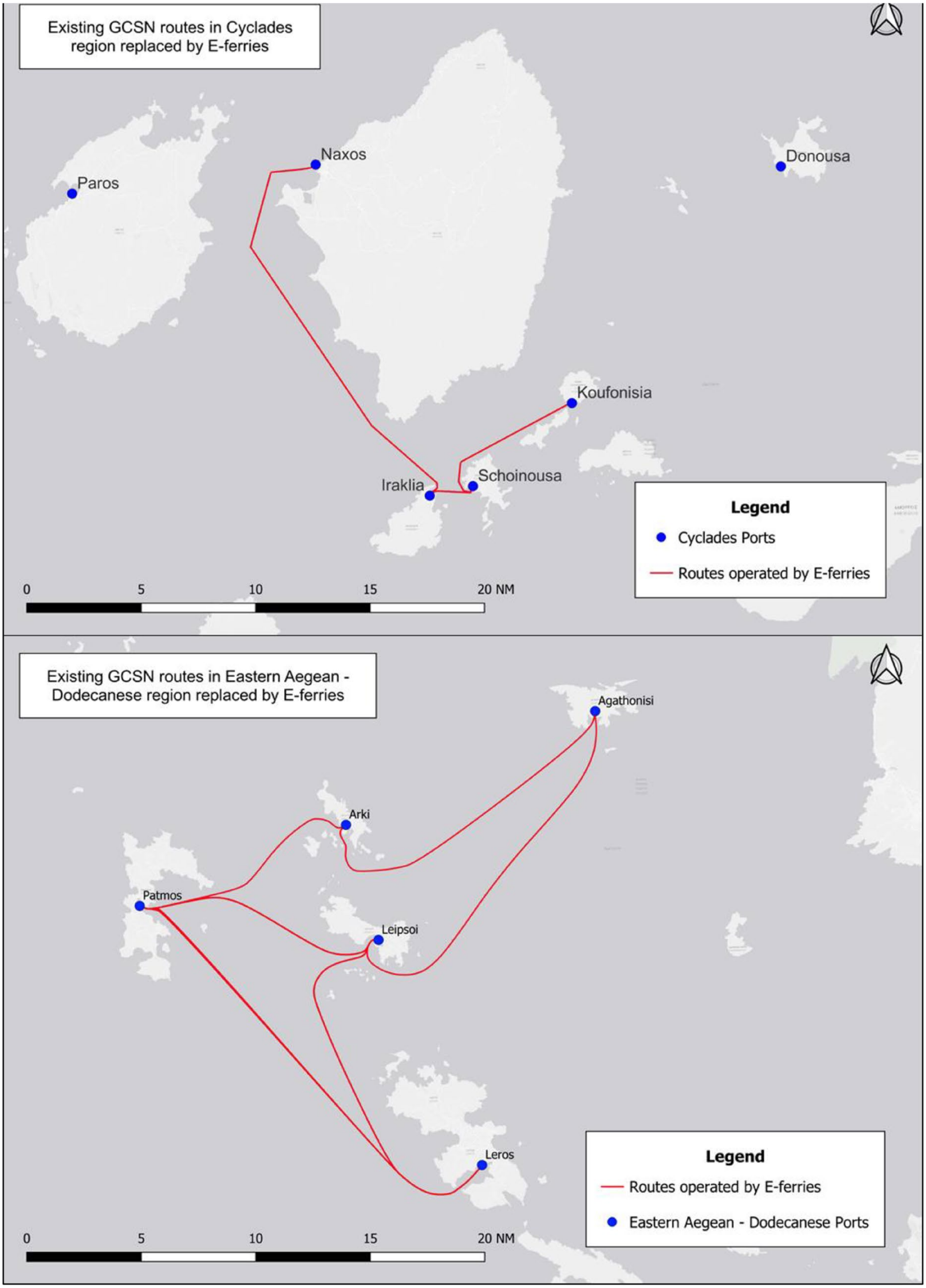


Fig. 8 Existing GCSN routes to be replaced by battery-powered zero-emissions ferries in regions under study

Table 3 Route part IDs and ship characteristics for each route replaced for Cyclades

