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SITING ASSESSMENT OF AN OFFSHORE WIND FARM AND EXPLOITATION OF WIND ENERGY IN THE NORTHERN AEGEAN

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«ΔΙΕΡΕΥΝΗΣΗ ΧΩΡΟΘΕΤΗΣΗΣ ΥΠΕΡΑΚΤΙΟΥ ΑΙΟΛΙΚΟΥ ΠΑΡΚΟΥ ΚΑΙ ΑΞΙΟΠΟΙΗΣΗ ΑΙΟΛΙΚΗΣ ΕΝΕΡΓΕΙΑΣ ΤΟΥ ΒΟΡΕΙΟΥ ΑΙΓΑΙΟΥ»

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Το περιεχόμενο της ανά χείρας διπλωματικής εργασίας αποτελεί προϊόν της πνευματικής προσπάθειας του συγγραφέα. Ερωτήματα που αφορούν τη χρήση της εργασίας για κερδοσκοπικό σκοπό πρέπει να απευθύνονται προς τον συγγραφέα. Η δημοσίευση σε αυτή υλικού τρίτων, δημοσιευμένου ή μη γίνεται με δόκιμη αναφορά στις πηγές, που δεν επιτρέπει ασάφειες ή παρερμηνείες. Οι απόψεις και τα συμπεράσματα που περιέχονται σε αυτό το έγγραφο εκφράζουν τον συγγραφέα και δεν πρέπει να ερμηνευθεί ότι αντιπροσωπεύουν τις επίσημές θέσεις του επιβλέποντος, της εξεταστικής επιτροπής ή του Εθνικού Μετσόβιου Πολυτεχνείου.

Αθήνα, Ιούλιος 2024

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Athens, July 2024

Ευχαριστίες

Με την ολοκλήρωση της διπλωματικής μου εργασίας, κλείνει και το μεγάλο κεφάλαιο της φοίτησής μου στο Εθνικό Μετσόβιο Πολυτεχνείο. Αυτό το ταξίδι περιείχε χαρές, λύπες, επιτυχίες και αποτυχίες, όπως είναι φυσικό. Αποχωρώντας από τη Σχολή των Πολιτικών Μηχανικών, νιώθω έτοιμος να αντιμετωπίσω τις προκλήσεις του επαγγελματικού στίβου. Για αυτή την αυτοπεποίθηση θα ήθελα να ευχαριστήσω όλο το διδακτικό και ερευνητικό προσωπικό της Σχολής. Με πάθος και αφοσίωση προσπάθησαν να μεταδώσουν σε εμάς, τους φοιτητές τους, όχι μόνο τις γνώσεις τους αλλά και τις ανησυχίες τους.

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Abstract

A goal of zero greenhouse gas emissions has been set for 2050 and the European Union requires its member states to reduce greenhouse gas emissions by 55% by 2030. In addition to using all available renewable energy sources to meet these targets, all EU members want to ensure that their citizens live in a sustainable environment. Furthermore, since the beginning of the Russo-Ukrainian War in February 2022, Europe has come to the realization that its reliance on natural gas and fossil fuels for the production of electricity is unnecessarily high. This provides all nations with even more motivation to become independent of traditional energy production techniques.

The growth of the offshore wind farm industry is one of the main goals of the European Union. By 2030, EU aims to have at least 60 GW of offshore wind and by 2050, 300 GW. Greece is ideally suited to achieve this goal. Greece's large marine area and abundant wind resources provide the perfect environment for the growth of offshore wind farms. Also, as the installation of onshore wind farms is creating more and more opposition among locals and society as a whole, offshore wind farms are a permanent solution to this problem. Simultaneously, the best way to maximize the utilization of Greece's wind resources is thought to be through the deployment of floating wind turbines, which work best at depths exceeding 50 to 100 m.

The approach for determining the best location for an offshore wind farm that will meet Alexandroupolis' needs is presented in this thesis. This approach fully conforms to the renewable energy sources' legislative framework in Greece. The best locations for installing the offshore wind farm are chosen using the Geographic Information System. The synthetic wind speed time series for the following 25 years is then computed using stochastic methods. The energy generated over the project's lifetime is computed using the power curve of the chosen wind turbine model and the synthetic time series. Then, based on the energy consumption of the municipality of Alexandroupolis for the past 5 years, and in combination with the population growth of the municipality, the energy demands for each year of the project life are projected. Finally, the exact location of the offshore wind farm and the number of wind turbines is decided and the energy production and coverage indicators are presented.

Περίληψη

Για το 2050 έχει τεθεί ο στόχος μηδενικών εκπομπών αερίων του θερμοκηπίου και η Ευρωπαϊκή Ένωση απαιτεί από τα κράτη μέλη της να μειώσουν τις εκπομπές αερίων του θερμοκηπίου κατά 55% έως το 2030. Εκτός από τη χρήση όλων των διαθέσιμων ανανεώσιμων πηγών ενέργειας για την επίτευξη αυτών των στόχων, όλα τα μέλη της ΕΕ θέλουν να διασφαλίσουν ότι οι πολίτες τους ζουν σε ένα βιώσιμο περιβάλλον. Επιπλέον, μετά την έναρξη του Ρωσο-Ουκρανικού πολέμου τον Φεβρουάριο του 2022, η Ευρώπη συνειδητοποίησε ότι η εξάρτησή της από το φυσικό αέριο και τα ορυκτά καύσιμα για την παραγωγή ηλεκτρικής ενέργειας είναι επικίνδυνα υψηλή. Αυτό έδωσε σε όλα τα έθνη ακόμη περισσότερα κίνητρα για να ανεξαρτητοποιηθούν από τις παραδοσιακές μεθόδους παραγωγής ηλεκτρικής ενέργειας.

Η ανάπτυξη της βιομηχανίας υπεράκτιων αιολικών πάρκων αποτελεί έναν από τους κύριους στόχους της Ευρωπαϊκής Ένωσης. Μέχρι το 2030, η ΕΕ στοχεύει να διαθέτει τουλάχιστον 60 GW υπεράκτιων αιολικών πάρκων και μέχρι το 2050, 300 GW. Η Ελλάδα είναι ιδανική για την επίτευξη αυτού του στόχου. Η μεγάλη θαλάσσια έκταση της Ελλάδας και το άφθονο αιολικό δυναμικό της, παρέχουν το τέλειο περιβάλλον για την ανάπτυξη υπεράκτιων αιολικών πάρκων. Επίσης, καθώς η εγκατάσταση χερσαίων αιολικών πάρκων δημιουργεί όλο και περισσότερες κοινωνικές και περιβαλλοντικές αντιδράσεις, τα υπεράκτια αιολικά πάρκα αποτελούν ιδανική λύση στο πρόβλημα αυτό. Ταυτόχρονα, ο καλύτερος τρόπος για τη μεγιστοποίηση της αξιοποίησης των αιολικών πόρων της Ελλάδας θεωρείται η εγκατάσταση πλωτών ανεμογεννητριών, οι οποίες λειτουργούν καλύτερα σε βάθη που ξεπερνούν τα 50 έως 100 μέτρα.

Στην παρούσα διπλωματική παρουσιάζεται η προσέγγιση για τον προσδιορισμό της βέλτιστης θέσης για ένα υπεράκτιο αιολικό πάρκο που θα καλύψει τις ανάγκες της Αλεξανδρούπολης. Η προσέγγιση αυτή συμμορφώνεται πλήρως με το νομοθετικό πλαίσιο για τις ανανεώσιμες πηγές ενέργειας στην Ελλάδα. Οι καλύτερες θέσεις για την εγκατάσταση του υπεράκτιου αιολικού πάρκου επιλέγονται με τη χρήση του Γεωγραφικού Συστήματος Πληροφοριών. Η συνθετική χρονοσειρά ταχύτητας ανέμου, για τα επόμενα 25 έτη, υπολογίζεται με τη χρήση στοχαστικών μεθόδων. Η ενέργεια που παράγεται κατά τη διάρκεια ζωής του έργου υπολογίζεται χρησιμοποιώντας την καμπύλη ισχύος του επιλεγμένου μοντέλου ανεμογεννήτριας και τη συνθετική χρονοσειρά. Στη συνέχεια, με βάση την ενεργειακή κατανάλωση του δήμου Αλεξανδρούπολης για τα τελευταία 5 χρόνια και σε συνδυασμό με την αύξηση του πληθυσμού του δήμου, προβάλλονται οι ενεργειακές ανάγκες για κάθε έτος της διάρκειας ζωής του έργου. Τέλος, αποφασίζεται η ακριβής θέση του υπεράκτιου αιολικού πάρκου και ο αριθμός των ανεμογεννητριών και παρουσιάζονται οι δείκτες παραγωγής ενέργειας και κάλυψης.

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1. Introduction

1.1. Research objectives

The goal of the current study is to provide a methodological framework for the placement of maritime wind farms by identifying regions in Greek territorial and international waterways that are ideal for the installation of floating wind farms and generally offshore wind farms (OWF). In terms of excluding certain sectors, the hierarchy of possibilities is based on isobaric criteria rather than criteria with varying importance. This approach aids in decision-making by considering several options and assessing various factors. Since the goals of multi-criteria decision-making methods (MCDM) are frequently at odds, the solution must be an agreement that heavily weighs the decision-maker's preferences (Pohekar, Ramachandran, 2004).

Following the process of identifying and choosing the best location, and deciding the number of wind turbines, an analysis of the floating wind farm's potential to supply the island of Alexandroupolis with energy is conducted. Assessing the OWF's efficiency and dependability is the objective of the thesis.

Figure 1. Offshore Wind Turbine (Source: Wind Europe)

1.2. Thesis outline

Chapter 2 of the thesis offers a comprehensive analysis of the significant advancements in the wind energy industry, focusing on offshore projects and the prevailing circumstances in Greece. This chapter examines the various categories of offshore wind turbine bearings and explores the primary advantages and drawbacks associated with offshore projects.

An overview of the current legal system, the principles defining the limitations on wind farm development, and the requirements for installing renewable energy sources at sea are provided in Chapter 3.

In Chapter 4, a detailed process for generating the overall exclusion map is carried out. Based on the specific siting criteria, the minimum distances, as derived from the General Spatial Planning Framework for Greece, and the depth of the wind turbine placement.

The approach used to simulate the operation of the proposed installed floating OWF, which is based on supplying Alexandroupolis with energy, is presented in detail in Chapter 5 of the thesis. First, an analysis is done on the research area's features about energy statistics. Subsequently, it delves deeper into wind statistics, population fluctuations throughout the project, and an approximation of OWF's energy output.

In chapter 6, the exact location of the offshore wind farm and the exact number of wind turbines are selected. Based on the energy they produce, the coverage rates of energy demand and the total amounts of energy produced are presented and analyzed.

In the 7th and last chapter of the thesis, the general and specific conclusions are drawn from the above-mentioned chapters for the two parts of the thesis, the main conclusions, and the general and specific conclusions for the two parts of the thesis. At the same time, the thesis concludes with suggestions for future research on the installation and operation of floating thermal power plants in Greece.

2. Overview of Offshore Wind Farm Plants

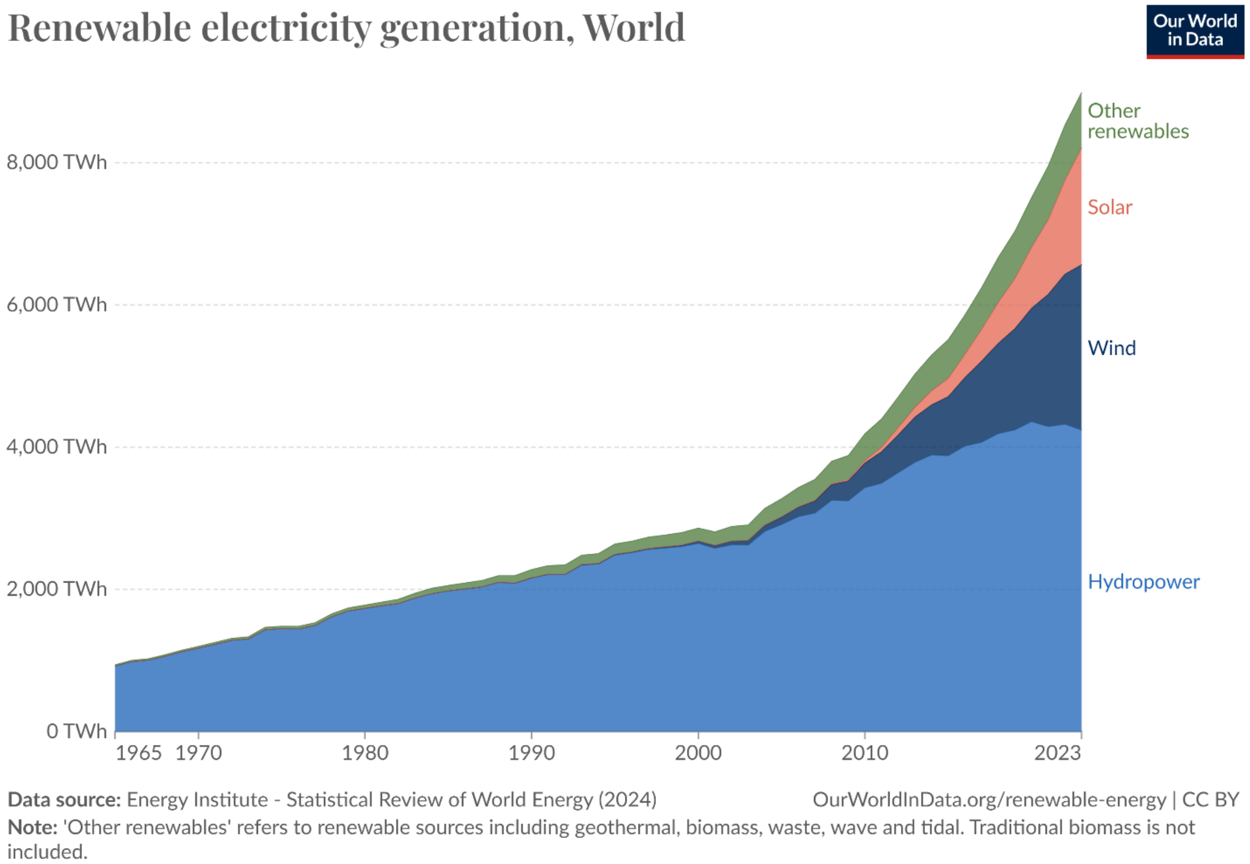
2.1. Renewable Energy Sources

Energy sources are classified into two distinct types. In conventional and renewable energy sources (RES). Conventional energy sources, such as fossil fuels, are depleted over time. Renewable sources, on the other hand, are derived from natural sources that are almost unlimited due to their quicker production rate compared to consumption. RES include solar, hydroelectric, wind, geothermal, ocean, and biomass energy. Crucially, they do not need any further processing (such as mining, pumping, or combustion). Moreover, these energy sources are sustainable and ecologically benign, since they do not release dangerous compounds or pollutants (Tsarnas, 2016).

The need for continuous energy consumption will grow more and more. Consequently, the hazards that lead to the destruction of the environment and the exacerbation of climate change would be significantly amplified. Electricity consumption is forecasted to see a significant rise of 50% by the year 2060 (Deshmukh et al., 2023). In February 2022, the European Commission introduced "REPowerEU: Joint European action for more affordable, secure, and sustainable energy" as a reaction to Russia's invasion of Ukraine (Lonergan, 2022). That means Europe must expedite the phase-out of fossil fuels. Including the above, the need is imperative for Europe's transition to renewable energy sources.

Even now, with the RES market having seen significant technological advancements, the cost of RES electricity remains higher than that of conventional methods (Bull, S. 2001). On the other hand, capital investment in renewable energy sources follows to the concepts of economies of scale, meaning that average costs diminish as production volume increases. Put another way, the cost of energy produced from renewable sources will decrease with increased production (Galanou, 2012).

Figure 2 shows a graphical evolution of electricity generation through RES over the last 7 decades. Figure 2 illustrates that, up until the mid-1980s, hydropower projects accounted for the entire global share of renewable energy in electricity generation. Early in the 1990s, wind energy was fiirst used to generate electricity; starting in 2009, there was a noticeable increase in its use.



Data source: Energy Institute - Statistical Review of World Energy (2024) OurWorldInData.org/renewable-energy | CC BY

Note: 'Other renewables' refers to renewable sources including geothermal, biomass, waste, wave and tidal. Traditional biomass is not included.

Figure 2. Renewable Energy Generation via RES. (Source: ourworldindata.org)

Greece, following the global trend, has invested in RES over the last 3 decades. In 2008, the contribution of RES in the country's energy mix (excluding large hydroelectric plants) was 4,3% (Bravakou, 2011). In 2023, Greece produced the largest share of electricity from RES, covering 57% of the country's energy mix, increasing this share by 7 percentage points compared to last year (ipto.gr).

Figure 3 shows the share of RES in electricity production in Greece. Here, it has been observed that there has been a significant increase in the participation of wind energy in electricity generation since 2008, but the rise is not constant and shows fluctuations.

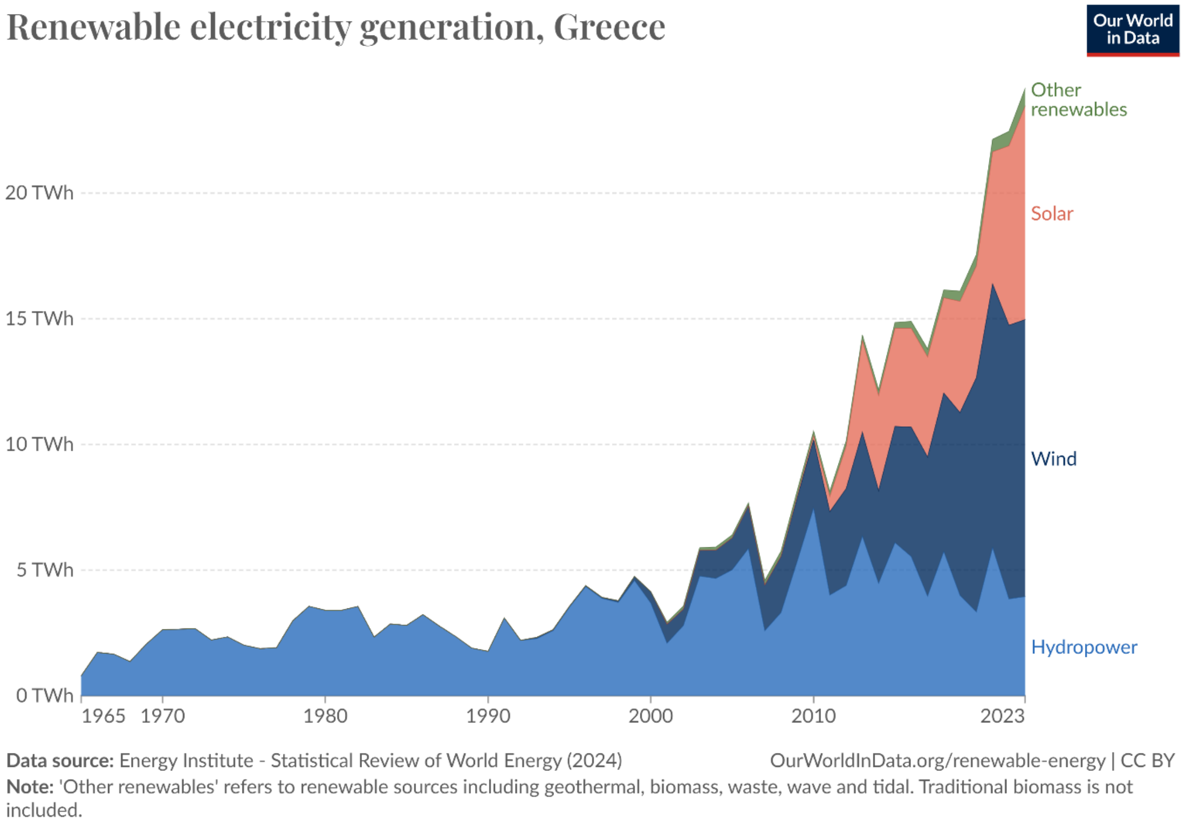


Figure 3. Renewable Energy Generation via RES in Greece. (Source: ourworldindata.org)

2.2. Wind energy

The current state of the weather can be described by a number of variables in the science of meteorology. Temperature, humidity, wind speed, and precipitation are the primary meteorological variables used in short-term local meteorological forecasting (Theodoropoulos, 2013). These pressures are created by the heating of the earth by the sun (Herbert et al., 2007).

Wind is defined as the synoptic motion of air masses with potential and kinetic energy (Sahin, 2004). They occur of pressure differences converting potential energy into kinetic energy. Although the wind is a three-dimensional vector, the phrase is nearly primarily used to refer to the horizontal wind since the vertical component of the wind is significantly smaller than the horizontal wind. Therefore, because horizontal winds cover larger areas, they are beneficial for wind engineering applications.

Since wind is a vector quantity, it is necessary to know both its direction and its magnitude, or wind speed. According to meteorology, a wind's specified direction is the direction from whence it originates; for example, the north wind originates in the north. To quantify wind speed, Admiral Beaufort created a numerical scale with values ranging from 0 (tame) to 12 (hurricane). This scale has the tremendous benefit of allowing an experienced observer to determine wind speed without the need for equipment.

Wind power is harnessed for a minimum of 3000 years. Wind energy was originally employed for ship sailing on the Nile River 5000 BC. Simultaneously, windmills were used in China to mechanically extract water. The first documented evidence of wind turbines dates back to the time of Alexander the Great, when a basic horizontal axis wind turbine design was described. Evidence suggests that the Persians used vertical-axis wind turbines as early as 700 BC. Windmills are brought to the western world at the beginning of the 12th century by Islamic culture (Sahin, 2004).

Initially, traditional windmills were used for mechanical propulsion, with over 100,000 windmills found in northern Europe. The era concluded with the invention of the steam engine, facilitated by the abundant supply of wood and coal. From 1890 to 1930, the widespread availability of electricity prompted the exploration of windmills as an alternative means of producing power.

Following the 1973 oil crisis, renewable energy sources began to emerge as a priority, leading to a notable increase in interest in wind energy. Due to thorough research conducted on this subject, wind energy has lately been used in many businesses, therefore emerging as a competitive alternative to other energy sources.

Today, the main system for converting wind energy into electricity is wind turbines. Wind turbines harness the kinetic energy of wind and turn it into mechanical energy, which is then transformed into electrical energy via a generator. The international trend towards wind farms is not only necessary but also advantageous, as countries benefit both environmentally and economically. More specifically (Maradin, 2021):

1. Environmental protection (reduced greenhouse gas emissions)
2. Reduced fossil fuel consumption
3. Reduced energy import dependence
4. Stimulating the development of innovation and the economy
5. Increasing employment
6. Rural development
7. Reduction of energy scarcity (expansion of rural electrification capacities)

The wind conditions, also known as the wind potential of a location (Fotiou, 2011), are the most essential aspect in determining whether or not an investment in a wind farm would be regarded economically plausible. This is where the most significant drawback of wind energy comes into play, and that is the stochasticity and unpredictability of the phenomenon's fluctuation. (Giannaka, 2010) It is thus difficult to utilize generator sets alone for an integrated power generating system since the distribution network of the energy grid is susceptible to issues of instability in the power distribution system. These problems dictate that it is impossible to use generator sets exclusively. According to the latest WWEA report, it is estimated that the global installed capacity of wind farms at the end of 2023 will reach 1046 GW worldwide. China is the country that generates the most electricity from wind power with an estimated 450 GW of wind plants, followed by the US and Germany with 152 GW and 69 GW respectively (WWEA Report, 2024).

Table 1 presents the leading countries in wind power energy per year. The leading country in installed wind power is China, followed by the United States of America.

Greece ranks 21st in terms of installed wind power worldwide with an increase of 11,2% compared to 2022.

Table 1. Total installed wind power capacity per country, worldwide. (Source: WWEA Report, 2024)

Rank	Country	2023	Growth 2022/2023(%)	2022	2021	2020
1	China	470.630	19,0	395.630	346.670	290.750
2	United States	150.455	4,4	144.053	135.177	121.510
3	Germany	69.475	4,9	66.242	63.924	62.708
4	India	44.736	7,5	41.600	39.800	38.625
5	Spain	30.748	2,0	30.159	28.143	27.294
6	United Kingdom	30.215	5,0	28.763	25.748	24.458
7	Brazil	28.580	20,8	23.661	21.567	18.010
8	France	23.474	12,2	20.915	19.084	17.949
9	Canada	16.986	11,7	15.212	14.206	13.627
10	Sweden	16.251	13,8	14.278	12.173	10.068
11	Italy	12.012	8,9	11.647	11.322	9.305
12	Turkey	11.697	3,1	11.405	9.126	7.296
13	Australia	11.482	2,6	10.540	11.100	9.305
14	Netherlands	11.015	34,1	8.215	6.570	5.953
15	Poland	9.383	18,0	7.950	7.846	6.784
16	Mexico	8.310	13,6	7.312	7.262	6.789
17	Denmark	7.107	2,30	6.949	6.181	6.102
18	Finland	6.946	22,4	5.677	3.256	2.586
19	Portugal	5.804	1,3	5.730	5.612	5.502
20	Belgium	5.315	5,2	5.041	4.883	4.670
21	Greece	5.226	11,6	4.683	5.105	3.866
22	Japan	5.214	10,3	4.727	4.574	4.372
23	Norway	5.130	0,5	5.105	4.452	4.113
24	Vietnam	4.910	23,8	3.966	4.332	4.323
25	Chile	4.800	4,1	4.527	3.444	2.829
26	Ireland	4.713	26,0	3.810	3.291	3.120
27	Austria	3.885	8,8	2.572	3.291	2.818
28	Argentina	3.705	12,0	3.309	3.444	513
29	South Africa	3.560	0,0	3.560	3.256	2.495
30	Romania	3.077	0,0	3.077	3.029	3.029
	Rest of the World	31.939	8,6	29.402	26.445	21.790
	Total	1.046.780	12,5	929.717	844.313	742.559

2.3. Wind energy in Greece

The first wind farm in Greece was established in Kythnos in 1982 (Hatziargiriou et al, 2020) with a total capacity of 100 KW and a total number of 5 wind turbines. The wind farm of Kythnos was the beginning of efforts to exploit wind energy in Greece to produce electricity. In the mid-1990s, however, the development of wind energy received a significant boost when private investment was made easier. Numerous wind farms have been erected since then in locations including in Crete in 1992 with 17 wind turbines and total installed capacity of 5,1 MW (Bastakis, 2016), and Evoia in 1993 with total installed capacity of 5 MW (Keroulis, 2014).

Unfortunately, there are many issues preventing wind energy from developing in Greece. Even while installed capacity has increased significantly in recent years, it is widely acknowledged that this rise pales in comparison to Greece's abundant wind potential. It is very difficult to fully utilize this potential since the Aegean islands, which have the most efficient winds of up to 9 m/s on average are not connected to the system.

The wind potential in the Greek water regions is displayed in Figure 4. The areas with the greatest wind potential are east and west of Crete, in the area of the Cyclades and finally northeast of Lesvos as well. In these places, average wind speeds can reach 10–11 m/s and higher.

