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Energy Islands in Greece: Are they Feasible in Aegean Sea?

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Abstract

The future development of energy islands in North Sea is going to assist the further growth of offshore wind farms in a territory characterized by rich wind energy resources. The development of offshore wind farms in Aegean Sea, which is characterized by high mean annual wind velocities, is in the initial phase while it is foreseen that by 2050 the electricity generated by offshore wind farms will have a high share in the energy mix in Greece. The future interconnection of the electric grids of the small islands in Aegean Sea with the grid of continental Greece is going to trigger the development of new renewable energy installations in these islands reducing the current use of oil-based fuels in them. The development of offshore wind farms in Aegean Sea could be combined with green hydrogen production, when it is profitable, while it could be also used in the future for electricity generation from sea waves. The future development of physical energy islands in the Archipelago combined with the development of offshore wind farms and the interconnection of the small islands' grids could promote the further development of the rich solar and wind energy resources in Aegean Sea assisting the de-carbonization of the Greek power system. The current work could be useful to policy makers, to local and regional authorities as well as to energy companies which are willing to invest in renewable energy systems in Aegean Sea.

Keywords: Aegean Sea, Energy Islands, Energy Storage, Grid Interconnection, Hydrogen, Offshore Wind Farms

1. Introduction

The achievement of the global target for net-zero emissions by 2050 requires the increasing use of renewable energies which are not fully exploited in many territories so far like offshore wind energy. The development of artificial energy islands is North Sea assisting the further growth of offshore wind farms in this area has been investigated [1, 2, 3, 4]. Apart from offshore wind farms the feasibility of offshore solar-PV systems in several areas has been also examined [5, 6]. Co-production of green hydrogen and wind electricity in offshore wind farms has been also studied [7, 8, 9]. The development of renewable energy systems minimizing the use of fossil fuels in small non-interconnected Greek islands located in Aegean Sea has been also investigated [10, 11, 12]. Offshore wind farms in the region of Aegean Sea which is rich in wind energy resources have not been developed so far [13].

Aims of the present study are:

a) *The investigation of the future development of offshore wind farms and green hydrogen production in Greece,*
b) *The investigation of developing new renewable energy systems in small islands located in the Aegean Sea Archipelago after the interconnection of their grids, and*
c) *The investigation of the possibility of future development of energy islands in Aegean Sea.*

The structure of the paper is as follows: After the literature survey the development of energy islands in North Sea and the future development of offshore wind farms and green H_2 production in Greece are examined. Next, the interconnection of the grids of the small islands located in Aegean Sea and the development of zero-energy islands in the Archipelago are analyzed. The text continues with the possibility of developing energy islands in Aegean Sea followed by the discussion of the findings, the conclusions drawn and the citation of the literature used. The current study is innovative taking into account the lack of similar studies in Greece while it fills the existing gap regarding the development of energy islands in Aegean Sea. The results could be useful to policy makers, to local authorities as well as to energy companies which are interesting to invest in large-scale renewable energy systems particularly in offshore wind farms and in green H_2 production.

2. Literature survey

The literature survey is separated in two sections: The first is related with the development of energy islands in North Sea and the second with the development of onshore and offshore renewable energy systems in Aegean Sea and in other territories.

