European Commission

# Clean energy for EU islands: **Electryone 2.0**

## Halki, Greece

# Electryone

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# Summary

Following the technical assistance provided by the Clean energy for EU islands secretariat as part of Electryone project (2021), the Municipality of Halki and the Energy Community of Halki were selected for the second round of technical assistance with this study, with three main tasks:

1. Determine how the current fossil-based ferry transport could be electrified from a technical perspective
2. Analyse the wind energy potential of the offshore zone between Halki and Alimia and estimate the Levelised Cost Of Energy (LCOE).
3. Model the energy system and determine the impact of the ferry electrification, the inclusion of offshore wind, and a battery energy storage system.

For the analysis of the ferry electrification, first, an overview has been provided of the current status of electric marine transport, including relevant case studies of pioneers that have already electrified (part of) their marine fleet. Secondly, an energy baseline of all ferries that dock in Halki throughout the year has been determined. Thirdly, a technological review has been performed to evaluate which ships could be electrified based on their traveling distance and frequency. The results show that by electrifying and hybridising Halki's marine transportation, the consumption of marine gas oil can be reduced by 2.4 GWh while an additional 1 GWh of electricity would be required. Assuming this electricity comes from renewable energy, this means a reduction of 650 tons of $CO_2$eq per year.

For the analysis of the wind potential, we have focused on floating offshore wind as the coastline of Halki and Alimia are quite unsuitable for bottom-fixed offshore wind turbines due to water depths of more than 50 m. Furthermore, floating offshore wind is less invasive and has lower visual impact on the coastline. The results obtained show the mean wind speed in this offshore zone is favourable for wind exploitation. For the purposes of this study, the horizontal axis wind turbine Siemens-Gamesa SG155 6.6 MW was proposed as an indicative model. A layout with ten of these wind turbines has been considered, leading to an annual production of about 180 GWh, or a capacity factor of 31.2%. The cost of floating offshore wind, this is currently in the order of €180/MWh to €200 /MWh but is expected to drop to drop below €100 /MWh by 2025 and under €40 /MWh in 2050.

Finally, the energy system of the island was modelled using Homer Energy. This includes the electrification of marine transport, the inclusion of offshore floating wind, and a potential additional storage component to better align local electricity production and demand. The results show that if the goal is to generate electricity to fulfil Halki's needs, neither floating offshore wind, nor a battery storage system would be interesting from a financial point of view. With the assumptions considered, installing additional 739 kWp of solar PV is the optimal solution. This is due to several reasons: first, the cost of offshore floating wind is still high compared to the cheaper alternative of solar PV at €54 /MWh. Second and more importantly there is a mismatch between total production and local consumption. One offshore floating wind turbine produces 21 GWh/year, which is eight times more than the total consumption on Halki, including the electric ferries. This shows that adding offshore floating only makes sense from the perspective of becoming an energy exporter. In terms of storing energy, the current interconnection to Rhodes already acts as electricity storage as it allows injecting the excess renewable electricity and taking electricity in times of curtailed local production. Installing a battery becomes interesting if the power price surpasses €0.25 /kWh and the injection remuneration stays below €0.05 /kWh.

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# Introduction

Halki is a Greek island located in the Aegean Sea, 9 km west from Rhodes (Figure 1). With an area of nearly 28 km$^2$, it is the smallest inhabited island of the Dodecanese archipelago. It has a permanent population of 400 to 550 inhabitants (478 according to 2011 census). Population increases up to 1 100 during the summer months, concentrated, mostly, in the village Emborio. Halki is interconnected to Rhodes and gets its electricity exclusively through this interconnection. In turn, in Rhodes, electricity is produced in thermal power plants burning heavy diesel fuel.

As part of Halki's will to decarbonise, the island applied for Technical Assistance from the Clean energy for EU islands secretariat in April 2022. Halki's Electryone 2.0 project has the following four objectives/tasks:

1. Determine how the current fossil-based ferry transport could be electrified from a technical perspective
2. Analyse the wind energy potential of the offshore zone between Halki and Alimia and estimate the Levelised Cost Of Energy (LCOE). To this end, a wind resource map has been produced. In addition, a configuration conception and a yield assessment have been performed.
3. Model the energy system and determine the impact of the ferry electrification, the inclusion of offshore wind, and a battery energy storage system.


Figure 1: Site location

# Task 1 Marine transport electrification

Halki relies on marine transportation for the goods and services required on the island as no other means of transportation between the island and other major logistics hubs exist. Therefore, marine traffic and the corresponding emissions are a significant factor to the overall environmental footprint of the island. Following the current electrification trend in the marine industry and Halki's aim to act as a pioneering island, this section looks at how the current fossil-based marine transport could be electrified.

First, an overview is given of the status of electric marine transport, including relevant case studies of pioneers that have already electrified (part of) their marine fleet. Secondly, the amount of energy that is currently consumed by all marine transport to Halki is determined. Thirdly, a technological review is performed to evaluate whether and/or which ships can be electrified based on their traveling distance and frequency. Finally, the reduction in emissions is estimated, as well as the additional required electricity on Halki for marine transport.

## 1.1 The status of electric marine transport

One of the most promising propulsion technologies are battery-powered ships. Batteries provide the ability to directly store electrical energy for propulsion, opening many other opportunities to optimise the power system. Recent advancements in battery technology and falling costs thanks to the growing worldwide demand for batteries have made this technology more attractive to shipping, especially for ships running on short distances since the weight of batteries is too high for longer distances due to their low energy density. As ferries travel shorter distances, dock more frequently, and can thus charge more often, they provide a suitable use case for electrified marine transport.

This has resulted in ships running on electricity becoming more common, as illustrated in Figure 2. In 2022, 494 battery-powered ships were in operation and an additional 157 are under construction to be completed by 2026. Of all ships in operation, 224 were used as ferries, which is almost half (45%). Not all battery-powered ships are fully electric though, the majority (51%) are a mild hybrid, while 22% are plugin-hybrid and 23% pure electric ships[1] [1]. On a full-electric ship, all the power—for both propulsion and auxiliaries—comes from batteries. A plug-in hybrid ship, similar to a plug-in hybrid car (PHEV), is able to charge its batteries using shore power and has a conventional engine in addition. The ship can operate on batteries alone on specific parts of the route, when manoeuvring in port, during stand-by operations. A hybrid ship uses batteries to increase its engine performance and does not use shore power to charge its batteries [12]. When looking only at ferries, pure electric ferries are more common though, reaching 44% of all ferries while mild hybrids only constitute 30% and plug-in hybrids 21%[2]. Table 1 gives an overview of four ferries that have already been electrified, either fully electric or as a plug-in hybrid.

[1] The remaining 4% are unknown
[2] The remaining 5% are unknown

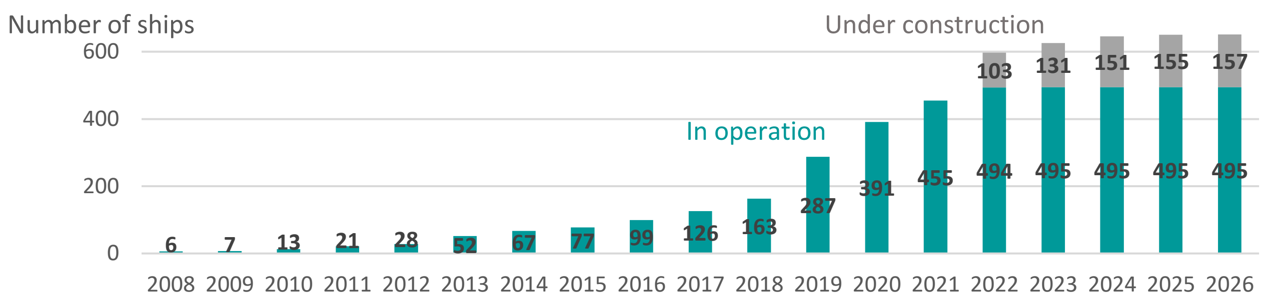


Figure 2: Growth of battery-powered ship fleet (source: Alternative Fuel Insights [11])

Table 1: Case studies of electrified ferries (source Siemens Energy [13])

| **Vessel** | **Ampere** | **Color Hybrid** | **Elektra** | **Bastø Electric** |
|---|---|---|---|---|
| Length overall [m] | 81 | 160 | 98 | 143 |
| Breath [m] | 21 | 27 | 16 | 21 |
| Gross tonnage | 1 598 | 27 000 | 1 275 | 7 911 |
| Build year | 2015 | 2019 | 2017 | 2020 |
| Construction | Catamaran aluminium hull | Conventional hull | Conventional hull | Conventional hull |
| Route | Norway: Lavik-Oppedal, Sognefjorden | Norway/Sweden: Sandefjord-Strømstad, Oslofjorden | Finland: Parainen-Nauvo, Turku Archipelago | Norway: Moss-Horten, Oslofjorden |
| Length of route | 20 min 6km | 2h30 | 15 min 1.6 km | 30 min 1.8 km |
| Trips per day | 34 | 4 | 25 | 20 -24 |
| Capacity | 399 pax, 120 cars | 2000 pax, 500 cars | 375, 90 cars | 600 pax, 203 cars |
| Propulsion type | Fully electric | Hybrid (diesel electric + battery) | Hybrid (diesel electric + battery) | Fully electric |
| Propulsion power | Two electric motors of 450 kW | 2 x 6L (3.6 MW) and 2 x 8L (4.8 MW) Electric generators: 2 x 4450 kWh | 2 x 900 kW (+3x diesel generator) | 4 x 1100 kW electric generators (+4x backup diesel generators |
| Battery capacity | 1040 kWh Lio-ion battery | 4.7 MWh battery system | 1 MWh total (160 Li-ion batteries) | 4.3 MWh |
| Charging system | 410 kWh battery quayside both sides, allowing "quick charging" upon arrival (1 MW in 9 minutes) | 11.5 kV charging system (only in Sandefjord (for now) | Charges directly from grid | Direct fast-charge |
| Charging power | 1.2 MW, 1250-1650 A | 7 MW | NA | Up to 9000 kW in both Moss and Horten |
| Charging time | 10 min + overnight | 25 min at lunch stop + overnight | 5.5 min + overnight | "Within minutes" |
| Comments | World's first fully electric car ferry. During the transit, the ferry is estimated to use between 130-200 kWh per crossing. It was named "Ship of the year" (Skipsrevyen) 2014 | Battery capacity for 2x30 min (12 nm) sailing. Current operational profile of 30 min out of 2.5 h sailing on electric saves about 20% of fuel (and $CO_2$). It was named "Ship of the Year" (Skipsrevyen) 2019. | Deploys diesel generators to handle ice conditions in winter. Fitted with several solar panels, which feed into the power system. It was named "Ship of the Year" (Sulphur Cap Conference in Amsterdam) 2020 | World's largest fully electric car ferry. Crossing the Oslo fjord, Norway's busiest ferry crossing. Yearly transports 3.8 m pax and 1.8 m vehicles on 36 000 departures (2019). |