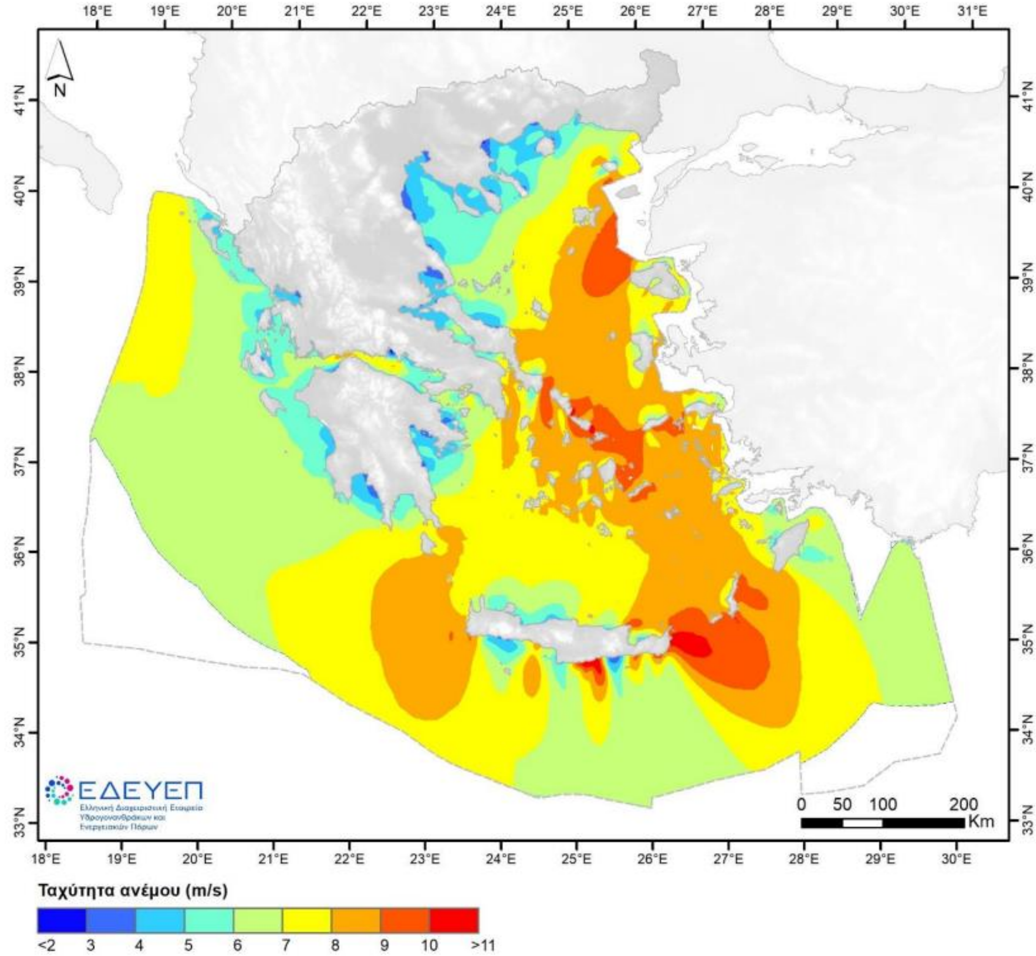


Figure 4. Spatial distribution of wind speed (Source: HEREMA)

Greece is a nation blessed with a long coastline and an enormous number of islands. The development of wind energy in Greece is aided and particularly valued by the high winds that are mostly found on the island and in coastal regions. According to estimates, Greece's entire power demands may be met by 13,6% of its exploitable wind potential (Krystalidis, 2022). Wind energy development initiatives have started nationwide, even though this potential is still mostly unrealized. This is partly because of the European Union's RES policy, which promotes and subsidizes these soft energy projects. Internally, the laws on renewable energy sources (3486/06) and development (3299/04) provide particularly potent incentives, especially for small-scale wind energy projects.

Greece's installed capacity growth from 1999 to the present is depicted in a diagram in Figure 5. Installed wind power increased significantly starting in 2019 as a result of new EU regulations. Figure 6 shows the wind power generated per regional unit. In the first half of 2023, the annual statistics of the Hellenic Statistical Society of Greece and the Wind Energy Association show that wind power in Greece reached 4.935 MW. In terms of geographical distribution of installed capacity, the leader is Central Greece with 2.110 MW, followed by the Peloponnese with 639 MW.

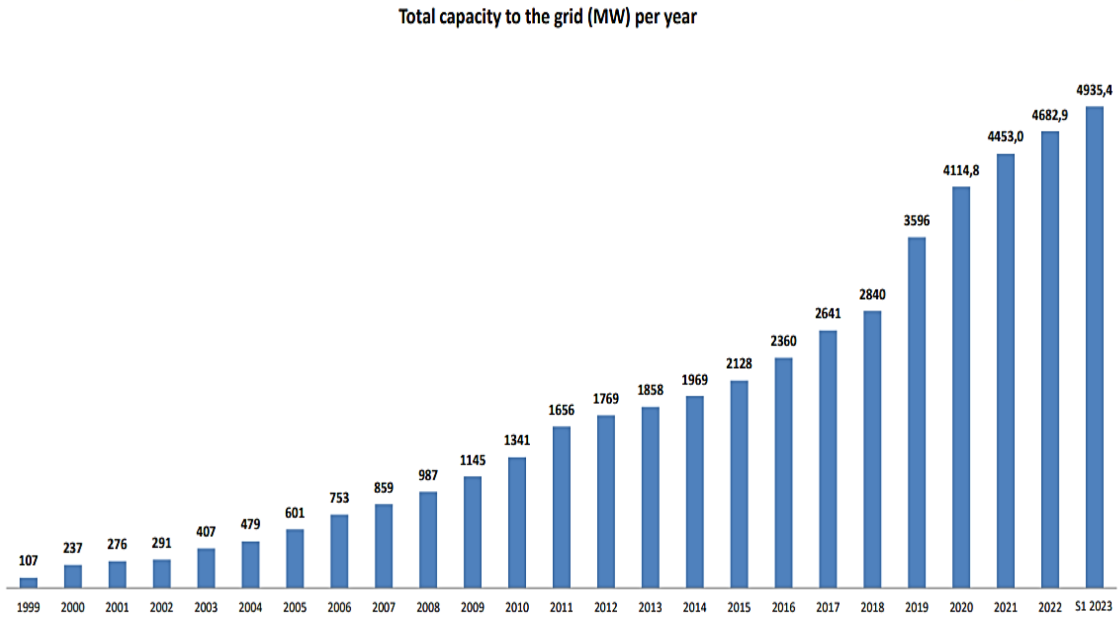


Figure 5. Annual installed capacity in Greece. (Source: HWEA Wind Energy Statistics, 2023)

Figure 6. Installed wind power per region, in Greece. (Source: inzeb.org)

2.4. Offshore Wind Farms

Offshore wind turbines and onshore wind turbines have a similar construction. Most commercial offshore wind turbines are three-bladed, horizontal-axis devices that are powered upwind by torque-generating blades attached to the hub, an integral element of the nacelle, and other above-sea components. The generator, gearbox (if any), and main shaft are all housed in the nacelle. The tower has an outside deck that allows operators to access both the tower and the nacelle. Power cords flow down from the nacelle through the tower to the supporting structure (Asim et al., 2022).

The global installed capacity of offshore wind power has increased by 14% and 17% respectively over the past two years. On the contrary, although there is a growing increase in the percentages of the nominal installed power for onshore wind farms, they are lower than those of offshore wind energy with rates of 12% and 8% for the year 2022 and 2021 respectively. This demonstrates the global trend for a shift in the energy industry towards offshore wind energy (International Renewable Energy Agency, 2024).

Figure 7 shows a floating wind turbine and the parts it consists of. Figure 8 shows the mechanism of the wind turbine located inside the nacelle, and also shows the mechanism for converting wind energy into electricity.

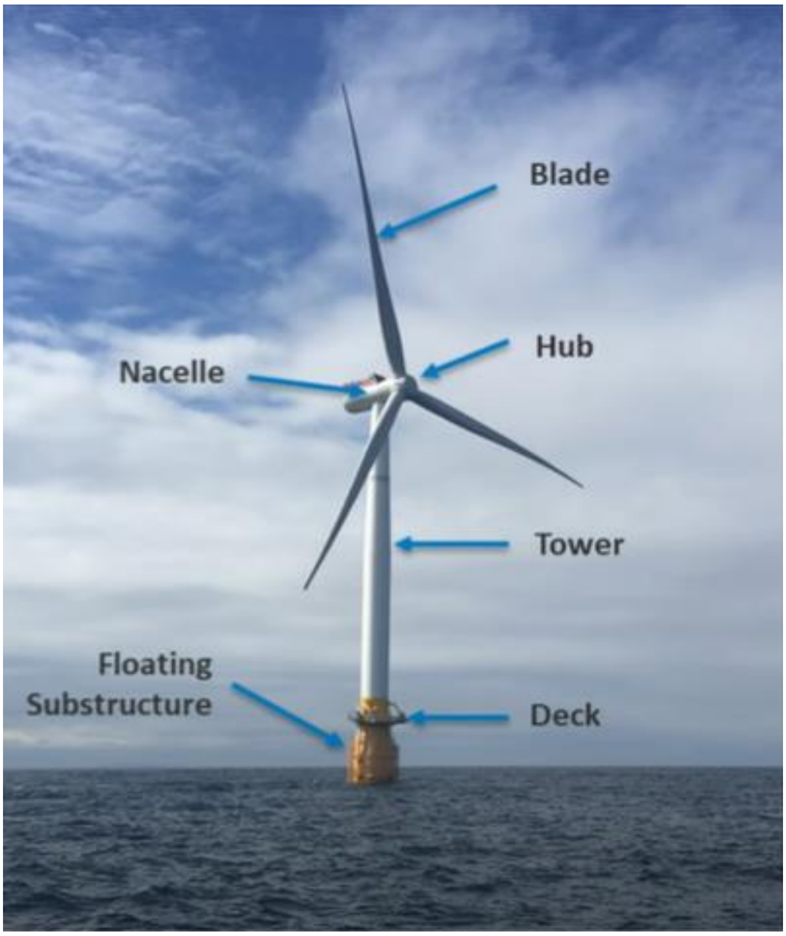


Figure 7. Offshore Wind Turbine. (Source: Asim, et al, 2022)

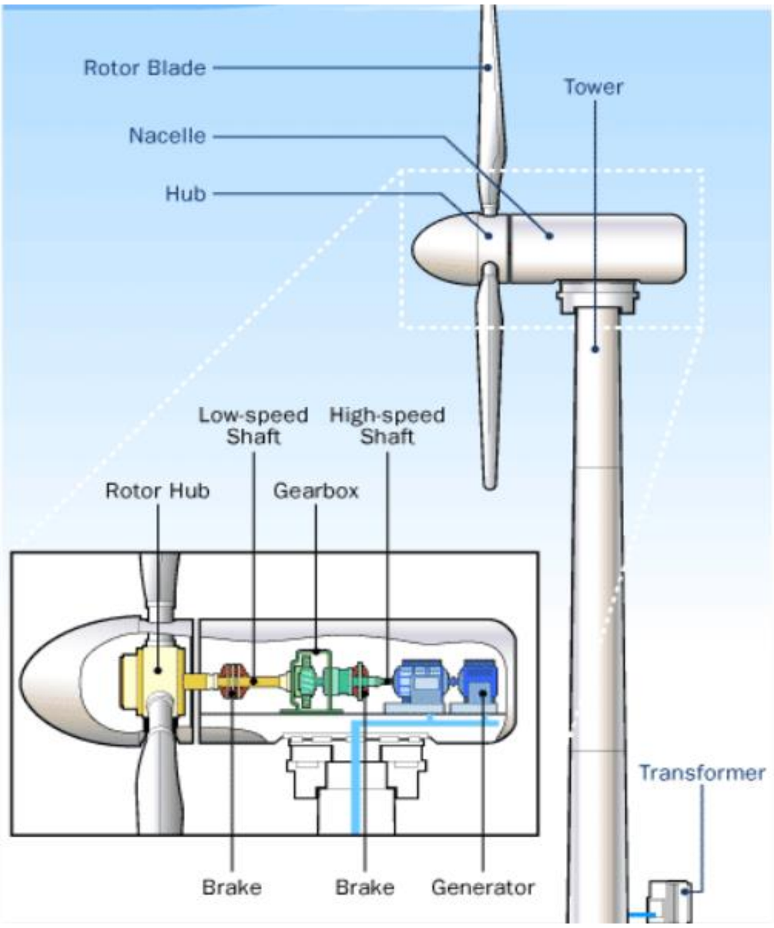


Figure 8. Nacelle's Interior of a wind turbine. (Source: long-intl.com)

2022 had the second-highest number of offshore wind installations in history with 8,8 GW of new offshore wind being fed into the grid, which is 58% less than the record-breaking year of 2021 (Deng et al., 2024). With the 8,8 GW of new installations, the overall capacity of offshore wind power worldwide has reached 64,3 GW, indicating a 16% year-on-year increase and accounting for 7% of all offshore wind installations worldwide, over 380 GW of offshore wind capacity, across 32 markets, is predicted to be added in the next ten years (2023-2032). Nearly 41% of that growth is expected to come from Europe (Global Wind Energy Council, 2023).

By the end of 2021, Europe installed 28 GW of cumulative installed offshore wind power, mostly generated via fixed-acting OWF. The majority of the total offshore energy production, which amounts to 27,5 GW out of 28 GW, is generated by well-established offshore facilities, both fixed and floating, located in the following countries: a) United Kingdom (12,5 GW), b) Netherlands (3 GW), c) Denmark (2,3 GW), d) Germany (7,8 GW), and e) Belgium (2,3 GW) (Global Wind Energy Council, 2023).

In Greece, no wind power plant has been installed in marine space so far. The OWF location is explicitly mentioned in the revised National Energy and Climate Plan (NECP). The draft of the new NECP states that goals of 1,9 to 2,5 GW of offshore wind power (including pilot offshoring wind projects) by 2030 and 17,3 GW by 2050 are anticipated, which will also be in line with the announcements made by the European

Commission on Blue Development and Blue Energy for renewable energy production with an OWF facility (NECP, 2019).

The National Development Program of Overseas Parks which was presented in October 2023, and hosted by Hellenic Hydrocarbons and Energy Resources Management Company (HEREMA). The plan has already been submitted to the Ministry of Energy and Environment's Directorate of Spatial Planning, and it favors a tank of options from ten areas for development by 2030–2032, with a total capacity of roughly 4,9 GW, primarily involving floating land projects. The above areas do not include the marine area between Evros and Samothrace, which is defined as a pilot project development area. More specifically, the eligible areas are:

- In eastern Crete (Agios Nikolaos), where it is estimated that projects with a total capacity of 800 MW will be developed.
- In southern Rhodes, with a maximum installed power ranges between 300 MW and 550 MW.
- In the central Aegean (Donoussa, Giaros), with a maximum installed power between 200 MW and 450 MW.
- On the axis of Evia (Holy Apostles) - Chios, with a maximum installed power of 300 MW.
- In the Ionian Sea, with a maximum installed power of 450 MW.

2.4.1 Fixed Substructure

How offshore wind turbines are physically supported is the primary distinction between onshore and offshore wind turbines. Offshore wind turbines may be classified into two main categories: fixed-support and floating. Floating offshore wind turbines have floating support structures that are attached to the seabed by mooring cables, and fixed-support offshore wind turbines have foundations that are fixed to the seabed. There are six primary categories of offshore wind turbine foundations, as shown in the Figure 9 (Oh et al., 2018).

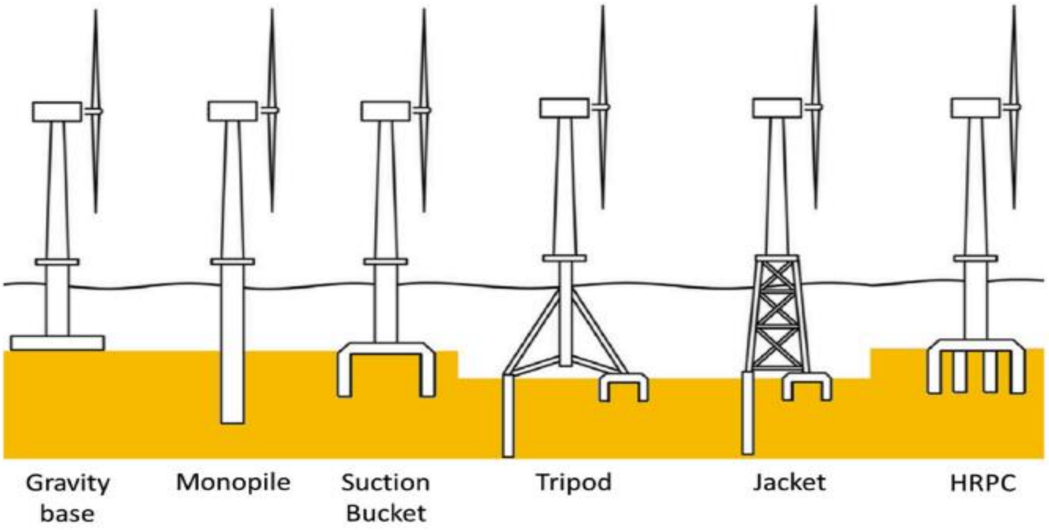


Figure 9. Offshore wind turbines foundation. (Source: Oh et al, 2018)

Gravity Based foundation was the first installed type for OWF. This foundation was very popular in Denmark in 90's, and has two main features. The inexpensive materials (steel and concrete) required for its construction and the swallow waters that can be settled. The deepest wind farm with this type of foundation is at 12- 27 m in Belgium (Kim et al., 2024). Monopile foundation is the type of offshore wind farm foundations that is most used. Due to how simple and inexpensive the installation is. Swallow to medium depth water is the ideal depth conditions (Ma et al., 2024). A suction bucket looks like an inverted large-diameter bucket with a closed top and an open bottom. Although the range at foundation depths is from shallow waters up to more than 35 m depth, this type of foundation is not very common (Zhang et al., 2024). Stability is a major benefit of a Tripod foundation. Compared to other fixed foundations for offshore wind farms, they are perfect for deeper depths and extreme weather conditions. This indicates the expensive and difficult construction. The water depths for this construction are 25 to 50 m (Lozano-Minguez et al., 2011). In terms of foundation depth, jacket-based foundations are better than fixed foundations. Its foundation depth spans a wide range of 30 to 80 m. Its disadvantage is the complexity of construction, but it is also distinguished by the stability of the structure, much like the tripod foundation (Wang et al., 2018). High rise pile caps foundations are frequently used to prevent underwater construction and satisfy the superstructures' bearing capacity and settling requirements (Zou et al., 2010). Also, high rise pile caps are very environmentally friendly but has many drawbacks in extreme wave conditions (Chen et al., 2016).

Fixed support offshore wind turbines may only be erected at maximum seabed depths of 60 meters, which is its main limitation. Fixed-support structures lose their economic viability in deep seas (>60 m), meaning that the installation costs rise significantly. The most common types of offshore wind turbines are ground based. However, there are several serious problems with this technique. The main problem is that over 80% of offshore wind energy is found offshore, or in deep seas (seabed depth of >60 m), far from land. The largest installed rotor diameter of a fixed-support wind turbine is 80 meters, and its rated output is 1,8 megawatts. This is another constraining aspect of these wind turbines. These kinds of offshore wind turbines have a visually striking effect (Asim et al., 2022). Table 2 shows, for each type of fixed foundation offshore wind farm, the average foundation depth, average cost, and total number of turbines per continent.

2.4.2. Floating Substructure

Onshore projects make up the majority of the wind energy market. While offshore wind energy is still in its infancy with only 73 GW of installed wind power, onshore wind energy reached 945 GW in 2023 (International Renewable Energy Agency, 2023). However, the bottom-fixed varieties are not suitable for places with deep waters, because of the installation restriction of water depths. Floating offshore wind turbines (FOWTs) may be a useful tool for tapping into the amazing wind resources found in waters deeper than 35 m. This is because the wind is more consistent and has a faster speed, resulting in less turbulence and better power production efficiency. In contrast to fixed offshore wind turbines, FOWTs rely on floating foundations, which come in several types, including spar, semi-submersible, barge, and TLP types, as seen below (Ha et al., 2021).

A semi-submersible platform attached to the seafloor by vertical tendons is known as a Tension Leg Platform (TLP). TLPs can be utilized in water up to 2.000 m deep (Gomes, 2014). High stability and ease of construction are characteristics of this kind of floating bearing; however, high stresses at the mooring and anchorage points lead to higher and faster failures (Tsakiri, 2022). Semi-submersible foundation is ideal for depths between 50-300 m. One of the main advantages of this type of foundation is the exploitation of the wave cancellation event. the "wave cancellation effect" occurs when wave forces acting on submerged objects in different phases cancel each other out as a result of a phase shift (Liu et al., 2016). The Spar foundation is a vertical cylinder of large diameter with deep immersion, which makes the structure less sensitive to wind, waves and sea currents. It is perfect for adverse conditions because of its deep immersion (Du, 2021).

Figure 10 shows the different types of floating bearings.

Table 2 Characteristics and Global distribution of offshore wind foundations. (Source: Díaz, Soares, 2020)

Foundation	Water depth (m)	Cost (M€)	N of turbines	Percentage of wind farms by foundation (%)			
				Worldwide	Europe	Asia	America
Monopile	19	2,3	3854	63	70	43	0
Gravity-base	8,3	0,9	329	12	14	7	0
Figh rise pile cap	5,7	1,2	337	12	1	40	0
Jacket	25,8	4,1	220	7	7	7	100
Tripod	37,4	5	212	4	5	0	0
Suction bucket	7,5	1,4	55	1	0	0	0
Others	7,1	0,5	18	3	2	3	0

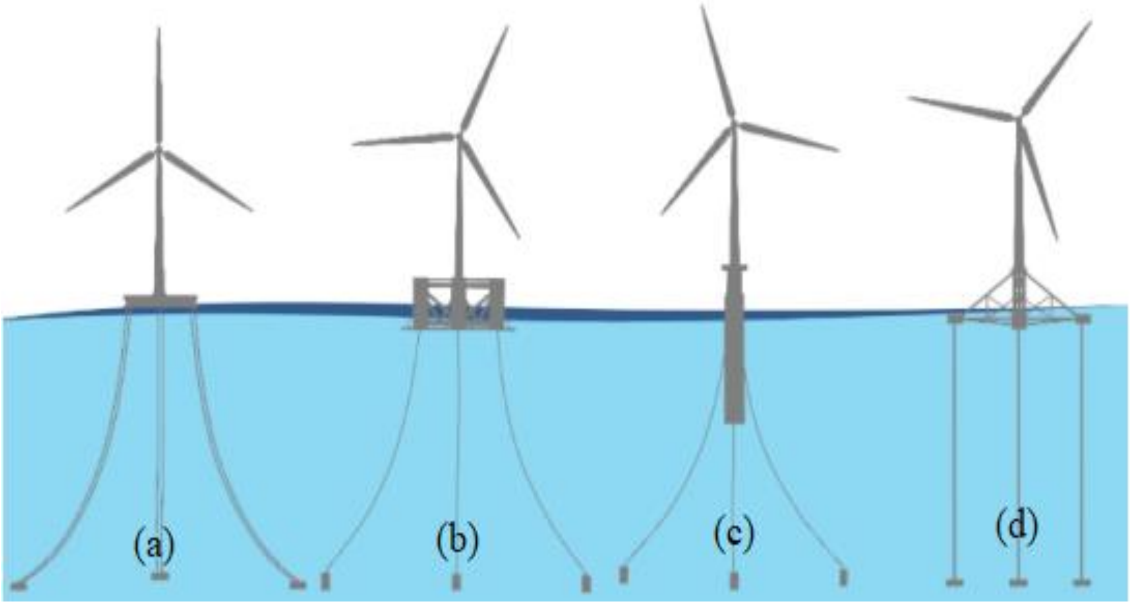


Figure 10. (a) Barge, (b) semi-submersible, (c) spar, (d) tension leg platform (TLP). (Source: Ha et al., 2021)

2.4.3 Advantages of Offshore Wind Farms

Offshore wind energy offers several benefits in comparison to onshore wind farms, particularly with wind capacity. Offshore regions see greater average wind speeds and lesser variability in wind power compared to onshore wind power. Consequently, the turbines of the air conditioners experience stress, resulting in less wear and tear. Simultaneously, an escalation in wind velocity results in a rise in the efficiency of the offshore wind farm, increasing it from 25% to 40% (Tsakiri, 2022).

The visual and auditory impact is often reduced compared to onshore environments. People's physical and mental health may be negatively impacted by wind turbine noise in a number of ways, including anxiety, headaches (Pedersen, 2011), sleep disorders, and even hearing loss (Punch et al, 2010). There are two types of visual annoyance. influence on the field and visual impact (Kaldellis et al., 2016). The impact on the field is a variable that can be calculated. In contrast, aesthetic impact is a subjective and more complex variable to analyze. The ideal distance for a wind turbine and wind turbine to coexist peacefully is between 300 and 400 m (Kaldellis et al., 2012).

It is possible to deploy wind turbines of a larger size. The rationale for permitting the installation of bigger wind turbines at sea is the relatively diminished significance of noise generation compared to land-based locations. Also, larger turbines allow for greater exploitation of the wind potential while not affecting visual disturbance due to the distance from land (Byrne, Houlsby, 2003).

The speed of offshore wind often rises as you go further away from the coast, increasing energy production because it is directly proportional to the cube of the wind speed (Lynn, 2011). Fewer wind turbines are required to meet energy needs as a result of increased annual energy production.

Insufficient availability of appropriate land for wind farms: This issue is particularly prominent in heavily populated regions or nations with relatively flat terrains. The scarcity arises from the need to allocate the land for various reasons, with agriculture being the most prevalent (Karaisas, 2019).

2.4.4. Disadvantages of Offshore Wind Farms

Indeed, the market for offshore wind energy is expanding significantly due to rising demand for renewable energy sources and advancements in technology. But even with its potential, the industry has a number of drawbacks and difficulties that will need to be resolved as it develops.

The offshore environment is characterized by a higher degree of uncertainty and difficulty compared to onshore, resulting in increased costs and risks. The offshore environment necessitates the transportation of staff to and from offshore turbines, resulting in escalated expenses for equipment, time, and insurance because of heightened dangers. Offshore work is subject to heightened risks of storms, which may impact the duration of maintenance and installation activities. Consequently, these factors have a direct impact on both capital and operational expenses.

Offshore circumstances are destructive to electrical and structural equipment, necessitating the marinization of turbines with cathodic and humidity protection (Snyder, Kaiser, 2009). So, the increased expenses associated with the development and maintenance of offshore wind generating facilities located far from the shoreline counterbalance the advantages of greater energy generation. Offshore wind turbines are now around 50% pricier than onshore installations, although it is anticipated that their prices will decrease by up to 35% by 2025 (Tsakiri, 2022).

Marine creatures and birds have negative consequences. Marine mammals and fish face the highest level of danger during the building period. Specifically, the act of driving piles and the transportation of equipment and workers using heavy boats are the primary factors responsible for generating loud sounds and negatively impacting many creatures (Richardson et al., 1995).

While the wind farm is in operation, the primary concerns revolve around the impact on migrating populations of birds and seabirds in the vicinity, in addition to the ongoing effects on marine animals and fish, mostly caused by the noise generated by the wind farm. The impact of birds colliding with the wings of the offshore wind farm (OWF) and subsequently dying will have consequences for the migratory populations in the vicinity as well as the wetlands in the surrounding region. Furthermore, when in operation, the wires responsible for transporting the generated power will also release electromagnetic fields. This might impact the locomotion and orientation of species that are responsive to electro- or magnetic fields (Bailey et al., 2014).

2.4.5. Strategies for addressing the aforementioned issues

Offshore wind farms represent a significant advancement in the quest for sustainable and renewable energy sources. For the renewable energy market to fully exploit the potential of offshore wind farms, ways must be found to address the disadvantages of offshore construction. Firstly, it is needed to specify the scope of influence Identifying the specific region in which biological impacts may occur to gather first data. Assessing the connection between important groups of people and potential locations for wind energy projects.

Then, determine the magnitude and importance of population-level effects. The need is to establish the specific groups of organisms, determine which groups are present inside the wind energy site and the surrounding region that may be affected, and assess their current condition. The need for demographic data and information on vital rates to establish a connection between individual reactions and the repercussions at the population level (Bailey et al., 2014). Research to verify and confirm the assumptions and parameters used in the modeling process. Licensing - the utilization of the sea: the procedure and allocation among various entities is crucial. The significance of the procedure and distribution of responsibility, risk, and expense in the licensing of OWFs. Lastly, gain insights from many sectors to enhance risk evaluations and evaluate the efficacy of mitigation strategies, such as offshore oil platforms.

3. Legislative Framework

3.1. Historical background and current state

The Public Power Corporation, often known as PPC, had a monopoly in power production until 1994, when Law 2244/1994 let individuals to participate in the industry. Law 2773, enacted in 1999, granted RES power plants precedence in selling their excess energy compared to PPC, which relied on more traditional sources of electricity generation. Additionally, led to the establishment of the Regulatory Authority of Energy (RAE), an independent and autonomous administrative authority, which was under the supervision of the Ministry of Development. The primary duty was overseeing the electrical system, ensuring its proper functioning, advocating for fair competition, and providing guidance on the issuance of licenses for generation and supply in various market sectors (Mpailas, 2008). RAE underwent a name change and is now known as the Regulatory Authority for Energy, Waste, and Water (RAEWW), as mandated by Law 5037/2023.

Law 3468/2006 promotes the production of electricity from RES and high efficiency combined heat and electric power plants. This legislation, inspired by the German approach, implemented a "feed-in tariff" strategy wherein it set predetermined (elevated) rates for the sale of renewable energy (Papakonstantinou, 2012). According to the above law, issuing a production license includes an environmental licensing procedure, which concerns the approval of environmental conditions (Koutsopoulos, 2002; Nakou, 2007).

Another legislation about renewable energy is Law 3851 of 2010, titled "Accelerating the Development of RES to address climate change". The national objective is to have 20% of total domestic energy consumption derived from renewable energy sources by 2020. It harmonizes with Directive 2009/28/EC (EUR-Lex, 140/2009) and replaces Law 3468/2006 (Gkogkidis, 2018). This law made it much easier to license solar and wind energy projects (Roussos, 2023).