2.1 Development of energy islands in North Sea

The legal framework for artificial energy islands in northern seas has been studied [1]. The authors stated that Belgium, Denmark and the Netherlands have expressed their interest in constructing "*energy islands*" to enable the integration of large-scale offshore wind energy into the energy system. They also mentioned that a compromise between the Unities Nations convention law of the sea and the EU law should be achieved regarding this issue. The pioneer role of Denmark in the development of energy islands has been analyzed [2]. The authors stated that Denmark is going to develop two energy islands in North Sea which are going to be ready by early '30s. They also mentioned the necessary conditions which should be fulfilled for the successful implementation of an innovative and complicated project. Additionally, they stated that a total wind power at 300 GW could be developed in North Sea by 2050**.** The impacts of the two planned North Sea energy islands, including Bornholm Island and an artificial island, on national markets and grids have been studied [3]. Taking into account that these two islands are the first-of-their-kind projects the authors stated that these offshore energy hubs in Northern Europe will increase the welfare in EU countries. However, they mentioned, the benefits will not be equally distributed among countries the legal status of the development of a sand-based offshore energy island under the Dutch jurisdiction has been assessed [14]. The authors stated that it is currently unclear how an energy island would be defined legally. They also mentioned that there is lack of an appropriate definition in the international law for various forms of sea infrastructures such as energy islands. A discussion paper regarding the undersea electric cables of Bornholm Island has been published [15]. Bornholm Island is being developed as a hub for wind electricity generation transmitted via undersea cables to Denmark and to Germany. The market dialogue is expected to facilitate the optimization of the energy infrastructure for electricity transmission. The plans of Denmark to develop two energy islands in North Sea have been reviewed [16]. These islands are the existing Bornholm Island and a new artificial island which will be constructed. The artificial island will host offshore wind farms with capacity at 3 GW which could be expanded at 10 GW. The new artificial energy island consists of a change of paradigm in conventional offshore wind power generation and transmission. The report also mentioned that this pioneer project faces many challenges during its construction and operation while in the case of failure the removal of a 10 GW power generation system could potentially black out the whole EU electricity grid. A report regarding the development of energy islands as renewable energy hubs has been published [17]. The report stated the plans for the development of two Danish energy islands in North Sea with capacity at 5 GW by 2030. Other studies were also related with the development of other energy islands focused on multiple activities such as generation of offshore wind electricity, production of green electrolytic H_2, offering maintenance services to nearby located offshore wind parks and promotion of aquaculture, fishery and marine research. The development of artificial islands in North Sea to cover the energy demand in Europe has been analyzed [4]. The author analyzed the concept of the North Sea energy hub which is going to integrate approximately 10-15 GW of offshore wind power into European electricity network. He also mentioned that the island of Bornholm, with an area at 588.3 Km^2 and approximately 40,000 residents, is going to host 1-5 GW offshore wind power. Additionally, the author stated that there are two possibilities for the planned artificial energy island in North Sea regarding the generated wind power. The first is to generate and transmit electricity via a HVDC system and the second to produce green electrolytic hydrogen combined with wind electricity. A report for the development of offshore energy islands in North Sea has been published [18]. The report investigated the possibility of developing energy islands with wind power capacity at 2 GW, 5 GW and 10 GW. It is stated that the development of artificial islands in North Sea has several aspects related with legal, regulatory, technical and economic issues while the generated wind electricity can be either transmitted onshore or part of it used for H_2 production. The development of artificial islands has been studied [19]. The authors stated that artificial islands have several economic, geopolitical, strategic and maritime impacts. They are constructed in a variety of shapes and sizes using highly sophisticated machinery, technology and engineering skills. Existing artificial islands include: The Upper Zakum in Abu Dhabi, the Kansai international airport island in Japan, the forest city in Malaysia and the artificial islands in the South China Sea in China. A report on offshore renewables has been published by IRENA [20]. The report stated that at the end of 2020, the global installed offshore wind capacity was more than 34 GW. More than 70% of the installed offshore wind power capacity was in Europe either in North Sea or in the Atlantic Ocean. It is also mentioned that IRENA's analysis indicated that a cumulative global installed offshore wind power capacity of more than 380 GW by 2030 and at 2,000 GW by 2050 is feasible. The possibility of H_2 production through offshore wind farms in Europe has been evaluated [7]. The authors estimated the levelized cost of H_2 (LCOH) in European scale assessing technical and economic parameters as well as the availability of resources. Their results indicated that the LCOH will be in the range of 1.5-3.0 €/kg in 2050 due to the reduced costs of wind turbines and electrolyzers. The optimization of coupled offshore wind-electrolytic H_2 storage systems in Denmark has been studied [8]. The authors investigated the possibilities of a) producing electrolytic H_2 in offshore wind farms and sell it directly to end-users, and b) to store the produced H_2 and use it later for power generation with fuel cells when it is valuable. They calculated that it is more beneficial to sell the produced H_2 directly to end-users. The concept of energy islands has been analyzed [21]. The authors stated that the term "energy islands" encompasses contradicting interpretations. They conceptualized energy islands as a spatial interaction between three boundaries, a) a physical boundary, b) a political boundary, and c) an electricity service boundary. Combining these three boundaries the authors have identified six different types of energy islands which facilitate a better understanding of their concept. The first artificial energy island in the world, located in North Sea, has achieved environmental permit [22]. The artificial energy island, named "*Princess Elizabeth Island*", will act as an energy hub by connecting new offshore wind farms. The island owned by Belgian transmission system operator will have a total capacity of 3.5 GW while its construction will start in 2024 and it will be completed in 2026. Cost reductions in solar and wind power generation systems enable offshore H_2 production in the coming decades [23]. Energy islands could be integrated into the existing energy systems assisting their de-carbonization. Although the priority of offshore renewable energy installations is the generation of green electricity, another option is the production of green electrolytic H_2. The trade-offs between H_2 production and electricity generation in energy islands have been studied [24]. The authors investigated the possibilities of generating offshore wind electricity and transmitted it onshore via electric cables and alternatively using offshore wind electricity for water electrolysis and H_2 production. The authors stated that it is more beneficial to generate electricity from close-to-shore wind farms and to transmit it onshore with undersea cables. They also mentioned that in far-away energy islands water electrolysis and H_2 production is more valuable.