ID	Route	Route code	Nautical miles	Operating vessel for calculations (2019)	Ship mean fuel consumption (kg/n.mile)
1	Naxos-Iraklia	D-62	19.36	AQUA JEWEL*	71.17
2	Schoinousa-Koufonisia	D-62	7.49	AQUA JEWEL*	71.17
3	Iraklia-Schoinousa	D-62	2.22	AQUA JEWEL*	71.17
4	Iraklia-Naxos	D-64	19.36	AQUA JEWEL*	71.17
5	Koufonisia-Schoinousa	D-64	7.49	AQUA JEWEL*	71.17
6	Iraklia-Schoinousa	D-64	2.22	AQUA JEWEL*	71.17
7	Schoinousa-Iraklia	D-17	2.22	BLUE STAR NAXOS	127.48
8	Naxos-Iraklia	D-17	19.36	BLUE STAR NAXOS	127.48
9	Schoinousa-Koufonisia	D-17	7.49	BLUE STAR NAXOS	127.48

Asterisks (*) indicate replacing ships for data availability in emissions calculations

showing a high number of spoke ports in proximity. In addition, such features show high clustering and positive spatial autocorrelation with neighboring islands regarding both variables, meaning that they can service as many passengers as possible while also being able to service nearby islands with the use of electric ferries. On the other hand, features shown as Low–High show low clustering of the value of the first variable, which in this case is passenger flow, but high values regarding the second value, which is the proximity to neighboring ports. As a result, while such ports are less popular regarding passenger flows, they are more spatially clustered, making them ideal candidates to operate as spoke ports of a zero-emission sub-network and, therefore, be serviced by electric ferries. To better understand why these two categories are highly important in this study, Moran's scatterplots are exploited. Figure 3 shows off-diagonal quadrants of Moran's scatterplots for the two insular groups.

Regarding the Cyclades group, Naxos exhibits positive spatial autocorrelation and is classified as a High-High entity, as it shows high yearly passenger traffic flows, as do the neighboring islands of Mykonos and Paros. However, the difference in this case is made by the second variable, which shows the number of ports in proximity of an electric ship's operating range, with Naxos being able to service up to 5 different islands with electric ferries. On the other hand, the island of Tinos has a fairly high demand, and its major advantage is the opportunity to serve the neighboring islands of Syros and Mykonos as it is located in the middle of the distance between them. Nevertheless, it is classified as a High-Low entity compared to its neighboring islands (Syros and Mykonos), as these islands can in turn only service Tinos, and all three islands can only service a maximum of two ports with the use of electric ferries. The opposite happens in the case of Koufonisia, Iraklia, and Schoinousa (Low–High entities), which all have a high number of ports they can service in between them, thus showing high spatial clustering, but moderate to low demand while also neighboring with ports of higher values of the examined variables, as is for instance the port of Naxos.

As for the Dodecanese and Eastern Aegean island group, Leros and Patmos are two islands ranked 3rd and 4th in terms of passenger flows among the other islands of the group studied. Due to their position and high centrality, they are identified as High-High entities. Islands of Low–High classification show demand that is more than 35 times less than Patmos, but even so, spatial proximity cannot be neglected,

Table 4 Fuel reduction and CO_2 emission reduction for each route part in the Cyclades

ID	Fuel consumption (kg per trip)	CO_2 emissions (kg per trip)	Trips in 3-month period (13 weeks)	Fuel reduction (tons/3 m)	CO_2 reduction (tons/3 m)
1	1377.64	4289.96	78	− 107.46	− 334.62
2	532.92	1659.52	78	− 41.57	− 129.44
3	157.93	491.78	78	− 12.32	− 38.36
4	1377.64	4289.96	78	− 107.46	− 334.62
5	532.92	1659.52	78	− 41.57	− 129.44
6	157.93	491.78	78	− 12.32	− 38.36
7	282.89	880.91	78	− 22.07	− 68.71
8	2467.69	7684.40	78	− 192.48	− 599.38
9	954.60	2972.61	78	− 74.46	− 231.86

Table 5 Route part IDs and ship characteristics for each route replaced for Eastern Aegean-Dodecanese