According to Government Gazette 4893/B/2019, "Ratification of the National Plan for Energy and Climate," the government revised the target for the participation of RES in gross final energy consumption by 2030 from the 31% to at least 35% by 2030 (Kapsalis, 2023), while it should be noted that currently, the share of RES in gross energy consumption is 18% (Venizelos, 2023). In the electricity generation sector, renewables will be the main source of domestic electricity generation, with a share of over 65% by 2030 and 60% in gross final consumption (Koutsoukanidou, 2023). In addition, the aim was to lift the energy isolation of the islands and interconnect them with the mainland system. For those islands that are not interconnected or will be interconnected in the next phase, the aim is to operate hybrid renewable energy systems for the benefit of consumers. Ultimately, another target is the complete withdrawal of lignite from the domestic power generation system by 2028 (National Energy and Climate Plan, 2019).

Figure 11 shows the Renewable Energy share in gross energy consumption (left), and renewable energy share in gross electricity consumption (right).

Figure 12 is displaying the amounts of electricity production by fuel type or renewable energy source for the last 7 years.

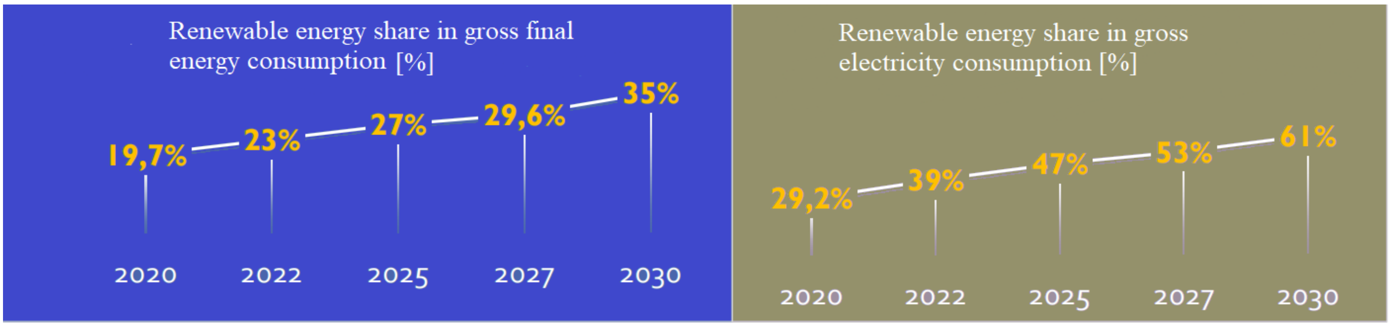


Figure 11 Evolution of renewable energy share by target and sector for the year 2030. (Source: Government Gazette 4893/B/2019)

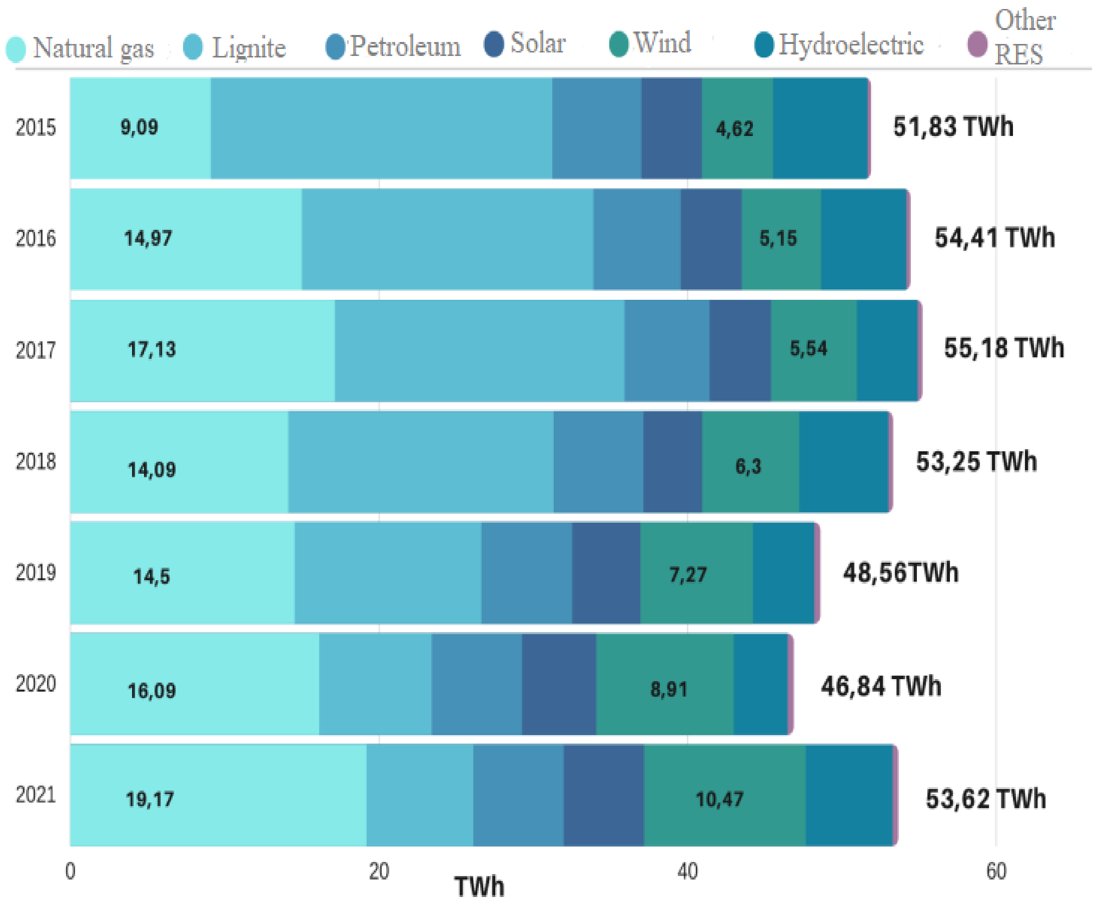


Figure 12 Electricity production share by type of fuel/ sources in Greece. (Source: Herema)

Law 4964/2022 and Chapter H, develops the "Framework Development of Offshore Wind Farms". According to Article 65 of the above-mentioned law, an offshore wind farm is defined as an array of wind turbines located in the maritime area, whether they are fixed to the seabed or floating on the seabed, connected to the seabed by mobile means. Through the Hellenic Hydrocarbon and Energy Resources Management

Company the Greek State has the exclusive competence to determine the Areas of Organized Development of Offshore Wind Farms and the areas for the installation of wind farms.

Article 174 of the same law defines an area suitable for the development of wind farms as the maritime area extending south of the coastline of Evros' regional unit and north-northeast of Samothrace, with the total authorized capacity for area is 600 MW. For the pilot implementation of this project, the above-mentioned article sets the minimum distance between wind turbines of the same type as the one in question at 4D, where D is the largest diameter of the neighboring wind turbines. Consequently, the distance between wind turbines of the same project from the boundaries of the relevant OWF installation site shall not be less than 3,5 D. It follows from paragraph 3 of the same article that the maximum power estimated to be capable of being installed in an area of an organized OWF development may not be less than 200 MW.

3.2. Special framework for spatial planning and sustainable development for RES

Following Community Directive 2001/77/EC, Laws 3299/2004 and 3468/2006, the recently adopted "Special Framework for Spatial Planning and Sustainable Development for Renewable Energy Sources" (Government Gazette 2464/B/2008) aims to develop policies for the placement of renewable energy projects. The above-mentioned GG describes in Article 4 the following objectives;

1. To identify appropriate places, based on wind potential data, that can accommodate wind projects and provide economies of scale in the necessary networks, taking into account their geographical and environmental qualities.
2. The development of guidelines and standards for determining suitable locations and requirements that will enable the construction of wind energy facilities that are environmentally friendly and seamlessly blend into both natural and man-made surroundings.
3. Establishing an effective approach to determine the optimal locations for wind farms, ensuring the highest level of alignment with national and European regulations.

3.2.1. Spatial planning of wind farms

Since wind energy had a lot of potential to supply energy, laws that regulate the locations of wind farms had to be put in place. Article 5 of the Government Gazette 2464/B/2008, for the siting of wind farms, environmental characteristics, distinguishes between the following.

a. On the mainland, including the mainland, including Evia.
b. In Attica, which is a special category because of its metropolitan character.
c. The inhabited islands of the Ionian and Aegean Sea, including Crete.
d. Offshore maritime space and uninhabited islands, which include our study area.

In order to ensure the protection of people, the environment and social and cultural activities, certain exclusion zones are required. Article 6 discusses the need to prohibit the building of wind farms inside certain areas;

1. Of the declared preserved monuments of the world's cultural heritage and other monuments of major importance as well as the designated archaeological protection zones A that have been defined under the provisions of Article 91 of Law No. 1892/1991 or established in accordance with the provisions of Law No. 3028/2002.
2. The areas of absolute protection of nature and nature protection determined in accordance with the provisions of Articles 19 and 1650/1986.
3. The boundaries of Wetlands of International Importance (Ramsar wetlands).
4. the cores of national parks and declared national parks and aesthetic forests which are the core of the not included in the areas of the case (b) of this Article.
5. The priority habitats of locations within the State that have been designated as sites of community value in the NATURA 2000 network, as determined by the decision 2006/613/EC.
6. Of projects included by city plans and settlement borders of towns before 1923, or regions with a population of fewer than 2,000.
7. Of Areas of Integrated Tourism Development of Article 29 of Law no. 2545/1997, the Areas of Organized Development of Productive Activities of the tertiary sector under Article 10 of the v. 2742/1999, theme parks and tourist ports.
8. The atypically shaped, within the framework of the non-planned construction, tourist and residential areas. As atypically formed tourist and residential areas for the purposes of this Convention are those areas that include at least 5 built properties with use of a tourist or residential property, each are located at less than 100 m and total capacity of 150 beds or more. For the calculation of capacity, each built property with residential use is considered equivalent to 4 beds regardless of area. The above areas will be recognized within the Preliminary Environmental Assessment and Evaluation.
9. The bathing beaches included in the water quality monitoring program are coordinated by the Ministry of Environment, Spatial Planning, and Urban Development.
10. Parts of quarry areas and mining and extraction zones that are in operation.
11. Other areas or zones are currently subject to a special land use regime, based on which they do not allow the siting of wind farms for as long as they are in force.

3.2.2. Distancing criteria of wind farms

In order to have clarity on the distances of wind farms from points of interest and to avoid conflicts of interest, a detailed and separate presentation of the distances was required. Determining and establishing the precise distance requirements for offshore wind farm installations in relation to various sensitive and significant areas requires a methodical approach. The Government Gazette (G.G.) 2464/B/03.12.2008 defines the minimum distances from human activities, land usage, Special Protection Areas, and Areas of Conservation.

Tables 3 and 4 show the minimum distances from points of environmental interest and cultural heritage respectively.

Table 3. Distances from areas of environmental interest. (Source: G.G. 2464/B/2008)

INCOMPATIBLE USE	**MINIMUM INSTALLATION DISTANCE FROM THE INCOMPATIBLE USE**
Areas of absolute protection of Nature of Article 19 Paragraph 1 of Law 1650/86 (A΄160)	According to the approved Special Environmental Study or the relevant presidential decree (Article 21 of Law No. 1650/86) or the relevant Joint Ministerial Decision (Law 3044/02)
Cores of the National Parks, declared natural monuments, and aesthetic forests not included in the previous paragraph. Priority habitats of areas of the territory included in the list of sites of community importance of the NATURA 2000 network according to Commission Decision 2006/613/EC	Judged on a case-by-case basis within the eco-development protection company
Worthy coasts and beaches (e.g. sandy)	1500 m.[1]
Birdlife SPAs	Judged on a case-by-case basis within the eco-development protection company, after a specific ornithological study

Table 4. Minimum distances from cultural heritage sites and features. (Source: G.G. 2464/B/2008)

INCOMPATIBLE USE	**MINIMUM INSTALLATION DISTANCE FROM THE INCOMPATIBLE USE**
Inscribed on the World Heritage List and other major monuments, archaeological sites and historic sites of Paragraph 5. (Subparagraph B) of article 50 of Law 3028/02	3000 m.
Absolute Protection Zone (Zone A) of other archaeological sites	A = 7d, where (d) is the diameter of the wind turbine blade, at least 500 m.
Declared cultural monuments and historic sites	A = 7d, where (d) is the diameter of the wind turbine blade, at least 500 m.

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[1] The indicated distance should not be taken into consideration when a wind turbine's nacelle is not visible from the incompatible region

Table 5 shows the minimum distances from settlement activities, such as towns, traditional settlements, sacred monasteries. It can be seen that the minimum distances vary according to the type of land use.

Table 5. Minimum distances from residential activities. (Source: G.G. 2464/B/2008)

INCOMPATIBLE USE	MINIMUM INSTALLATION DISTANCE FROM THE INCOMPATIBLE USE
Cities and settlements with population >2000 or settlements with a population of < 2000 inhabitants classified as dynamic, touristic, or significant	1.000 m from the boundary[2] of the settlement or town plan, if applicable
Traditional settlements	1.500 m from the boundary[2] of the settlement [3]
Other settlements	500 m from the boundary of the settlement
Organized building of A' or B' residence (P.E.R.P.O., Co-operatives etc.) or developed areas for B' housing, as identified in the environmental impact assessment of each individual wind farm installation	1.000 m from the boundaries of the plan or the landscaped area, respectively
Holy Monasteries	500 m. from the boundaries[2] of the Monastery
Single residence (legally existing)	Ensurance of a minimum noise level of less than 45 dB.

The wind turbine needs to be placed so that the closest residential building in a settlement is no more than 45 dB away from it. The maximum noise disturbance caused by wind turbines ought to be even lower, particularly at night. This settlement's closest house's sound level is the same as an air conditioner running (Krystallidis et al, 2012).

Table 6 shows the minimum distances from productive activities such as farms, agricultural land, quarrying zones.

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[2] In cases where the settlement has not been delimited, the distance is calculated from the center of the settlement plus 500 meters and, in any case, at a distance of more than 500m. from the last residence of the settlement

[3] In case a wind farm, antenna park, or radar park already exists at a distance of less than 1500 m. from its boundaries, the minimum distance of any new wind farm installation from them is set as compensation at 2500m.

Table 6. Distances from zones or installations of productive activities

INCOMPATIBLE USE	MINIMUM INSTALLATION DISTANCE FROM THE INCOMPATIBLE USE
High-productivity agricultural land, afforestation zones, and irrigated land	Safety distance 1,5d
Fish farms	Safety distance 1,5d
Livestock farming units	Safety distance 1,5d
Quarrying zones and activities	As defined in the applicable legislation.
Operating surface mining zones and activities	500 m.
Areas of organized tourist development and other areas of organized development of productive activities in the tertiary sector, theme parks, tourist ports, and other statutory or designated tourist areas (as identified in the environmental impact assessment for each individual facility).	1000 m. from the zone/area boundaries[4]
Medium and large tourist accommodation, special tourist infrastructure, tourist ports	1000 m. from the boundaries of the unit

Table 7 shows the minimum distances from artificial infrastructure projects such as road network, railway lines, high-voltage lines.

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[4] The indicated distance should not be taken into consideration when a wind turbine's nacelle is not visible from the incompatible region

Table 7. Minimum distances from zones or establishments of production processes. (Source: G.G. 2464/B/2008)

INCOMPATIBLE USE	MINIMUM INSTALLATION DISTANCE FROM THE INCOMPATIBLE USE
Main roads, roads under the responsibility of local authorities and railway lines	Safety distance of 1,5d from the boundaries of the expropriation zone of the road or railway network, respectively
High-voltage Lines	Safety distance of 1,5 d from the limits of the crossing limits of the HV lines.
Telecommunications infrastructure (antennas), RADAR	Where appropriate, after obtaining the opinion of the competent body
Installations or activities of aviation	Where appropriate, after obtaining the opinion of the competent body

Table 8 illustrates the maximum distances at which wind turbines can operate efficiently.

Table 8. Distances to ensure the functionality and efficiency of wind installations. (Source: G.G. 2464/B/2008)

PARAMETERS AFFECTING THE FUNCTIONALITY OF THE INSTALLATION	INSTALLATION DISTANCE
Maximum distance from an existing land access road of any category	For installed capacity or units below 10 MWe: In priority wind energy areas and Attica: 20 km of track -In wind energy suitability areas: 15 km, regardless of the installed capacity or unit -On islands: 10 km, regardless of the installed capacity or unit.
Maximum distance from the High Voltage electricity transmission system	As defined by DESMIE in terms of connection of the installation (high voltage) and PPC (medium and low voltage)
Minimum distance (A) from significant fixed elements of direct interference (natural or man-made) that prevent the exploitation of the wind	7 times the height of the fixed direct interpolation element (A = 7xY)
Minimum distance (A) between wind turbines	2,5 times the diameter (d) of the wing of the wind turbine (A=2.5d)

Table 9 presents the minimum distances within Attica and its Marine Area and for the Residential Islands.

Table 9. Factors determining the incorporation of wind farms into the natural environment. (Source: G.G. 2464/B/2008)

Points of great interest	Within Attica and Marine Area	Residential Islands
The nearest limit of inscribed World Heritage and other major monuments, archaeological sites and historic sites	6 km	6 km
Established core of a National Park, an aesthetic forest or other point of natural interest	0,8 km	1 km
Nearest point of an established traditional settlement	6 km.	6km
Nearest town or settlement boundaries >2000 inhabitants and settlements	2 km	3 km
Nearest limit of an established or designated tourist area medium and large tourist accommodation, special tourist infrastructure, tourist ports	2 km	3 km

3.2.3. Special criteria for the placement of offshore wind turbines

The area of study of this work falls under article 10 of the Government Gazette 2464/B/2008, which sets out the specific criteria for the placement of wind turbines in marine areas or in uninhabited islands.

Specifically, the specific criteria for the placement of offshore wind farms are as follows:

1. Wind installations may be placed in all marine areas of the country that have wind exploitability conditions, if they are not part of a special institutional framework expressly prohibited establishment or do not constitute a zone of exclusion, such as established marine or underwater parks or certified passenger shipping lines.
2. Minimum distances to ensure the functionality and performance of wind installations as set in Table 8.
3. Installation of wind turbines is prohibited at less than 1.500 m from the coasts are included in the monitoring program of the coordinated bathing water quality by the Ministry of the Environment, Urban Planning and Public Works.
4. It is prohibited to install wind turbines in closed vessels with an opening range of <1.500 m.
5. Minimum installation distance from peripherals and elements of cultural heritage: as defined in Table 4.
6. Minimum installation distance from settlements as set in Table 5.
7. Minimum installation distance from production animals or activities of the tertiary sector as defined in the Table 6.

8. The depth of the foundation or anchorage of the wind turbine base is determined by the capabilities of the current technology and the corresponding static and dynamic behavior studies.
9. The construction of the wind farm must ensure sufficient interconnection and transmission of the electricity produced either to the mainland system or to the grid of the system of non-interconnected islands.
10. Maximum overland distance from an interconnection substation: 20 km.
11. Minimum distance required from areas of environmental interest, as set in Table 3.
12. Guidelines for the landscape (preventing visual disruption), as stated in Table 9.

4. Practical implementation of the best location selection for Floating Wind Farms

This chapter explores into the practical application of deploying offshore wind farms within the maritime environment of Greece, leveraging the capabilities of Geographic Information Systems (GIS). GIS represents a sophisticated and organized collection of tools, software, geographical data, and proficient personnel, all of which are utilized to collect, store, update, analyze, and display a variety of geographical information (Mpismpas, 2014). The versatility of GIS is evident in its extensive range of applications. Geographic analysis through GIS involves a comprehensive suite of systems that integrate principles from a multitude of disciplines, including agriculture, botany, computer science, surveying, zoology, geography, and more (Maguire, 1991).

The accuracy and reliability of the results generated by GIS are directly dependent on the accuracy and reliability of the data fed into the system. Human expertise is indispensable in managing and analyzing this data, addressing complex geographical challenges, and creating precise cartographic representations. Additionally, humans are essential in the interpretation of GIS outputs, ensuring that the insights gained are both meaningful and actionable for the planning and implementation of offshore wind farms in Greece (Nakou, 2007; Koutsopoulos, 2002).

4.1. Area of Study

The research area under consideration covers a significant expanse of the maritime regions of both the Aegean Sea and the Ionian Sea. This area stretches from the coastline of Greece outward to the 800 m depth contour, commonly referred to as the 800-meter isobath. The designated research zone includes not only the international waters but also the territorial waters that are under the jurisdiction of Greece. The scope of this research thus encompasses a diverse range of maritime environments, from the shallower coastal waters adjacent to the Greek mainland and islands to the deeper offshore regions. This extensive area is crucial for selecting the optimum location.

4.2. Siting Criteria – Exclusion Areas

The siting criteria for offshore wind farms include both excluding factors and the identification of an ideal site. Exclusion criteria are indicated by the Preliminary Positioning of Wind Parks – Phase 1 conducted by the Ministry of the Environment, Energy and Climate Change on 2010. The exclusion zones are the following:

1. The regions included by the NATURA 2000 network and an 800 m radius around them,
2. The protected eco-development areas and radius 800 m around them,
3. The areas under the jurisdiction of national forests and a radius of 800 m around them,
4. The areas covered by international treaties (e.g. Monastic community of Mount Athos) and radius 800 m around them,

5. Designated regions for military exercises and the firing ranges of the three branches of the Greek army, as announced each year by the hydrographic service of the Navy, and a radius of 2 km around them,
6. The areas confirmed are shipping lines, i.e. points of high maritime traffic density and a radius of 3 km in favor of safety,
7. The marine peripherals are at 2 km from the Greek shore.

The criteria for optimum positioning are the bathymetry of the Ionian and Aegean seas and the wind potential of their respective regions. Depths less than 100 m are excluded, as they are mainly located at distances less than 20 km from the coast, eliminating practical problems of visual disturbance and noise from the operation of wind turbines. At the same time, this distance ensures the placement of offshore floating park away from ports or docks. In addition, an upper limit of depth up to 800 m is set, as this is the upper limit of current advancements in floating wind turbine installation technology.

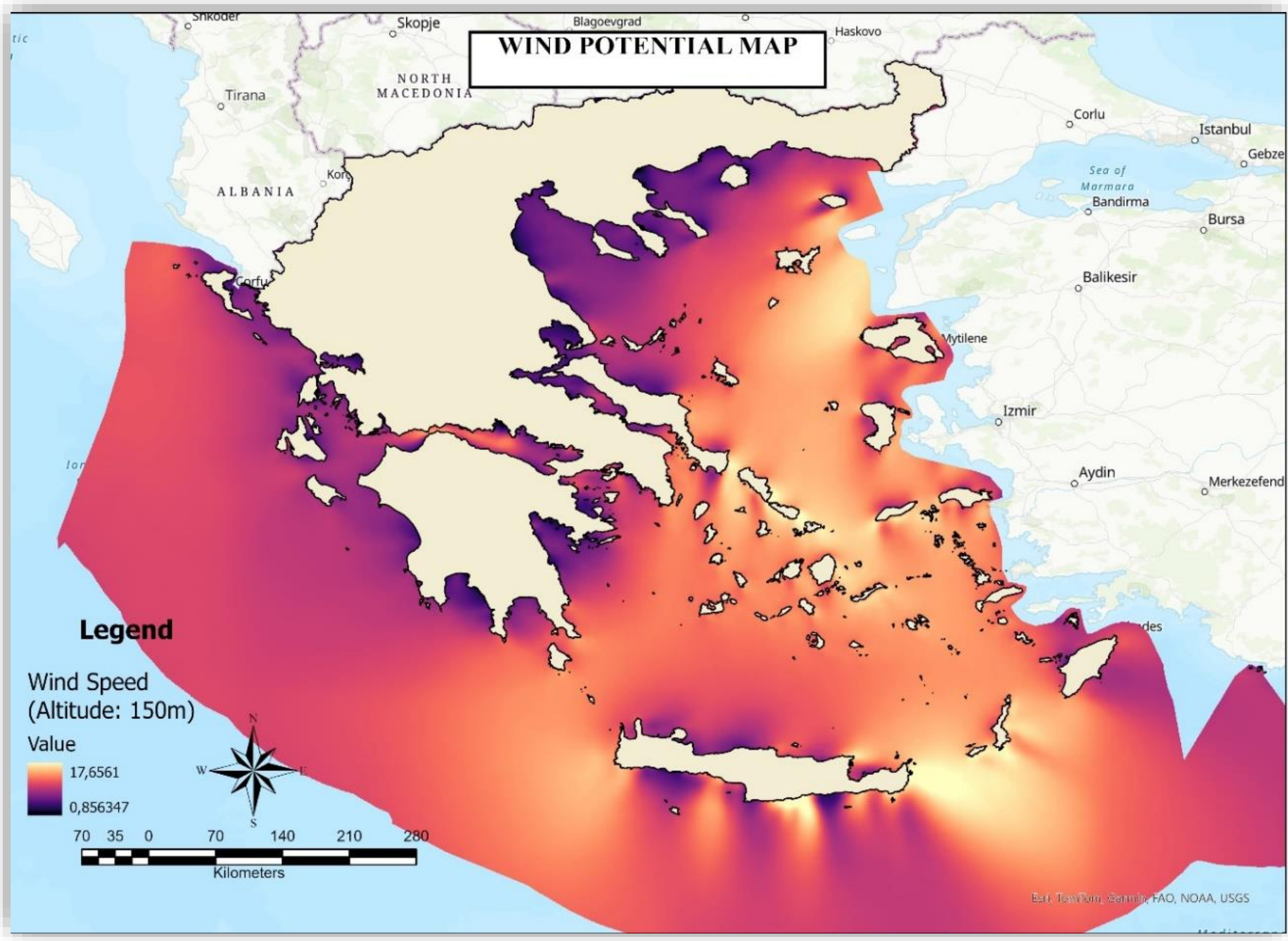
Gravitational factors are unrelated to the chosen criteria. Rather, they concentrate on pinpointing domains that ought to be disregarded. Areas that satisfy these exclusion standards are inherently considered unfit for additional categorization or examination. In essence, any region that fits within these exclusionary criteria is deemed unsuitable for the thesis. This method guarantees that only regions that satisfy particular, pertinent criteria are taken into account, improving the classification process's overall accuracy and dependability. Consequently, the exclusion criteria function as a filter to weed out areas that don't match the requirements, enabling the research to concentrate on more promising sites (Kırcalı, Selim, 2021).

4.2.1. Wind Potential Map

As mentioned above, wind power is a criterion for optimal positioning. Certain areas are more favorable than others because maximizing energy output requires high and consistent wind speeds (Tercan et al., 2020). The following map shows the territorial distribution of the average wind speed in Greece.

The findings indicate that in Greece, the wind capacity at an absolute height of 150 m varies between 0,85 m/s and 17,65 m/s. When considering the maritime environment, it is evident that the areas with the most elevated wind velocity are:

- In Cyclades (especially in the region from Andros to Mykonos)
- In the area between Lesvos and Lemnos,
- In the area between Crete and Karpathos.

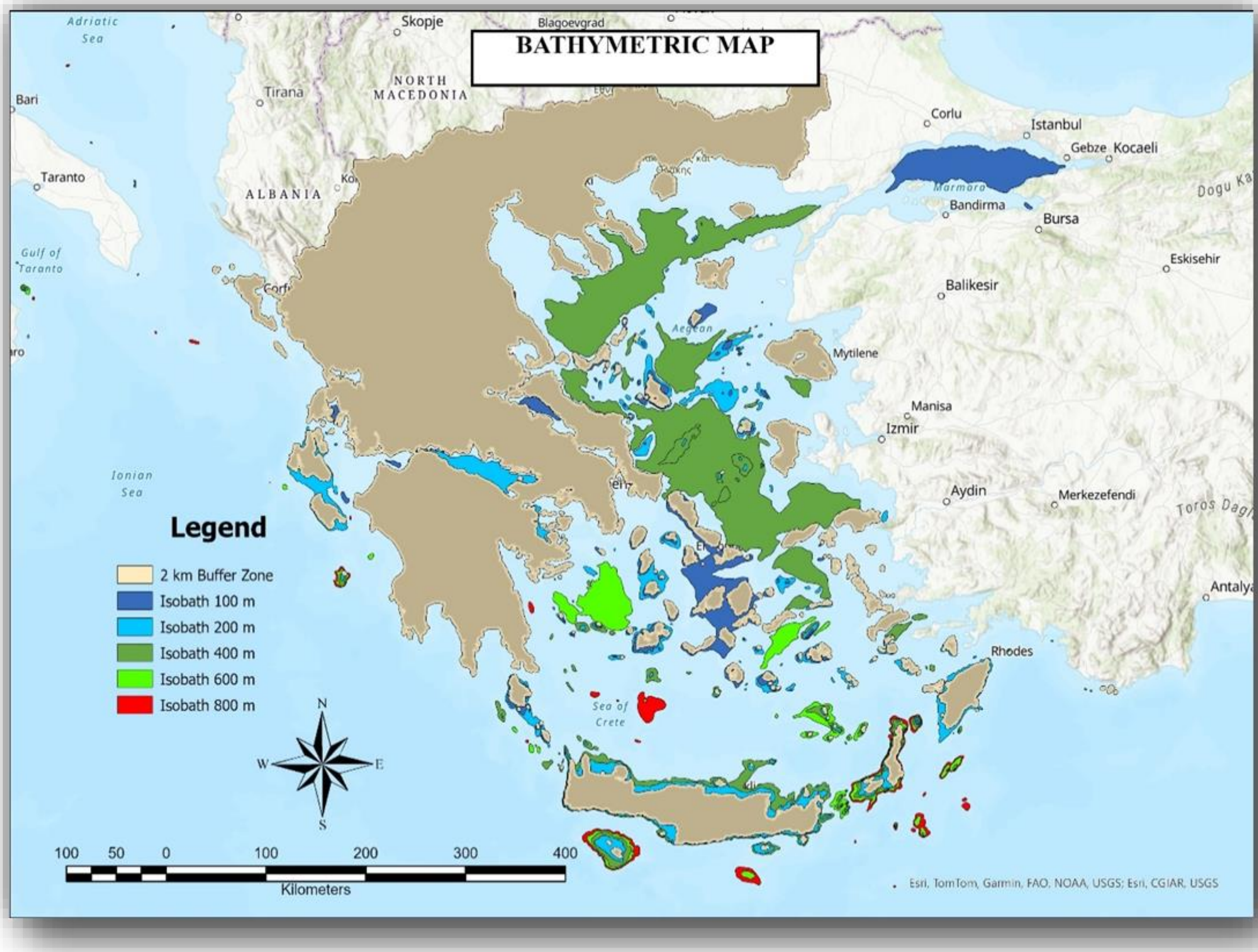


Map 1. Wind Potential Map of the Greek maritime area inside the Exclusive Economic Zone (EEZ) at an altitude of 150 meters. (Source: European Centre for Medium-Range Weather Forecasts (ECMWF)

4.2.2. Bathymetry map of Greece's marine area

The bathymetry of Greek waters determines the type of foundation or not of the wind turbines. Excluding the depth of 100 m, the installation of wind turbines with foundation is automatically eliminated. Another reason to exclude the 100 m for an optimal siting of a wind turbine is the low wind speeds blowing at these depths in comparison at greater depths. Beyond 25 km from the shore, the depths primarily surpass 200 m.