2.2 Development of onshore and offshore renewable energy systems in Aegean Sea and in other territories

A conceptual design of a floating sustainable energy island to enhance the energy independence of Crete has been developed [25]. The authors stated that there is immense potential of solar and wind energy around Crete complemented by sea-wave energy. They mentioned that floating modular offshore platforms could be developed for the installation of wind turbines and solar-PV systems generating electricity which could be transmitted in the mainland. Floating photovoltaic structures for the marine environment have been studied [5]. The authors stated that floating photovoltaic plants are exposed to permanent loads, operational loads, environmental loads including wind, waves, sea currents and tides, installation loads and accidental loads. A floating solar photovoltaic system with reference the island of Lambedusa, Italy has been described [6]. The authors stated that the island has an area at 20.2 Km^2 while its annual electricity consumption, in 2015, was 36.2 GWh. They proposed the construction of a floating solar photovoltaic system in a distance from the shore at around 3 Km and at sea depth at around 70 m. They estimated the surface of the floating structure at around 14 ha, the nominal power of the solar-PV system at 32.2 MW_p and its annual electricity generation at 47.6 GWh which is slightly higher than the island's power demand. An offshore floating wind farm located near the island Pantelleria, Italy to cover the island's electricity demand has been evaluated [26]. The authors stated that a floating offshore wind power system requires high capital investments due to the high cost of the floating substructure. They examined three scenarios for floating offshore wind farms in three different sites with very high wind energy potential. Their calculations indicated that the LCOE was quite high compared with other offshore wind power projects. The optimum site selection for offshore wind farms in South Aegean Sea, Greece has been examined [27]. The authors evaluated four criteria for choosing the best sites including: a) wind velocity, b) population served, c) shipping density, and d) distance from environmentally protected areas. They mentioned that after the completion of the preliminary study 15 areas were initially identified as suitable for the installation of offshore wind farms. The LCOE in offshore floating wind turbines has been evaluated [28]. The authors stated that their LCOE is strongly dependent on the sea-depth and their distance from the shore while the sea-depth is the dominant parameter to determine the optimum cost-efficient site. They also mentioned that the LCOE in large-scale floating wind turbines in sea depths at around 50-150 meters is comparable to bottom-fixed turbines while the LCOE of optimally sited floating wind turbines is in the range of 82.0-236.7 €/MWh. The interconnections of the Aegean Sea islands with the mainland power system have been studied [29]. These islands were grouped in three clusters including: a) Cyclades islands, b) Dodekanese islands, and c) North East Aegean islands while different scenarios regarding their interconnections were examined. It was proposed that grids' interconnection will allow the development of new renewable energy installations in these islands with total power at around 1,000 MW. The authors mentioned the challenges and the benefits of the abovementioned interconnections which will promote the optimal economic, secure and resilient electricity supply to local residents. The H_2 production from large-scale offshore wind farms has been evaluated [9]. The authors stated that nearly 80% of the world's offshore wind resources are in waters deeper than 60 m where bottom-fixed wind turbines are not feasible. They examined different system typologies regarding centralized/decentralized and onshore/offshore wind-power electrolysis mentioning the advantages and drawbacks in each typology. The electricity generation from wave power in Canada has been estimated [30]. The authors focused on five locations in the Atlantic and Pacific Ocean examining the economic performance of different sea waves-to electricity devices with annual capacity factor higher than 20%. Their results indicated that a wave-power plant at 25 GWh/year could be profitable over a 25-years period in two locations if a price of electricity between \$0.10-\$0.15 per KWh could be secured. The possibility of installing a hybrid offshore energy farm in the island Fuerteventura, Spain has been investigated [31]. The authors studied various aspects of energy generation from a hybrid offshore wave power and wind power farm located in the west coast of the island where the wind and wave energy resources are high. Their results indicated that the hybrid energy system can generate significant amounts of electricity covering the power needs of the island which has been declared as UNESCO Biosphere Reserve. The effect of islands' grid interconnection to the mainland power system and the positive impacts on RES deployment have been examined [32]. The authors emphasized the importance of the electric grids' interconnection on the development of new RES installations and the positive economic and environmental impacts. The Greek National Plan for Energy and Climate [33] predicts that the power of offshore wind farms in Greece will be at 1.9 GW by 2030 while the scenario for 2050 foresees that the power of offshore wind farms will be at 17.3 GW having a share at 22.88 % in the total power of renewables installed in the country by 2050. The environmental impacts study regarding the development of offshore wind farms in Greece has been published [13]. The study has identified 23 sites fulfilling the criteria for the installation of offshore wind farms in the Greek territorial waters while the most of them are located in Aegean Sea. The de-carbonization of small remote islands in Greece has been studied [34]. The authors investigated the clean energy transition of Patmos Island reducing its CO_2 emissions. They stated that solar and wind energy could cover around 80% of the island's energy demand while renewable energies can also contribute in sea water desalination and in re-charging the batteries of electric vehicles in the island. The status of electricity generation in non-interconnected islands in the Aegean Sea region has been assessed [10]. The authors stated that the share of RES in the energy mix of the non-interconnected islands of the Aegean Sea region is currently low at around 15% to 18%. They also mentioned that the cost of electricity generation in these islands is very high due to the operation of small-size thermal power stations. The energy autonomy of a very small island in Aegean Sea, Greece, the Agathonisi Island has been studied [35]. The authors stated that the tiny Agathonisi Island can cover all its energy demand based exclusively on the local renewable energy sources. Energy autonomy can be achieved with wind turbines, solar photovoltaic panels, electric batteries and small-scale power generation with biogas. They also mentioned that excess green electricity can be used for sea water desalination in the Island. The electrification of Tilos Island located in Aegean Sea has been examined [11]. The author stated that in many small and isolated islands the energy generation is dominated by oil-based fuels. The small Greek island Tilos has rich potential in solar and wind power resources. He mentioned that the operation of solar and wind energy systems combined with electricity storage in batteries could minimize the use of oil-based fuels in energy generation in Tilos island. The development of renewable energies and electricity storage systems in Greek islands has been examined [12]. The authors assessed the possibility of developing renewable energy systems combined with electricity storage in these islands. They mentioned that a hybrid power plant with wind turbines and electricity storage in batteries can be installed in Astypalaia Island increasing the use of local benign energy sources and minimizing the use of oil-based fuels. The clean energy transition in Greek islands combined with the emergence of energy communities has been studied [36]. The authors stated that the clean energy transition of Greek islands consists of a major challenge and a great opportunity for social and economic development. They have provided an overview of their clean energy transition combined with the development of local energy communities.

