European Commission

Clean energy for EU islands: **Electryone**

Halki, Greece

Clean energy
for EU islands

Electryone

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Summary

The present project has been developed for Halki (Greece) in order to support the island representatives in their will to:

1. Analyse the wind energy potential through a wind resource map and give advice on measurement campaigns
2. Investigate the potential of a solar-powered district cooling system
3. Model the energy system and determine whether wind turbines and/or battery storage are financially interesting

For the analysis of the wind potential, the terrain at the site has been modelled in detail, including elevation, roughness and obstacles to the wind flow. A wind atlas has been created using the software WindPro at different, relevant heights above ground level (AGL). Subsequently, the most significant locations for the exploitation of wind energy have been traced. Two configurations of vertical axis wind turbines have been envisaged: Fairwind F100 at 18 m with nominal power of 10 kW and Fairwind F180 at 32 m with nominal power of 50 kW [2]. This study indicates that a Fairwind F180 at 32 m with nominal power of 50 kW could produce 125.58 MWh of electricity over a project lifespan of 20 years, based on a P50 probability.

The solar-powered district cooling system which has been investigated would be located at the existing island's water reservoirs and would deliver cooling energy via a piping to network to the medical centre, the local school, the city hall and 20 private houses along the way. This study indicates that such a solar cooling network is not feasible in Halki due to (1) the heat losses in long pipe runs with distribution to many different buildings, (2) the large parasitic power required, (3) the stagnation of the system for extended periods, (4) the low utilisation and base load due to climate fluctuation, and (5) the inefficient fossil fuel back-up (no waste heat re-use or biogas available).

For the third task, the energy system of the island was modelled using Homer Energy. This includes the already existing 1 MWp PV plant that has recently been constructed, the possibility of installing vertical axis wind turbines (as investigated in the first task), and the possible inclusion of a battery storage system. According to the obtained results, neither vertical axis wind turbines, nor a battery storage system would be interesting from a financial point of view. While wind turbines could try to fill the gaps when solar is not producing, they tend to produce the most in winter, when demand is rather low due to absence of tourism. In fact, adding one wind turbine would result in 38% of the produced energy to be sold to the grid or curtailed. A battery storage system on the other hand is better suited to fill up the gaps when solar PV is not producing. Both storage and wind turbines can become financially interesting when the grid power price and the price at which electricity is sold to Rhodes surpass a certain limit. Both are also effective at increasing the renewable fraction of electricity consumed on the island, but battery storage can do this the most cost-effective.

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Glossary

AGL / ASL	Above Ground Level / Above Sea Level
CAPEX	Capital Expenditure
Corine Land Cover	The Corine Land Cover database is an inventory of land cover in 44 classes. It was initiated in 1985 by the European Union and has been taken over by the EEA. 3E associates roughness information to each class in order to create roughness maps that are used in the wind flow models.
LCOH	Levelised Cost of Heat
NPC	Net Present Cost
WACC	Weighted Average Cost of Capital
WAsP	WAsP (Wind Atlas Analysis and Application Program) is a software package that simulates wind flows for predicting wind climates, wind resources, and power productions from wind turbines and wind farms. WAsP is developed and distributed by DTU Wind Energy, Denmark. It has become the wind power industry-standard PC-software for wind resource assessment.
WindPRO	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.

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 1100 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 May 2021. Halki's Electryone project will consist of the design, implementation and operation of decentralised renewable energy sources on the island. In particular, the project will investigate three different technologies: wind energy, solar PV and solar thermal for cooling.

Within the framework of Electryone, the technical assistance from the Islands secretariat (presented in this report) has the following three objectives/tasks:

1. Analyse the wind energy potential on the island. To this end, a wind resource map has been produced. In addition, advice is given on how measurement campaigns could be conducted on the island
2. Investigate the potential of a solar-powered district cooling system
3. Model the energy system and determine whether wind turbines and/or battery storage are financially interesting

Figure 1: Site location

Wind potential

The wind potential in Halki has been studied by elaborating wind map for vertical axis wind turbines. Halki would like to focus on vertical, as opposed to the more common horizonal axis turbines, given their minimum visual and audio impact. These characteristics are likely to help with public acceptance

The wind resource map has been created for Halki as well for the smaller, neighbouring island of Alimia. Alima is under the authority of the municipality of Halki and is located 7.8 km NE of the island. The smaller island is of special interest, as it can act as an example of how small uninhabited islands can flourish again, under a solid and sustainable master plan for their development. This plan should integrate energy sources with zero or minimum environmental impact

Methodology

At this preliminary stage of the project, in the absence of measurements on site, the Global Wind Atlas [1] were used as the wind resource. The wind flow model WAsP was used to extrapolate the wind regime vertically and horizontally. Terrain elevation is modelled within a radius of 15 km (in line with WAsP recommendations [3]) based on EU-DEM data (25 m gride). Height contour lines were then generated with an elevation difference of 5 m between two successive lines. Given that roughness length is closely related to land use, terrain roughness was modelled using a land-use database. The Corine Land Cover (2018) database was used and roughness length values specific to each land use were applied according to 3E's methodology [4]. Following WAsP recommendations, the terrain roughness has been modelled within a radius of 20 km.

Results for Halki

For the whole island, a wind atlas has been created using the software WindPro[1]. The Wind Climate from the Global Wind Atlas [1] has been used to calculate a wind resource map of Halki. Wind resource maps have been generated at four different heights above ground level: 18.0 m, 32.0 m, 50.0 m and 100.0 m. The first two correspond to potential hub heights of the turbine types which can be considered. They are presented in the figures below.

The wind predominantly blows from north-north-west (NNW) sector. The wind energy rose depicts that most of the energy production comes from this sector as well (Figure 2). The mean wind speed on site ranges between 1.4 m/s and 12.0 m/s at 18.0 m and between 2.2 m/s and 12.9 m/s at 32 m depending on the location on the island, as shown in the resource maps in Figure 3 and in Figure 4.

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[1] 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.