ID	Route	Route code	Nautical miles	Operating vessel for calculations (2019)	Ship mean fuel consumption (kg/n.mile)
1	Patmos-Leipsoi	D-1	11.59	BLUE STAR CHIOS	187.02
2	Arki-Agathonisi	D-76	15.489	CHAMPION JET2*	142.48
3	Leipsoi-Agathonisi	D-77	17.908	CHAMPION JET2*	142.48
4	Leipsoi-Leros	D-73	16.448	CHAMPION JET2*	142.48
5	Leipsoi-Patmos	D-73	11.59	CHAMPION JET2*	142.48
6	Leipsoi-Patmos	D-78	11.59	CHAMPION JET2*	142.48
7	Leros-Leipsoi	D-76	16.448	CHAMPION JET2*	142.48
8	Leros-Leipsoi	D-78	16.448	CHAMPION JET2*	142.48
9	Patmos-Arki	D-76	9.707	CHAMPION JET2*	142.48
10	Patmos-Leipsoi	D-72	11.59	CHAMPION JET2*	142.48
11	Patmos-Leipsoi	D-76	11.59	CHAMPION JET2*	142.48
12	Patmos-Leipsoi-Leros	D-20	28.038	BLUE STAR CHIOS	187.02
13	Patmos-Leros	D-33	21.011	BLUE STAR 2	258.37
14	Patmos-Leros	D-34	21.011	BLUE STAR 2	258.37
15	Patmos-Leros	D-8	21.011	BLUE STAR 2	258.37

Asterisks (*) indicate replacing ships for data availability in emissions calculations

with these islands showing positive spatial clustering. It is clear that the islands classified as High-High entities (i.e., Naxos, Leros, and Patmos) have the highest probability of eventually becoming hub ports from which zero-emission routes will originate. As a result, a new sub-network can be introduced in the Cyclades between the hub port of Naxos and the spoke ports of Antiparos, Iraklia, Koufonisia, Paros, and Schoinousa. As for the Dodecanese and Eastern Aegean group, sub-networks can be introduced between the hub port of Patmos and the spoke ports of Arki, Fournoi, and Leipsoi. The aforementioned sub-networks are shown in Fig. 2, with the analysis results of the study variables shown in Fig. 3.

An evaluation of Moran's scatterplots facilitates the selection of both hub ports and spoke ports. Those ports that can operate as hubs can ideally be found in the top right quadrant of the scatterplot, as this is the area where High-High features are located. The top right quadrant shows features that have high values of both variables and, as a result, shows ports that are located in ideal positions to reach as many other ports as possible while also showing high passenger flows. As a result, as the quadrant shows more popular ports with higher passenger demand, larger ships can service the island, transferring both passengers traveling to the hub port and those seeking transfer to nearby islands, thus affecting fewer passengers in terms of

Table 6 Fuel reduction and CO_2 emission reduction for each route part in the Eastern Aegean-Dodecanese

ID	Fuel consumption (kg per trip)	CO_2 emissions (kg per trip)	Trips in 3-month period (13 weeks)	Fuel reduction (tons/3 m)	CO_2 reduction (tons/3 m)
1	2167.56	6749.79	26	−56.36	−175.49
2	2206.80	6871.96	26	−57.38	−178.67
3	2551.44	7945.19	52	−132.67	−413.15
4	2343.43	7297.44	52	−121.86	−379.47
5	1651.29	5142.10	52	−85.87	−267.39
6	1651.29	5142.10	26	−42.93	−133.69
7	2343.43	7297.44	26	−60.93	−189.73
8	2343.43	7297.44	26	−60.93	−189.73
9	1383.00	4306.68	26	−35.96	−111.97
10	1651.29	5142.10	52	−85.87	−267.39
11	1651.29	5142.10	26	−42.93	−133.69
12	5243.67	16,328.78	26	−136.34	−424.55
13	5428.68	16,904.92	26	−141.15	−439.53
14	5428.68	16,904.92	26	−141.15	−439.53
15	5428.68	16,904.92	26	−141.15	−439.53

travel delays. With the selection of hub ports, the second task for the determination of a zero-emission sub-network is the identification of its spoke ports. Those can be located on the top left quadrant of the Moran's scatterplot, as this shows ports of low passenger demand but with high spatial clustering between them, which are ideal to be serviced by smaller electric ferries due to low demands in passenger traffic and smaller operational distances. Consequently, ports denoted as Low–High are considered the best ones to operate as spoke ports.