3. Development of energy Islands in the North Sea

The rich wind energy potential in the North Sea has triggered the development of offshore wind farms. North Sea has already a large share in the global offshore wind power generation. Belgium, Denmark and the Netherlands have already decided to develop physical and artificial energy islands in this area. The development of physical and artificial energy islands in this territory is going to enable the additional growth of offshore wind farms in North Sea assisting the de-carbonization of the European power system. The pioneer development of energy islands in North Sea, with capacity in the range of 3-10 GW, consists of a paradigm shift in the integration of offshore renewable energy into the power system. The development of artificial energy islands has many legal, regulatory, technical, economic, geopolitical, strategic, environmental and maritime impacts which sometimes are difficult to be resolved. The generated wind electricity in energy islands can be either transmitted onshore, with undersea electric cables, or part of it used for H_2 production with water electrolysis. Hydrogen can be either transported onshore, with undersea pipes, or stored in-situ and used later for electricity generation with fuel cells when it is profitable. Apart from wind electricity and H_2 production the energy islands in the North Sea could be used in the future for electricity generation from sea-waves.

4. The future development of offshore wind farms and green hydrogen in Greece

The urgency to reduce substantially carbon emissions requires the fast development of energy generation from zero-emission benign energy sources. Although offshore wind electricity is not generated so far in Greece the rich potential of wind energy in Aegean Sea enables its future generation from offshore wind farms. The generated offshore wind electricity can be transmitted via undersea electric cables in the mainland. The interconnection of the electric grids in the Aegean Sea islands with continental Greece will allow the transmission of offshore wind electricity to the large consumption centers. The current environmental impacts study for the development of offshore wind farms in Hellenic seas has identified 23 sites fulfilling the required criteria including a) sea depth, b) mean annual wind velocity, c) feasibility of connection with the mainland grid, and d) wind farm power and the distance from the coast. The 23 sites were located in the Hellenic territorial waters in a distance of six (6) nautical miles from the coast while the most of them are located in Aegean Sea. It should be mentioned that Greece has the right, according to UN's Treaty on the Law of the Sea (UNCLOS), to extend its territorial waters to twelve (12) nautical miles which are currently limited to six (6) nautical miles. Two types of offshore wind farms have been considered including the fixed bed turbines for sea depths up to 60 meters and floating wind turbines located at higher sea depths. Green hydrogen is not produced so far in Greece. Hydrogen can be produced with water electrolysis using the generated wind electricity in offshore wind farms. Then, hydrogen can be transported via undersea pipes in the mainland. The future development of offshore wind farms in Greece according to the *Greek National Plan for Energy and Climate, 2023* until 2050 is presented in table 1 while the future production of green H_2 in Greece as well as the capacity of the renewable energy systems necessary for its production in Table 2.

Table 1: Power of offshore wind farms according to the Greek National Plan for Energy and Climate until 2050

Year	Power of offshore wind farms (GW)	Total power of several renewable energy systems (GW)	%, Electricity generation by offshore wind farms to overall electricity generation by renewable energy systems
2030	1.9	29.2	6.51
2035	6.2	38.5	16.10
2040	9.8	50.0	19.6
2045	15.4	68.2	22.58
2050	17.3	75.6	22.88

Source: [33]

Table 2: Forecast regarding the production of green hydrogen in Greece (2025-2050)

Year	2025	2030	2035	2040	2045	2050
Production of green H_2 (mil. tons)	9	135	522	1,012	1,978	2,300
Electrolytic capacity for its production (MW)	15	1,739	6,958	13,474	26,352	30,643
Required capacity of RES powering water electrolysis (GW)	-	3	12	23	44	52

Source: [33]