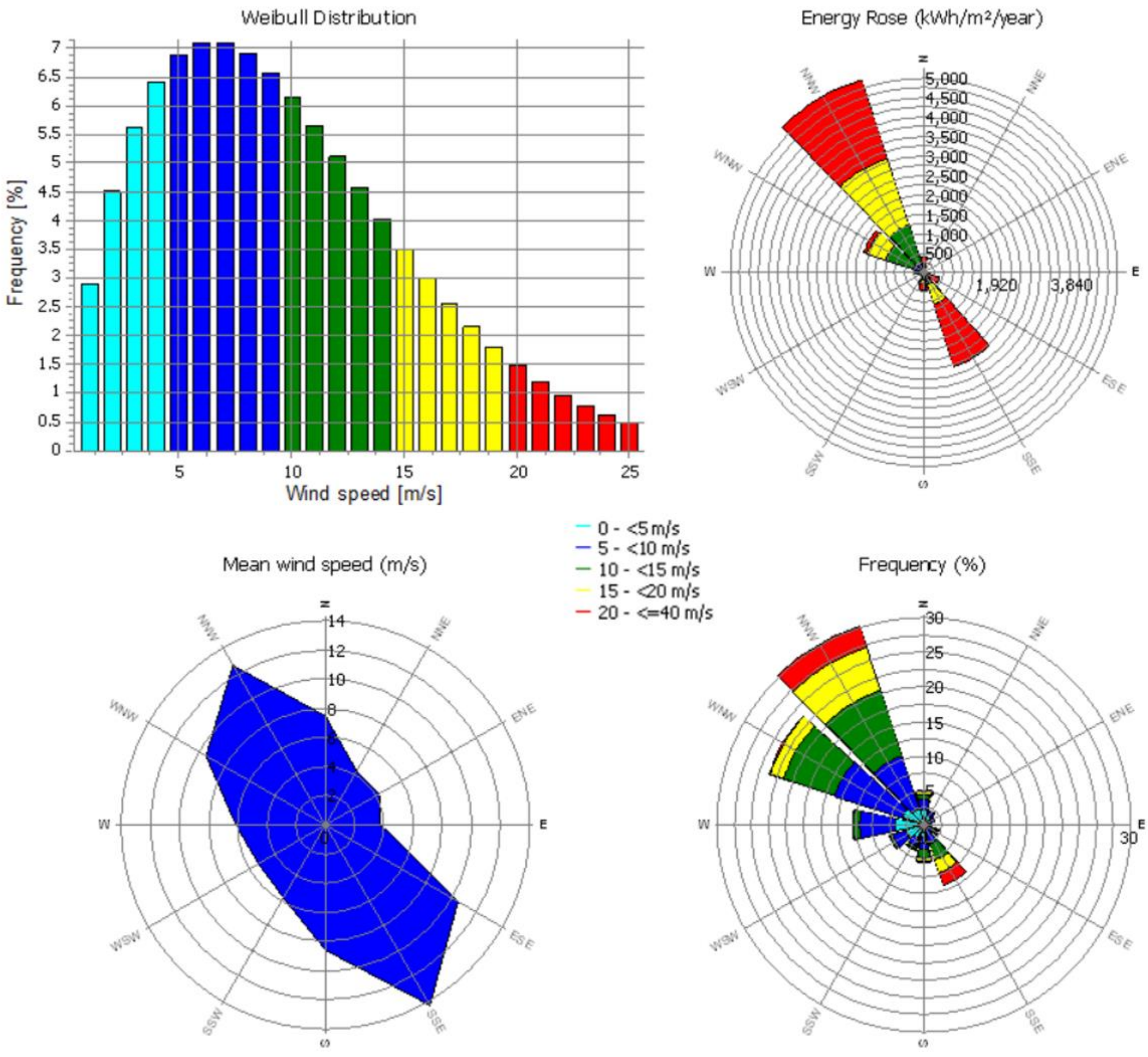

Figure 2: Wind distribution on the central part of the island at 100 m of height. (Exact location: 36.23N and 27.57E)

The highest wind speeds can be found in specific locations in the central part of the island, mainly in correspondence of the highest altitudes. The island's coast has typically lower wind speed. An analogous wind speed pattern was observed for all the heights considered in the study.