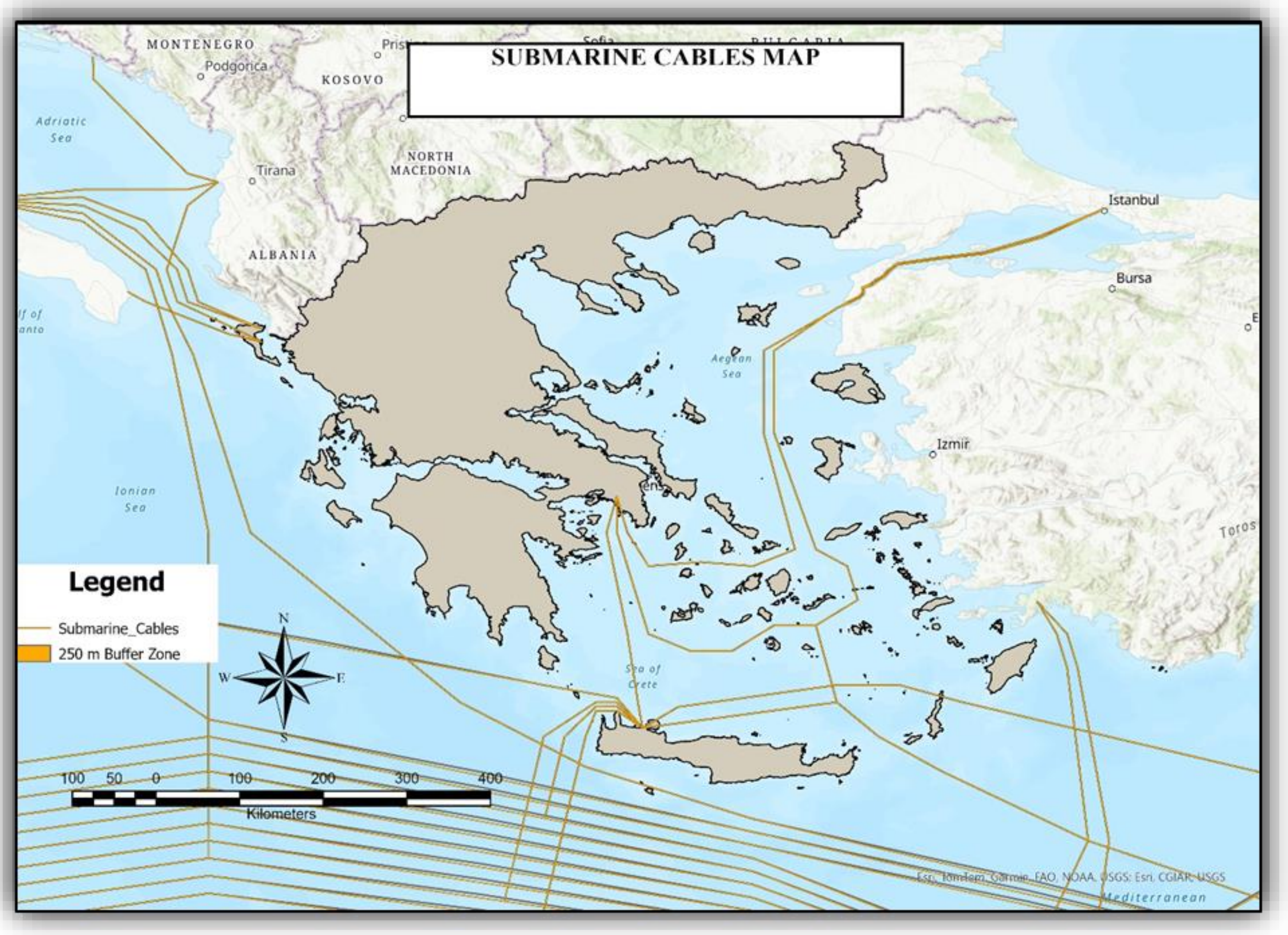
Utilizing advanced floating wind farm technology, the anchors of the wind farm may be securely and effectively established at depths of up to 800 m. This innovation maximizes the potential for energy production and increases the number of sites that are feasible for offshore wind farms in Greece by taking advantage of deeper waters, where wind speeds are generally higher and more consistent.



Map 2. Bathymetry map of Greece's marine area. (Source: GEODATA)

4.2.3. Submarine Cables Map

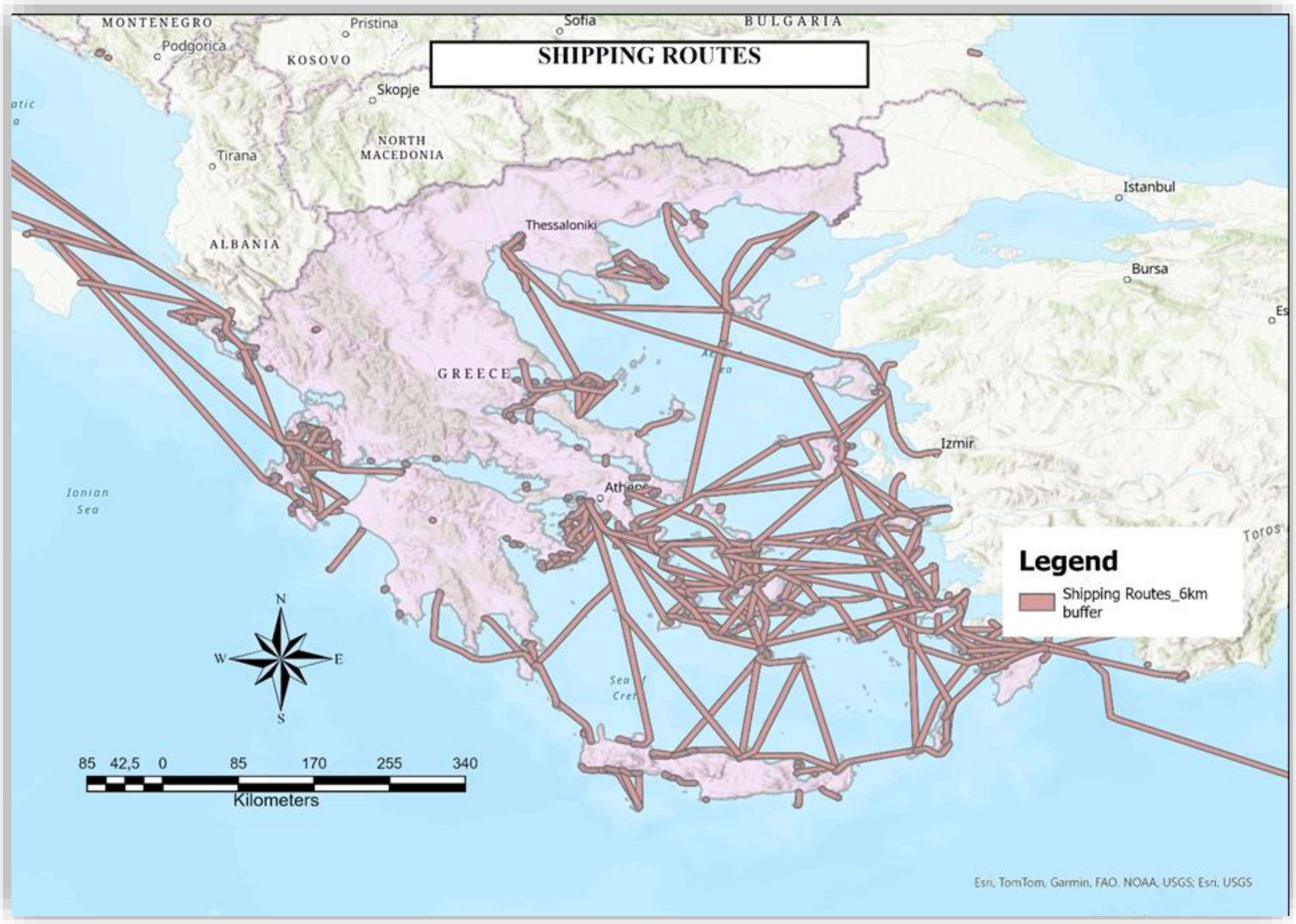
Submarine cables are a crucial factor in determining the locations that should be excluded. The suggested method by Saleous et al. (2016) involves converting a blocking radius into a 250 m zone surrounding the specified location. EMODnet (European Marine Observation and Data Network) provides the geographical coordinates of the cables.



Map 3. Submarine Cables. (Source: GEODATA)

4.2.4. Shipping Routes Map

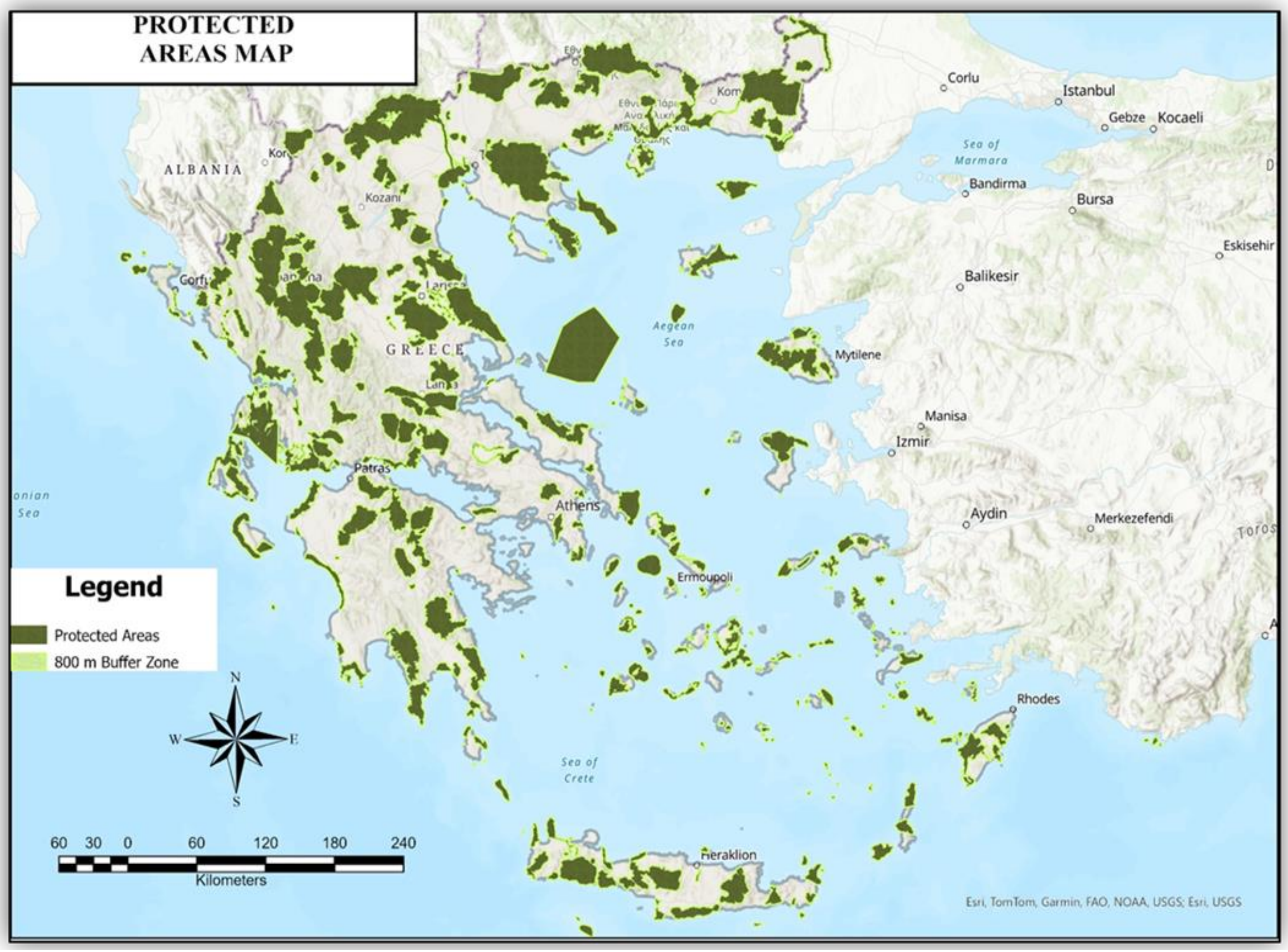
The Aegean and Ionian Sea have a high quantity of shipping lines. According to the data obtained from the Hellenic Competition Commission, the total number of shipping lines in Greece is 2.195, including all shipping companies. In this thesis, only the main shipping lines have been digitized. The Automatic Identification System (AIS) is used by Marine Traffic to measure the density of maritime activity. The ArcGIS software is used to digitize the density map, which captures the primary routes of ships. A 3 km safety zone is created on both sides of these routes to ensure safety.



Map 4. Shipping Lines. (Source: GEODATA)

4.2.5. Protected Areas Map

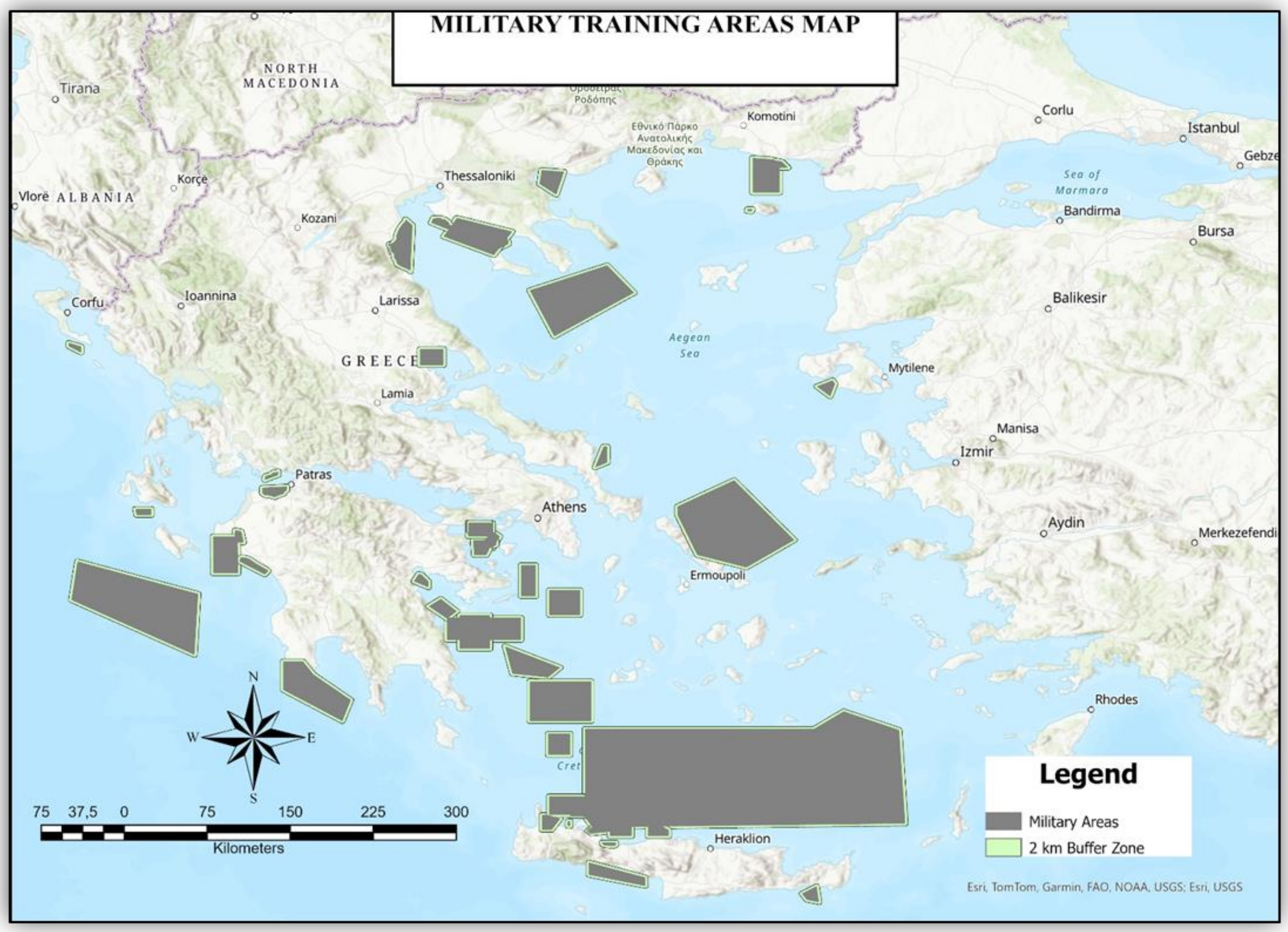
Greece has an extensive network of protected areas, which is among the most expansive in Europe. The Natura 2000 network encompasses 446 areas, which account for 28% of Greece's land and 20% marine surface area. Additionally, Greece has 11 national parks, 2 large marine parks which are created to safeguard marine and coastal biodiversity. Also Greece has 10 wetlands of international significance protected by the Ramsar Convention, 19 aesthetically pleasing forests, and numerous monuments of significant environmental and cultural value. The wetlands are essential for preventing flooding, cleaning the water, and giving migratory birds and other wildlife habitats. They are essential to international initiatives for sustainable use and wetland conservation.



Map 5. Protected Areas. (Source: GEODATA)

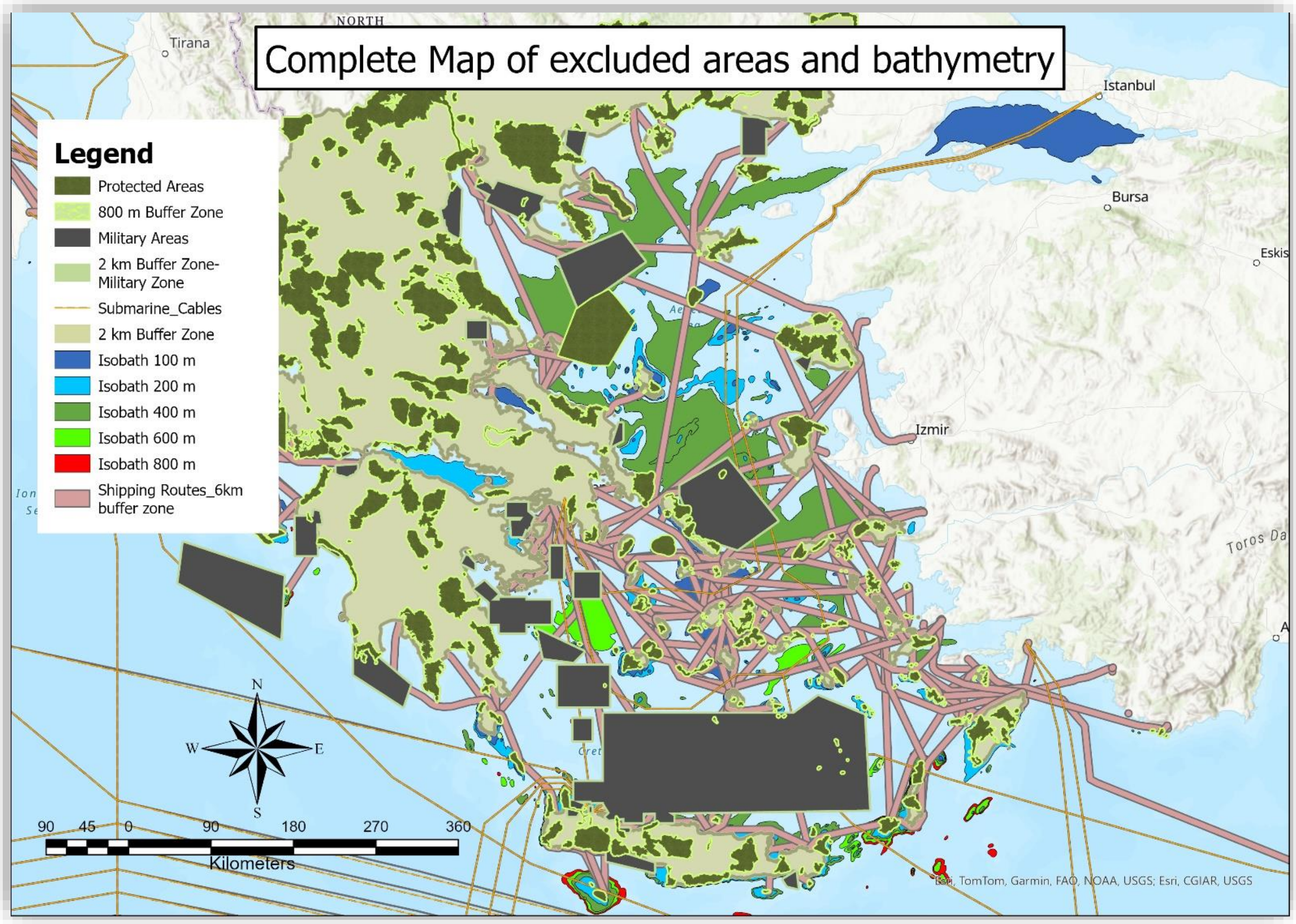
4.2.6. Military Training Areas Map

The Greek military consists of the Ground Army, the Naval Forces, and the Air Force. The firing fields of each service unit are derived from the Greek hydrographic service. These places are designated as either permanent or emergency zones, depending on the circumstances, and therefore these areas constitute blockage areas for OWF. Based on the map provided, the most extensive training areas may be found to the north of Crete, in the Cyclades region to the southwest of Athos, and to the south of Alexandroupolis.



Map 6. Military Training Areas. (Source: GEODATA)

4.2.7. Complete Map of excluded areas



Map 7. Complete Map of excluded areas and bathymetry. (Source: GEODATA)

Map 7 completes the GIS process for selecting the location and siting of the offshore wind farm. If we were aiming for offshore wind farm siting with a fixed foundation, we would also have to consider the exclusive economic zone areas according to the Law of the Sea. This is not the case in this study as wind turbines will be installed with a floating foundation, which is not affected by the above law.

The area to be further investigated in order to meet its energy needs is **Alexandroupolis**. This decision was made because Maps 1 and 7 show that the north and northeast of the Aegean initially have rich wind potential, and afterwards, there are significant expectations with the spatial sea availability due to the reduced shipping line load. Furthermore, Alexandroupolis is one of the biggest cities in Greece, and the way it is positioned strategically, being in close distance to Turkey, Bulgaria, makes it seem like the perfect place to meet its energy needs. Finally, despite the significant opportunity for offshore development, North Aegean Sea has received little research.

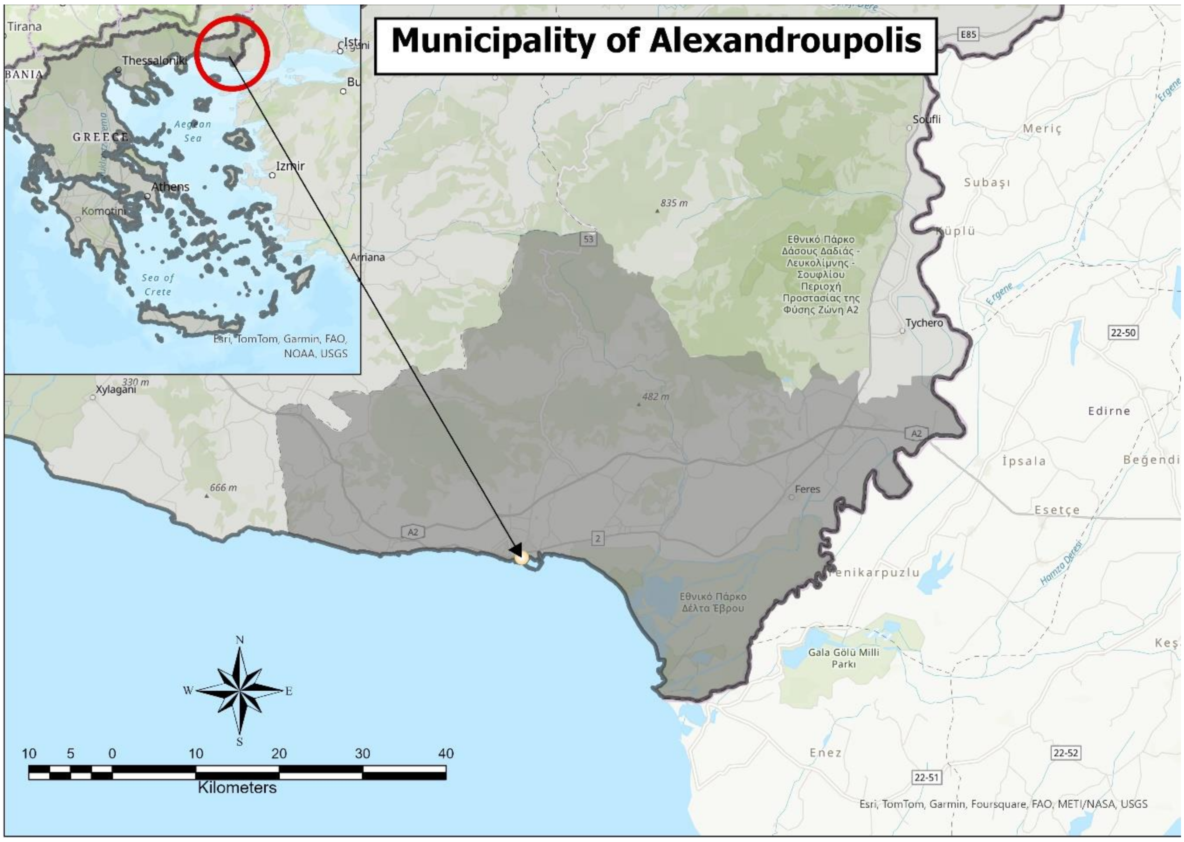
5. Meeting energy needs of Alexandroupolis via Floating Wind Farm – Methodology

The city's geographical, administrative, and demographic features ought to be discussed first. The municipality's energy consumption is then shown using data from the DEDDIE for the years 2018–2022. Additionally, the results of the stochastic method are presented along with the creation of a synthetic wind speed time series spanning the next 25 years. Finally, the energy demands for the first and 25th year of the project are projected based on the city's population growth. These demands are expressed in terms of hours, days, months, and years.

5.1. Alexandroupolis – Main characteristics

The municipality of Alexandroupolis is a municipality of the region of Eastern Macedonia and Thrace, where it is the most populous municipality of the region. The area of the municipality is 1.217 km^2 and its distance from Athens is 797 km and the Turkish border is 13 km and approximately 35 km from Bulgarian border. Thus, Alexandroupolis is a hub for regional trade, transport and cultural exchanges. The main road of Alexandroupolis is the Egnatia road. The Egnatia Road connects Alexandroupolis with Komotini, Thessaloniki and even Igoumenitsa. Alexandroupolis is also connected to Komotini and Thessaloniki by railway lines, while a system of railway lines also connects it to Bulgaria and Istanbul.