The above results show that in both island groups, a new zero-emission sub-network can be introduced. For the Cyclades group, a new sub-network can be introduced, with Naxos operating as a hub port and Koufonisia, Schoinousa, and Iraklia serviced by electric ferries as spoke ports. For the Dodecanese/Eastern Aegean group, Patmos is considered the best possible port to operate as a hub port, with Agathonisi, Arki, and Leipsoi operating as spoke ports serviced by electric ferries. In the case of the second group, while Leros can also operate as a single hub port or in conjunction with Patmos, if only one was chosen, it would be Patmos, as it shows higher passenger demand. Overall, spatial autocorrelation is found between two key variables that are essential for the design and operation of the GCSN. Ports chosen to operate as hubs must be located in strategic positions while also being able to service as many ports in close proximity as possible with electric ferries. As spatial relationships are evaluated, the above results are considered spatially optimal solutions.

An additional evaluation of the resulted ports and areas under electrification, considering their RES infrastructure and capabilities, is necessary to assess whether there is potential in supporting the zero-emission routes through renewable sources, thus leading to zero-emission islands and their respective connections. In order to assess the potential for RES facilities, mainly wind farms and photovoltaic parks, data from the World Bank Group's Global Wind Atlas and Global Solar Atlas were used, as shown in Figs. 4 and 5. Considering wind power density data, these are selected on a 150-m height, as there are several locations both in the Aegean Islands and uninhabited islets that meet such a criterion and could potentially be selected for future wind farm installations. For the assessment of existing infrastructure, RES open data were acquired from the Regulatory Authority for Energy, consisting of already operational and under construction wind turbines in islands. Considering photovoltaic parks, there are no reported state-owned existing or under construction parks in the Greek islands supporting the electric grid, except private ones for household needs. As a result, only existing operational wind turbines are shown in Fig. 6. For a better comparative analysis of the data under study, fuzzy membership functions were applied to wind data, solar data, and existing RES infrastructure, which in this case only consisted of existing wind turbines on islands. The fuzzy membership functions were applied so that all data would then be transformed into a 0–1 scale in order for their final combination to be an output raster after conducting a fuzzy overlay on all three raster datasets. More specifically, considering solar and wind data, which consisted of photovoltaic electricity output and wind power density, an MS large membership function was used, which calculates membership based on the mean and standard deviation of the input data, where large values have high membership, with a value of 1 for the mean multiplier and 2 for the standard deviation multiplier. However, in order to transform existing wind farm infrastructure data to a 0–1 scale, a linear membership function was used, as absolute values (existing wind turbines per island) were considered. In the case of a linear membership function, a membership value of 0 is assigned as the minimum value and a membership value of 1 as the maximum.

After evaluating all available data, it is clear that the existing RES infrastructure in the Aegean Islands is still limited. However, there is a lot of potential regarding renewable resources for future investments, especially in the case of wind farm installations overall, in the Aegean, and in the resulted areas, which could prove vital for the future establishment of zero-emission ferry networks and, consequently, zero-emission islands. After combining all available fuzzy membership scaled data, a final raster is generated through the use of a fuzzy overlay increasive function with an aggregate (sum) overlay type, thus considering, for the purposes of this study and in this case, that a combination of existing infrastructure and potential resource data is more important than each standalone dataset. The aggregate RES capability score for all islands under study is shown in Fig. 7, while the RES existing infrastructure and the overall potential RES capabilities score for the resulted islands are shown in Table 2.

After determining the potential electrification areas for ferry transport and their RES capabilities, it is also important to evaluate the overall environmental benefits of the proposed methodology. The methodological framework proposed results in certain areas of a given network to operate as zero-emission areas and, therefore, certain routes servicing islands of lower demand being fully operated by e-ferries. As a result, ships operating such routes from a certain hub to the aforementioned islands will, in turn, be replaced by battery-powered ferries, which will lead to operational emission nullification on the given routes. In order to better determine the environmental benefits of GHG emission mitigation through this method, reported maritime CO_2 emission data from the European Union Monitoring, Reporting, and Verification system or EU-MRV (European Maritime Safety Agency 2019) are utilized, with the mean operational fuel consumption of the ships operating in such routes used for the calculations of both fuel savings and CO_2