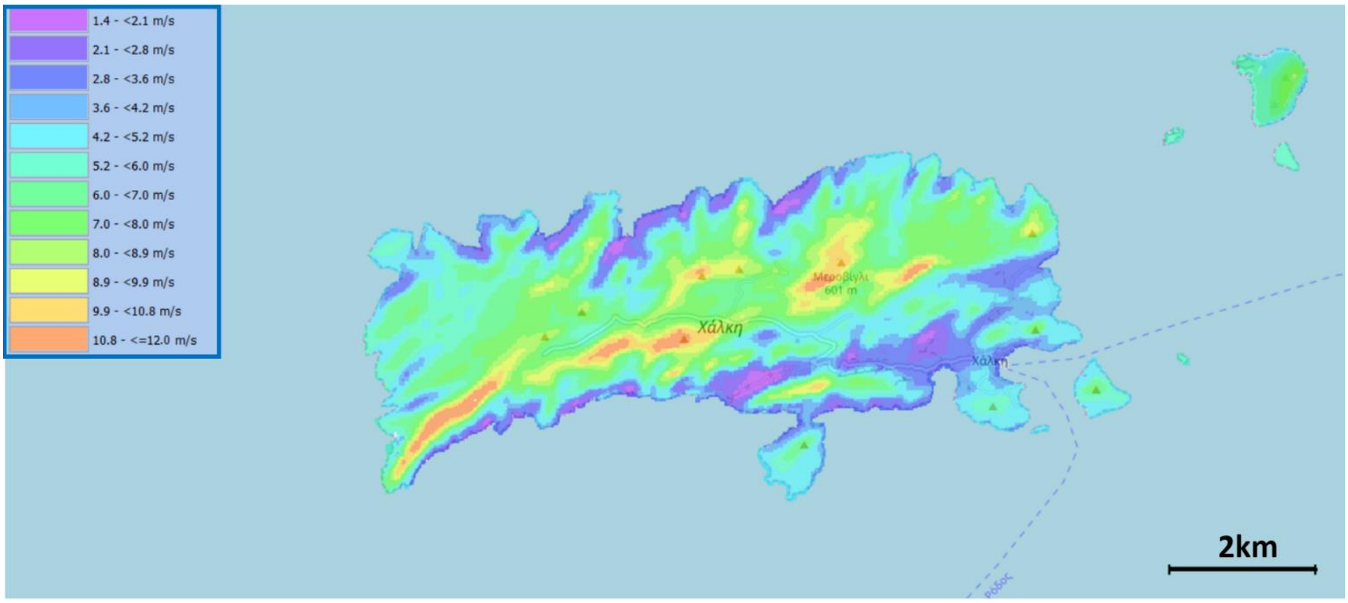

Figure 3: Mean wind speed at 18.0m AGL

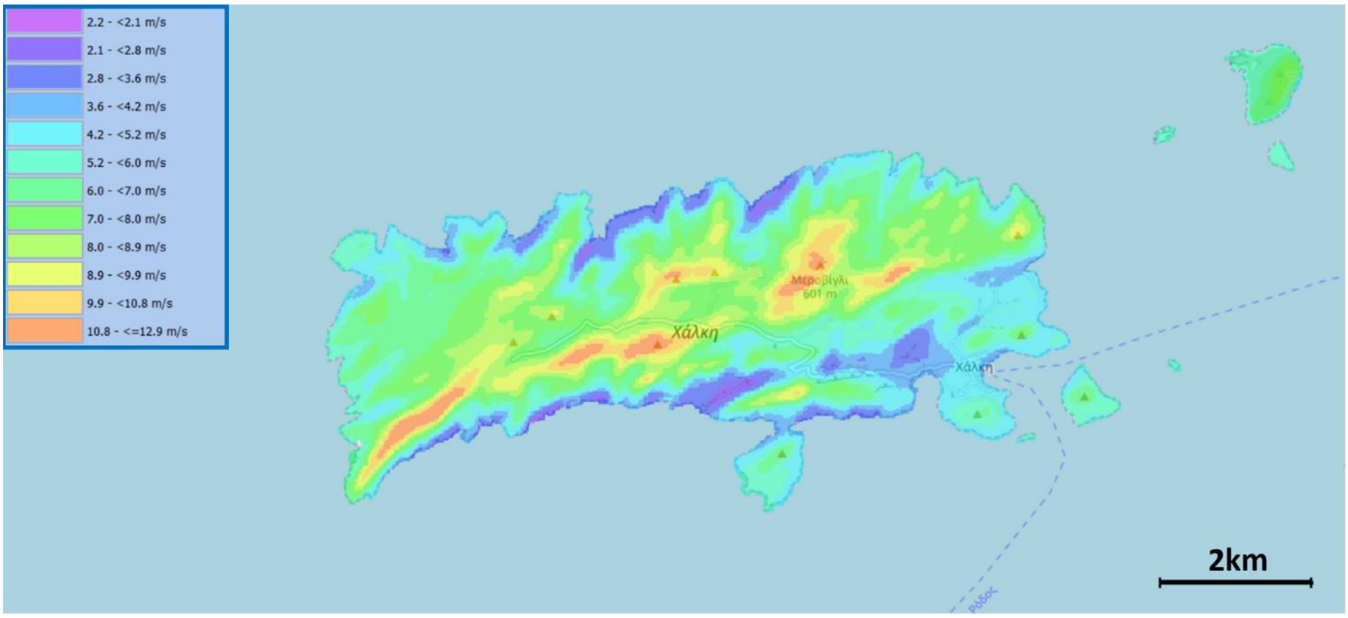

Figure 4: Mean wind speed at 32.0m AGL

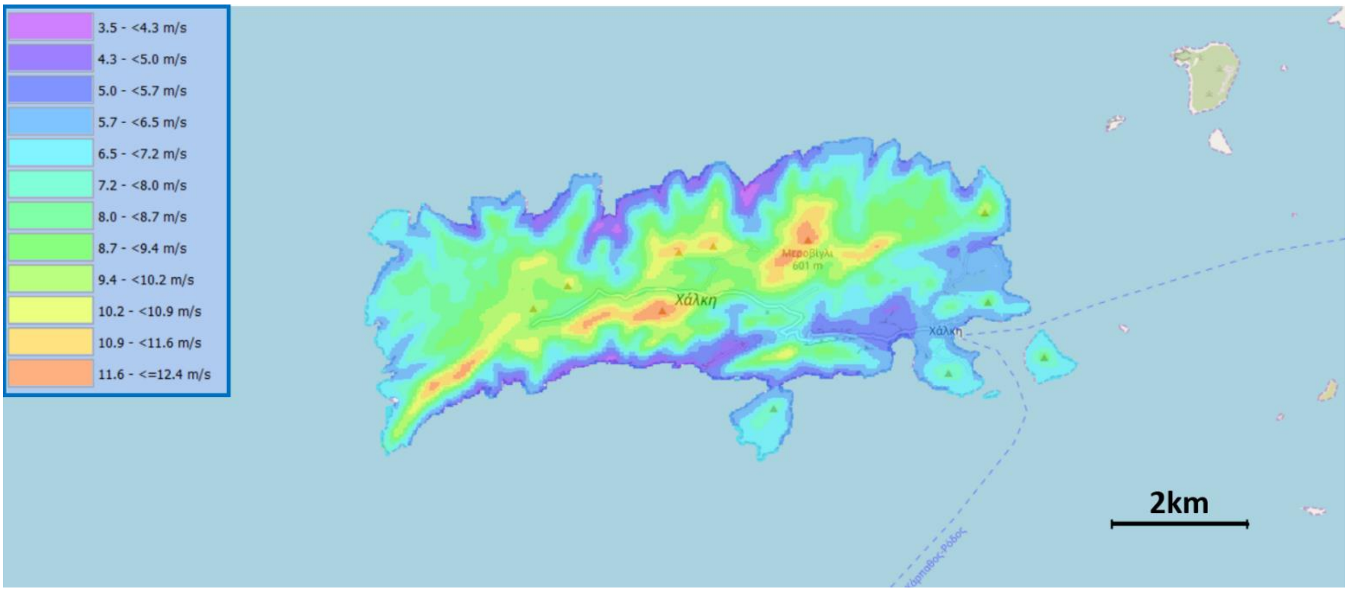

Figure 5: Mean wind speed at 50.0m AGL

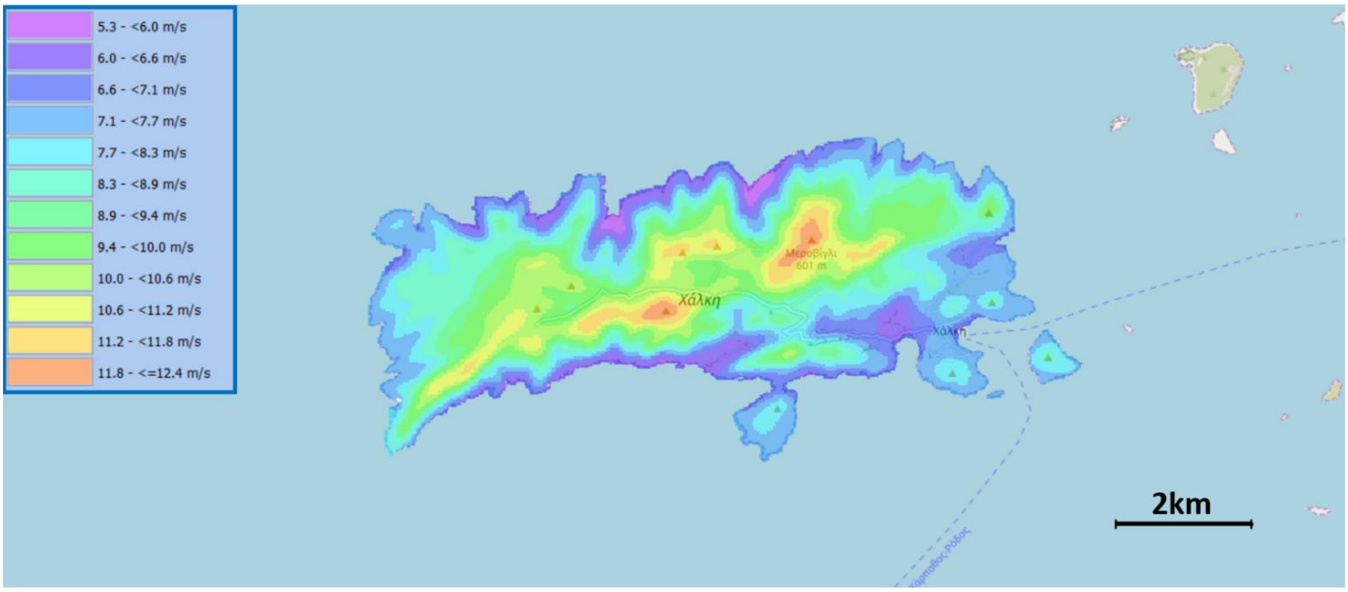

Figure 6: Mean wind speed at 100.0m AGL

A wind resource map in terms of annual production MWh/year has been generated at 18.0 m and 32.0 m above ground level based on exemplar vertical axis wind turbines: Fairwind F100-10 10 kW and F180-50 50 kW. The choice of vertical axis wind turbines was requested by the island, as these turbines have a limited size, which is expected to favour public acceptance.

The results show that the average wind potential on the island at 18.0 m ranges between 2.9 MWh/year and 51.9 MWh/year for the Fairwind F100-10 10 kW (Figure 7), while at 32.0 m it ranges between 19 MWh/year and 203 MWh/year for the Fairwind F180-50 50 kW (Figure 8). Higher values are typically found where higher altitudes are located. However, different additional criteria have to be fulfilled before suggesting feasible areas for wind energy exploitation. Stemming from the analysis of the topography on site, this solution needs to be investigated also in terms of its feasibility regarding access (roads/ elevations) and distance from the main grid, located in Emborio, in the south-east area of the Island.