## 1.2 Determining the marine transport energy baseline

Five different ferries include Halki as a stop in their trajectory. These ferries are summarised in Table 2, the data was provided by an island representative. The table gives an overview of the trajectory of each of these ferries, as well as the distance, the fuel consumption, the total trips per year, and the yearly energy consumption and equivalent emissions. Overall, 6.7 GWh of energy are required for ferries travelling to Halki, leading to a total of 1 800 t of $CO_{2\text{-eq}}$. The next section aims to determine how many of these ferries could be electrified and how this would impact the energy consumption and carbon emissions.

Table 2: Energy baseline of ferries travelling to Halki

| Ferry name | Trajectory | One-way distance | One-way Transit time | Trips per year | Fuel consumption | | Primary energy consumption[3] | $CO_2$ emissions[4] |
|---|---|---|---|---|---|---|---|---|
| | | | | | One way | Per year | | |
| | | [km] | | | [l] | [l] | [kWh] | [kg $CO_2$eq] |
| Dodekanisos pride | Rhodes - Halki<br>Tilos - Nisyros<br>Kos - Kalmynos | 218 | 4 h - 5 h | 86 | 700 | 120 400 | 1 342 460 | 362 464 |
| Dodekanisos express | Rhodes - Halki<br>Tilos - Nisyros<br>Kos - Kalmynos | 218 | 4 h - 5 h | 20 | 700 | 28 000 | 312 200 | 84 294 |
| Fedon | Halki - Rodes | 25 | 50 min | 194 | 175 | 67 900 | 757 085 | 204 413 |
| Sebeco II | Halki - Tilos<br>Rhodes | 60 | 1h 30 | 194 | 350 | 135 800 | 1 514 170 | 408 826 |
| Nissos Halki | Halki - Rodes | 25 | 40 min | 1,001 | 125 | 250 250 | 2 790 288 | 753 378 |
| | | | | | **TOTAL** | **602 350** | **6 716 203** | **1 813 375** |

## 1.3 Technological review of which ships can be electrified

It is estimated that nearly 50% of ferry emissions typically happen in port and within the first hour of travel. These emissions can be cut by investments in standard technology that is already available which allows fully electrify ferries with a transit duration of 60 min or less and a length of up to 150 m [13]. The other half of the emissions, linked to longer voyages, can be tackled by hybrid electrification. In the short term, this might still require conventional fuel, but does not automatically cause a fossil fuel lock-in, as this can be replaced by low and zero emission fuels such as hydrogen, ammonia, biofuels, or carbon capture.

An intriguing opportunity arises nowadays, as the ferry fleet in Europe is on average 35 years old, with 65% of the vessels more than 20 years old. This implies that during this decade, more than half of the fleet will be subject to replacement. Therefore, full-electric vessels should be incentivised to replace older vessels on all routes up to one-hour in duration. Such vessels might also need to be dedicated to specific routes, which can deviate from what current fleet operations dictate. When replacing vessels with new builds, better hull and propeller design and lighter materials will make them far more energy efficient, extending the range significantly. And during this decade, hydrogen

[3] Assuming Marine Gas Oil (MGO) with an energy density of 11.15 kWh/l
[4] Assuming Marine Gas Oil (MGO) with an emission factor of 0.27 kg $CO_2$/kWh

and ammonia will be available as fuel alternatives for the shipping sector replacing fossil fuels like diesel and LNG [13].

Considering the 60 min transit and assuming that one hour of transit equals around 31.5 km (17 knots), every kilometre below 31.5 km is assumed to be done using solely electric propulsion, while everything above 31.5 km is assumed to use combustion engines with Marine Gas Oil (MGO). The shorter ferries (Fedon, Sebeco II, and Nissos Halki) are assumed to be able to charge one time in Halki, while the longer ferries (Dodekanisos Pride and Dodekanisos Express) are assumed to be able to charge two times in Halki, once on the trip back and once on the trip forth. While the charging requirement of the ferries might be quite a bit different as they could potentially charge on each stop, this report assumes that only Halki offers a charging location as the main goal is to determine the new electricity demand on Halki. Additionally, this report does not actively take into account charging time, but assumes sufficient time is available to charge the ferries.

The assumptions above allow roughly calculating how much additional electricity[5] demand would be required on Halki and how much MGO[6] is still required for the ferries. On a yearly basis, just over 1 GWh of electricity would be needed on Halki, and another 4.3 GWh of MGO, as indicated in Table 3. The sum of both is lower as before since electric motors work at a higher efficiency than combustion engines. This also reduces emissions by 650 tons of $CO_2$eq at around 1 150 tons per year[7]. Important to note is that the bulk of the electricity demand comes from the shorter ferries as these do significantly more trips on a yearly basis. Furthermore, considering their transit time and their stopover periods, they are suitable candidates to be fully electrified.

In Task 3, a potential power system will be modelled that includes the electrification of the Fedon, Sebeco II, and Nissos Halki. This power system will have to meet the new electricity demand, not just on a yearly basis, but also for each hour of the year.

Table 3: Energy baseline once ferries travelling to Halki are electrified

| | One way | | | | Consumption round trip | | Yearly consumption | | |
|---|---|---|---|---|---|---|---|---|---|
| Ferry name | Distance [km] | Transit time | Fuel consumption [l] | Trips /year | Electricity on Halki[5] [kWh] | Conventional energy[6] [kWh] | Electricity on Halki [kWh] | Conventional energy [kWh] | $CO_2$ emissions[7] [kg $CO_2$eq] |
| Dodekanisos Pride | 218 | 4h-5h | 700 | 86 | 1 002[8] | 13 354 | 86 213 | 1 148 481 | 310 090 |
| Dodekanisos Express | 218 | 4h-5h | 700 | 20 | 1 002[8] | 13 354 | 20 050 | 267 089 | 72 114 |
| Fedon | 25 | 50 min | 175 | 194 | 867**Error! Bookmark not defined.** | 1 954 | 168 241 | 378 543 | 102 206 |
| Sebeco II | 60 | 1h30 | 350 | 194 | 911**Error! Bookmark** | 5 756 | 176 653 | 1 116 700 | 301 509 |

[5] Based on the following formula: $\frac{\min(D,31.5)}{D} \cdot F \cdot E_d \cdot \frac{\eta_c}{\eta_e}$ for Fedon, Sebeco II, and Nissos Halki and $\frac{\min(D,31.5)}{D} \cdot F \cdot E_d \cdot \frac{\eta_c}{\eta_e} \cdot 2$ for the Dodekanisos line

[6] Based on the following formula: $\frac{D-\min(D,31.5)}{D} \cdot F \cdot E_d + F \cdot E_d$ for Sebeco II and Nissos Halki, $F \cdot E_d$ for Fedon, and $\frac{D-\min(D,31.5)}{D} \cdot F \cdot E_d \cdot 2$ for the Dodekanisos line; with D= one-way distance, F = round trip fuel consumption, $E_d$ = MGO energy density (11.15 kWh/l), $\eta_c$ = combustion engine efficiency (40%), $\eta_e$= electric motor and battery efficiency (90%)

[7] Assuming an emission factor of 0.27 kg $CO_2$/kWh for MGO and zero emissions for renewable electricity

[8] Assuming that the ferry can be charged two times Halki, once on the trip back and once on the trip forth

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | **not defined.** | | | | |
| Nissos Halki | 25 | 40 min | 125 | 1 001 | 619**Error! Bookmark not defined.** | 1 394 | 620 064 | 1 395 144 | 376 689 |
| | | | | | | **TOTAL** | **1 071 221** | **4 305 956** | **1 162 608** |

# Task 2 Floating offshore wind

In August 2022, the Greek Parliament approved Greece's first Offshore Wind Law, a key milestone to kick-start offshore wind development. The Law appoints the State-owned exploration company Hellenic Hydrocarbon Resources & Energy Resources Management to lead site investigation, allocation, and concession development. The national transmission system operator ADMIE will be responsible for providing the onshore and offshore grid infrastructure.

First, the Greek Ministry for the Environment and Energy will commission Strategic Environmental Impact Assessments to define broader offshore wind development areas. They will then assign exact installation zones within these areas. This will include the exact terms for offshore wind development in each installation zone. These zones will be defined in consultation with other societal interests, such as military, fisheries, or tourism. Afterwards, developers will be able to apply for non-exclusive research permits for the broad offshore wind development areas. This will allow them to undertake resource assessment studies and sea space surveys. The first offshore wind auctions could take place as early as 2025-2026 and will only be eligible for developers with a research permit.