5. The interconnection of the isolated electric grids in Aegean Sea islands

Aegean Sea has more than 1,000 islands. Less than 200 of them are inhabited while some of them host less than 100 residents. The most of the inhabited islands have isolated electric grids. Electricity is generated in these islands with small-size thermo-electric power stations using fuel and diesel oil. The interconnection of the grids will withdraw the oil-fired power plants from the power system reducing the operating cost of electricity generation in Greece. The island of Crete, which is the largest Greek island with more than 650,000 inhabitants, has an isolated electric grid which is currently interconnected with the continental grid with two undersea electric cables. The future interconnection of the grids in Aegean Sea islands will allow the development of many new RES installations exploiting the rich local solar and wind energy potential. Additionally, it will allow the development of several hydro-pumped storage systems using the favorable geomorphological characteristics of these islands. This will increase the share of RES in the country's energy mix reducing its carbon footprint. The levelized cost of electricity (LCOE) after the interconnection of the grids will be around 211 EUR/MWh which is significantly lower than the current LCOE in the non-interconnected islands which is around 500 EUR/MWh [29]. It will also secure the electricity supply in the islands during normal and emergency operating conditions. For this purpose, it will be required to maintain in cold reserve status some thermal-power plants on these islands. Additionally, the interconnection of new offshore wind farms which will be developed in the broad area can be achieved using the new interconnection infrastructure. The new installations of renewable energy systems in several Aegean Sea islands which could be developed after the interconnection of their electric grids are presented in Table 3.

Table 3: New installations of renewable energy systems in several Aegean Sea islands which could be developed after the interconnection of their electric grids

Islands	Power of new renewable energy systems (MW)
Limnos, Lesvos, Chios, Samos	360-480
Skyros	100-130
Kos, Rodos, Karpathos	390-570
Total	1,000-1,030

Source: [29]

6. The development of zero-energy islands in Aegean Sea

The rich solar and wind energy resources in Aegean Sea allow the development of nearly-zero or zero-energy islands. The large number of small and tiny non-interconnected islands in the Archipelago use currently oil-based fuels in local small-scale thermal power plants for covering their electricity demand. The cost of electricity generation in these small-scale power plants is very high. The islands are also characterized by water deficit while they are threatened by desertification. Several local benign energy sources and technologies can be used in these non-interconnected islands covering their energy demand. These include:

1. Use of solar thermal energy for heat generation and hot water production,
2. Use of solar photovoltaic energy for power generation,
3. Use of wind energy with wind turbines for power generation,
4. Use of biogas produced by anaerobic digestion of organic matter for power generation in small-scale systems,
5. Construction of hydro-pumped storage systems for electricity storage,
6. Use of electric batteries for storing green electricity, and
7. Use of green electricity for re-charging the electric batteries of electric vehicles in the island.

The use of locally available renewable energies for energy generation, replacing the use of fossil fuels, reduces the carbon emissions and decreases the cost of electricity in the Greek power system. In the case of future interconnection of the islands' electricity grids the existing thermal power plants will be removed from the power system. Several new installations of solar and wind power systems will be developed in these islands generating carbon-free electricity. The new green power installations will facilitate their clean energy transition or even the generation of more carbon-free electricity than their annually consumption.

7. The possibility of developing physical and artificial energy islands in Aegean Sea

Physical and artificial energy islands could be developed in the future in Aegean Sea. Their creation will be combined with the development of offshore wind farms in the Archipelago which is foreseen in the coming years. There are many small-scale islands in Aegean Sea which are not inhabited. These physical islands can be used as energy islands instead of developing artificial energy islands like in North Sea. The geopolitical status in Aegean Sea regarding the issue of the Greek territorial waters is very sensitive and the development of artificial islands in a distance longer than six nautical miles from the coast is currently not desirable. The proposed sites for the development of offshore wind farms in Aegean Sea are also located in the Greek territorial waters in the abovementioned distance of six nautical miles from the islands' coast. In energy islands or nearby them onshore and offshore wind farms could be installed generating electricity which could be transmitted in the mainland's grid using the future interconnection of the islands' grid. Apart from wind electricity electrolytic H_2 could be produced in these energy islands. The H_2 can be either transported to end-users or used for electricity generation via fuel cells when it is valuable. Taken into account the high solar irradiance in Aegean Sea solar-PV electricity could be also generated in these energy islands combined with wind electricity. Although current studies indicate that electricity generation from sea waves is not economically viable in Mediterranean Sea future technological breakthroughs in this sector could allow its production. The geomorphological characteristics of the small islands in Aegean Sea could allow the development of hydro-pumped storage systems. The development of energy storage systems would allow the local development of new renewable energy systems. In this case the energy island could be transformed in a hub generating green electricity using solar energy, wind energy, sea waves energy while they can also store part of the generated green electricity. Additionally, they can use green electricity for the production of hydrolytic H_2. The evaluation criteria for selecting the optimum sites for installing offshore wind turbines in Aegean Sea are presented in table 4 while the activities which could be developed in energy islands in Table 5.