emission reduction. For the calculation of CO_2 emissions, the emission factor for HFO (heavy fuel oil) is used, as it is the most widely used type of fuel for commercial ships such as the ones operating in the Aegean. Regarding route frequencies, summer period data were collected for round trips, with the trips' frequencies consisting of 3rd quarter 3-month period data (July to September). The routes that can potentially be replaced by battery-powered ferries with zero emissions for the Cyclades and Eastern Aegean-Dodecanese regions are shown in Fig. 8. The results for the Cyclades region regarding ship characteristics operating the replaced routes, fuel, and CO_2 reductions are shown in Tables 3 and 4, while the results for the Eastern Aegean-Dodecanese region are shown in Tables 5 and 6. It is worth noting that in Tables 3 and 5, ships with an asterisk replaced the existing operating ones for the purposes of the study, as data were not available for the ones actually operating on the route under study due to them being less than 5000 GT and therefore having no obligation to report fuel consumption and CO_2 data to the EU-MRV system. More specifically, the ships used for the calculations were selected in such a way that their capacity capabilities (passengers and cars) and engine characteristics were roughly the same as the ones they replaced. In regard to the available data, "Aqua Jewel" replaced "Express Skopelitis" for the Cyclades routes, while "Champion Jet 2" replaced "Dodekanisos Express" and "Dodekanisos Pride" for the Eastern Aegean-Dodecanese routes. Between the two regions, the Eastern Aegean-Dodecanese region shows more promise, considering a 3-month period with more frequent routes, with 4183.52 metric tons of CO_2 mitigated and 1343.46 metric tons of fuel reduced. A much smaller reduction is shown in the Cyclades region, with only 611.69 metric tons of fuel reduced and an additional 1904.79 metric tons of CO_2 mitigated, although this is expected as the proposed routes to be replaced are fewer and the ports operating in the proposed system are in a more compact region, considering distances between ports.

Considering the above results, there are clear benefits to be gained from the shift to battery-powered zero-emission ferries where this is feasible. While the methodology applied provided promising results, it is still important for future studies to include more variables in the framework. For instance, the operation of newer types of ships and the restructuring of the network will require extensive analyses of the optimal weather routing of such ships to limit power loss while also considering environmental factors. In addition, port infrastructure should also be considered a distinct variable for the evaluation of potential hub ports for the GCSN. Last, although potential areas for the introduction of sub-networks with electric ferries and hubs were determined, it is highly important for future studies to consider optimal routing for such sub-networks while also assessing the effects on passenger travel times.

Conclusions

The GCSN is a complex network with many parameters to be considered for its restructuring and improvement. The objective of this study is to present a framework for the evaluation of different ports in insular groups by determining which could potentially operate as hubs for the introduction of zero-emission sub-networks. Due to the complexity of the GCSN and the accessibility issues of many islands, the proposed methodology aims to facilitate the decision support process regarding the restructuring of the network and the overall reduction of its emissions. As a spatially significant problem was addressed in relation to environmental aspects, the use of the multivariate LISA model showed promising results about the potential of the GCSN toward its electrification and, therefore, emission mitigation. An additional evaluation of the renewable energy sources (RES) existing infrastructure and potential capabilities on the islands is conducted to assess whether the resulted areas could benefit from RES facilities for their energy needs, relative to the available resources of the areas under study. The proposed methodology shows that high-accuracy results can be provided by considering spatial and non-spatial characteristics of spatially complex networks and aims to provide an easily adaptable framework for its implementation in other cases with different parameters. The results showed promise both in the implementation of zero-emission networks by introducing battery-powered ferries servicing the resulted routes, with more than one port found as a possible hub, and in addition to the RES capabilities of the resulted areas. In conclusion, optimal routing between the resulted hub and spoke ports is also of great importance and therefore an area where future studies for coastal shipping electrification should focus while considering the spatial characteristics of complex networks.

Author Contribution All authors contributed to the study conception and design. Material preparation and data collection was performed by Georgios Kagkelis. All authors contributed to the analysis and interpretation of results. The first draft of the manuscript was written by Orfeas Karountzos, and all authors commented on the previous versions of the manuscript. All authors read and approved the final manuscript.

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Data Availability The initial datasets used for the emissions analyses of the current study are available in the EMSA\THETIS-MRV repository, https://mrv.emsa.europa.eu/#public/emission-report.

Results generated through the analyses of the current study, by utilizing the above openly available data, are available from the corresponding author on reasonable request.

Declarations

Ethical Approval All authors certify that no ethical approval was required for the subject matter or materials discussed in this manuscript. All authors certify that the research subject of this manuscript does not raise any ethical concerns.

Informed Consent All authors certify that no informed consent was required for the subject matter or materials discussed in this manuscript.

Competing Interests The authors declare no competing interests.

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