The city's port is also of key importance for the service of citizens and tourists, as well as for commercial and military activities. The Alexandroupolis' port served for 2023, 181.840 passengers. It also has the state airport of Alexandroupolis "Democritus". According to the latest updated data from ELSTAT, for 2016, Democritus airport served 2.832 flights and a total of 161.1635 passengers.



Map 8. Municipality of Alexandroupolis. (Source: ArcGIS Pro*)*

5.2. Geographical - Administrative characteristics

Alexandroupolis is the closest city to the borders of Turkey, as far as mainland Greece is concerned. The municipality of Alexandroupolis was established in 2011 with the Kallikrates program, after the merger of the preexisting municipalities of Alexandroupolis (62.936), Traianoupolis (2.315) and Feres (6.500). The municipality's ancient capital is at Feres, although its current capital is Alexandroupolis. The objective of this program was to simplify administrative tasks and decrease the number of municipalities in order to modernize and rationalize Greece's local government structures. It was a component of larger initiatives to enhance national control.

Four rivers flow from the municipality of Alexandroupolis, the most well-known of which is the Evros, which also serves as a natural border between Greece and Turkey. Three of the four rivers flow into the Delta Evros National Park. The Delta of Evros is one of 3 in total SPAs that located in the municipality of Alexandroupolis. The Evros delta has a total area of approximately 200.000 m^2. It is among Europe's most significant wetlands. It is listed under the Ramsar International Convention's list of protected areas. The migration and wintering of numerous bird species is the delta of Evros' most significant ecological contribution.

5.3. Demographic Characteristics

The municipality of Alexandroupolis has 71.751 permanent residents, according to the ELSTAT official census for 2021. The change in the number of permanent inhabitants over the past 40 years is shown in Table 10.

Table 10. Permanent Population Censuses of Alexandroupolis. (Source: ELSTAT)

	1991	2001	2011	2021
Municipal Community of Alexandroupolis	38.220	53.459	58.138	59.723
Municipality of Alexandroupolis	52.556	66.125	72.905	71.751

49,3% of the Regional Unity's total population resides in the municipality of Alexandroupolis. There is a crowding of 85% of the population in the municipal Community of Alexandroupolis. (Community's Operational Plan of Alexandroupolis 2020-2024, 2019).

With only 7% of the population employed in the primary sector, it is the municipality of Alexandroupolis' most powerless industry. The municipalities of Feres and Traianoupolis are the areas with the strongest livestock and agricultural character. After that, the secondary sector employs 13% of locals. The village of Avantos is home to Alexandroupolis business park. It is one of the nation's 25 industrial parks (VI.PE.). Three of the 500 biggest factories in the nation, which specialize in food items, textiles, wood and wood products, are situated in Alexandroupolis, while the other one is in Feres. It also has three minefields: two of them are 11,5 km northwest of Alexandroupolis and the third is 22 km northwest of Alexandroupolis in the municipality of Feres. The third sector is the main employment sector with a percentage of 80%. The main employment in the third sector is in public services, such as education, health and social care. In addition, a large percentage of workers are observed in catering and accommodation stores, while the repair sector of cars and motorcycles is increasing (Community's Operational Plan of Alexandroupolis 2020-2024, 2019).

5.4. Energy Network

The PPC primarily uses fuel oil, diesel, and fossil fuels to generate electricity. Komotini is home to the power generating system (485MW) for the regional unit of eastern Macedonia and Thrace (PPC.gr). Numerous issues arise from this reliance on conventional energy sources, including the need for modernization to meet modern energy demands and the impact on the environment and the economy.

The installation of a power plant, at the Alexandroupolis' VIPE, was granted a license in February 2023. The unit will run on natural gas and be powered by a combined cycle. The installation is anticipated to be finished in 2025's fourth quarter. The plant is anticipated to generate 5 TWh of electricity annually once it is operational. Because of Alexandroupolis' advantageous location, improvements to the energy infrastructure in the area are expected, with the possibility of elevating Alexandroupolis to the status of an energy hub in the Balkans and Southeastern Europe.

Chart 1 shows the total consumption of the municipality of Alexandroupolis from 2018 to 2022. There is a drop in consumption in 2020 due to the Coronavirus pandemic and in 2022, because of the energy crisis caused by the Russian-Ukrainian War. Greece must achieve energy independence in order to prevent another energy crisis, as this chart demonstrates.

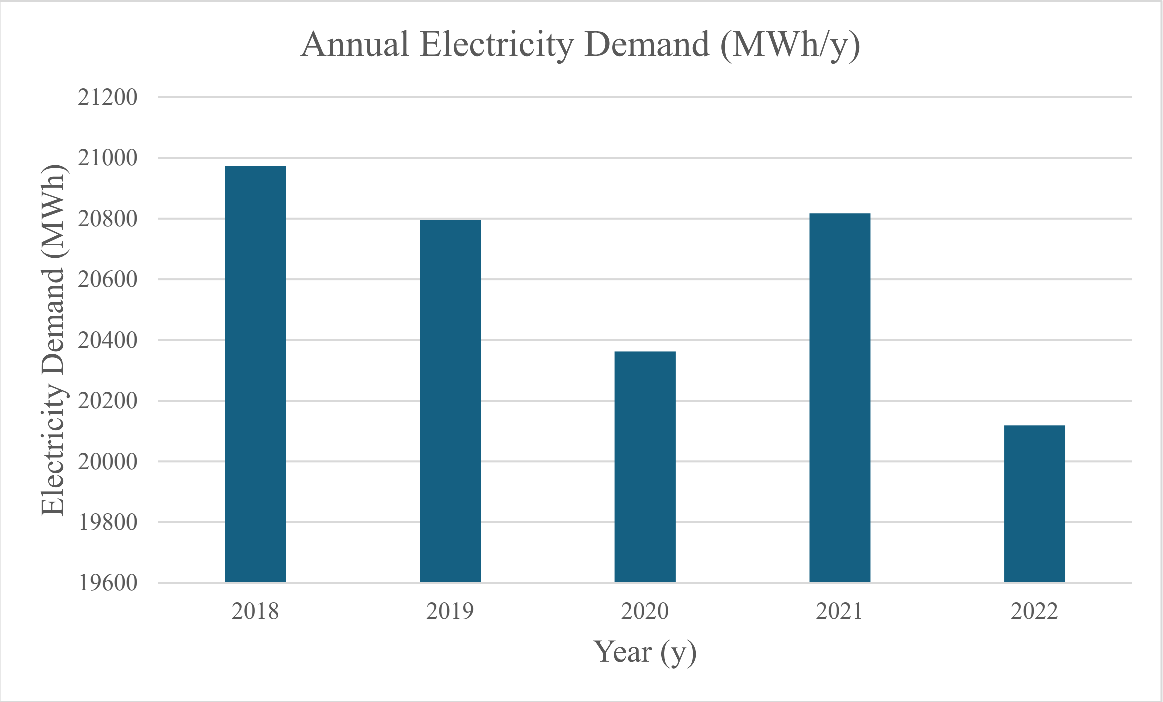


Chart 1. Annual Electricity Demand of Alexandroupolis. (Source: DEDDIE)

The average monthly consumption for the municipality of Alexandroupolis from 2018 to 2022 is displayed in Chart 2. As is typical, there is a spike in consumption during the summer, but there is also a noticeable increase from January to February. This is because the area experiences consistently low temperatures, necessitating the use of energy for heating. The average temperature in January and February is 5 degrees Celsius and 6 degrees Celsius, respectively, according to HNMS.

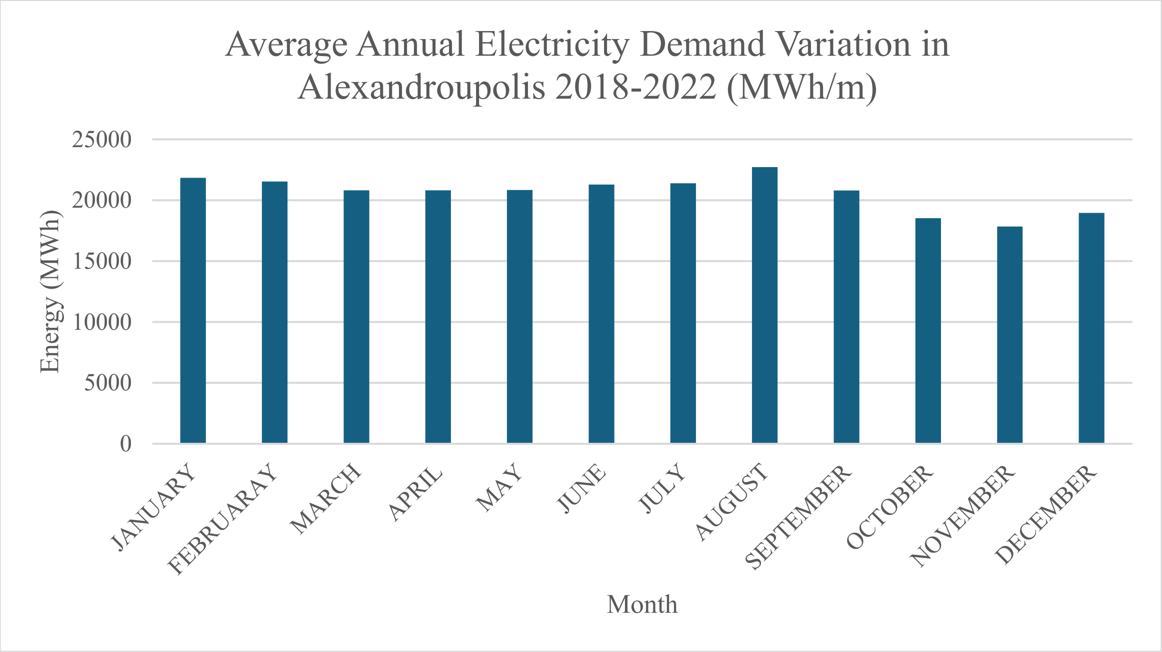


Chart 2. Average Annual Electricity Demand Fluctuation, 2018-2022. (Source: DEDDIE)

Chart 3 shows the forms of electricity use in the municipality. The two energy uses that have the highest percentage are household and commercial use. As discussed above, the third sector dominates the daily life of the municipality. So the high percentage is normal. On the contrary, energy use in the primary sector, such as agriculture, shows low rates.

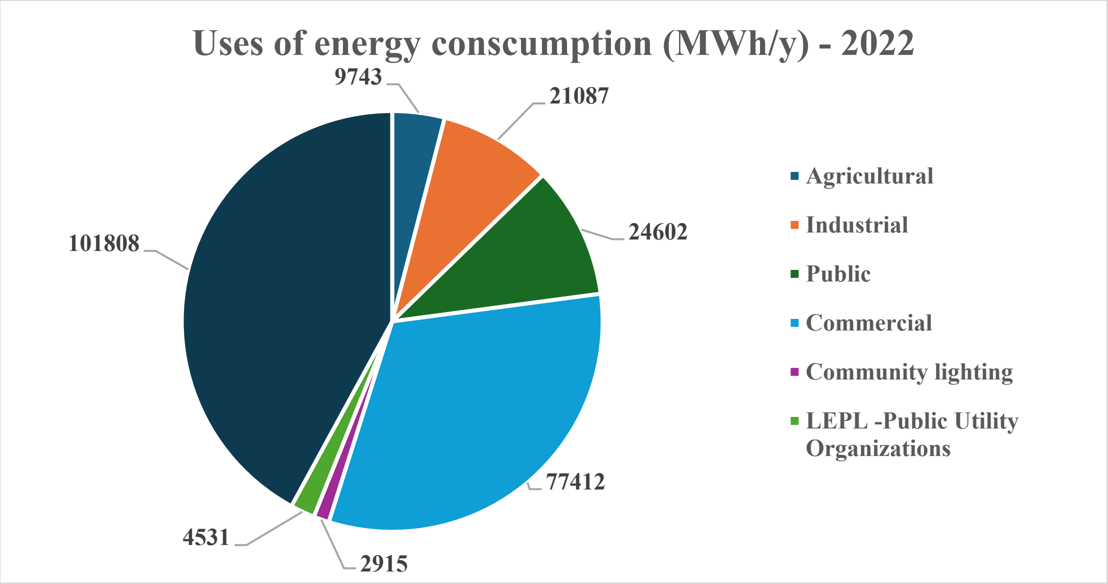


Chart 3. Energy Uses (MWh/y). (Source: DEDDIE)

5.5. Estimation of Energy Production

This sub-chapter examines two distinct approaches, calculating the amount of energy generated. The results are then analyzed and compared.

5.5.1. Generation of synthetic time series

Using the Negra et al. (2007) approach, the synthetic wind time series is created from the historical data. The method uses the results of the historical time series as input data to produce the values of the 1-year synthetic time series in increments of three hours. Due to the 25 years that the research will last, the technique is performed an equal number of times. To meet the hourly electricity needs and provide accurate results, the 3-hour synthetic time series is transformed into an hourly step synthetic time series.

The stages in the stated above process are as follows:

1. Based on the wind speed data, a table of classifications is constructed.

2. The probability of a class (State Probability) occurring, is computed, hereafter referred to as $p_{ws,I}$:

$$p_{ws,i} = \frac{\sum_{j=1}^{M_{ws}} D_{ws,ij}}{\sum_{k=1}^{M_{ws}} \sum_{j=1}^{M_{ws}} D_{ws,kj}} \tag{1}$$

Where:

- $p_{ws,i}$: the probability of occurrence; and
- $D_{ws,i,j}$: the time spent in each class before moving to the next class

The next step is to calculate the frequency of occurrence. The frequency with which the wind value shifts from the next or previous class to the one under consideration is indicated by this term. The relationship is used to carry out the procedure:

$$f_{ws,i} = N_{ws,i,j} + N_{ws,i,j-1} \tag{2}$$

Where:

- $f_{ws,i}$: the frequency of occurrence
- $N_{ws,i,j}$: movement to the class under consideration from the next class
- $N_{ws,\, i,\, j\text{-}1}$: movement to the class under consideration from a previous one

3. Two frequencies are then computed. First, the wind's frequency of movement from the previous class to the class under consideration (Up) and second, its frequency of movement from the previous class to the class under consideration (Down).

4. Each class's average duration of stay is computed using the formula:

$$d_{ws,i} = \frac{p_{ws,i}}{f_{ws,i}} \qquad (3)$$

Where:

- dws,i: is the average duration of stay.

5. The coefficients $\lambda_{ws,i+}$ and $\lambda_{ws,i-}$ are related to the probability of moving to the immediately preceding or immediately following class and are calculated from the equation:

$$\lambda_{ws,\, i\pm1}=N_{ws,i\pm1}/p_{ws,i} \qquad (4)$$

6. As a result, every required parameter is found and recorded. The following process for creating the synthetic time series at the matching time step of the historical time series that currently exists are:

    1. The average wind speed value of the historical time series is used as the initial value for the wind speed vector in the first step.

    2. Two random numbers, $U1^i$ and $U2^i$, which take values in the interval [0,1], at each time step. The likelihood that the velocity vector will change to the following or immediately prior class is indicated by these numbers.

    3. Through relationships:

$$TTU^i = \frac{h}{\lambda_{up}} \ln(U_1^i) \qquad (5)$$

$$TTU^i = \frac{h}{\lambda_{down}} \ln(U_2^i) \qquad (6)$$

- TT: the transition time
- h: the historical time series (simulation period in three hours), the transition time to the next and next previous class is calculated. Which of the values of (5) and (6) is the smallest determines which state the new wind speed vector will be in.

    4. Since one of the 2 values (TTU or TTD) equals zero, the following procedure is followed: If TTU^i=0, then it is assumed that the wind cannot shift to a higher class and therefore shifts to the next lower class in time TTD^i. Conversely, if TTD^i=0, then it is assumed that the wind cannot shift to a lower class and therefore "shifts" to the next higher class in time TTU^i.

What this process practically implements are the following: when the value of the wind speed is zero, it shifts it to a
larger class. Similarly, the wind cannot take values larger than those that have never been observed in the historical time series.

5. If $TTU<TTD$, then the wind speed vector increases by one unit (the current state of wind speed "goes up" class after TTU hours) and the vector ws and the variable t change to be true:

$$t_i=t_{i-1}+TTU^i \tag{7}$$

$$ws\,(t^{i-1}: t^i) = ws^{i-1} + 1 \tag{8}$$

Where by the term $(t^{i-1}: t^i)$, indicates " between t^{i-1} and t^i"

6. The steps are repeated until t is greater than or equal to h.

The above procedure is performed using the program MATLAB.

In order to preserve the hourly variation and seasonality of the wind, it is imperative that the model used to create the synthetic time series undergo a reliability assessment. Chart 4 shows how well the model mimics the natural wind patterns by comparing the historical and synthetic time series visually. This chart makes it clear that the model is highly dependable. The close alignment of peaks and troughs, regular seasonal trends, and comparable hourly fluctuations between the synthetic and historical data are important markers of this reliability.

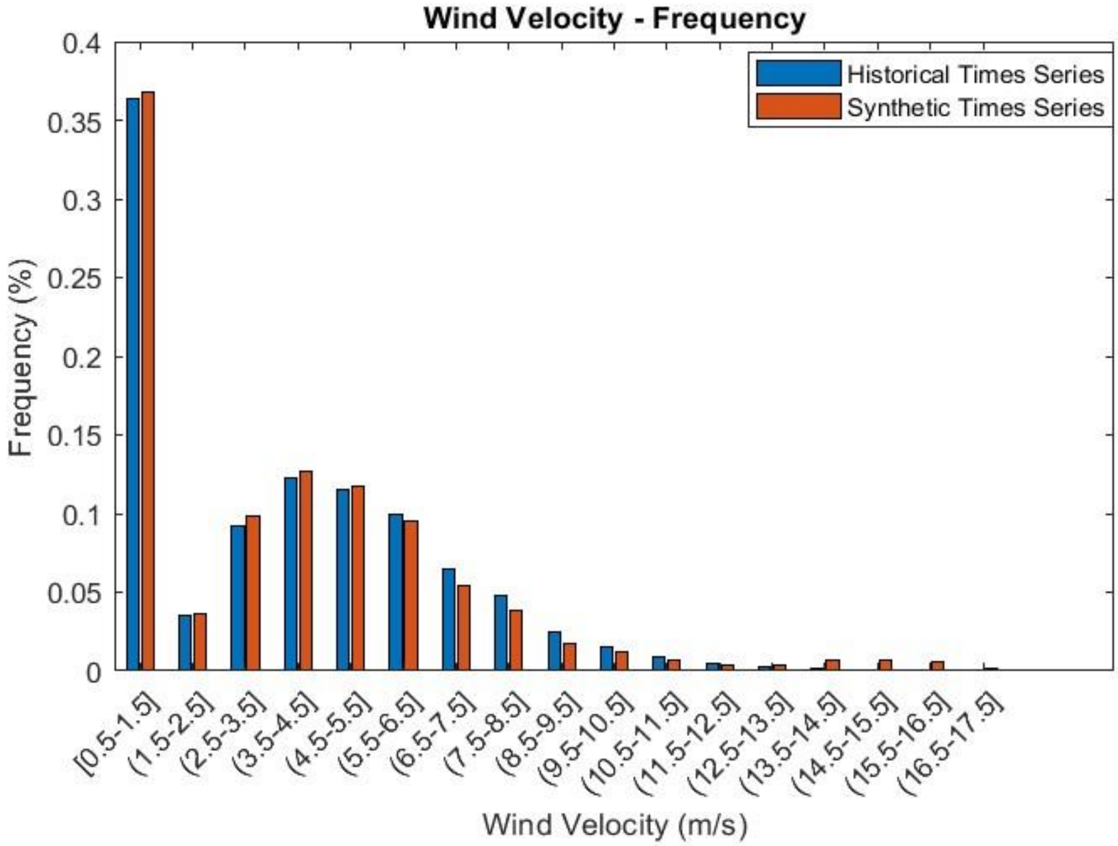


Chart 4. Wind velocity – Frequency Chart

5.5.2. Estimation of Energy Production

First and foremost, information about the demographic characteristics of the research area is required to correctly calculate the energy production. The municipality of Alexandroupolis is home to nearly 70.000 permanent residents, as it illustrated to paragraph 5.3. Over the past ten years, Alexandroupolis' population has decreased by roughly 1000 inhabitants, according to ELSTAT. Although it is not a large figure, it must be considered in order to precisely calculate the energy needs. Additionally, the project will last for 25 years due to conservative considerations. The electricity demand model employs an hourly step, just like the synthetic wind time series.

Table 11. Evolution of permanent population of the municipality of Alexandroupolis in the last 4 censuses. (Source: ELSTAT)

	1991	**2001**	**2011**	**2021**
Municipality of Alexandroupolis	52.556	66.125	72.905	71.751

Chart 5 illustrates how Alexandroupolis' permanent population has changed over the course of the previous four censuses. Although there has been a noticeable increase in population over the past 40 years, Alexandroupolis' population has dropped by 1.200 during the past ten years.

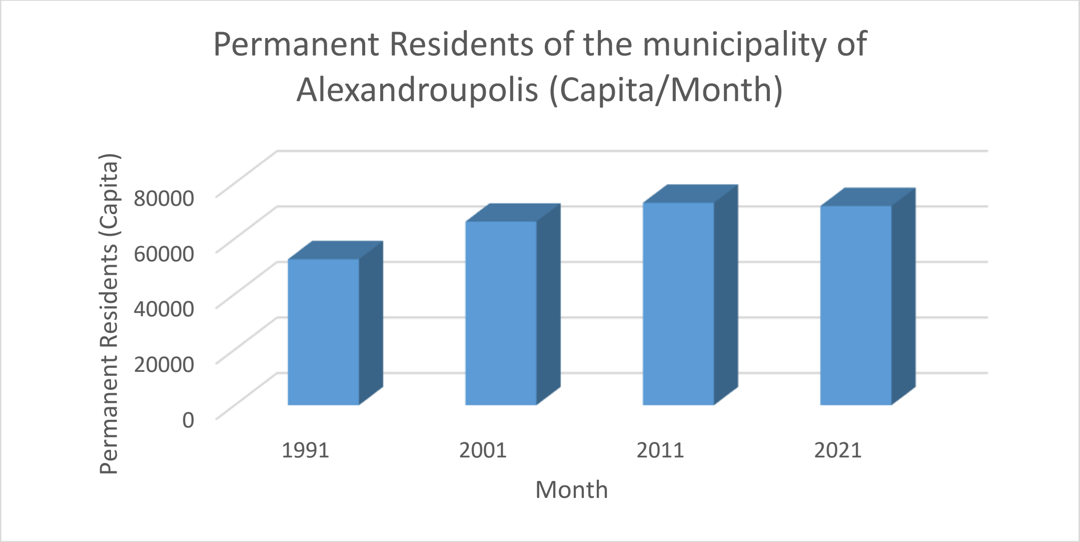


Chart 5. Evolution of permanent population of the municipality of Alexandroupolis in the last 4 censuses. (Source: ELSTAT)

Apart from the permanent residents, the town of Alexandroupolis has in recent years increased the influx of tourists throughout the year. This is because, apart from the summer months, when the number of tourists is maximized, many Turkish tourists come during the period of Ramadan (religious holiday), which lasts a month and is a mobile holiday. Therefore, the city's energy needs change every year. Holidaymakers are considered for the study to be equal to 11% of tourists, for safety reasons.

Table 12 displays the number of tourists and vacationers per month and Chart 6 displays the variation in the total population (permanent residents and tourists) over the course of the year.

Table 12. Structure of the total population of Alexandroupolis by month for the year 2021. (Source: ELSTAT)

Month	Tourists	Vacationers	Permanent Residents	Total
January	3.373	371	71.751	75.495
February	3.906	430	71.751	76.087
March	5.010	551	71.751	77.312
April	6.877	757	71.751	79.385
May	11.046	1.215	71.751	84.012
June	19.550	2.150	71.751	93.451
July	30.789	3.387	71.751	105.927
August	35.262	3.879	71.751	110.892
September	18.204	2.002	71.751	91.957
October	7.048	775	71.751	79.575
November	5.478	603	71.751	77.832
December	6.423	706	71.751	78.880

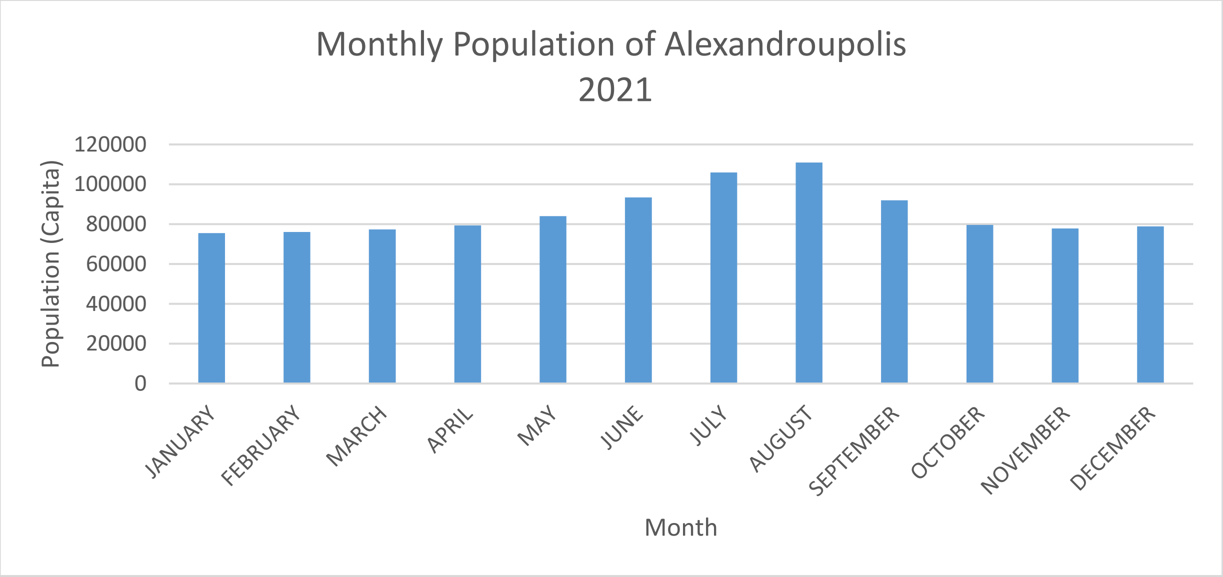


Chart 6. Monthly population fluctuation 2021

Accurately projecting Alexandroupolis' population in the future necessitates taking into account both past census data and the geometric change in the overall population. According to ELSTAT, the population of Alexandroupolis has declined during the past ten years. This reduction, for each year i, is calculated through the retrospective relationship (Tsakiris, 2010):

$$P_i = \alpha \cdot P_{i-1} \tag{9}$$

Where:

$$\alpha = 1 + \gamma \tag{10}$$

$$\gamma = \frac{P_i - P_{i-1}}{P_{i-1}} \tag{11}$$

As indicated by Table 13, the population is expected to rise to 72.399 in the first year of the project and reach 77.795 in the last year. Despite being cautious for safety, this increase is not significant. The parameters and outcomes of the geometric population growth exercised are displayed in Table 14. Population growth overall is 8,4%.

Table 13. Reduction Factors of the Total Population of Alexandroupolis for the next 25 Years

n	Year	Population	n	Year	Population
1	2024	72.399	**14**	2037	75.274
2	2025	72.616	**15**	2038	75.499
3	2026	72.834	**16**	2039	75.726
4	2027	73.052	**17**	2040	75.953
5	2028	73.271	**18**	2041	76.181
6	2029	73.491	**19**	2042	76.410
7	2030	73.712	**20**	2043	76.639
8	2031	73.933	**21**	2044	76.869
9	2032	74.155	**22**	2045	77.099
10	2033	74.377	**23**	2046	77.331
11	2034	74.600	**24**	2047	77.563
12	2035	74.824	**25**	2048	77.795
13	2036	75.048			

Table 14. Population reduction data of Alexandroupolis

Population Projection	
P_0	71.751
$\mathbf{P_{27}}$	77.795
n	27
α	1,003
γ	0,003
Percentage Population Increase	**8,4%**

The energy needs are estimated using the island's total monthly consumption in megawatt-hours during a five-year period, from 2018 to 2022. All the above data are exported from DEDDIE. The information represents the monthly total energy consumption (MWh/month) and is converted to daily demand. Lastly, this annual time series is converted to the population for the year 2024 in order to make the estimation of energy demands as precise as feasible over the project's lifetime, since the average hourly energy consumption for a year is determined.

The variation in energy consumption over each month is displayed in Chart 7. The variation in energy consumption for a typical day of each month is displayed in Chart 8. As expected, in both graphs, the highest consumption occurs in February and August.