Table 4: Evaluation criteria for selecting the optimum sites for installing offshore wind turbines

Criteria	Unit	Type
Wind velocity	m/sec	Economic
Population served	Residents	Operational
Shipping density	Number of ships	Financial and operational
Distance from environmentally protected areas	Km	Environmental

Source: [27]

Table 5: Activities which could be developed in energy islands in Aegean Sea

Activity	Technology	Generated energy or fuel
Use of wind energy	Wind farms	Electricity
Use of solar energy	Solar photovoltaic systems	Electricity
Use of wave energy	Onshore and offshore wave power devices	Electricity
Use of wind and solar electricity for water electrolysis	Water electrolysis	Hydrogen
Storage of electricity	Electric batteries or hydro-pumped storage systems	
Storage of hydrogen	Hydrogen storage systems	
Use of hydrogen for power generation	Fuel cells	Electricity
Electricity transmission from offshore wind farms to energy islands	Undersea electric cables	Electricity
Electricity transmission to onshore grids	Undersea electric cables	Electricity
Hydrogen transport to final end-users	Undersea pipes or ships	Hydrogen

Source: Own estimations

8. Discussion

The rich wind energy potential in Aegean Sea favors the future development of offshore wind farms while their operation could be combined with green hydrogen production. However, the selection of the optimum sites and sizes for the installation of offshore wind farms is in the initial phase while the interconnection of the electric grids of many small islands in the Archipelago has not been realized yet. The interconnection of the electric grids of several small islands in Aegean Sea will allow the development of many new renewable energy installations exploiting the rich solar and wind energy resources of the Archipelago minimizing the use of fossil fuels in them. The small island Tilos is progressing towards its clean energy transition replacing the use of fossil fuels with renewable energies. The future development of physical energy islands in Aegean Sea could facilitate the further exploitation of the rich solar and wind energy resources in this area. Our results indicate that the rich energy resources in the Archipelago and the interconnection of the electric grids of many small islands favors the development of onshore and offshore solar and wind energy systems in Aegean Sea assisting the de-carbonization of the Greek power system. The high number of small islands in Aegean Sea offer the possibility for the creation of physical energy islands facilitating the generation, storage and transmission of green electricity and green hydrogen to the mainland. The results of the study could be useful to policy makers, to local societies and to energy companies which are going to be involved in the interconnection of the electric grids of the small islands in this territory, the development of wind farms, solar-PV systems, energy storage systems and green hydrogen production systems. The results do not indicate the size of the onshore and offshore renewable energy systems which could be developed in Aegean Sea. They do not also indicate which energy islands could be developed in the Archipelago neither the size of the new RES systems that could be installed in them. Future research should be focused in the preliminary design of a physical energy island in this territory which could assist the development and the integration of several renewable energy technologies in the Archipelago.

9. Conclusions

The possibility of further development of onshore and offshore renewable energy systems in Aegean Sea Archipelago has been investigated combined with the possibility of developing energy islands and the interconnection of the isolated electric grids of the small islands in the territory. Our results indicate that:

1. The interconnection of the isolated grids in the small islands will enable the development of new renewable energy systems replacing the use of fossil fuels in them while they will allow the development of energy storage systems. It will also reduce the cost of electricity generation from the small-size thermal power plants currently operating in the small islands.
2. Several offshore wind farms are going to be developed in Aegean Sea Archipelago exploiting the rich wind energy potential of the area. The current environmental impacts study indicates the preferable locations for their installation. Green hydrolytic hydrogen might be produced in the offshore wind farms.
3. The creation of energy islands, acting as energy hubs, could assist the further development of wind power systems and the production of green hydrogen in Aegean Sea. However, due to the existence of many small physical islands in the area, which could be transformed in energy islands, the creation of artificial energy islands is not desirable in Aegean Sea.
4. The development of many renewable energy systems in Aegean Sea will assist the de-carbonization of the Greek power system while they will increase the energy security and self-sufficiency in these small islands

which are currently based on oil-based fuels.

The interconnection of the electric grids of the small islands in Aegean Sea is useful and profitable increasing the share of green electricity in the Greek power system. It will also assist the power transmission from the offshore wind farms to the mainland's grid facilitating the achievement of the national target for net-zero emissions by 2050.

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11. Conflict of interest

The author declares that he does not have any conflict of interest.