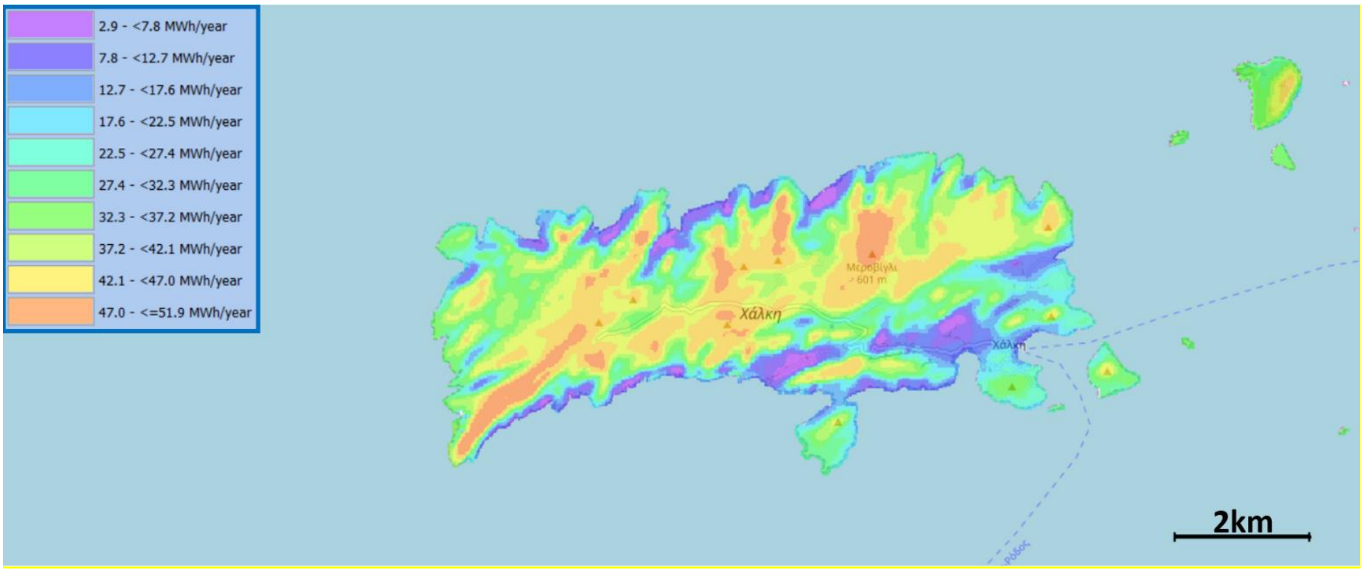

Figure 7: Annual wind production at 18.0m AGL based on the Fairwind F100-10 10kW wind turbine [MWh/an]

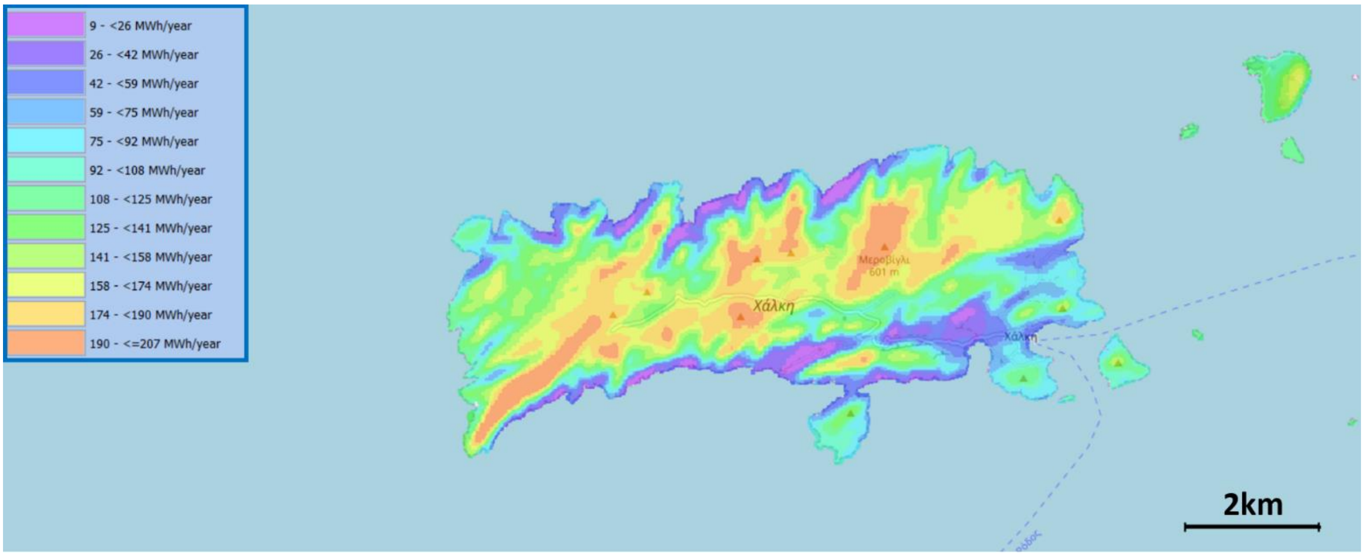

Figure 8: Annual wind production at 32.0m AGL based on the Fairwind F180-50 50kW wind turbine [MWh/an]

Results for Alimia

In addition to Halki, a wind resource map has been generated for the smaller island of Alimia. Wind resource maps have been generated at four different heights above ground level: 18.0 m, 32.0 m, 50.0 m and 100.0 m. The first two correspond to potential hub heights and turbine types. They are presented in the figures below.