Task 2 within this report aims to be one step ahead and already offer a rough estimation of whether and where around Halki floating offshore wind turbines could be built, and what their potential production could be. It also aims to put a first estimate of the Levelised Cost of Electricity (LCOE) of these floating offshore wind turbines.

.The Technical Assistance provided by the Clean energy for EU islands secretariat in 2021 (as part of project Electryone 1.0) indicated that with the existing 1 MWp solar PV plant, Halki already has quite a high renewable fraction and that small-scale onshore wind turbines would be sufficient to increase this to even higher figures. Placing just one bottom-fixed offshore wind turbine (generally in the range of 6-12 MW) would produce a several times what Halki requires in electricity demand. Thus, when placing offshore wind turbines, this must be done from the perspective of becoming an electricity exporter.

The focus of this study has been put on floating offshore wind, in contrast to bottom-fixed offshore wind Considering the characteristics of Halki and Alimia, with coastlines with water depths of more than 50 m, the space for placing bottom-fixed wind turbines is very limited, as can be seen in the sea depth map in Figure 3. Consequently, only a small number of bottom-fixed offshore wind turbines could be placed. Small offshore wind parks generally don't make sense from a financial and logistical point of view and contradict the idea of becoming an energy exporter for the region. We therefore concluded that it would be more interesting and innovative to solely look at floating offshore wind turbines in deeper waters, with a less invasive and lower visual impact on the coastline.

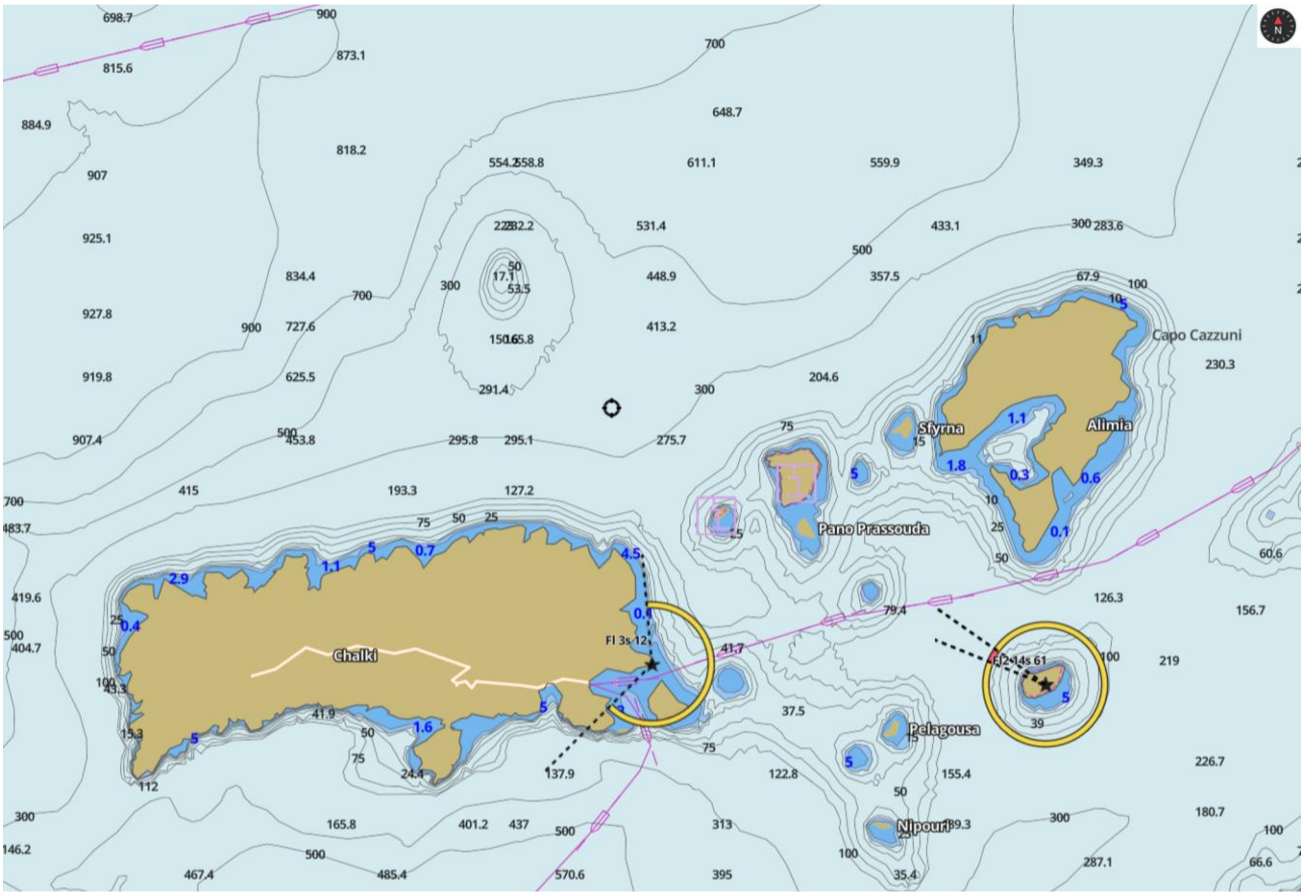

Figure 3: Sea depth map for the coastline around the islands of Halki and Alimia [4]

## 2.1 Wind resource potential

For the whole offshore area between Halki and Alimia, a wind atlas has been generated using the software WindPro[9]. The Wind Climate from the Global Wind Atlas has been used as input for WindPro to calculate a wind resource map [1]. Wind resource maps have been generated at three different and relevant heights above sea level: 100.0 m, 150.0 m and 175.0 m. These heights are in the range of potential hub heights for offshore wind exploitation.

The wind on the offshore zone between Halki and Alimia predominantly blows from north-northwest (NNW) and west-northwest (WNW). The wind energy rose depicts that most of the energy production comes from sectors north-northwest (NNW) and west-northwest (WNW)Figure 4.

[9] WindPRO is a software package for designing and planning wind farm projects. It uses WAsP to simulate wind flows. It is developed and distributed by the Danish energy consultant EMD International A/S. It is trusted by many investment banks to create wind energy assessments used to determine financing for proposed wind farms.

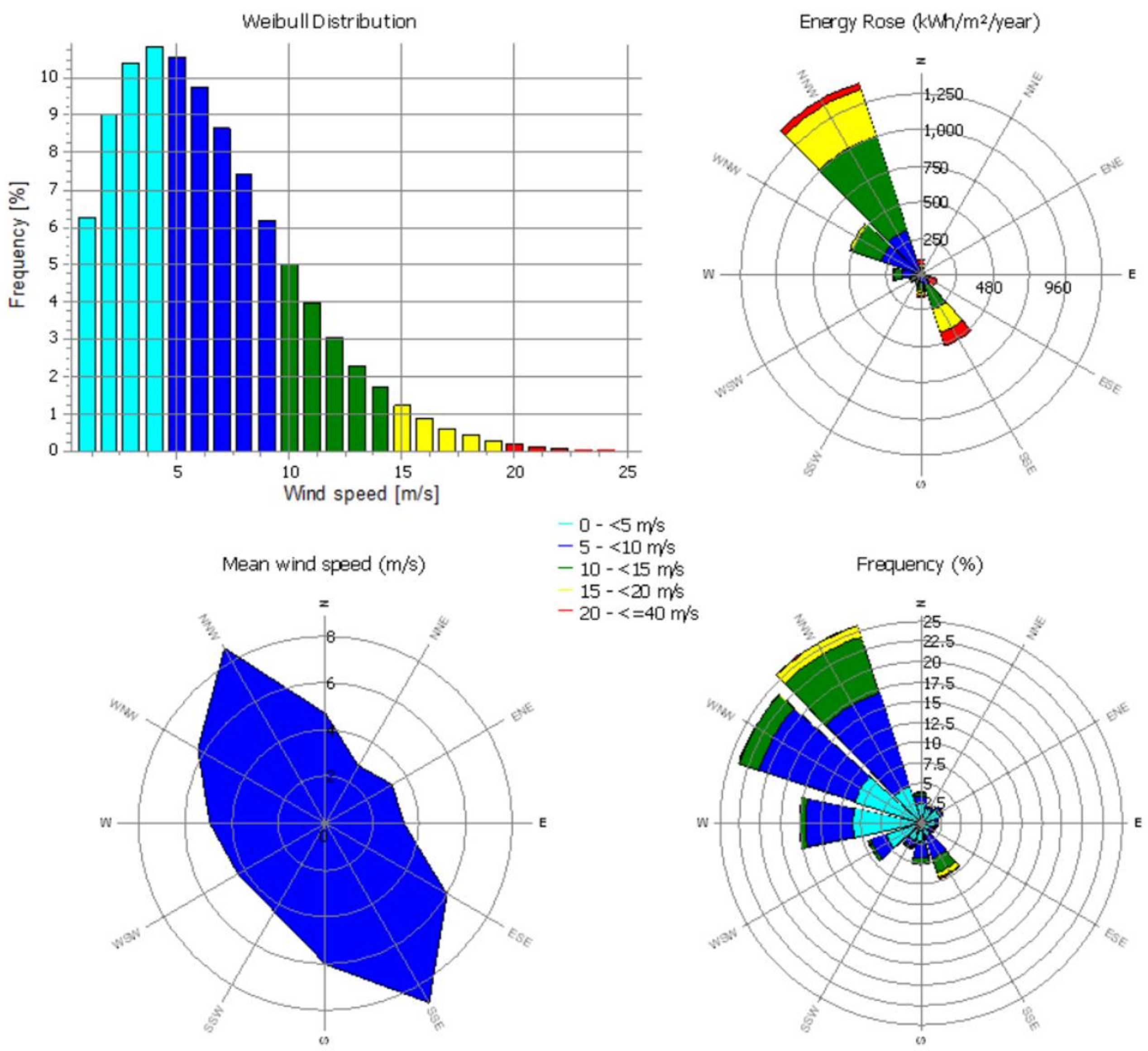


Figure 4: Wind distribution in the offshore zone between Halki and Alimia

The different wind resource maps are presented in the figures below The mean wind speed on site ranges between 4.8 m/s and 7.4 m/s at 100.0 m, between 5.5 m/s and 7.6 m/s at 150 m and between 5.7 m/s and 7.6 m/s at 175 m depending on the location on the island, as shown in the resource maps from Figure 5 to Figure 7.