12. References

1. Nieuwenhout C, Andreasson IM. The legal framework for artificial energy islands in the northern seas. The International Journal of Marine and Coastal Law. 2023; 38:1-34. Doi: 10.1163/15718085-bja10151
2. Østergaard J, Christensen ED, Halsnæs K, Riisager-Simonsen C, Lisbjerg D, Jensen AD, *et al*. Denmark as the Energy Island Pioneer. Technical University of Denmark. Retrieved from: https://www.dtu.dk/samarbejde/raadgivning/brancher-og-sektorer/projekterigang/sektorudviklingsprojekt-om-energioeer?id=8275c2f5-4381-4a19-bcc6-2e49d0e19a96
3. Tossato A, Martinez Besele X, Ostegaard J, Pinson P, Chatzivasileiadis S. North Sea Energy Islands: Impact on national markets and grids. Energy Policy. 2022; 167:112907. Doi: https://doi.org/10.1016/j.enpol.2022.112907
4. Chatzivasileiadis S. North Sea energy hub 2030: building artificial islands to cover Europe's electricity demand by offshore wind, 2019. Retrieved from: http://www.chatziva.com/presentations/Chatzivasileiadis_HPG2019_NorthSeaEnergyHub_final.pdf
5. Claus R, Lopez M. Key issues in the design of floating photovoltaic structures for the marine environment. Renewable and Sustainable Energy Reviews. 2022; 164:112502. Doi: https://doi.org/10.1016/j.rser.2022.112502
6. Ghigo A, Faraggiana E, Sirigu M, Mattiazzo G, Bracco G. Design and Analysis of a Floating Photovoltaic System for Offshore Installation: The Case Study of Lampedusa. Energies. 2022; 15:8804. Doi: https://doi.org/10.3390/en15238804
7. Rogeau A, Girard R, De Coatpont M, Vieubled J, Erbs G, Nobrega PA. Techno-economic evaluation and resource assessment of hydrogen production through offshore wind farms: A European perspective. Renewable and Sustainable Energy. 2023; 187(3):113669. Doi: http://dx.doi.org/10.1016/j.rser.2023.113699
8. Hou P, Enevoldsen P, Eichman J, Hu W, Jacobson MZ, Chen Z. Optimizing investments in coupled offshore wind-electrolytic hydrogen storage systems in Denmark. Journal of Power Sources. 2017; 359:186-197. Doi: http://dx.doi.org/10.1016/j.jpowsour.2017.05.048
9. Ibrahim OS, Singlitico A, Proskovics R, McDonagh S, Desmond G, Murphy JD. Dedicated large-scale floating offshore wind to hydrogen: Accessing design variables in proposed typologies. Renewable and Sustainable Energy Reviews. 2002; 10:112310. Doi: https://doi.org/10.1016/j.rser.2022.112310
10. Tzanes G, Zafeiraki E, Papapostolou Ch, Zafirakis D, Moustris K, Kavadias K, *et al*. Assessing the status of electricity generation in the non-interconnecting islands of the Aegean Sea region. Energy Procedia. 2019; 159:424-429. Doi: 10.1016/j.egypro.2018.12.065
11. Kaldellis JK. Supporting the Clean Electrification for Remote Islands: The Case of the Greek Tilos Island. Energies. 2021; 14:1336. Doi: https://doi.org/10.3390/en14051336
12. Fiorentzis K, Katsigiannis Y, Karapidakis E. Full-scale implementation of RES and storage in an island energy system. Inventions. 2020; 5:52. Doi: 10.3390/inventions5040052
13. Environmental Impacts Study for the development of offshore wind farms in Greece. LDK consultants & Nature conservation consultants (In Greek), 2023. Retrieved from: https://herema.gr/wp-content/uploads/2023/10/%CE%A3%CE%9C%CE%A0%CE%95_%CE%95%CE%B8%CE%BD%CE%B9%CE%BA%CF%8C-%CE%A0%CF%81%CF%8C%CE%B3%CF%81%CE%B1%CE%BC%CE%BC%CE%B1-%CE%A5%CE%91%CE%A0_%CE%95%CE%94%CE%95%CE%A5%CE%95%CE%A0.pdf
14. Pernot E, Roggenkam M. North Sea Energy, Legal assessment of the development of a sand-based offshore energy island. Appendix K Report, 2020. Retrieved from: https://north-sea-energy.eu/static/5c5faad6e2e2af28df654394f0036b79/8b.-FINAL-NSE3-D3.8-Appendix-K-Full-Report-Legal-Assessment-of-the-development-of-a-sand-based-offshore-energy-island.pdf
15. Bornholm Energy Island. Market Dialogue - Cables, Discussion Paper, Doc 23/04783-2. Retrieved from: https://bornholmenergyisland.eu/files/media/market-dialogue/market-dialogue-bornholm-energy-island-cables.pdf
16. Cutululis NA, Blaabjer F, Østergaard J, Bak CL, Anderson M, Silva FMFD, *et al*. The Energy Islands: A Mars Mission for the Energy system, 2021. Retrieved from: https://backend.orbit.dtu.dk/ws/portalfiles/portal/257234146/The_Energy_Islands_a_Mars_mission_for_the_Danish_energy_system.pdf
17. Energy islands. Developing Renewable Energy Hubs, Executive Summary Reports. Retrieved from: https://userstcp.org/wp-content/uploads/2020/11/3-EGRD-Developing-Energy-Islands-executive-summary-final.pdf
18. North Sea energy offshore energy islands. Deliverable D 3.8. Document number NSE3-D3.8, 2020. Retrieved from: https://north-sea-energy.eu/static/8f2afe7839a5c395666bf7d94bd450cd/FINAL-NSE3_D3.8-Final-report-on-the-techno-economic-environmental-and-legal-assessment-of-offshore-energy-islands-1.pdf
19. Sreekumar K, Gazi H. A study of artificial islands, CPPR Issue brief, Center for Public Policy Research, 2020, Kochi. Retrived from: https://www.cppr.in/wp-