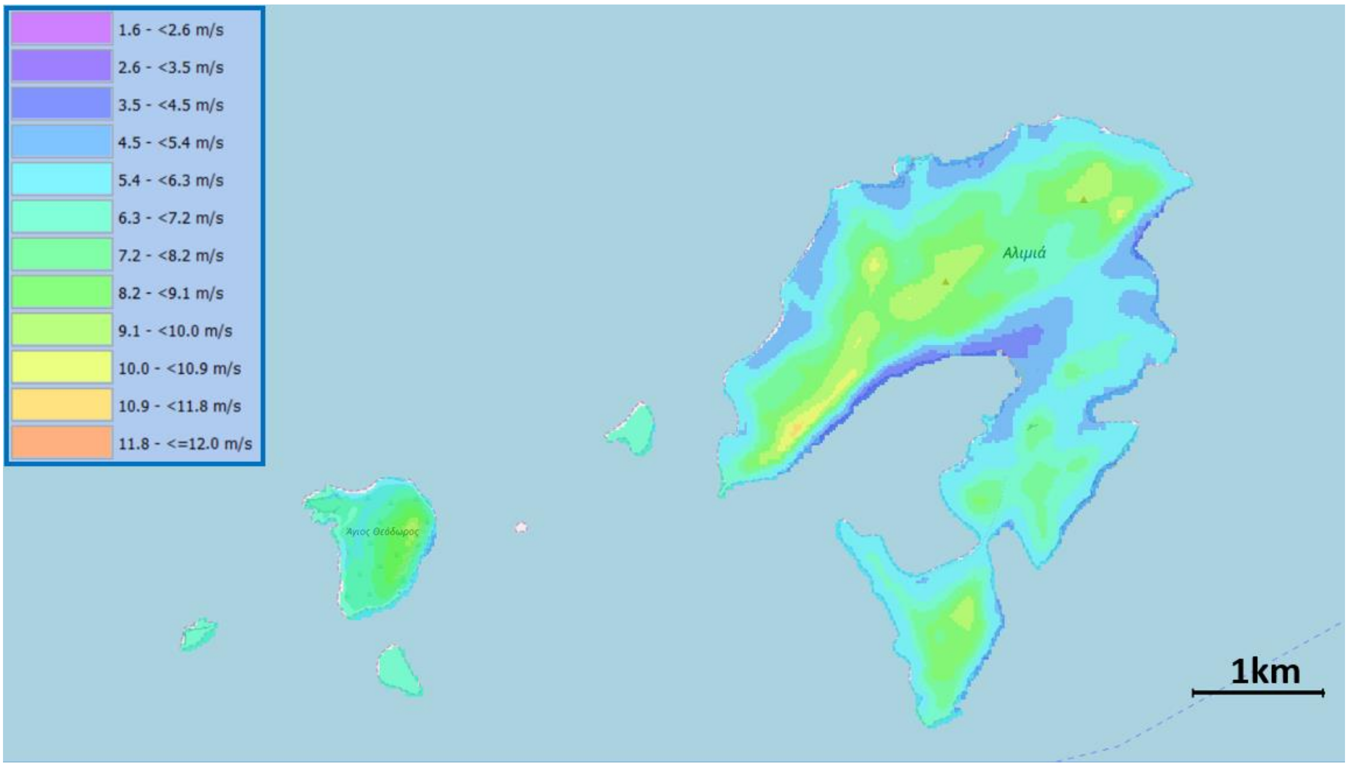

Figure 9: Mean wind speed at 18.0 m at Alimia island

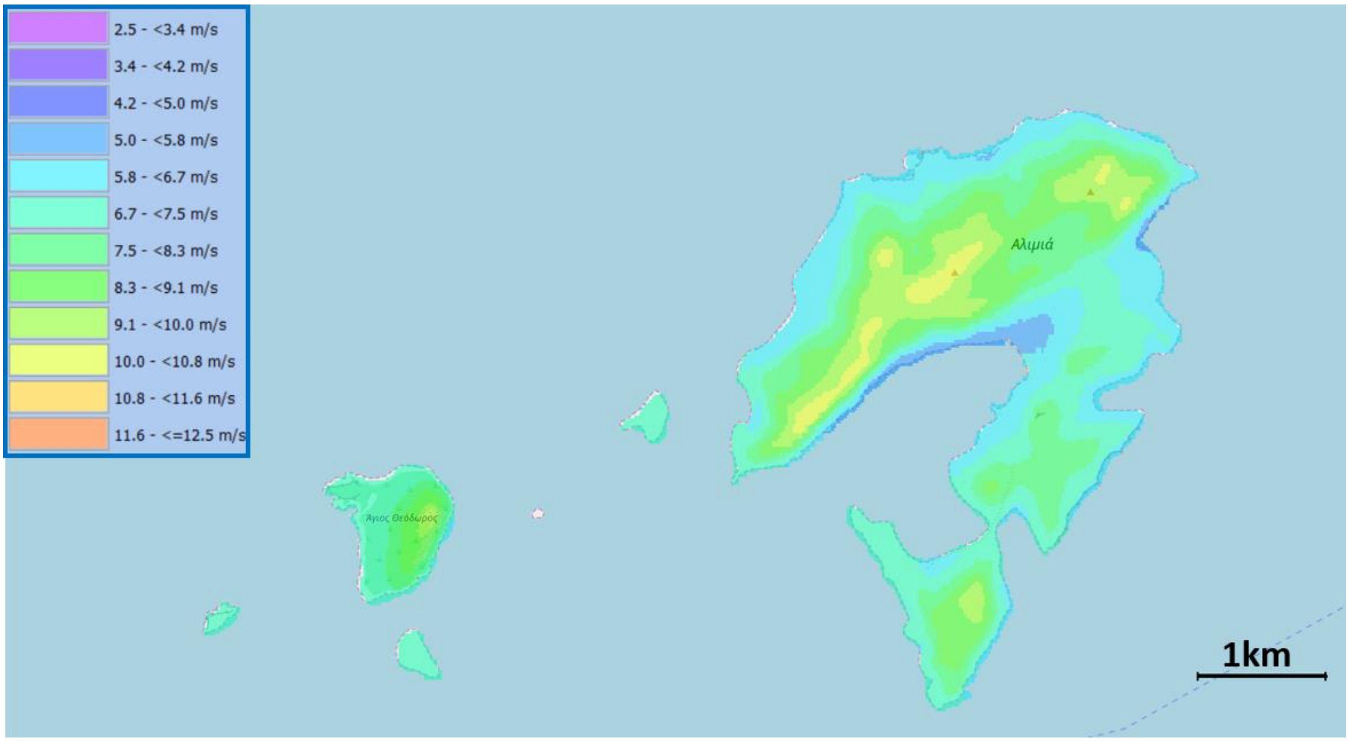

Figure 10: Mean wind speed at 32.0 m at Alimia island

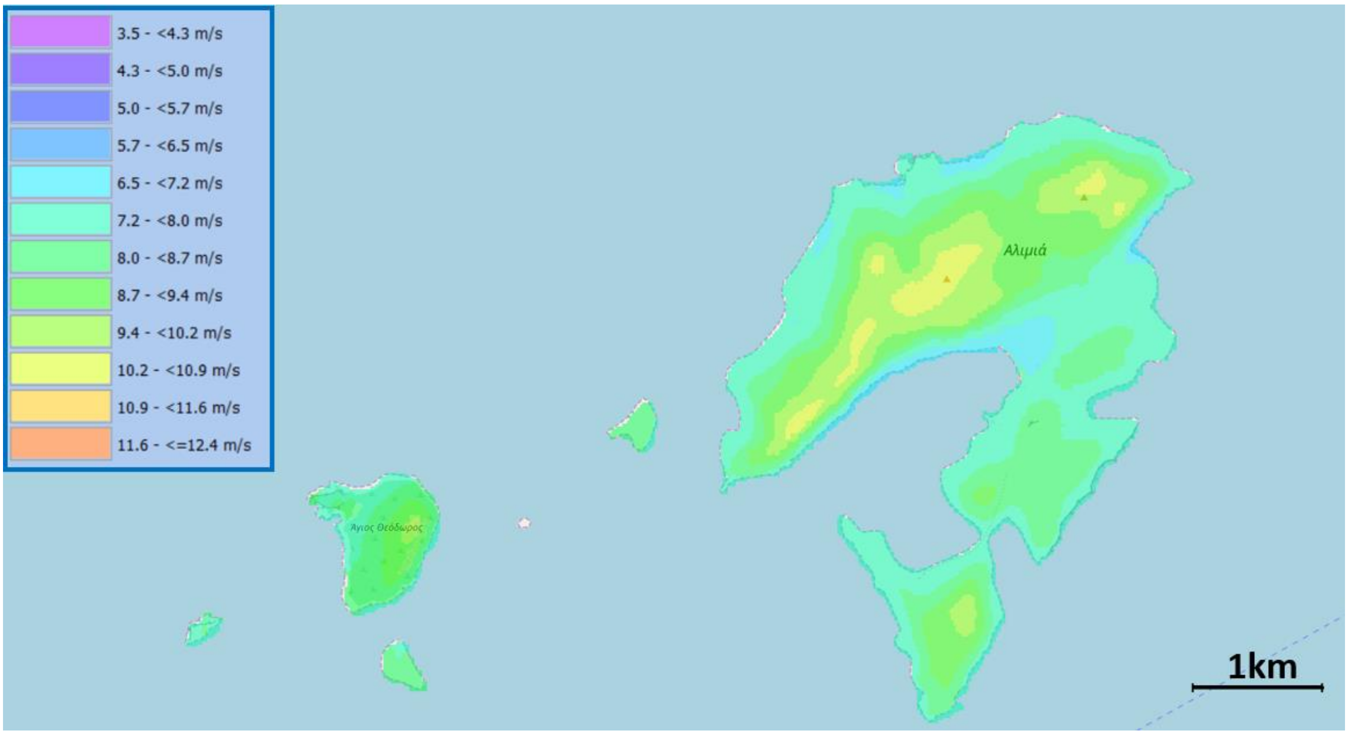

Figure 11: Mean wind speed at 50.0 m at Alimia island

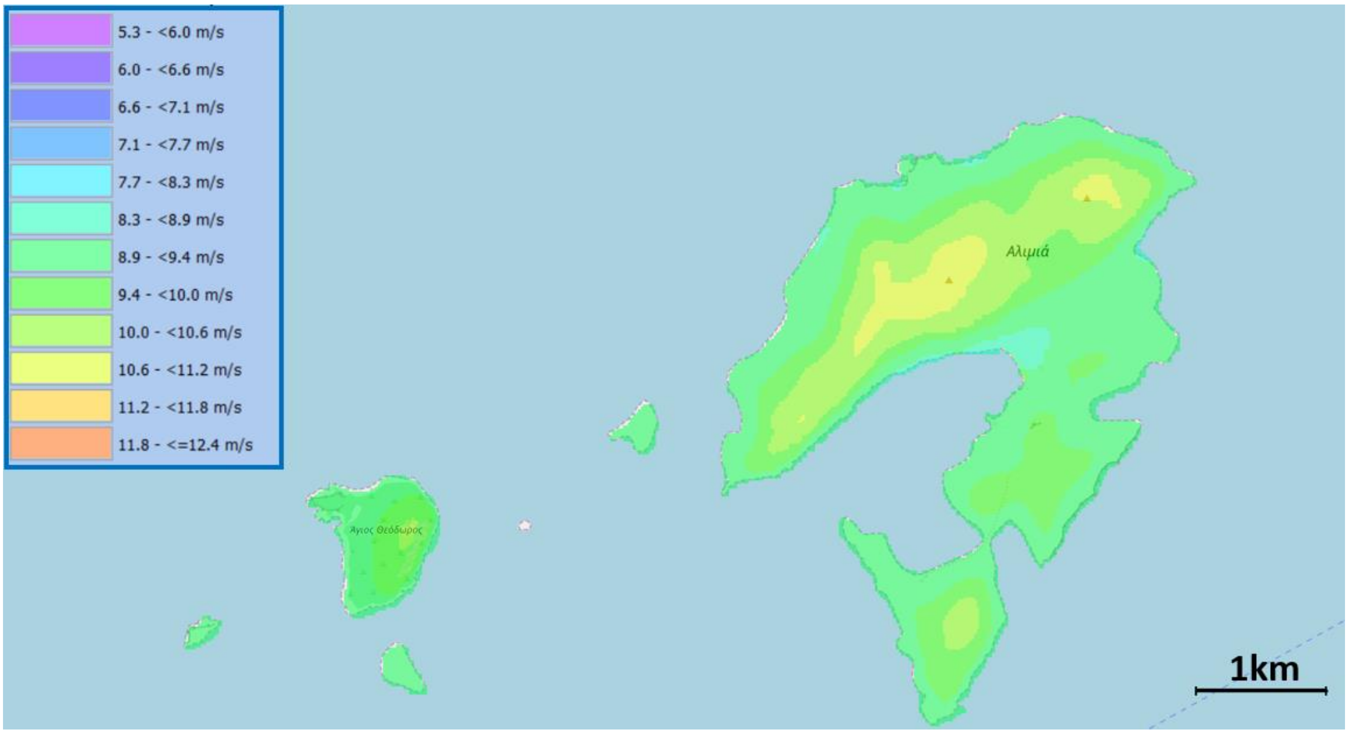

Figure 12: Mean wind speed at 100.0 m at Alimia island

Again, a wind resource map in terms of annual production MWh/year has been generated for the Alimia island at 18.0 m and 32.0 m above ground level based on exemplar wind turbines: Fairwind F100-10 10 kW and F180-50 50 kW. Figure 13 and Figure 14 confirm that higher values of average wind potential are typically found where higher altitudes are located. The central locations of the island (both on the north and south sides) seem to be suitable for wind exploitation. However, considering the topography on site, this solution needs to be investigated further in terms of its feasibility regarding access (roads/elevation).

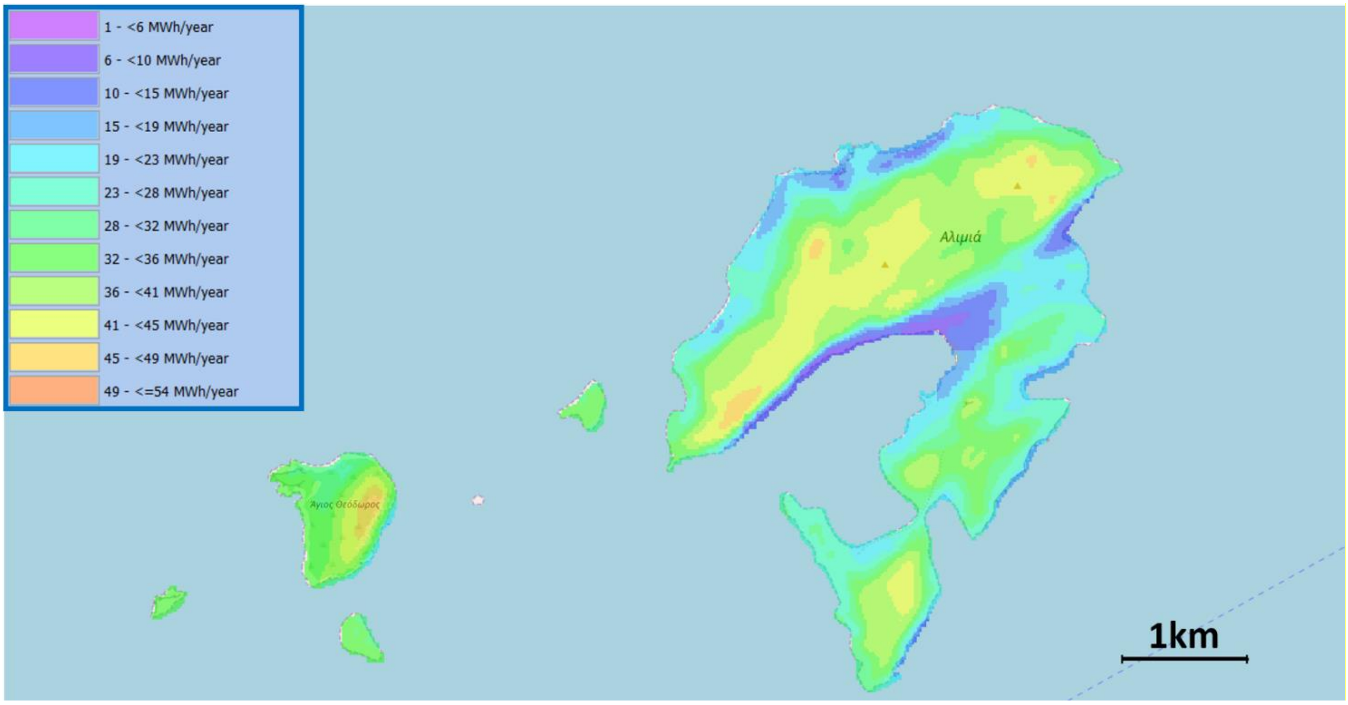

Figure 13: Annual wind production at 18.0 m with 10 kW wind turbine [MWh/an]