The wind speeds are homogeneously distributed all over the offshore zone, with the highest values located in the north-west and south-west areas, and the lowest ones around the coast of Alimia and close to Halki's coves. A similar wind speed pattern is observed for all the heights considered in this study.

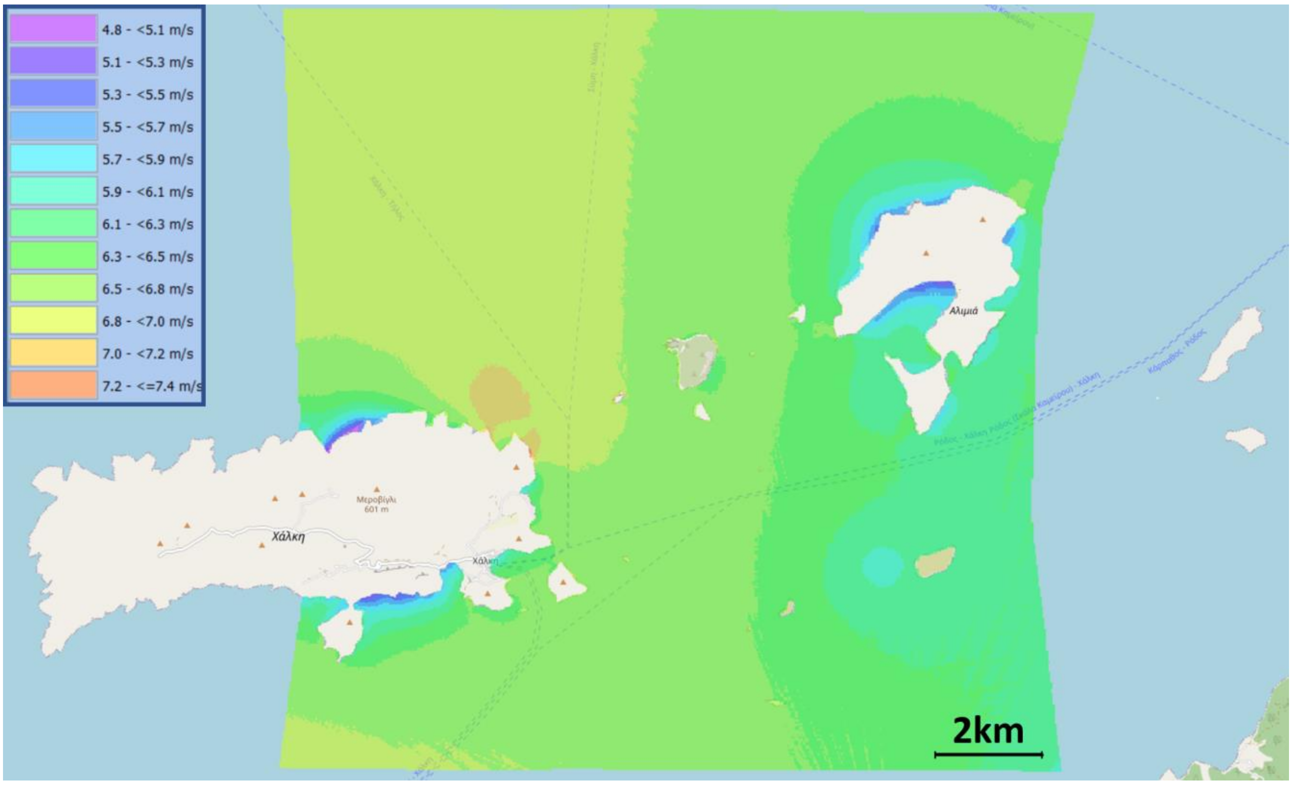


Figure 5: Mean wind speed at 100.0m AGL

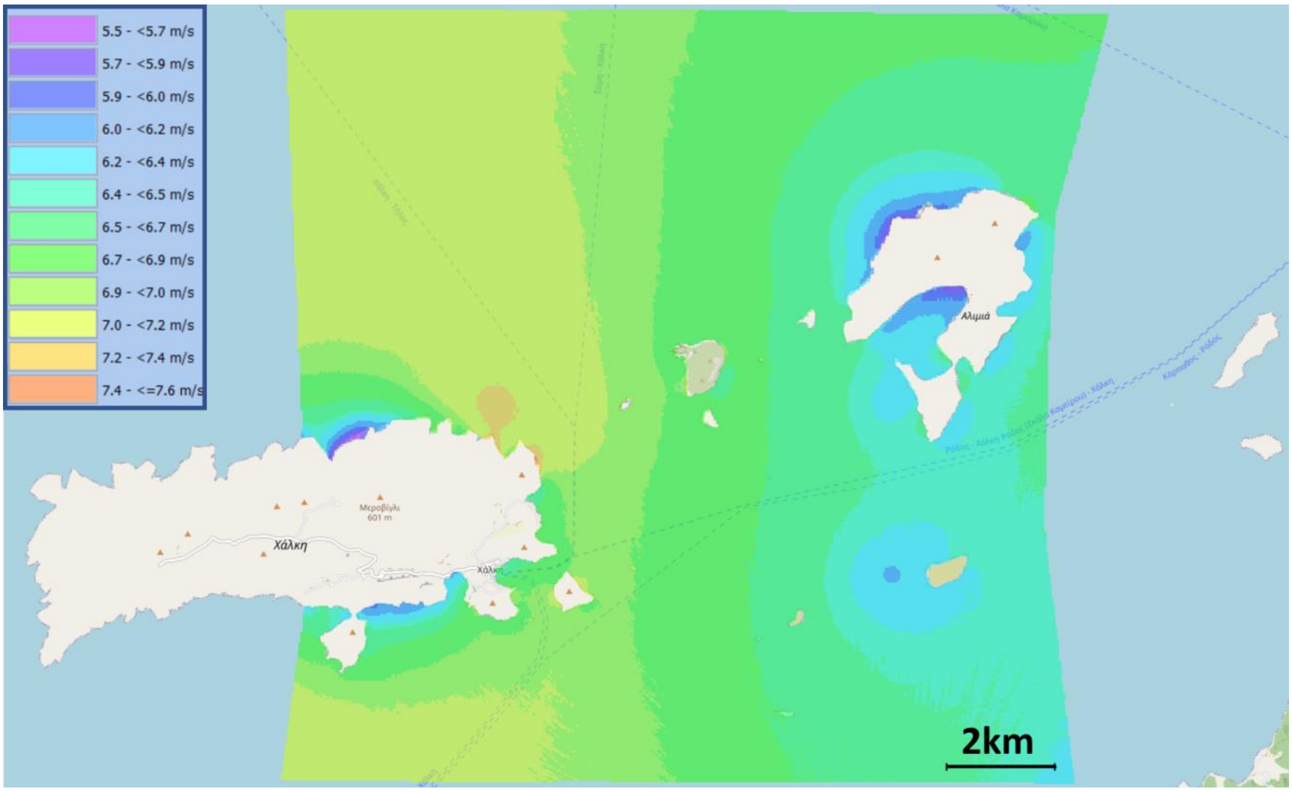


Figure 6: Mean wind speed at 150.0m AGL

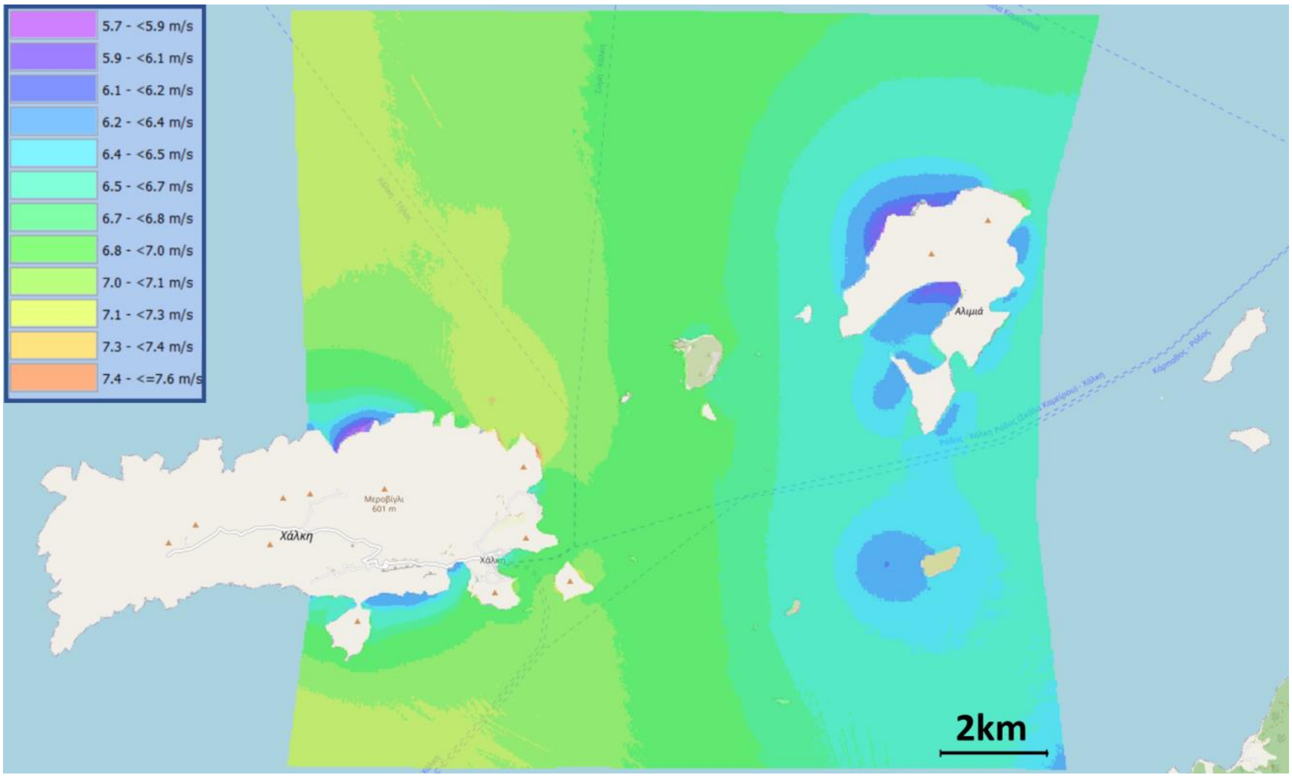


Figure 7: Mean wind speed at 175.0m AGL

A wind resource map in terms of annual production MWh/year has been generated at 100.0 m, 150.0 m, and 175.0 m above sea level based on the wind turbine Siemens-Gamesa SG155 with a nominal power of 6.6 MW. This model is suitable for offshore and has been selected as an indicative choice for the present study, based on the local wind resources, the size, and energy need of the island. Other turbine models are available in the market for offshore wind turbines and could be considered for this project. One example is the Vestas V236 15 MW: Vestas has confirmed that this model comes with a native compatibility for floating platform. However the power curves of the V236 have not been made available to the authors for this study; hence, their production could not be modelled for this application.