content/uploads/2020/11/A-Study-of-Artificial-Islands.pdf

20. Offshore renewables. An action agenda for deployment, a contribution to the G20 Presidency, IRENA, 2021. Retrieved from: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jul/IRENA_G20_Offshore_renewables_2021.pdf?rev=9e3ad6549dd44dc9aaaaedae16b747bb
21. Rettig E, Fischhendler I, Schlecht F. The meaning of energy islands; towards a theoretical framework. Renewable and Sustainable Energy Reviews. 2023; 187:113732. Doi: https://doi.org/10.1016/j.enpol.2022.112907
22. Elia wins environmental permit for world’s first artificial energy island, 2023. Retrieved from: https://www.power-technology.com/news/elia-environmental-princess-elisabeth-island/?cf-view&cf-closed
23. Are offshore energy islands the future of hydrogen and e-fuel production? Retrieved from: https://zpryme.com/insights/are-offshore-energy-islands-the-future-of-hydrogen-and-e-fuel-production/
24. Luth A, Seifert PE, Egging-Bradseth R, Weibezahn J. How to connect energy islands: Trade-offs between hydrogen and electricity infrastructure. Applied Energy. 2023; 341:121045. Doi: https://doi.org/10.1016/j.apenergy.2023.121045
25. Kurniawati I, Beaumont B, Varghese R, Kostadinovic D, Sokol I, Hemida H. *et al*. Conceptual Design of a Floating Modular Energy Island for Energy Independency: A Case Study in Crete. Energies. 2023; 16:5921. Doi: https://doi.org/10.3390/en16165921
26. Ghigo A, Cottura l, Caradonna R, Braco G, Mattiazzo G. Platform optimization and cost analysis in a floating offshore wind farm. Journal of Marine Science and Engineering. 2020; 8:835. Doi: 10.3390/jmse8110835
27. Vagiona D, Kamilakis M. Sustainable site selection for offshore wind farms in the south Aegean Greece. Sustainability. 2018; 10:749. Doi: 10.3390/su10030749
28. Myhr A, Bjerkseter C, Agotnes A, Nygaard TA. Levelized cost of energy for offshore floating wind turbines in a life-cycle perspectives. Renewable Energy. 2014; 66:714-728. Doi: http://dx.doi.org/10.1016/j.renene.2014.01.017
29. Karystianos ME, Pitas CN, Efstathiou SP, Tsili MA, Mantzaris JC, Leonidaki EA, *et al.* Planning of Aegean Archipelago Interconnections to the Continental Power System of Greece. Energies. 2021; 14:3818. Doi: https://doi.org/10.3390/en14133818.
30. Dunnett D, Wallace JS. Electricity generation from wave power in Canada. Renewable Energy. 2009; 34(1):179-195. Doi: https://doi.org/10.1016/j.renene.2008.04.034
31. Veigas M, Iglesias G. Potential of a hybrid offshore farm for the island of Fuerteventura. Energy Conversion and Management. 2014; 86:300-308. Doi: https://doi.org/10.1016/j.enconman.2014.05.032
32. Georgiou PN, Mavrotas G, Diakoulaki D. The effect of islands’ interconnection to the mainland system on the development of renewable energy sources in the Greek power sector. Renewable and Sustainable Energy Reviews. 2011; 15(6):2607-2620. Doi: https://doi.org/10.1016/j.rser.2011.03.007
33. Greek National Plan for Energy and Climate. Ministry of Environment and Energy, Athens, 2023. Retrieved from: https://energy.ec.europa.eu/system/files/2020-03/el_final_necp_main_en_0.pdf
34. Kaldellis JK Ktenidis P. The Clean-Green Decarbonization of Remote Islands: The GReco-Islands Concept. Environmental Sciences Proceedings. 2023; 26:208. Doi: https://doi.org/10.3390/environsciproc2023026208
35. Kaldelis J, Gkikaki A, Kaldelli E, Kapsali M. Investigating the energy autonomy of very small non-interconnected islands: A case study: Agathonisi, Greece. Energy for Sustainable Development. 2012; 16(4):476-485. Doi: http://dx.doi.org/10.1016/j.esd.2012.08.002
36. Katsaprakakis DA, Proka A, Zafirakis D, Damasiotis M, Kotsampopoulos P, Hatziargyriou N. *et al.* Greek Islands’ Energy Transition: From Lighthouse Projects to the Emergence of Energy Communities. Energies. 2022; 15:5996. Doi: https://doi.org/10.3390/en15165996