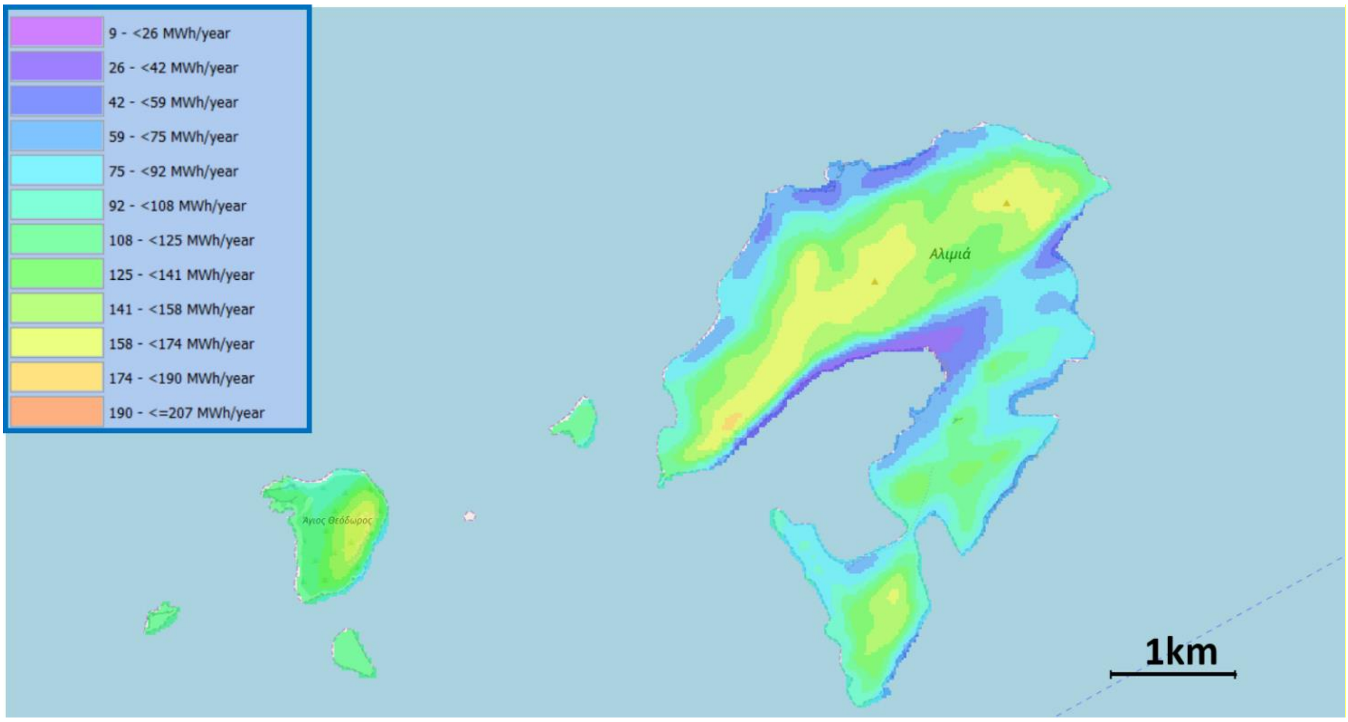

Figure 14: Annual wind production at 32.0 m with 50 kW wind turbine [MWh/an]

Recommendations on measurement campaigns

Potential locations for up to three wind masts have been identified, as shown in Figure 15 and in Table 1. These locations have been defined based on the wind resource map, the feasibility of building a wind farm close-by and their accessibility. More in detail, the choice of this location is related to the available wind resources, to the proximity to the grid/only village of the island and to the local orographic complexity. Tubular masts were proposed in place of lattice ones, due to the relatively low hub height of the proposed wind turbines configurations.

The measurement should cover 12 complete and consecutive months with availability of cleaned data higher than 90%. Moreover, specifications to adapt for the configuration of the tubular masts (number of sensors and orientation of the booms) are proposed.

First, the top wind speed measurement level has to be taller than 2/3 of planned hub height.

For side-by-side top mounted anemometers:

- Both side-by-side top mounted anemometers are more than 20 times boom diameters above the centre of the boom supporting it
- The side-by-side mounted top anemometers are separated from each other within the range of 2.5 m – 4 m
- There is no other instrument outside the 11:1 half cone within 4 m below the side-by-side mounted top anemometers,

Conditions for side-mounted anemometers:

- At all heights holding boom-mounted anemometers, anemometers are oriented 45° from main wind direction,
- All boom-mounted anemometers are farther than 6.1 tower diameters from the centre of the mast,
- All boom-mounted anemometers are farther than 20 times boom diameters above the centre of the boom supporting it.

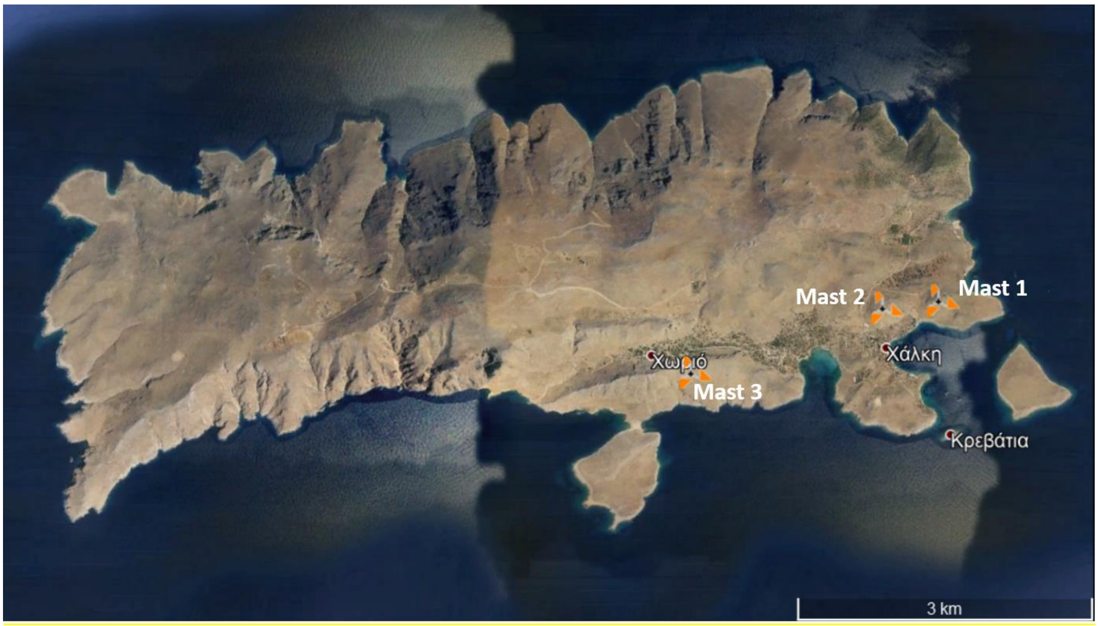

Figure 15: Locations suitable for installing wind masts

Table 1: Proposed locations for the measurement device (coordinate system: WGS1984 - UTM Zone 35)