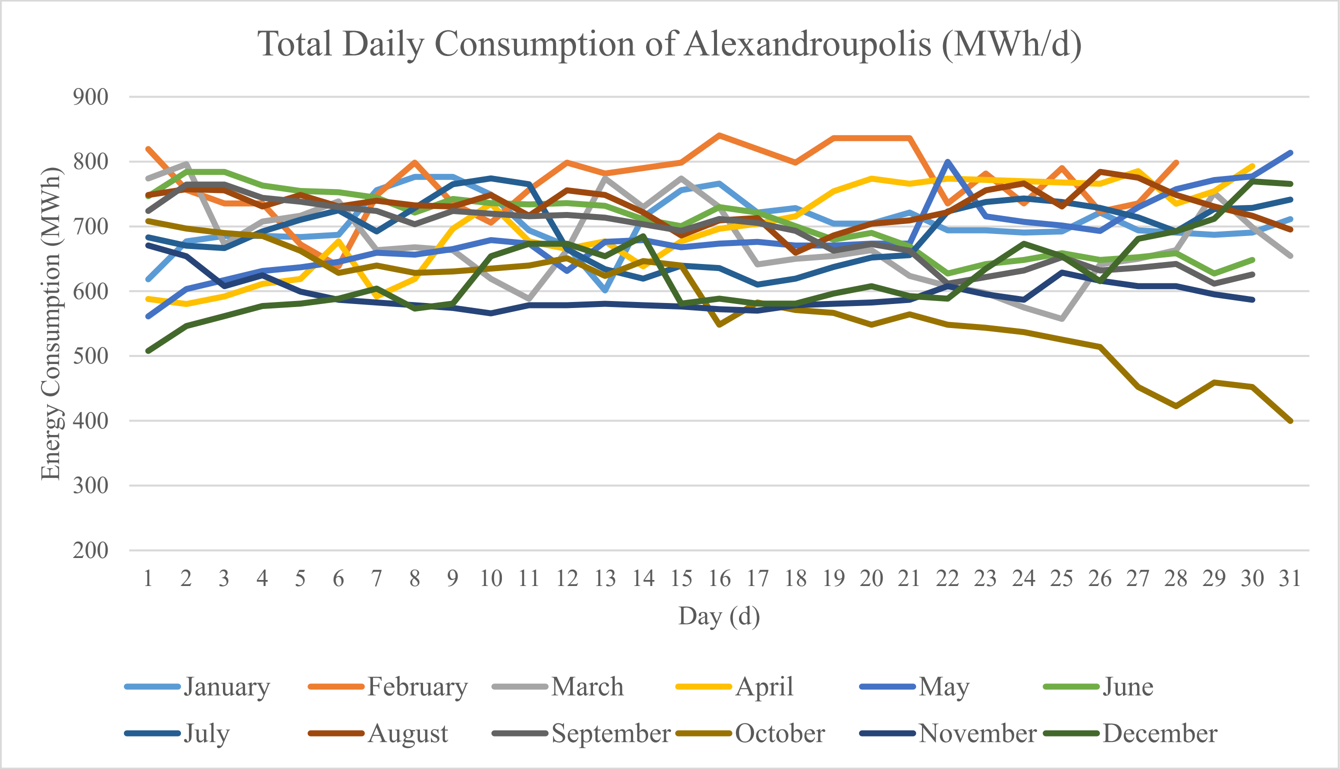


Chart 7. Average Daily Consumption of Alexandroupolis (MWh/d) - (2018-2022). (Source: DEDDIE)

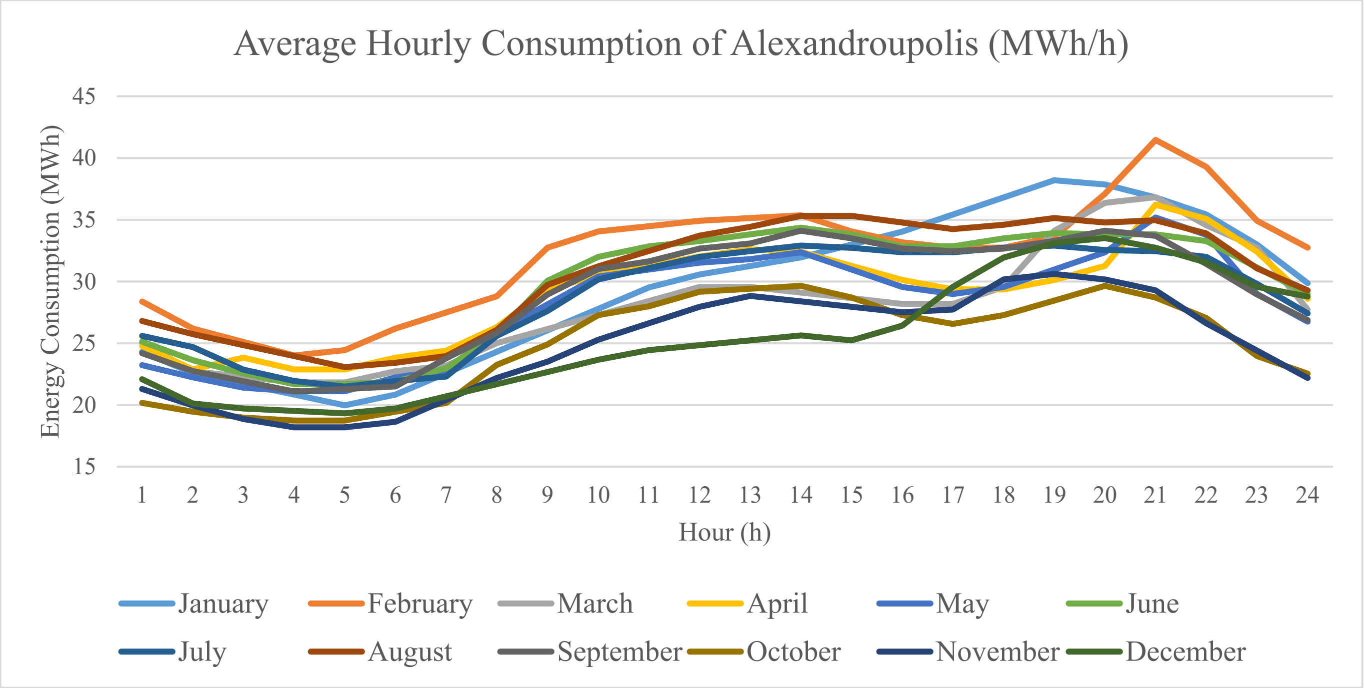


Chart 8. Average Hourly Fluctuation Consumption of Alexandroupolis (MW/h) - (2018-2022). (Source: DEDDIE)

These data are increased to the expected geometric growth of the municipality's population per year and thus the time series of energy needs, in hourly increments, for the lifetime of the project, i.e. 25 years, is obtained.

Table 15 and Table 16 as well as Charts 9 and 10, present the model estimates for monthly and daily energy consumption respectively, both in the first year of the simulation and in the 25th year. Although in Greece it is common for the highest consumption to occur in the summer months, in this case, due to the occurrence of low temperatures during the winter months, high consumption in the winter is inevitable.

Table 15. Projection of Monthly Energy Consumption of Alexandroupolis for the 1st and 25th year of the study.

Month	Average Monthly Demand 1st Year (MWh/month)	Average Monthly Demand 25th Year (MWh/month)
January	22.039	23.682
February	21.729	23.349
March	21.005	22.570
April	20.998	22.563
May	21.028	22.595
June	21.479	23.080
July	21.579	23.187
August	22.919	24.627
September	20.990	22.554
October	18.687	20.080
November	18.007	19.349
December	19.134	20.560

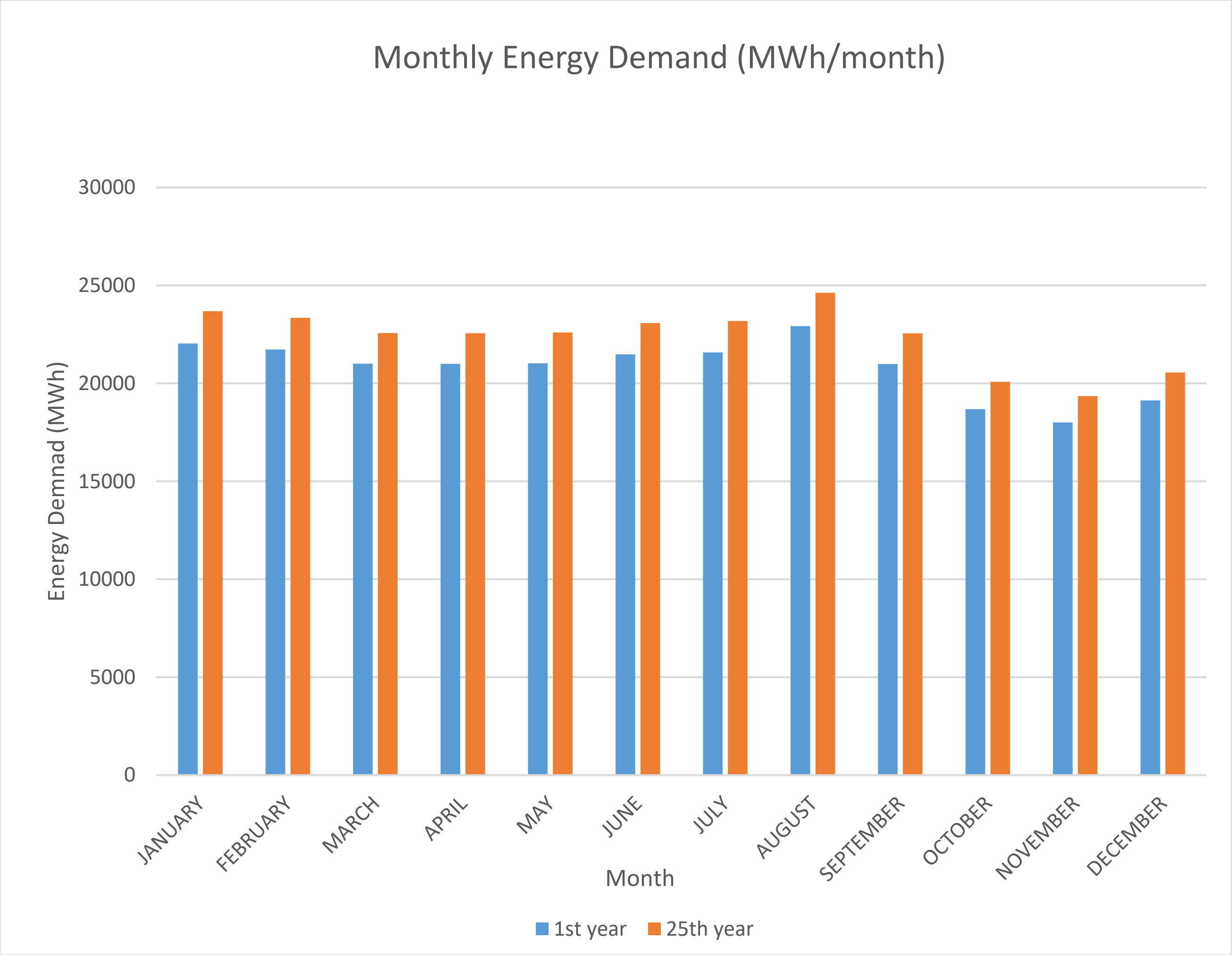


Chart 9. Mean Monthly Energy Demand (MWh/month) for the 1^{st} and 25^{th} year.

Table 162. Projection of Daily Energy Consumption of Alexandroupolis (MWh/d/month) for the 1st and 25th year.

Month	Daily Consumption 1st Year (MWh/d/month)	Daily Consumption 25th Year (MWh/d/month)
January	710,94	763,93
February	776,05	833,88
March	677,58	728,08
April	699,95	752,11
May	678,33	728,88
June	715,98	769,34
July	696,10	747,98
August	739,32	794,43
September	699,67	751,82
October	602,80	647,73
November	600,24	644,98
December	617,22	663,22

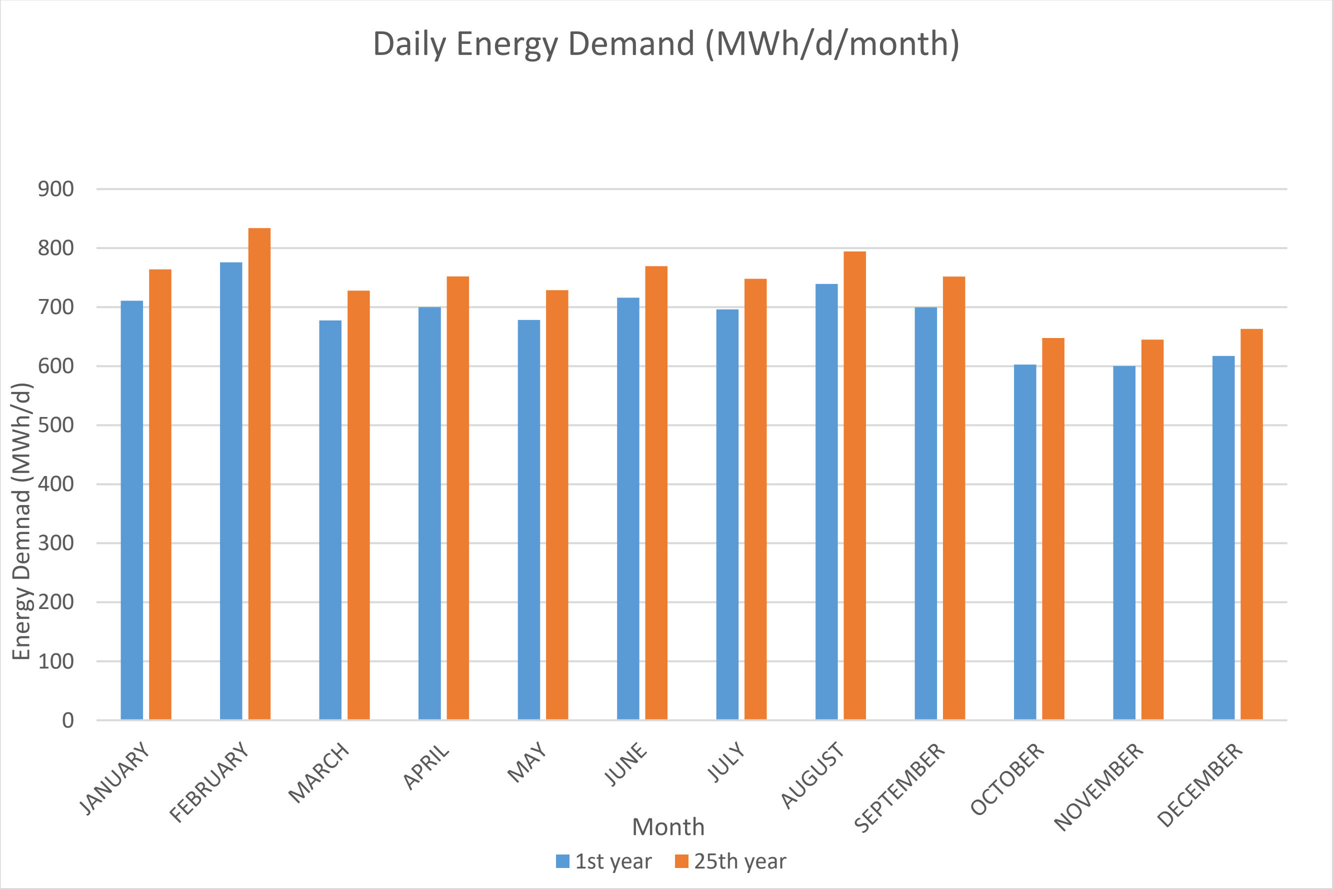


Chart 10. Mean Daily Energy Demand (MWh/d/month) for the 1st and 25th year.

Chart 11 displays the variation in hourly energy demand for an average day for each month for the first year of the project. As would be expected, the rise in the number of residents caused an increase in energy demand when compared to the data in Chart 8. The variation for the 25th and last year of the project is depicted in Chart 12; as anticipated, energy demand is the highest, and we are primarily required to meet this need.

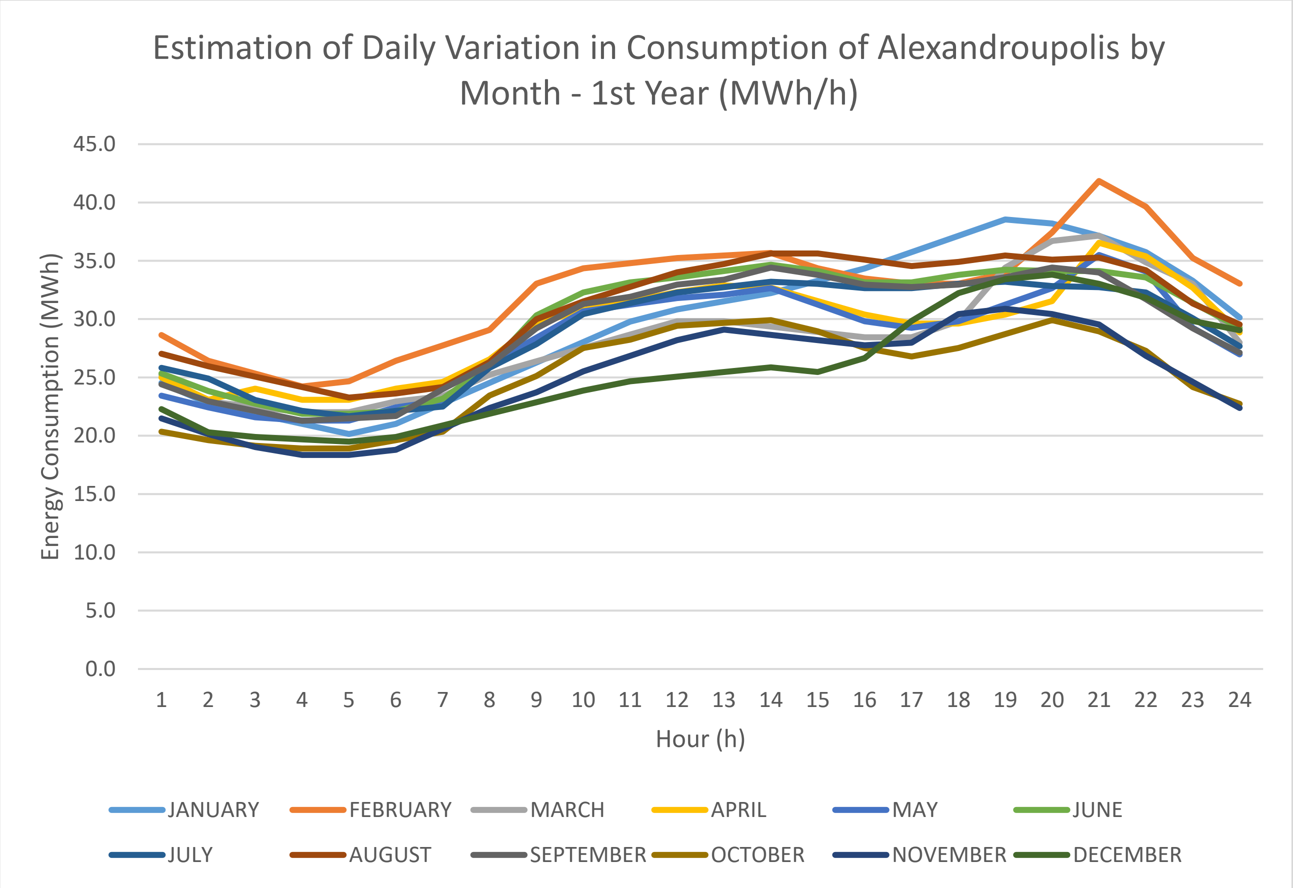


Chart 11. Daily Fluctuation of Energy Consumption of Alexandroupolis per Month for the 1st year of the study

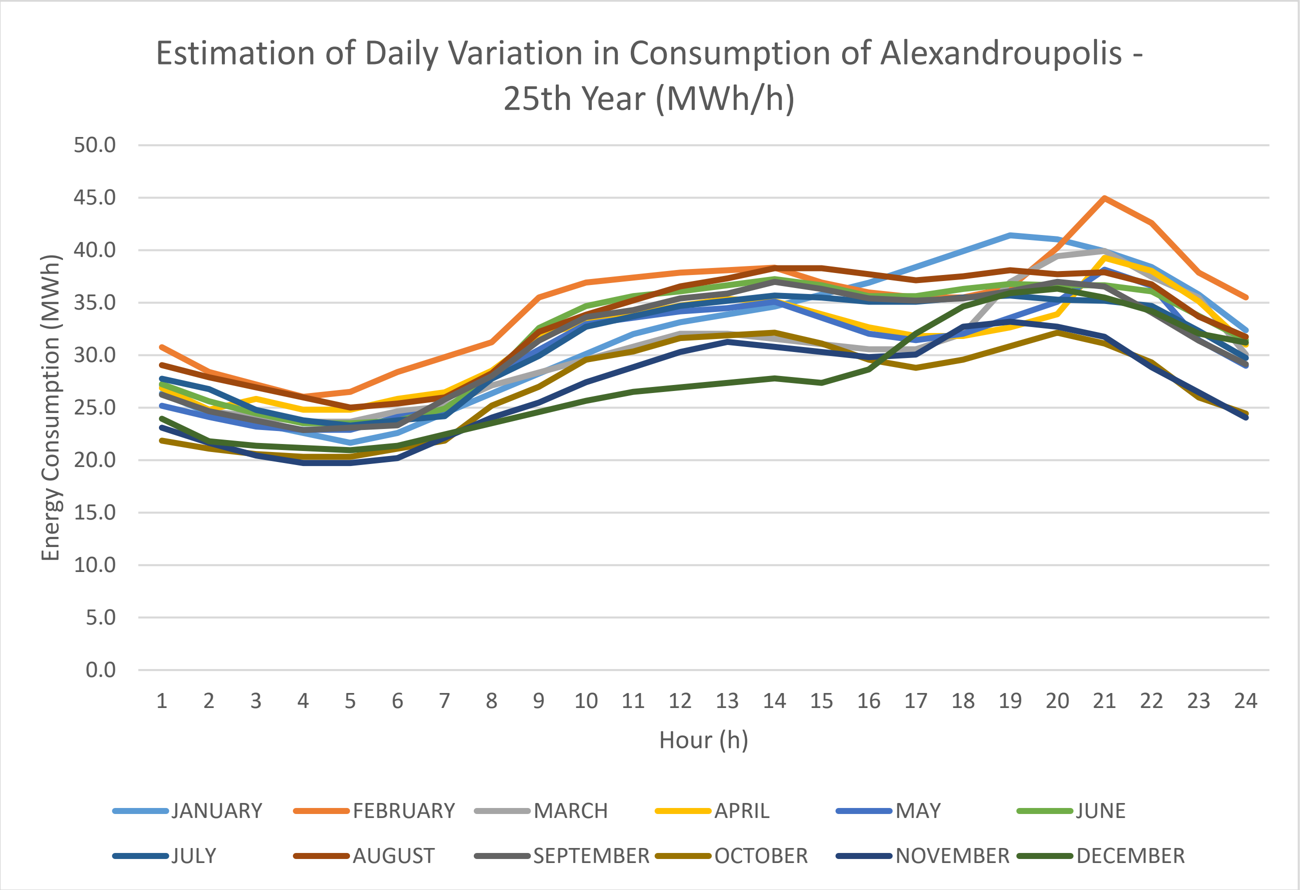


Chart 12. Daily Fluctuation of Energy Consumption of Alexandroupolis per Month for the 25th year of the study

5.5.3. Estimation of the produced energy

In the present thesis, it is proposed to build a floating wind farm in the proposed areas of total installed capacity of 64 MW. This power is derived from 8 wind turbines of 8 MW (Model: SG-8.0-167) of the company Siemens-Gamesa.

For the selection of the model, a comparative method was carried out between the model V112/3450, nominal power 3,45 MW, of the company Vestas and the SG-8.0-167, nominal power 8 MW, of the company Siemens Gamesa Renewable Energy. Both companies are the leading companies in the wind energy industry and pioneers in offshore wind energy. By combining the 25-year synthetic time series and the power curve of each model, the total energy produced at the end of the project's life is calculated. According to the results, SG-8.0-167 proved to be the most efficient. Hence the choice of this model.

Trial and error was used to determine the precise number of wind turbines. In order to prevent the project from being oversized, there shouldn't be any energy surplus each month due to the lack of an energy storage unit. Six out of the twelve months that the installation of nine wind turbines was tested revealed a sizable energy surplus. Installing eight wind turbines is therefore the best course of action, as it avoids energy surplus while providing adequate levels of energy coverage.

The specific offshore wind turbine (SG-8.0-167), has been used to the Hywind Tampen, in Norway, with the total installed capacity of 88 MW and a yield factor of up to 35% and it's the first renewable power for offshore oil and gas in the world. The installation depth of this wind farm is between 260-300 m, and it is 140 km off the coast of Norway. The type of foundation is a floating, type Spar.

Figure 13. Wind Turbines from the Hywind Tampen Norway. (Source: Equinor)

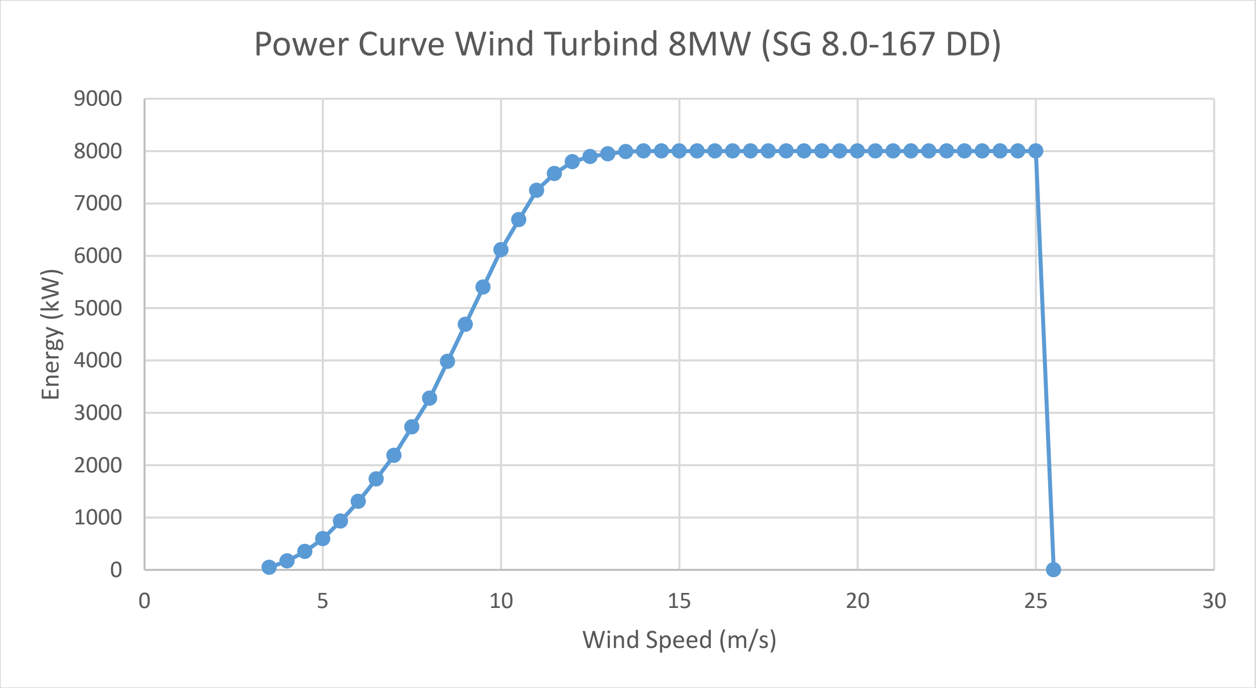


Chart 13. Power curve of the proposed wind turbine to be installed. (Source: WINDPOWER)

At 25 m/s, the wind turbine's impeller ceases to rotate in order to prevent destruction. With a rotor diameter of 167 m and a total altitude of 92 m.

The wind turbine's rotor is located 92 m above sea level, while the National Observatory of Athens reports that the Alexandroupolis station is 4 m above sea level. Therefore, the altimetric correction of the generated synthetic wind time series is applied using the relation (Koutsoyiannis, Xanthopoulos, 1999) since both the altitude of the meteorological station from which the wind observations originate and the altitude of the wind turbine placement are now known:

$$u_2 = u_1 \cdot ln\left(\frac{z_2}{z_0}\right) \cdot ln\left(\frac{z_1}{z_0}\right) \qquad (12)$$

Where in the correction

- u_2: the corrected wind speed at an altitude of z_2 = 92 m, corresponding to the rotor altitude of the Siemens-Gamesa SG-8.0-167 wind turbines
- u_1: the velocity from the synthetic time series referring respectively to the altitude of the station where the measurements were made z_1 = 4 m
- z_0: the ground roughness parameter, the values of which are varied according to Table 17. In this case, it is considered equal to 0,002, (the station is in grass up to 1-10 cm high as shown by aerial photographs at the station coordinates)

Table 17. Typical values of the parameter z_0 (Source: Koutsoyiannis, Xanthopoulos, 1999)

Typical values of roughness parameter z_0 for various natural surfaces (cm)	
Ice	0,001
Asphalt surface	0,002
Water surface	0,01-0,06
Grass height 1 cm	0,1
Grass height 1-10 cm	0,1-0,2
Grass - Grain height 10-50 cm	2-5
Plant Cover height 1-2 m	20
Tree height 10-15 m	40-70

According to Global Wind Atlas, the average wind speed in the siting area is 4,80 m/s (for 10 m altitude) while in the Alexandroupolis area the average wind speed is 4,07 m/s (again for 10 m altitude). After the altimetric correction to the height of the station (4 m altitude), the average wind speed is 4,04 m/s. According to the data form the National Observatory of Athens the mean wind speed of the Alexandroupolis area is 3,7 m/s. Thus, the percentage change is equal to 9,6%, so the time series is corrected accordingly.