The results show that for the Siemens-Gamesa SG155 with a nominal power of 6.6 MW the average wind potential on the offshore area at 100.0 m ranges between 9 191 MWh/year and 21,928 MWh/year. (Figure 8). At 150.0 m, it ranges between 12 958 MWh/year and 22 544 MWh/year (Figure 9) and, finally, at 175.0 m it ranges between 14 211 MWh/year and 22 564 MWh/year (Figure 10). Higher values are typically found at higher altitudes.

Before further suggesting feasible areas for offshore wind energy exploitation, additional criteria should be considered such as constrains related to the presence of protected areas/nature reserves and nautical routes. Taking the above into account, a layout with ten wind turbines is proposed in the following section.

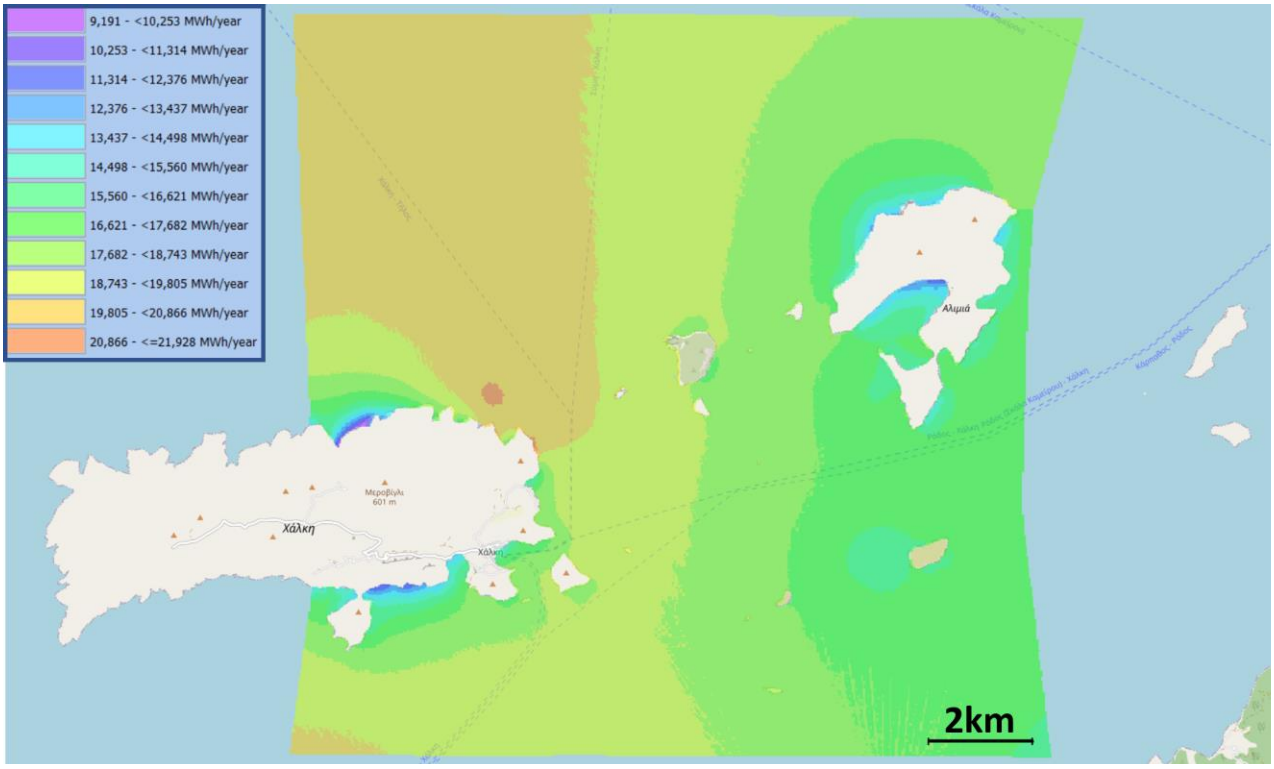

Figure 8: Annual wind production at 100.0m AGL based on the Siemens-Gamesa SG155 6.6 MW wind turbine [MWh/year]

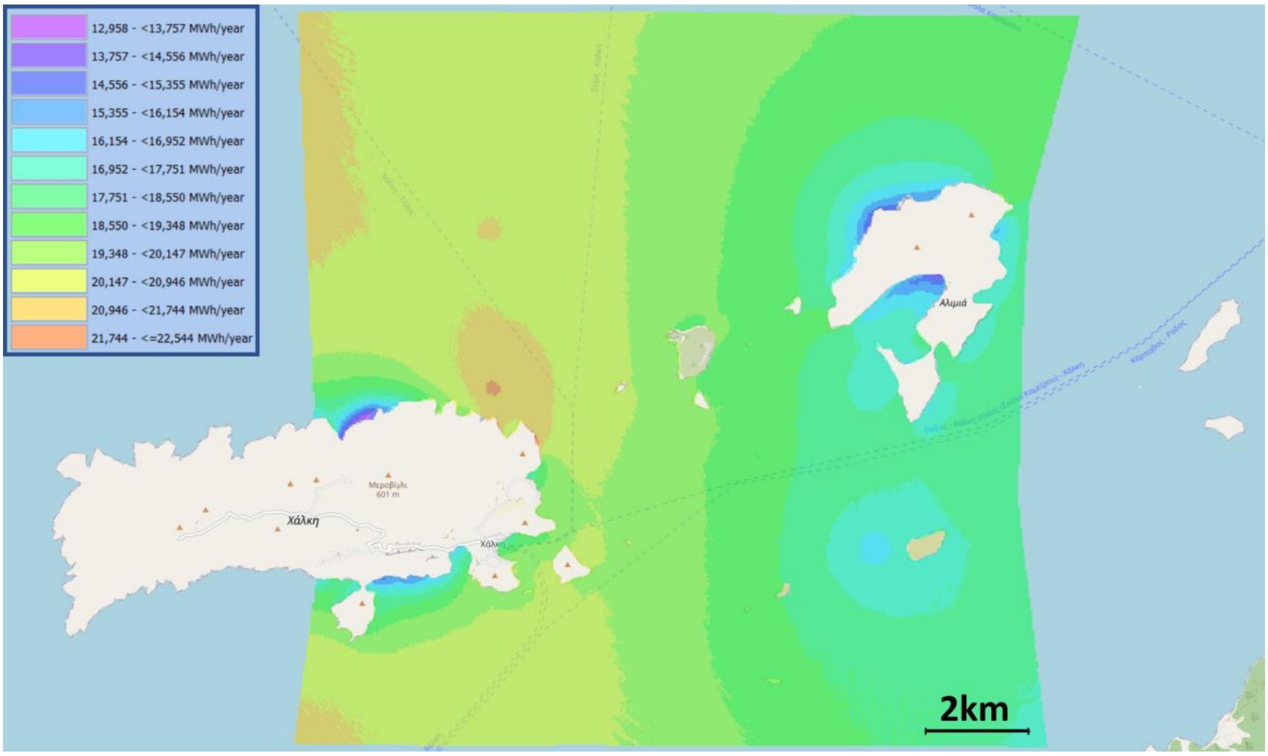

Figure 9: Annual wind production at 150.0m AGL based on the Siemens-Gamesa SG155 6.6 MW wind turbine [MWh/year]

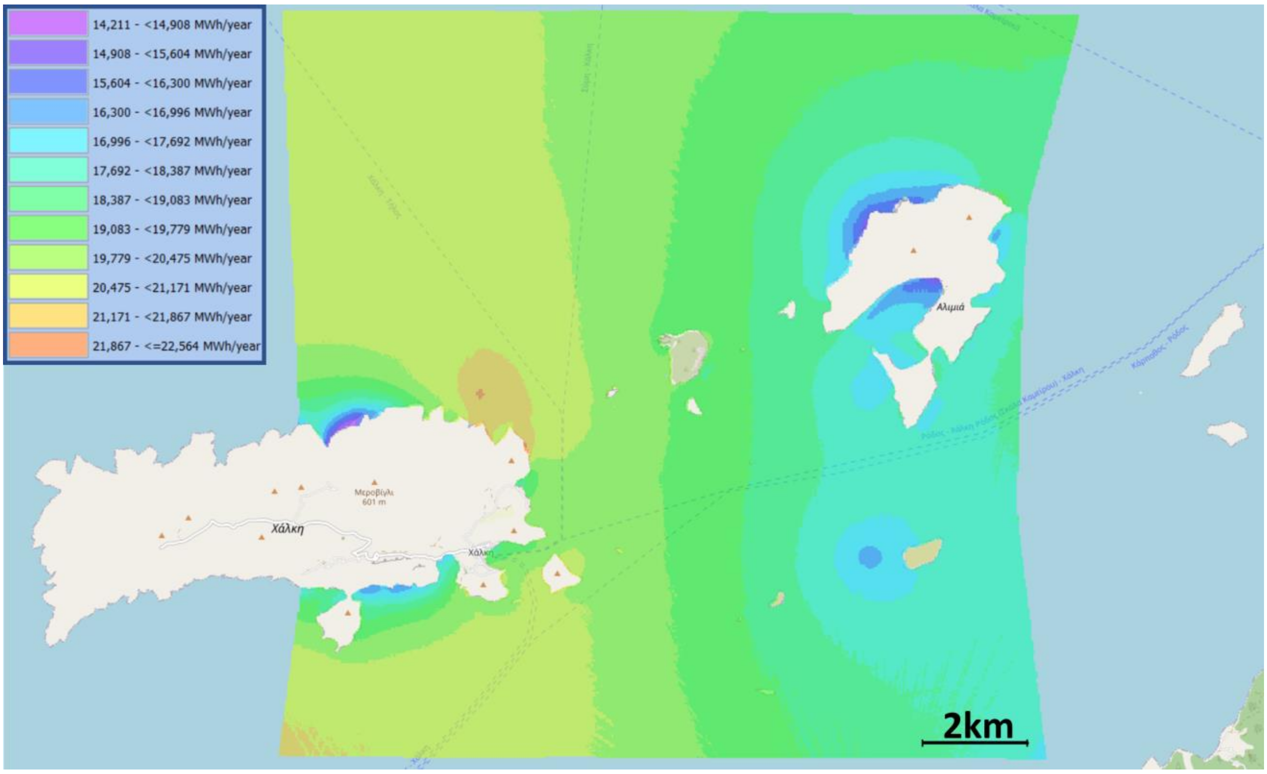

Figure 10: Annual wind production at 175.0m AGL based on the Siemens-Gamesa SG155 6.6 MW wind turbine [MWh/year]

The proposed layout, based on the wind resource map, includes ten SG155 wind turbines, in the northern sea area between Halki and Alimia, at a safe distance from nautical routes and respecting constraints related to nature reserves [5]. A proper intra-spacing is adopted for all of the turbines, in order to reduce the mutual wake impact. The layout is displayed in Figure 11. The coordinates in Geo [deg]-WGS84 are provided in Table 4.


Figure 11: Location of the two proposed floating offshore layout, highlighted in red.

Table 4: Wind turbine coordinates for the proposed layout

| **Coordinates** | Longitude [E] | Latitude [N] |
|---|---|---|
| WT1 | 27.57603° | 36.31277° |
| WT2 | 27.58650° | 36.31272° |
| WT3 | 27.59646° | 36.31267° |
| WT4 | 27.60710° | 36.31262° |
| WT5 | 27.61705° | 36.31256° |
| WT6 | 27.62684° | 36.31251° |
| WT7 | 27.58753° | 36.30465° |
| WT8 | 27.59766° | 36.30460° |
| WT9 | 27.60865° | 36.30455° |
| WT10 | 27.61860° | 36.30450° |

The results presented in this section are preliminaryTable 5, as they do not include additional losses related to potential curtailments (e.g., in favour of birds). Moreover, considering the innovative nature of floating wind technology, some of the production losses related to the oscillatory movement (non-standard inflow conditions) induced by the waves or, by the level of agitation of the sea are based on conservative hypothesis.

Table 5: Expected wind farm energy production figures

| | |
|---|---|
| **Mean wind speed** | 7.0 m/s |
| **Gross energy production** | 203 347 MWh/year |
| **Annual net energy production** | 180 156 MWh/year |

## 2.2 LCOE estimation

Given the characteristics of the Greek coastline with water depths of more than 50 m, much of the 2 GW Greece aims to build by 2030 will be floating offshore wind. Today Europe has just over 100 MW of floating wind across four projects operating in Scotland, Portugal and Norway, but the pipeline of new projects is growing.

This section focuses on determining the cost of producing electricity from the offshore wind turbines. The Levelised Cost Of Electricity (LCOE) is a metric that indicates the cost of one unit energy produced and is typically applied to compare the cost competitiveness of different power generation technologies.

$$\text{LCOE} = \frac{\text{Life Cycle Cost}}{\text{Electrical energy provided}}$$

The Life Cycle Cost includes all costs occurring in the lifetime of a floating offshore wind farm such as:

- The capital expense for the initial investment in the power plant including the manufacturing, transportation and installation and the cost entailed at the beginning of a project life cycle before the plant starts to operate.
- The expenses during the operation and the maintenance phase
- The decommissioning expenses at the end of lifetime.

Since the costs occur in different years they have to be discounted to their present value with a chosen discount rate.

The electrical energy provided refers to the total energy generated during the lifetime minus the energy losses that occur in generation, collection, and transmission of the energy.

Floating offshore wind has the potential to provide competitive LCOE values by having the ability to harness the best possible wind resources without depth constraints and using larger wind turbines to increase power generation. Furthermore, the ability to mount the turbine on the floating substructure dockside and to tow the fully assembled structure by tugboats to the offshore site provides a significant potential for cost reduction along the life cycle, because expensive, heavy lift jack-up vessels are avoided.

However, today only 113 MW of floating wind turbines are in operation in Europe [14]. This stands in stark contrast with the 28 GW of bottom fixed offshore wind that is already installed in Europe [15]. Given its early stage of development, floating offshore wind currently remains more expensive than bottom fixed offshore wind. However, with the right conditions, floating offshore wind could potentially decrease costs at an even greater speed than bottom fixed offshore wind. This development will be aided by momentum created in the sector now that various countries have announced their floating wind targets by 2030. Greece wants 2 GW, Spain 1 GW-3 GW and the UK 5 GW. Italy is considering a 2030 target of 3.5 GW while Portugal is looking at a potential 6 GW [14].

The cost of operational floating offshore wind in Europe today is in the order of €180 /MWh to €200 /MWh for pre-commercial projects [16]. As indicated before, these are small-scale projects and the industry expects significant cost reductions in the near future: below €100 /MWh[10] by 2025 and under €40 /MWh in 2050 [17].

[10] Due to floating wind's early stage of development, the authors did not aim to calculate an LCOE specific to Halki as many of the cost components are still uncertain. Not just the capital expenses specifically for the floating wind offshore components, but also the development of the regular Greece offshore wind sector is unknown.

# Task 3 Energy System Modelling

As a consequence of the potential electrification of marine transport, the electricity consumption on Halki will increase by 1 GWh, as indicated in Task 1. Furthermore, the potential introduction of floating offshore wind turbines will introduce additional, intermittent electricity onto the grid, as seen in Task 2. The question then arises on how these two possible developments will influence the already existing energy system of Halki, and whether an additional storage component needs to be added in order to better align the wind energy production and the marine transport demand.

## 3.1 Methodology

This study has been carried out using HOMER Pro, a software that allows finding the optimal power system configuration based on user input and requirements. It can integrate multiple types of renewables—such as solar PV, wind, and hydro—as well as energy storage, fossil fuel generators, and the mainland electricity grid itself.

This section first explains how the electricity demand on the island was estimated based on the available data. This electricity demand will then be used as input for the model. Thereafter, the various renewable technology components included in the model have been outlined. Finally, the general assumptions of the model are explained.

### Electricity demand

The annual electricity consumption on Halki is 1586 MWh, as estimated by the island representatives based on the number of houses and businesses. The same load profile as in the Electryone 1.0 report is used, which was created from a synthetic load profile based on the monthly electricity consumption of the water desalination unit. These results are illustrated as monthly electricity consumption in Figure 12, where a clear peak in electricity consumption can be appreciated in the summer months due to tourism.

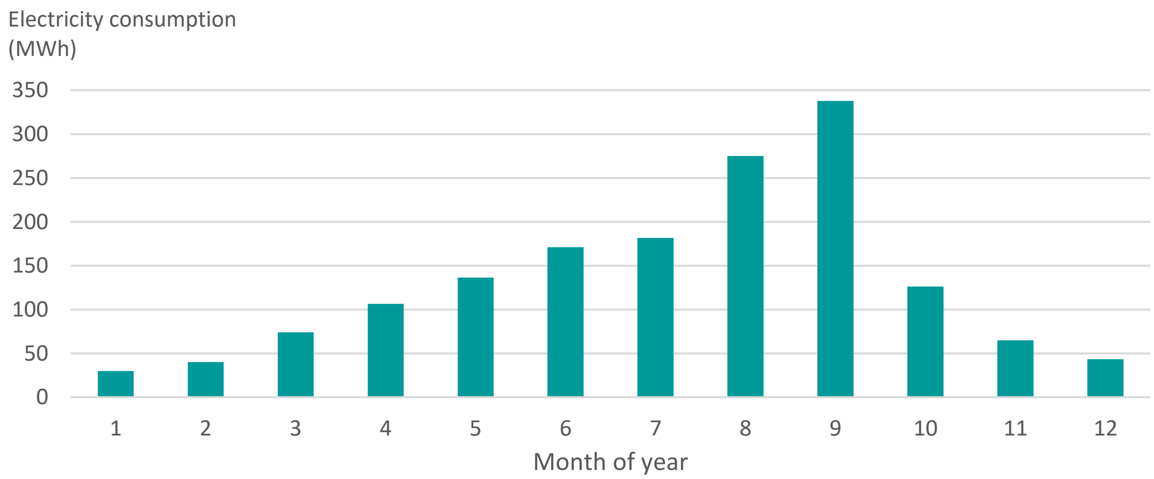


Figure 12: Estimated monthly electricity consumption on Halki

On top of the load profile shown in Figure 12, the extra electricity consumption due to the potential electrification of ferry transport is added. As indicated in Task 1, only the short-transit ferries (Fedon, Sebeco II, and Nissos Halki) are suitable to be electrified. This results in an increased electricity consumption of around 1000 MWh on a yearly basis. This was converted into an hourly load profile, based on the dates and times each of these ferries arrives in Halki. As they ferries stay docked in the port for several hours, it is assumed that that each ferry has three hours to recharge sufficiently for the trip back to Rhodes (Kamiros Skala).