6. Results – Discussion

6.1. Spatial Planning of the Offshore Wind Farm

The process of optimizing the location, design, and management of offshore wind farms involves a thorough integration of environmental, social, and economic factors through spatial planning. Planning well guarantees that offshore wind farms are socially, economically, and sustainably acceptable, which makes a major contribution to the world's shift to renewable energy sources.

6.1.1 Site selection for the OWF

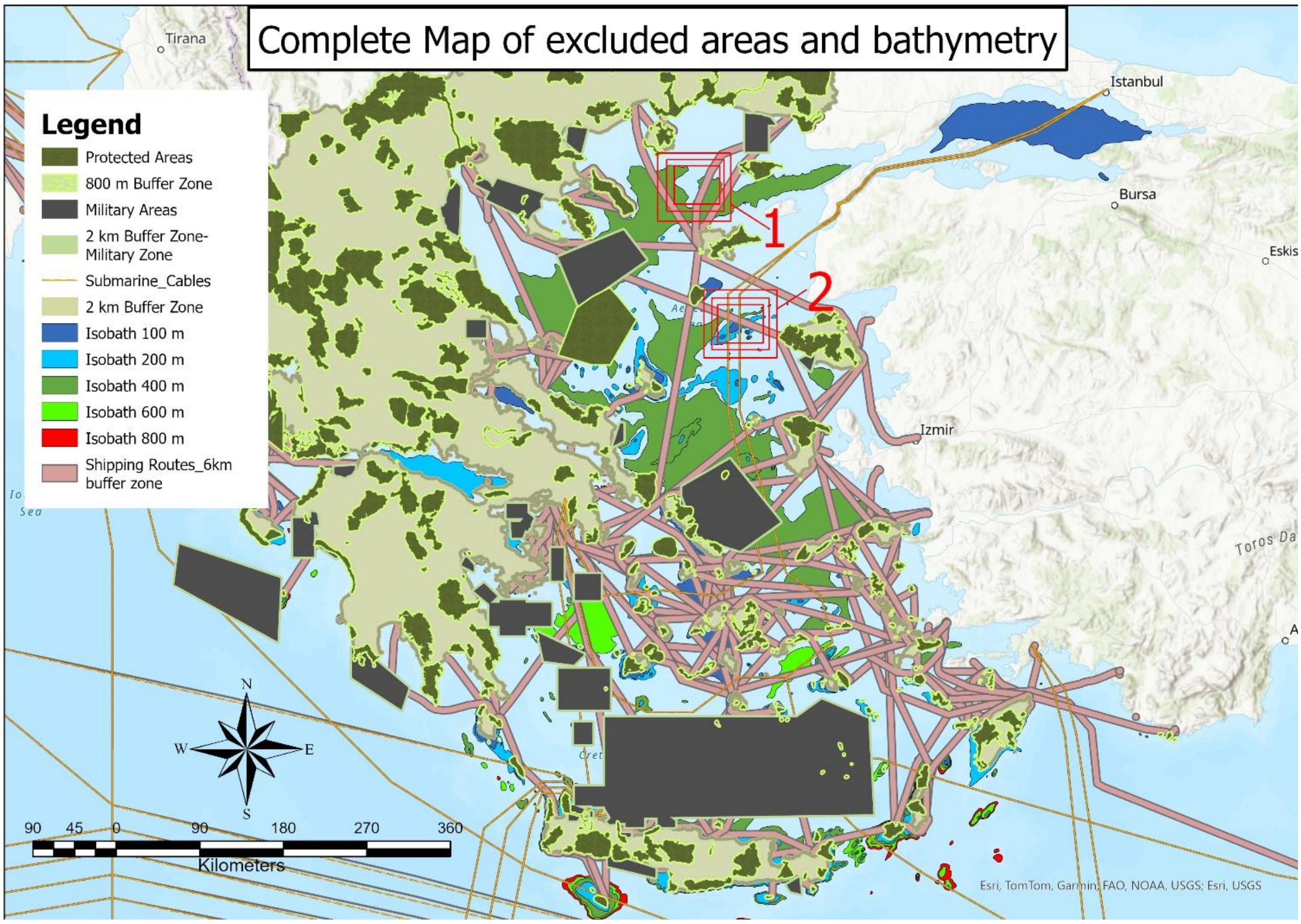
Following the process of exclusion and taking into account all the factors that influence the precise location of a wind farm, the next stage is to choose the exact area for the OWF. The first step to accurately locate the site of a marine wind farm is based on the map created in chapter 4.

For this study, initially, two areas are qualified.

-The first is southeast of Thassos and northwest of Lemnos,

-The second area, suitable for the siting of a wind farm, is north-west of Mytilene and south-east of Lesvos.

The locations of the offshore wind farm that will best serve Alexandroupolis' energy needs are depicted in Map 9. HEREMA has designated the sea area between Alexandroupolis and Samothrace as a pilot project development area for OWF development. As a result, this specific sea area is not qualified.

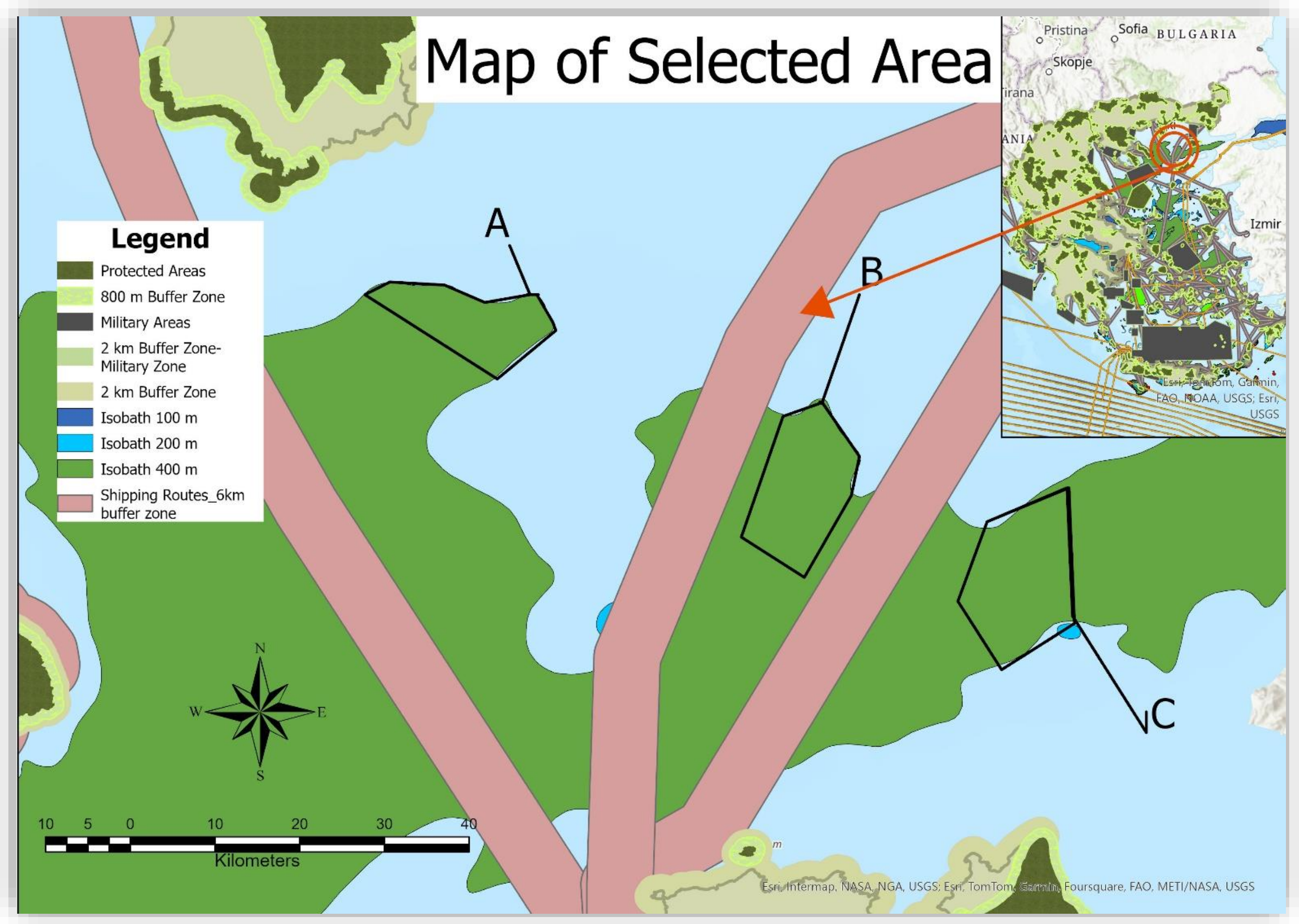


Map 9. Qualified placement areas for the offshore wind farm. (Source: ArcGIS Pro)

Between these two areas, the most suitable location for the marine wind farm is number 1. The decision was made because of the OWF's closer proximity to Alexandroupolis, as well as the lighter load on shipping lanes and submarine cables. That is, between the islands of Thassos and Lemnos. Map 10 shows a plan view of the selected area, as well as the sub-areas that are possible for the siting of the wind farm.

The selected area is located at an isobath of 400 m, ideal for the placement of offshore wind farms and the exploitation of wind potential.

- Area A has an area of 100 km^2 and the closest island to this area is Thassos, at 21 km.
- Area B has an area of 167 km^2 and closest island to this area is Samothraki, at 29,61 km.
- Area C has an area of 198 km^2 closest island to this area is Samothraki, at 16 km.



Map 10. Selected Area for the siting of the offshore wind farm. (Source: ArcGIS Pro)

The selected sub-area where the OWF will ultimately be located is **Area A**. As mentioned in Chapter 5, Area A has a wind potential of 4,7 m/s at a measurement height of 10 m, according to the Global Wind Atlas. Furthermore, the vast expanse of unrestricted sea front and rear of the location is another reason why Area A was chosen. Finally, to prevent visual disturbance to any island's residents, a 20 km buffer from the mainland is also accommodated in area A.

6.1.2. Detailed Design of OWF

The wake effect is a crucial component that needs to be taken into account while determining the precise locations of each wind turbine and the distances between them. Strong turbulence is produced in the air and the wind speed is decreased during wind turbine operation in order for the wind turbine to generate power. The downstream wind need a specific distance to reach its initial speed because it is moving at a slower pace. In addition, the wind's turbulent velocity causes it to interact with the sea as it goes downstream, affecting the wind turbines which are located by the sides. (Politis et al., 2011).

Figure 14 shows how the wake effect works. The air speed is constant upstream of the wind turbine. The air speed is not only lower but no longer constant downstream of the wind turbine, particularly at near-wake.

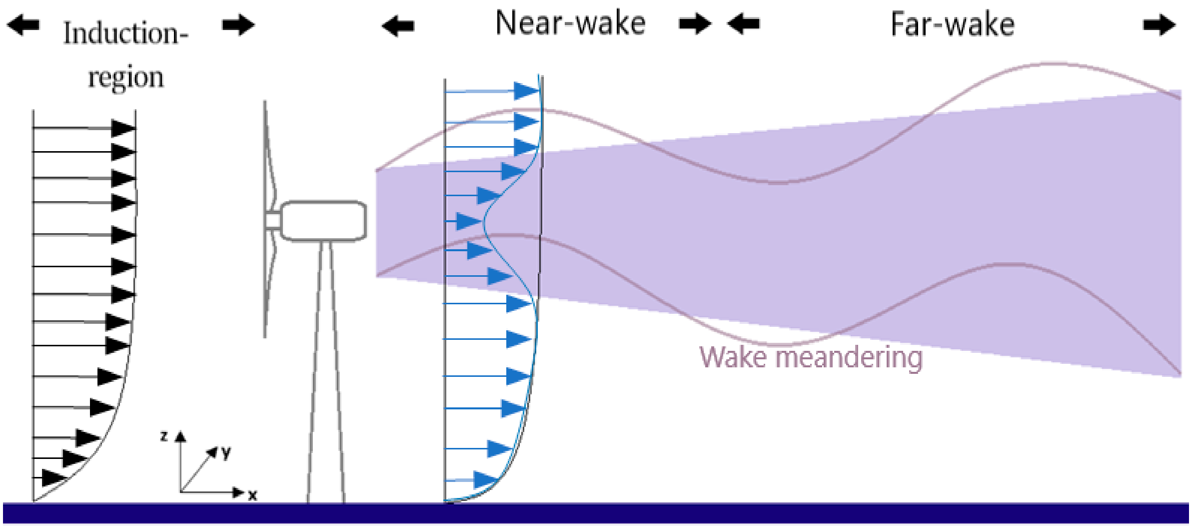


Figure 14. Wake effect. (Source: Alaoui-Sosse et al., 2022)

To address the above problem, a distance of 3-5 D (diameter) is required for wind turbines in the same row and 5-9 D for wind turbines in the same column (Masters, 2004). Figure 15 shows the allowable distances between the turbines so that the wake effect does not affect the productivity of the wind farm.

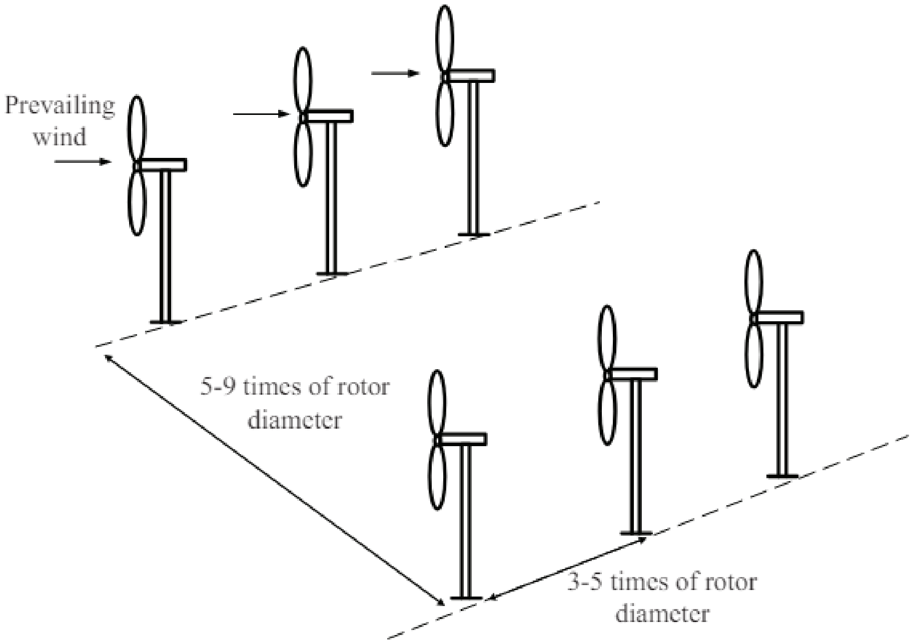
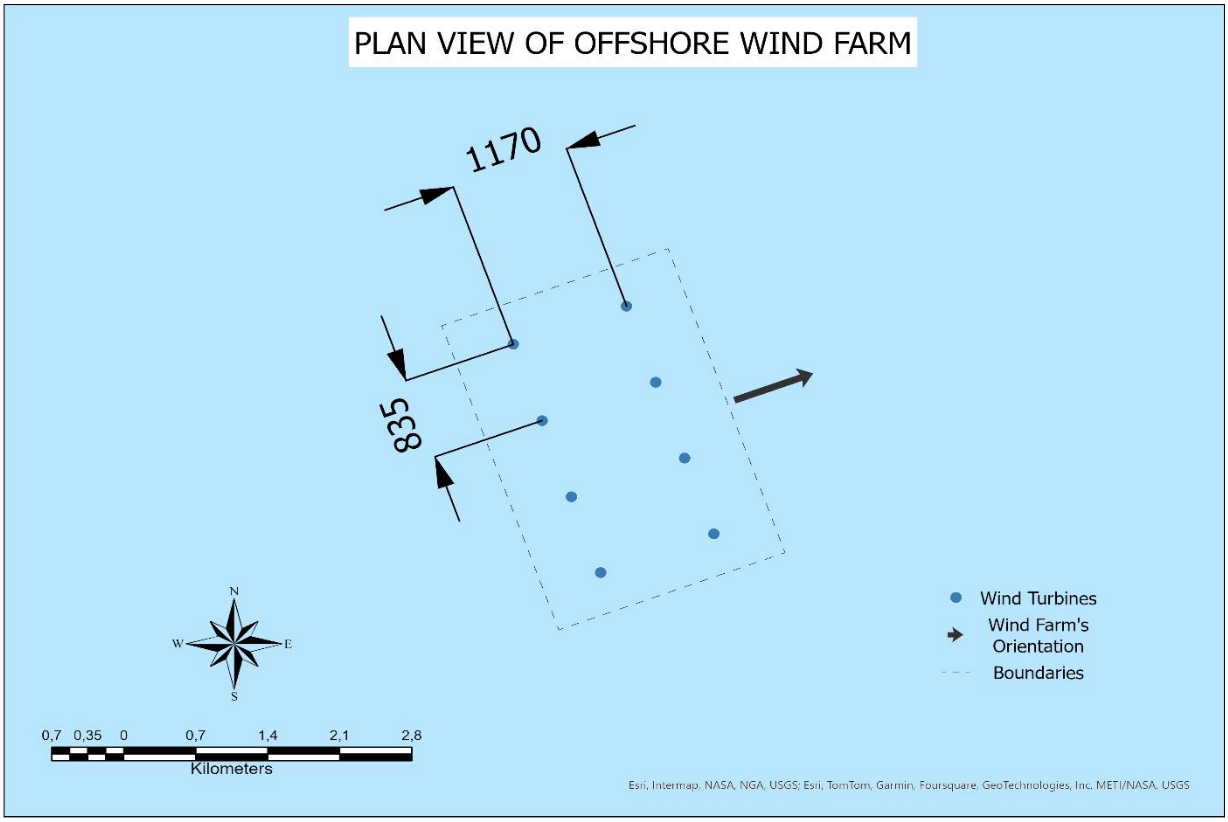


Figure 15. Distances between Offshore Wind Turbines. (Source: Gupta, 2016)

For this offshore wind farm, the selected distance for the wind turbines in the same row is 5D, i.e. 835 m and for the wind turbines in the same column is 7D, i.e. 1.170 m.

Additionally, fixed orientation wind turbines have been chosen as the specific type. As a result, the wind turbines' orientation must be precisely opposite to the direction in which the local wind blows. According to historical wind data obtained from HNMS, the wind speeds blowing in the area have an average origin from northeast, precisely 70 degrees.

Map 11 shows the layout of the offshore wind farm.



Map 11. Layout of the OWF. (Source: ArcGIS Pro)

The last step is to define the type of floating bearing of the wind turbines. The floating bearing chosen is a Spar buoy platform. The advantages for which this type of platform is chosen are listed below (Bashetty, Ozcelik, 2021):

- Lower impact from waves on the wind turbine's static
- Simple Design
- More efficient at great depths than other floating bearings.

For the accurate calculation of the dimensions of the floating bearing and the mooring cables, a detailed study of the waves in the area and their effect on the wind turbines is required. As this is not the scope of the current thesis, some characteristics of the floating foundation will be mentioned.

- Mooring cables must have a length at least 4 times larger than the sea depth, (Asim, et al, 2022)
- Mooring cables must have an angle of 120 degrees between them.

Mooring cables are a very important part of the anchoring of wind turbines. All floating wind turbines have a circle of free movement in the sea, known as a watch circle, with a usual diameter of 180 m (Asim et al, 2022). The length and quality of the cables (flexibility, durability) determine the movement of the wind turbines. Every component of the floating spar structure is depicted in Figure 15. The diameter of the floating structure increases as it descends from a few meters above sea level. The anchor cables are visible in addition to the anchors and the solar power cables.

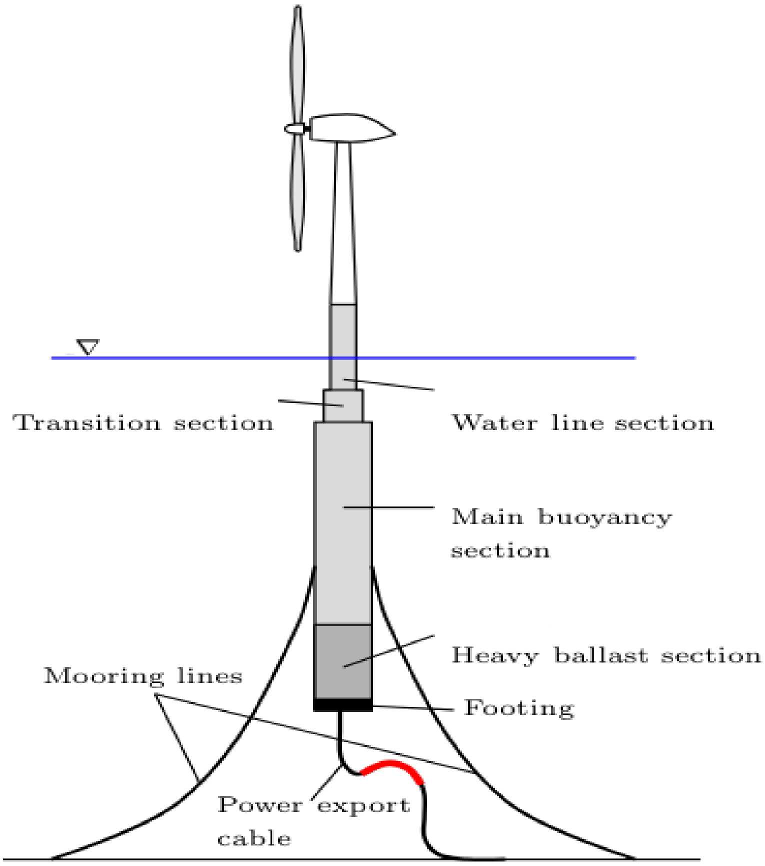


Figure 16. Section of a Spar buoy platform. (Source: Fylling, Berthelsen, 2011)

For a more realistic illustration of the above, a digital representation of both the offshore wind farm and Siemens Gamesa SG-8.0-167 is shown in Figures 17 and 18. The Siemens Gamesa SG-8.0-167 wind turbine, which is planned for installation at the offshore wind farm, is depicted in Figure 17 in front view along with its dimensions.
4 of the 8 turbines that will be installed are depicted in Figure 18, along with the distances between them.

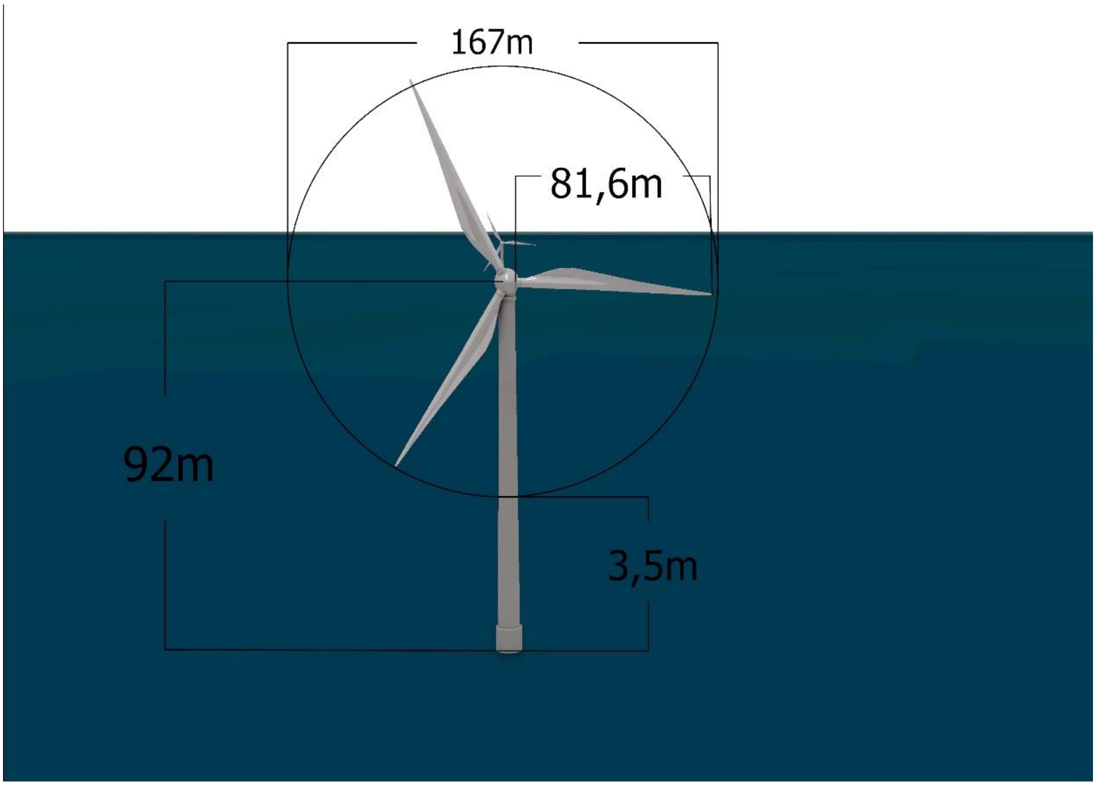


Figure 17. Front View of Wind Turbine, Siemens Gamesa SG-8.0-167. (Source: ArcGIS Pro)

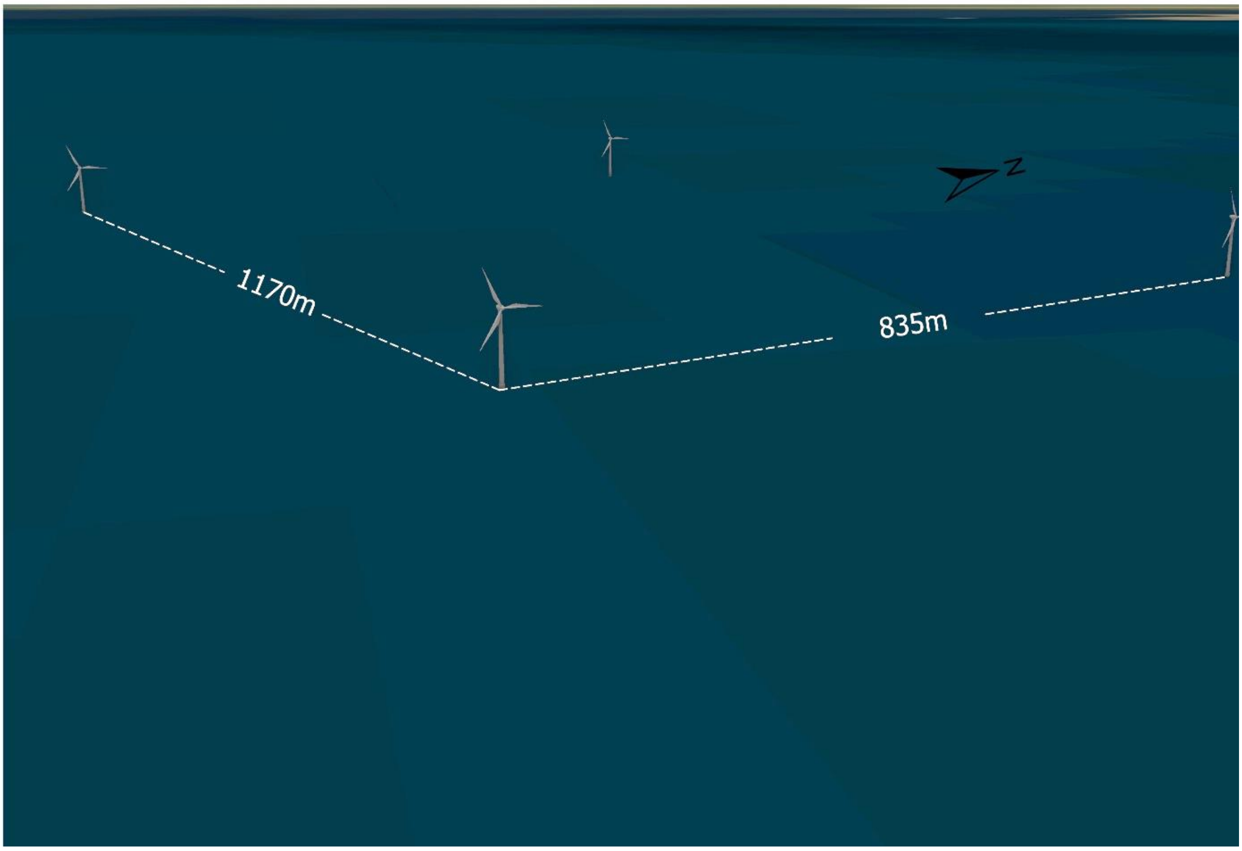


Figure 18. Plan View of OWF, and the distances between wind Turbines. (Source: ArcGIS Pro)

6.2. Coverage Assessment of Energy Needs of Alexandroupolis via OWF

The energy produced by the wind turbine is estimated using chart 13’s power curve of the model in question. The time series of the energy produced by OWF is generated with an hourly step based on the wind time series and the power curve. The following components are shown below in tabular and graphical form based on the data analysis.