The resulting load profile (the base load plus the new load of the ferries) is shown in Figure 13. The figure illustrates that there is still a strong seasonality in Summer as the ferry high season corresponds with the touristic season. The figure also shows two horizontal bands. The upper one corresponds to the natural peak of electricity consumption in the evening, while the lower one corresponds to the charging of the ferries, which mostly occurs in the morning when the ferries first dock.

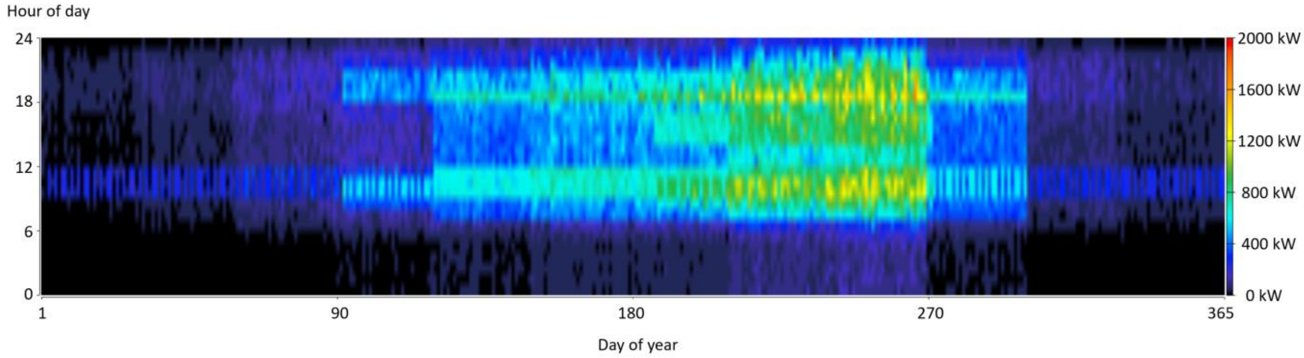


Figure 13: carpet plot of the combined electrical load (base + ferries) on Halki

## Components

The electrical components that are included in the model are:

**Wind turbines:** Siemens-Gamesa SG155 with 6.6 MW of nominal power and 165 m of hub height as described in Task 2 has been modelled. The capital cost is set at €13.2 million for the turbine itself, the installation, and the additional civil and electrical works, while the O&M costs are set €528 000 per year. These values have been chosen in agreement with common cost distributions for offshore wind, and in order to achieve the €100 /MWh LCOE over 20 years as described in Task 2.

**Solar PV:** The planned 1 MWp solar plant is modelled based on the PVGIS results received from the island representative. This system is oriented towards the south with a tilt of 25°. The PV panels are of the crystalline silicon type and the total losses equate 18.16%, including aging, wiring, connection losses, dust, shading, etc. The price of this component is set to zero as it is already built. The solar plant is part of an energy community on the island, which comprises households, businesses, and public authorities. The members of the energy community are not directly connected to the PV park, but instead will receive electricity credit for free commensurate to the solar park's generated energy, which operates under virtual net metering. The generated solar power feeds the local electricity of the islands of Halki and Rhodes in the south-eastern Aegean Sea.

**The undersea cable:** The 3 MW submarine cable transports electricity between Rhodes and Halki and is maintained by the national Distribution Network Operator HEDNO. At the time of writing, electricity prices in Europe have exploded. This disruption is not expected to last although the new energy price equilibrium will be higher than before. The imported electricity from Rhodes is therefore assumed to come at a cost of €0.15 /kWh in contrast to the €0.11 /kWh indicated by the Halki representative. Excess electricity from local production is assumed to be sold to Rhodes at an injection price of €0.03 /kWh via the submarine cables. Both of these prices are still speculative; therefore, a sensitivity analysis will be carried out to study whether higher or lower prices have a significant impact on the results.

Moreover, the assumption is that Rhodes can always take up the excess electricity. While this might currently not always be the case, it probably will not pose an issue in the future as the Transmission System Operator (TSO) aims to reinforce the grid connections between the islands in the Aegean Sea, including Halki and Rhodes who are part of the Dodecanese Islands [7] (see Figure 14). In Phase I of the interconnection project (2028), the TSO proposes a new interconnection of Rhodes with Kos-Kalymnos power system via Telos and Nisyros. This will allow Rhodes power station to supply power to the rest of the islands and allow Nisyros' geothermal power station (≈40 MW) to cover the islands' baseload power requirements. Phase II (2030) proposes the interconnection of Dodecanese islands with Crete with AC 2*280 MVA cables. This demonstrates that Halki will become better interconnected and hence will be able to sell its excess renewable electricity instead of having to curtail it.

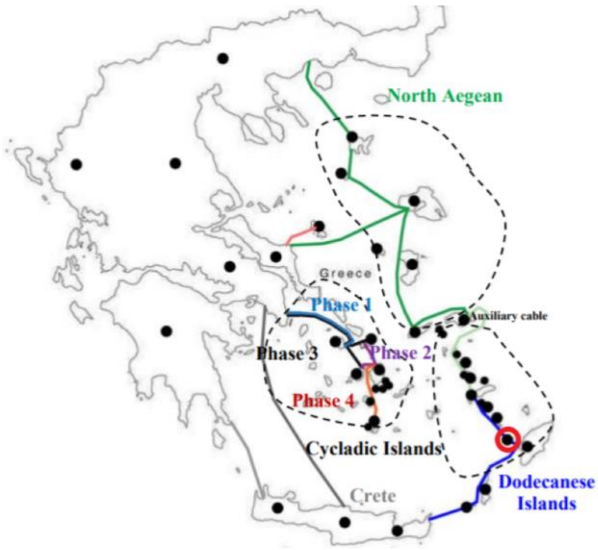

Figure 14: Greek islands grid extensions plan

**The battery:** A 4 h Lithium-ion battery in modules of 1 MW and 4 MWh was used to model the energy system. Li-ion batteries have the advantage of excellent round-trip efficiency, a relatively long lifetime, and a low self-discharge rate. They are the most used battery type nowadays, making up about 90% of the battery market and also rapidly decreasing in cost due to its widespread use and industrial fabrication. The capital cost was based on the IRENA "Electricity storage and renewables report."[18] and equals €1 000 000 for a 1 MW/4 MWh battery while the O&M cost are about €7 500 per year The battery module has a roundtrip efficiency of 90%, a lifetime throughput of 21 000 MWh, and an expected lifetime of 15 years.

### General assumptions

Several assumptions were made in order to run the simulations. These assumptions are drawn from experience in similar projects as well as international best practices. The input parameters for the HOMER model have been estimated as:

- Project lifespan: The systems are assumed to have a 20-year lifespan, which is the value used by most global renewable energy independent programmes.
- Discount rate: The nominal discount rate is 12%, based on the average weighted average cost of capital (WACC) for solar PV projects in Greece between 2009 and 2017 [9].
- Inflation: The average expected inflation rate in Greece is 1.36%, based on the projections of 2022 to 2026 [10].
- Cost reflectivity: There are no recoverable costs at the end of the lifespan of the system.

## 3.2 Results and discussion

Using the HOMER Pro model with the input outlined above, the most-cost efficient energy system for Halki has been sought taking into account the estimated load (including the electrified ferries), the production from the already existing 1 MWp solar PV plant, the researched offshore floating wind turbines, and possibly a battery storage system.

The results show that the optimal solution from a financial point of view is to meet the new ferry demand by installing additional solar PV. This section describes first this scenario, but also analyses scenarios when placing offshore floating wind turbines, and when placing battery storage. The impact of the grid electricity price is also studied to determine when battery storage become financially interesting.

### The optimal solution

The HOMER model revealed that the lowest cost energy solution for Halki is to rely on installing an additional 739 kWp of solar PV, on top of the existing 1 MWp plant, supplemented with grid power. This solution offers a renewable fraction — the percentage of load covered by renewable energy — of 52% over the entire year. This percentage value is due to the load profile: it experiences a sharp increase in summer due to tourism, following the production profile of the solar PV plant, see Figure 15.

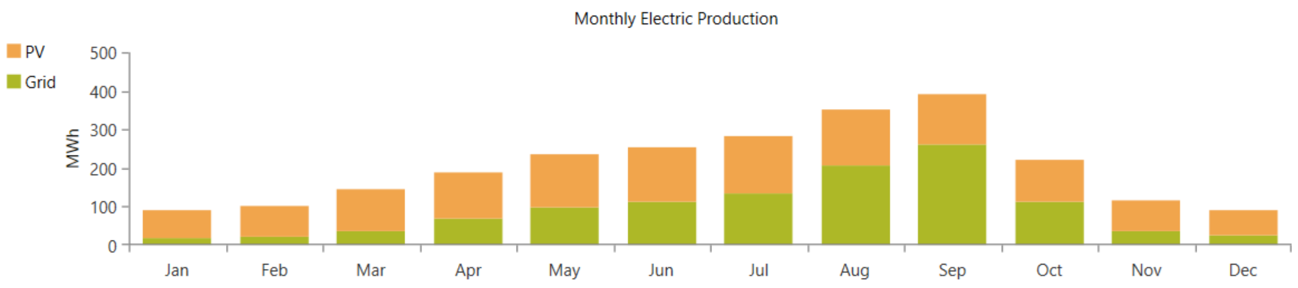


Figure 15:Monthly electricity production for a PV and grid-connected system

Looking at the daily variation throughout the year, Figure 16 shows that PV production actually exceeds the consumption on the island during the day—with the exception of the summer months. The excess of PV electricity production is sold to Rhodes at a price of €0.03 /kWh, while the PV consumed on the island is sold to the local consumers at €0.15 /kWh. In the evening, when PV is not producing, electricity consumed on the island comes from the interconnection cable.

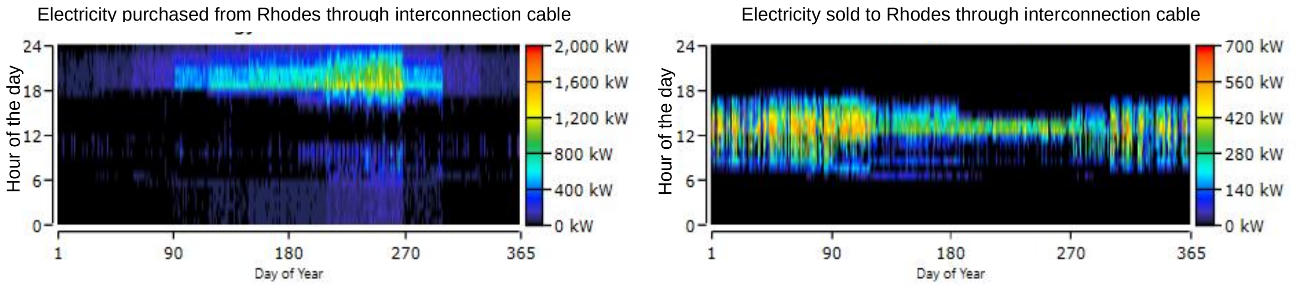


Figure 16: Grid purchases and sales throughout the year

Table 6 gives and overview of the annual energy balance for the optimal solution energy system in Halki. The solar production is presented in two different lines: one corresponding to the existing 1 MWp solar PV farm and the second to the additional 739 kWp that the model in Homer Pro recommends installing for this solution.

Table 6 Annual energy balance of lowest cost system

| **Description** | |
|---|---|
| **Power system** | |
| PV capacity | 1 739 kW |
| **Annual Energy balance** | |
| Total electricity production | 4 205 MWh |
| 1 MWp solar PV energy production | 1 762 MWh |
| 739 kWp solar PV energy production | 1 332 MWh |
| Grid purchase | 1 111 MWh |
| Total electricity consumption | 4 050 MWh |
| Electricity demand | 2 543 MWh |
| Grid sales | 1 507 MWh |
| Electricity lost in conversion (converter/storage) | 155 MWh |
| **Environment** | |
| Renewable fraction | 72.6% |
| **Finances**[11] | |
| Net present cost | €1 84 million |
| Total initial investment | €500 K |
| Operating cost | €163 K |
| Discounted payback time | 6.89 years |
| Net present worth compared to status quo | €368 K |

Source: Consultant analysis using Homer Pro results

[11] Calculated using the parameters described in **Error! Reference source not found.**. Only takes into account the new 739 kWp solar PV installation.

## Adding offshore floating wind

Offshore floating wind is not a part of the optimal solution due to two reasons. First, the LCOE of offshore floating wind was estimated at €100 /MWh, at least in within the coming years. This is almost twice as high as the cost of adding additional solar PV, which has an LCOE of €54 /MWh. Second, only one offshore floating wind turbine produces 21 GWh/year, which is eight times the total consumption on Halki, including the electric ferries. Adding offshore floating wind should thus only be done from the perspective of becoming an energy exporter.

## Adding battery storage

A battery storage solution could use the excess electricity produced by the solar PV plants during the day to charge and deliver this electricity in the evening. In the current price scenario, the battery electricity storage does not arise as financially interesting because the electricity grid already serves as storage, allowing to inject and consume electricity whenever needed.

Adding a battery storage system to the mix could become viable with higher electricity and lower injection prices. This is indicated in Figure 17 which shows that once the power price surpasses €0.25 /kWh and the injection remuneration stays below €0.05 /kWh, the optimum solution is to include one battery module of 1 MW/4 MWh. When the sellback rate reaches above €0.1 /kWh, the optimum solution is to include offshore floating wind since the enormous amounts of excess electricity can then be sold at a profit, as the offshore floating wind LCOE is €100 /MWh.

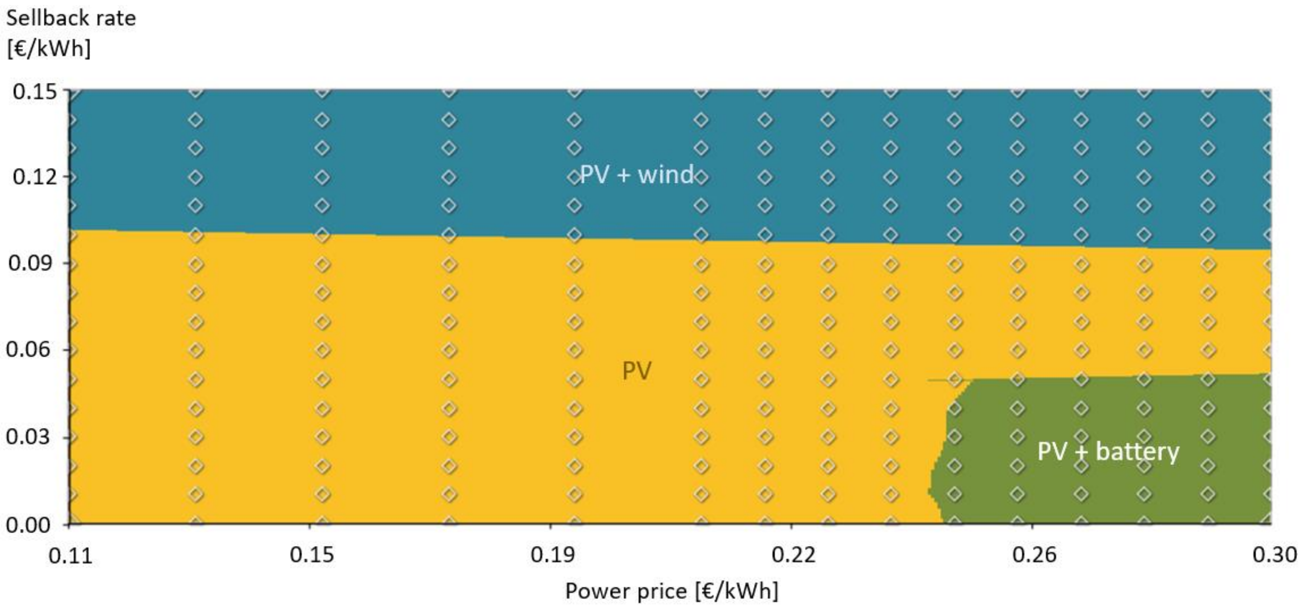


Figure 17: Impact of grid injection and consumption price on the battery capacity

# Conclusions

This Electryone 2.0 project has been carried out following on previous work of the Clean energy for EU islands secretariat for Halki. Three main tasks have been developed in this study: (1) an analysis of how marine transport could be electrified, (2) as assessment of the potential of floating offshore wind, including an estimation of the LCOE, and (3) a model of the energy system taking into account the two points above, to find the most feasible solution.

The analysis of electrification of marine transport included an estimation of its current consumption, and an evaluation of the ferries and boats that could be fully or partly electrified. This analysis shows that the emissions by marine transport could be reduced by 650 tons of $CO_2$eq per year.

Regarding the wind potential on the offshore zone between Halki and Alimia, the resource maps generated show favourable conditions for wind exploitation. Considering the limited local wind shear which leads to a limited increase of wind speed with height, lower hub heights with respect to the proposed configuration would still be suitable for the site.

The proposed horizontal axis wind turbine Siemens-Gamesa SG155 6.6 MW should be considered as an indicative model used for the purposes of this study. To increase the energy production, it would be meaningful to maximise the rotor diameter rather than increasing the hub height of the configurations under study. In this regard, another configuration suitable for the site is the Vestas V236 15 MW, which comes with a native floating configuration and would lead to higher energy production. This turbine could not be included in the model as the power curves have not been made available by Vestas to the authors.

The proposed Siemens-Gamesa layout with ten wind turbines leads, indicatively, to an annual production of 180 156 MWh/y. These results suggest that this site is suitable for wind exploitation.

Finally, a model of Halki in HOMER Pro has been developed to determine the viability of different energy mixes on the island, as a consequence of electrifying the ferries, including offshore floating wind, and adding a potential storage component to better align local electricity production and demand. The base-case scenario is defined as the interconnection with Rhodes together with the 1 MWp solar plant on the island.

The model shows that in the current electricity price scenario, the financial optimum is to include an addition 739 kWp of solar PV, on top of the existing 1 MWp solar PV plant.

Offshore floating wind is not a part of the optimal solution since its cost in the coming years is still quite high compared to the cheaper alternative of solar PV. One offshore floating wind turbine produces 21 GWh/year, which is eight times more than the total consumption on Halki, including the electric ferries. This exemplifies that adding offshore floating wind should thus only be done from the perspective of becoming an energy exporter as even one wind turbine already produces a multitude of what is required on Halki.

In terms of storing energy, the current interconnection to Rhodes could already act as electricity storage as it allows injecting the excess renewable electricity and taking electricity in times of curtailed local production. Installing a battery becomes interesting once the power price surpasses €0.25/kWh and the injection remuneration stays below €0.05 /kWh.

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