Table 18 shows the average energy produced per day and per hour for each month during the lifetime of the project. It also shows the standard deviation of the hourly energy produced for each month during the lifetime of the project.

Table 18. Wind power generated and other figures for each month during the project lifetime

Month	Average total daily wind energy generated (MWh)	Average Value of Produced Wind Energy (MWh/h)	Standard Deviation of Wind Energy Generated (MWh/h)	Average Coverage Value (%)
January	417,83	17,41	55,98	56,71
February	574,72	23,95	62,97	71,46
March	531,46	22,14	58,86	75,68
April	665,34	27,72	61,00	91,72
May	623,92	26,00	57,80	88,75
June	517,38	21,56	56,24	69,73
July	621,80	25,91	56,56	86,19
August	599,52	24,98	58,83	78,25
September	502,73	20,95	55,03	69,33
October	254,06	10,59	45,01	40,67
November	336,02	14,00	52,29	54,02
December	462,05	19,25	56,98	72,23

The average daily energy produced and consumed for each month are displayed in Chart 14. The summer months have a good coverage rate, although February, a month with a lot of energy demand, has a low coverage rate.

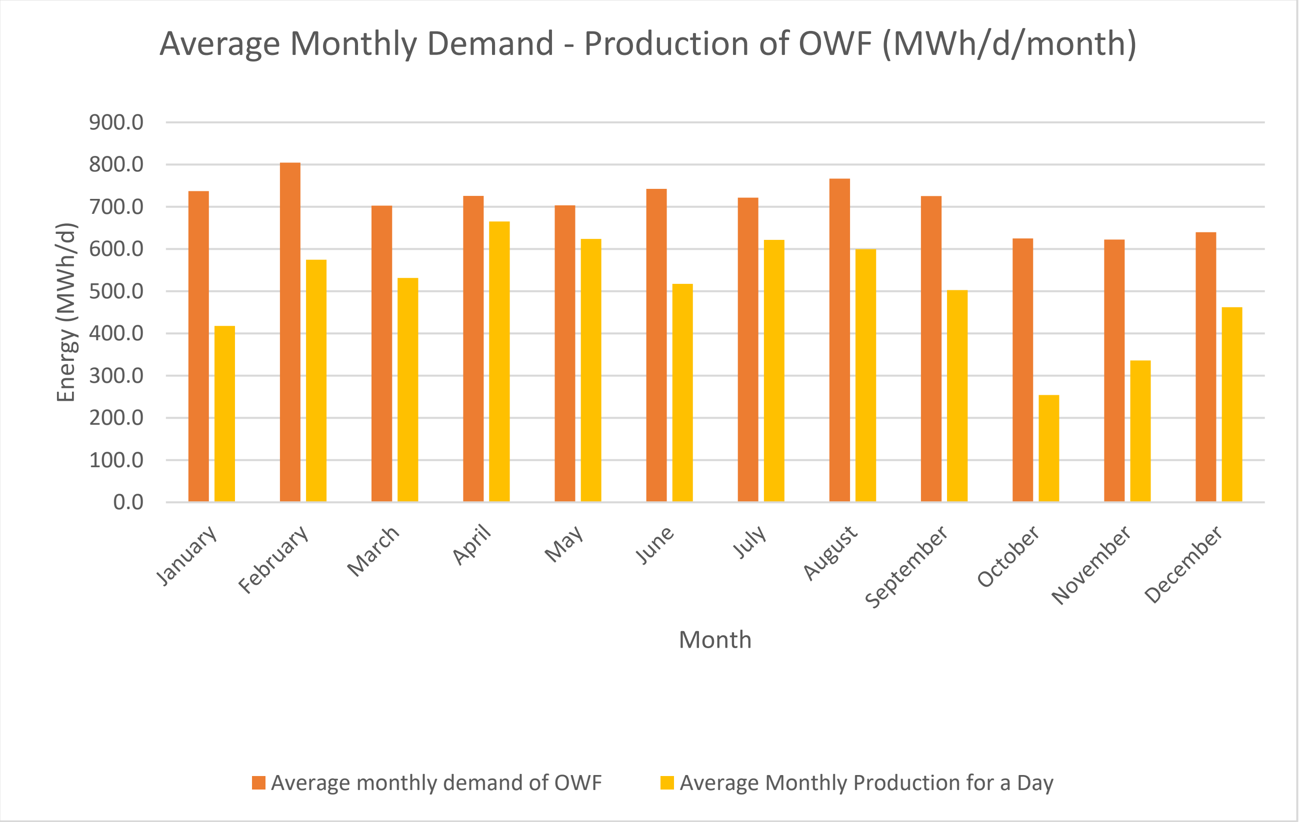


Chart 14. Average total daily wind energy generated from OWF (MWh/d/month)

Table 19 shows the average daily energy demands over the lifetime of the project. as expected, the summer months and February are the months with the highest energy demand.

Table 19. Average Monthly Demand for a Day (MWh/d)

Month	Average Monthly Demand for a Day (MWh/d)
January	737,1
February	804,6
March	702,5
April	725,7
May	703,3
June	742,4
July	721,7
August	766,6
September	725,4
October	625,0
November	622,4
December	640,0

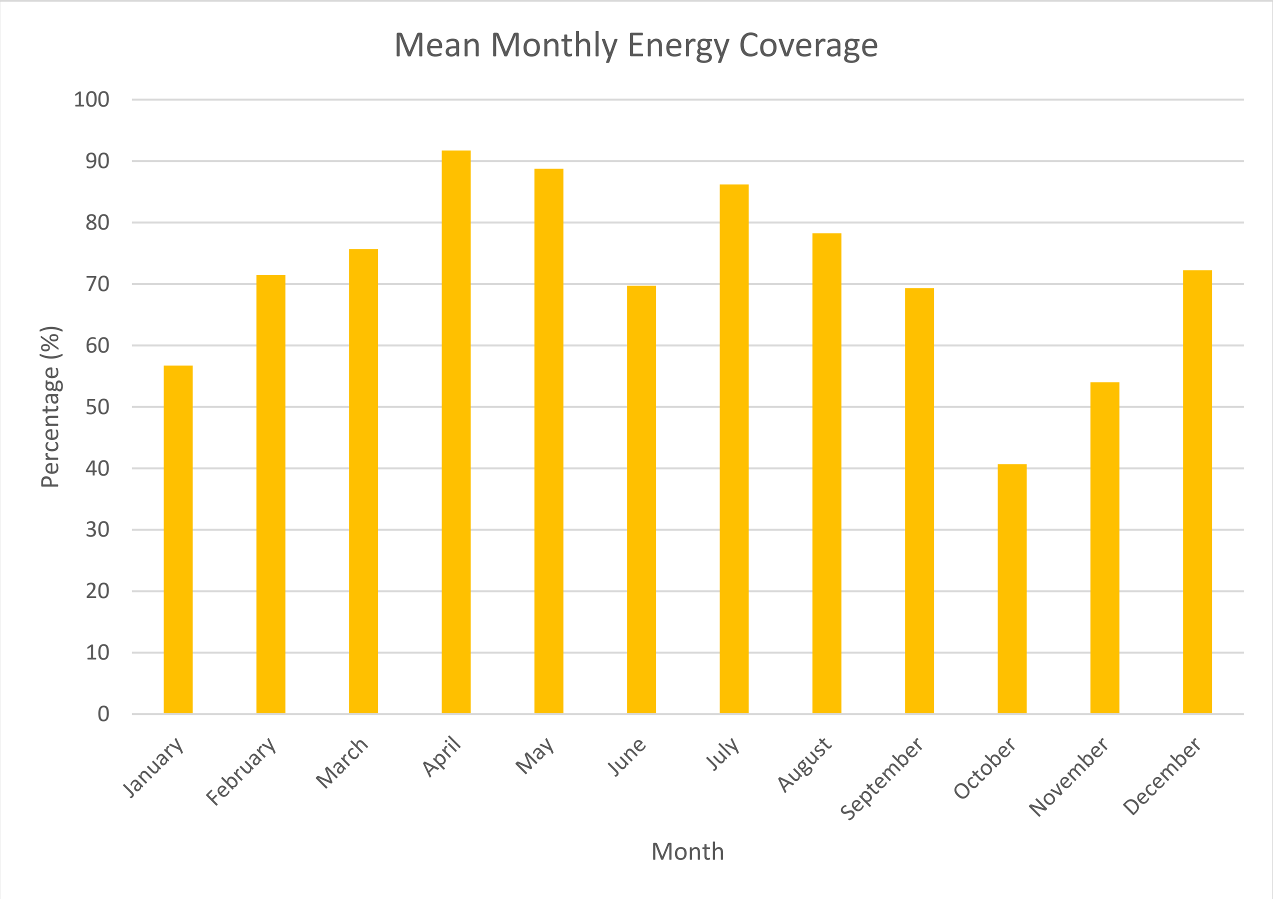


Chart 15. Mean Monthly Demand Energy Coverage of Alexandroupolis from the OWF

Based on Chart 15, it can be noticed that April has the highest coverage of energy demands, at 91,7%, while October has the lowest percentage, at 40,6%. This is due to the fact that October has the lowest wind potential of any month. With the exception of October, every other month's average has a rate of over 50%.

Chart16 shows the average hourly energy produced and the standard deviation over the lifetime.

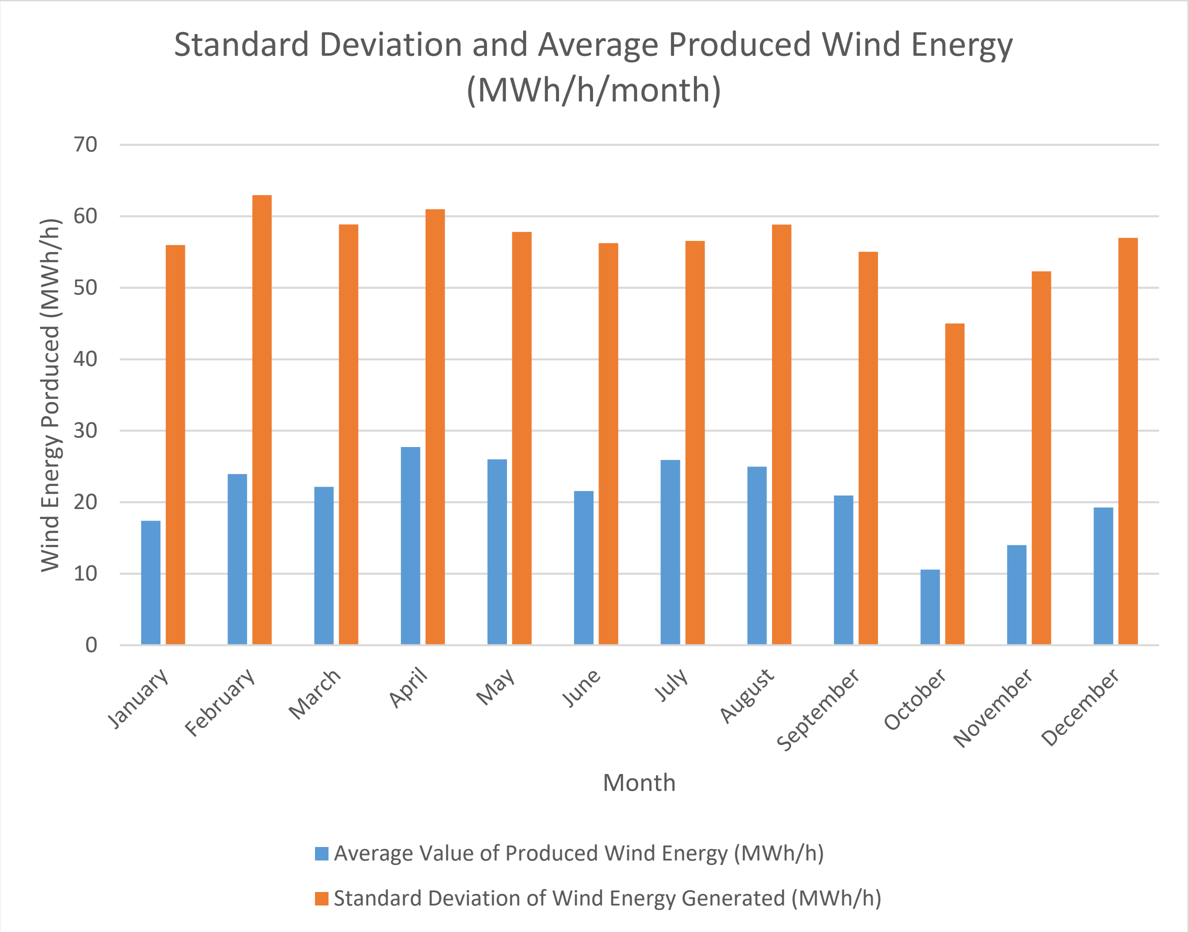


Chart 16. Mean Value and Standard Deviation for hourly and energy produced by month

The excess and deficit of wind energy produced in relation to demand for the 1st and 25th year of the project life are displayed in hourly increments in Chart 17 and 18.

As shown below, in the first year of project life, the largest excess wind energy produced is 43,72 MWh, while the largest deficit is 41,84 MWh. In the 25th year, the largest excess of produced wind energy is 42,21 MWh while the largest deficit is 44,96 MWh.

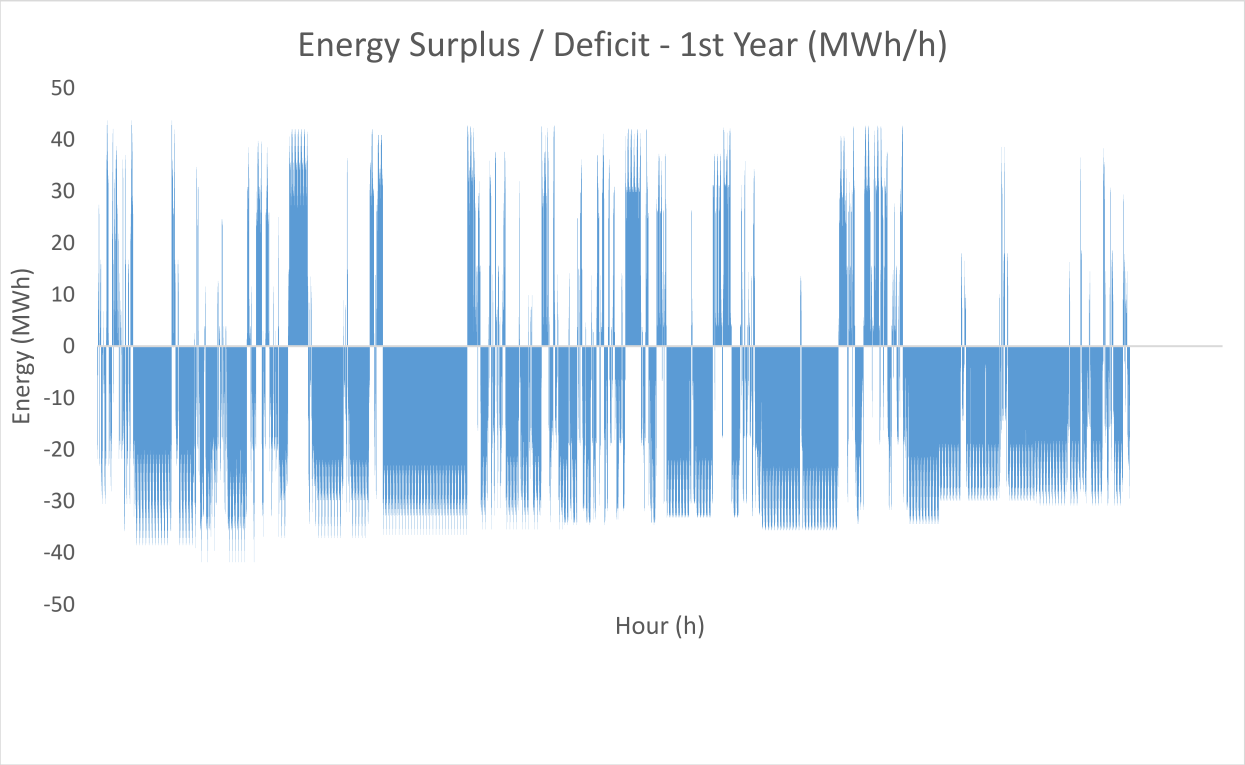


Chart 17. Energy Surplus and Deficit with hourly step for the 1st year

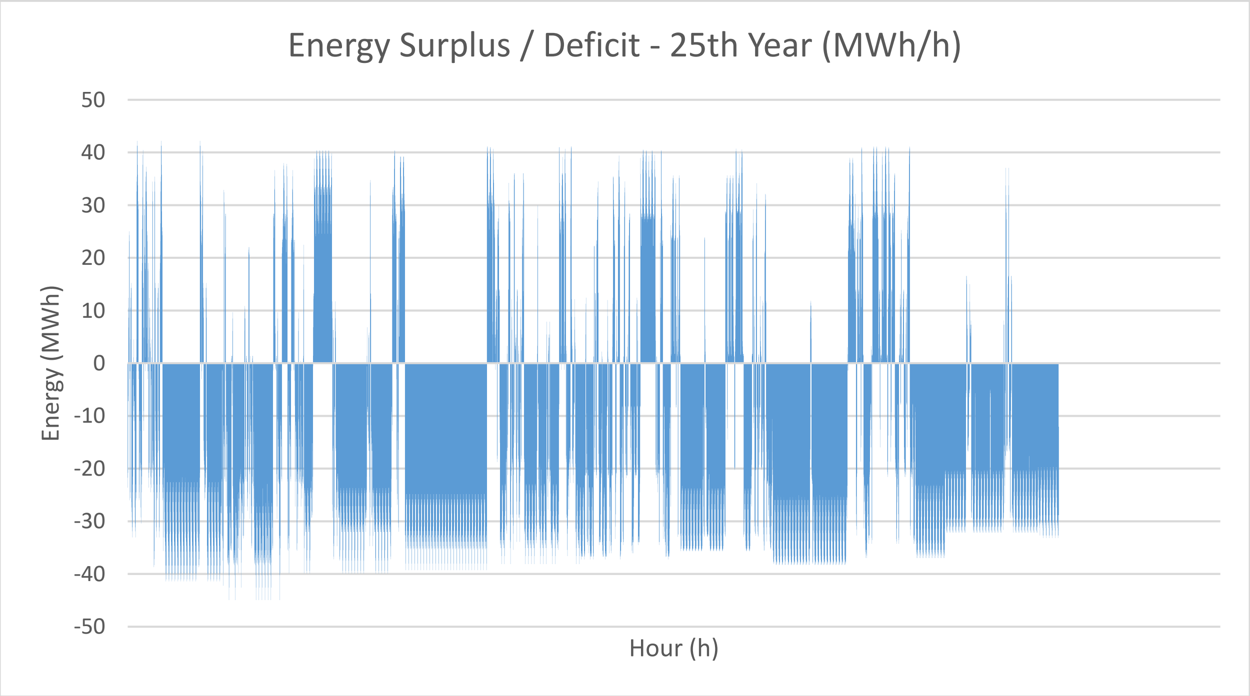


Chart 18. Energy Surplus and Deficit with hourly step for the 25th year

Table 20. Coverage percentage of energy needs (MWh/y)

Coverage percentage of energy needs by year			
Year	(%)	Year	(%)
2024	49,7	2037	65,6
2025	78,6	2038	77,1
2026	77,6	2039	70,7
2027	85,2	2040	68,7
2028	65,8	2041	70,3
2029	86,9	2042	68,3
2030	71,5	2043	59,4
2031	90,6	2044	58,0
2032	77,5	2045	67,9
2033	69,7	2046	58,8
2034	83,0	2047	64,3
2035	75,2	2048	78,5
2036	75,2		

According to Table 20, the year 2031 has the largest coverage percentage of energy needs met at 90,6%, while the first year of the project has the lowest proportion at 49,7%. This is due to the fact that, even though our energy needs in 2024 will be the lowest of the project's years, wind potential will also be the lowest.

Chart 19 and 20 show the percentage of energy requirements covered per year and the total energy production per year. The results in chart 19 show that coverage rates per year depend on both energy demand and wind potential each year.

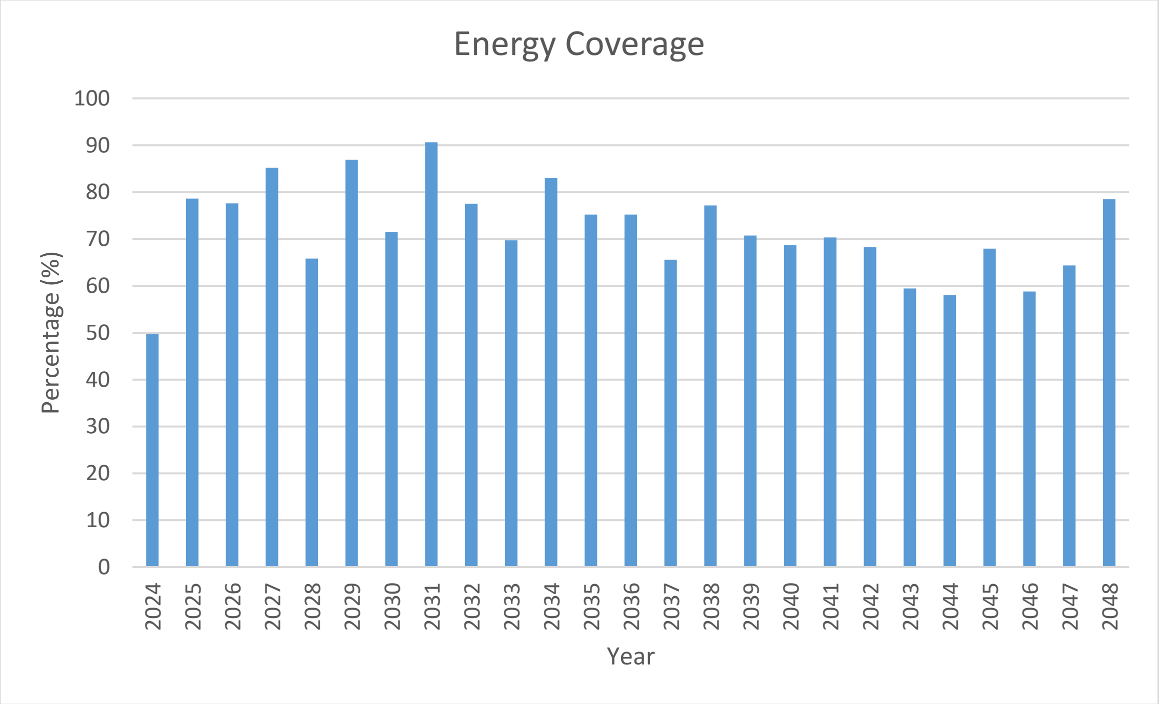


Chart 19. Coverage Percentage of Energy Needs by year.

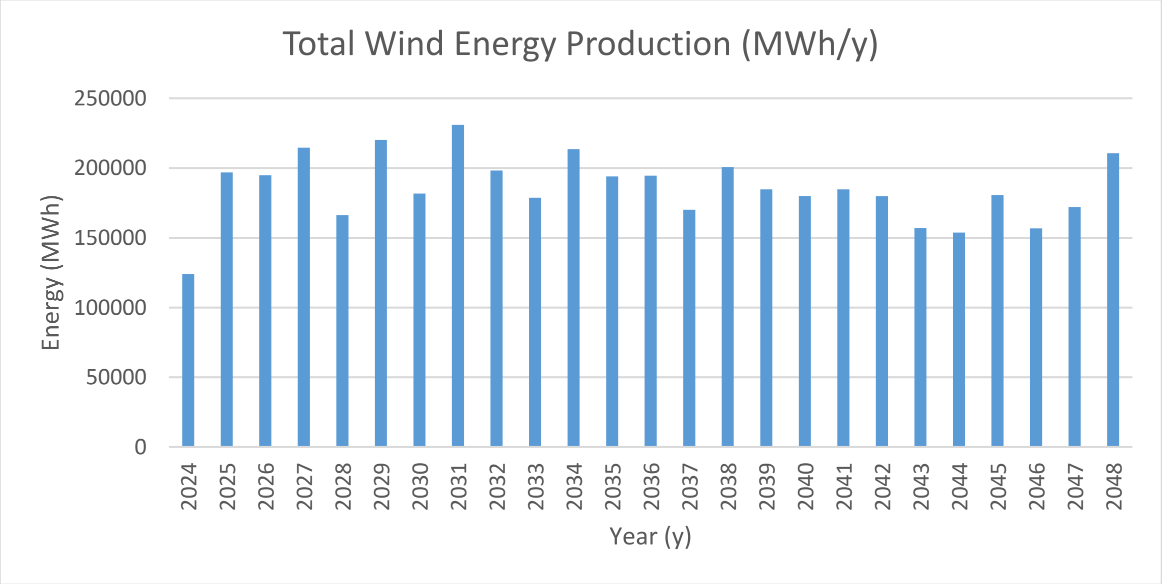


Chart 20. Total Amount of Energy Produced for every year of project life. (MWh/y)

7. Conclusions

7.1. Discussion

This thesis is focused on the siting of an offshore wind farm in Greek territorial waters and on the methodology of covering the energy needs of the municipality of Alexandroupolis by a wind farm. The best site for the floating wind farm was determined by taking into account the relevant laws, the technology of the wind turbines, the city's energy requirements, and the zoning of the national waters. The outcomes are extremely positive and demonstrate that the goal of Alexandroupolis' deglaciation is doable. Greece possesses considerable wind potential, as previously mentioned and illustrated, as well as a multitude of areas in marine waters that may be suitable for offshore wind farm placements.

In order to comply with EU regulations for 2030 and 2050, it is imperative that all relevant parties come together and launch projects that will immediately begin to utilize offshore wind potential. Socioeconomic factors also play a role in the pressing need for the development of these initiatives. A move to the water is unavoidable given the public's rising hostility to the construction of wind farms on land.

Applying OWF spatialization leads to some specific conclusions. First and foremost, wind energy utilization heavily depends on wind power. By selecting a location with a high wind potential, more energy is generated. As a result, energy requirements are met more affordably. Bathymetry significantly affects the choice of foundation method and wind turbine model but at the same time it is closely related to the wind potential mentioned above. The safe distance from the protected areas ensures the avoidance of disturbance of natural ecosystems and ensure the smooth coexistence of OWF and environment. Safe distance from the shipping lines is essential for continuing the smooth conduct of the social activities of the village. Safe distance from submarine cables is another very noteworthy element of applying OWF spatialization. Last but not least, the minimum distance from the land to avoid the visual and acoustic disturbance of the inhabitants is important. This achieves the coexistence of wind energy and wind.

It is important to note that the thesis researcher claims that all of the aforementioned factors were considered equally when determining the OWF's final position. The migratory bird pathways through Greece are also a significant consideration in the selection of the OWF location. They were not considered in this thesis, nevertheless.

As regards the application of the methodology of covering the energy needs of Alexandroupolis, the following conclusions were drawn. Firstly, despite the declining population over the last decade, in order not to lead the project to sub-dimensionalization, an estimation to a possible geometric increase in population has taken into consideration. This population growth leads to future energy needs that are favorable to security purposes. Secondly, the operation of the OWF will lead to reduced carbon dioxide emissions, as the energy needs of Alexandroupolis will now be served through wind energy and not through the PPC's lignite units.

7.2. Recommendations for future research

It is understood that the outcomes differ based on how the spatialization criteria are applied.

A number of observations made during the study call for more research. Fisrtly, the geological aspects. Geological studies are necessary to determine important characteristics of an offshore wind turbine such as type of anchor, weight of anchor, and type of mooring cables. Environmental studies must also be conducted in order to protect marine ecosystems and to develop technology for floating marine parks that also consider more environmental protection. To ensure precise calculations for the floating platform, anchor cables, and anchors, it is also essential to examine the wave behavior of the location of the wind farm. Lastly, to guarantee the protection of migratory birds, a thorough report of their travel routes must be made.

Furthermore, stochastic methods should be used to analyze the energy demand at the stage of the project's life in order to guide the research toward safer and more accurate conclusions.

Ultimately, since energy needs are being adequately covered, a technological and economic study should be conducted with the goal of expanding the wind farm in the future and exporting energy to neighboring nations in order to utilize Alexandroupolis' advantageous location.

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