Measurement device	Mast 1	Mast 2	Mast 3
Longitude (X)	555,586 m	555,011 m	553,048 m
Latitude (Y)	4,009,262 m	4,009,185 m	4,008,512 m
Altitude	95 m	120 m	214 m
Measurement heights AGL		40 m, 30 m, 20 m	

Table 2: Instruments for the proposed configuration of 50 m mast and calibration factors

Sensor	Height AGL	Orientation
Anemometer 1	**40 m**	**15 °**
Anemometer 2	40 m	285 °
Anemometer 3	30 m	15 °
Anemometer 4	20 m	15 °
Wind vane	35 m	15 °
Wind vane	25 m	15 °
Temp/Hygro	10 m	-
Barometer	5.5 m	-

Conclusions on wind potential

The estimated monthly and annual electricity consumption as well as the estimated number of habitants on the island have been provided by the local authorities. A reasonable population estimate is between 400 to 550 inhabitants. This estimate suggests that a configuration including 12 x 50 kW wind turbines, each of them producing 99 MWh annually at 5.5 m/s [2], may be suitable for the local electrical needs.

Given the island's low electricity consumption, equal to 1,586 MWh/year, wind power development on the island would require a tailor-made wind technology that matches the wind production with the island's needs.

Regarding the wind potential on Halki island, the mean wind speed ranges between 2.2 and 12.9 m/s at 32.0 m. Considering the limited number of inhabitants of the island, the proposed vertical axis wind turbines could be envisaged to cover the corresponding consumption. Among the two proposed, the most suitable configuration consists of 12 Fairwind F180, 50 kW turbines with 3 2 m of hub height. This farm configuration will ideally produce around 1.5 GWh/year.

Solar-powered district cooling network

The second part of the project investigates a solar-powered district cooling system, which would deliver cooling energy via a piping to network to the medical centre, the local school, the city hall and some 20 private houses along the way. First the system lay-out is explored. Secondly, the annual cooling demand is estimated based on input from Halki on the existing cooling system. Afterwards, the feasibility of the project is estimated based on official design guidelines. Lastly, the result of the Polysun simulation is discussed.

Design summary

The proposed layout of the solar thermal cooling system is shown in Figure 16. The main facility is shown in the light blue area, located at the proposed solar collector field installation. This is an old concrete rainwater collection slab. All the auxiliary equipment needed to produce chilled liquid solution is planned in the same location. The chilled liquid is then piped along the dark blue return line to supplement the medical centre, school, City Hall and approximately 20 residential homes.

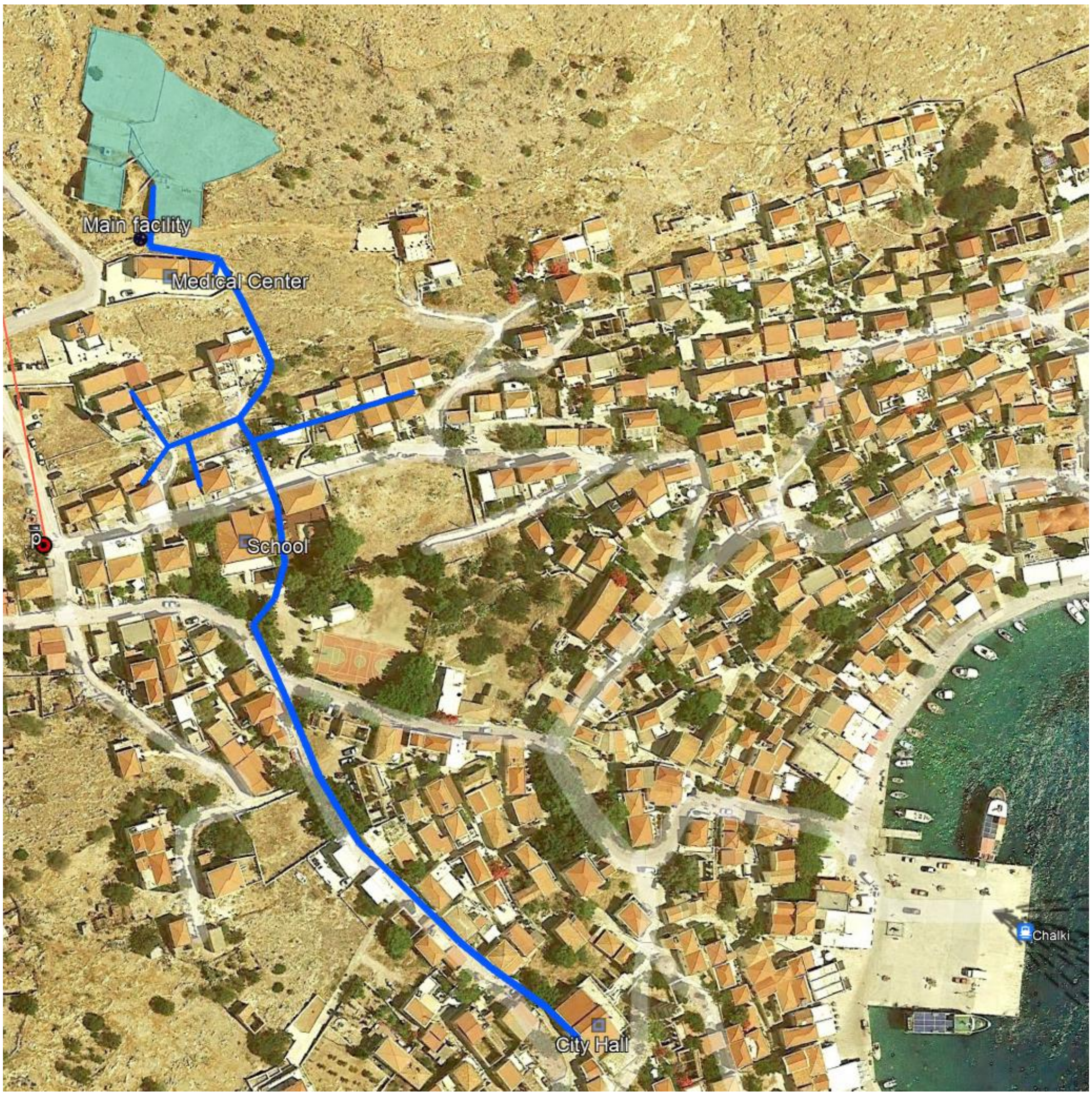

Figure 16: System layout in the village of Emporio

A base-case model was designed as a proof-of-concept for the solar cooling system. This system has not been optimised technically or economically but serves as an initial design. It consists of 611 flat plate collectors, which have a total aperture area of 1 222 m^2 and a solar fraction of 71%. Figure 17 shows a schematic of the components. The heat exchanger needed for the flat plate collectors has a capacity of 17 000 W/K, and the back-up heat pump has a capacity of 50 kW. The system has a 30 000 l hot water storage tank for the absorption chiller inlet and a 15 000 l cold water storage tank for the cold water output. The single effect absorption chiller has a capacity of 200 kW. Each building has a fan coil for absorbing heat from the room air into the cold water pumped through the network. When cooling is not needed, the HW generated in the flat plate collectors is transferred to a 15 000 l hot water storage tank with an internal heat exchanger. This is then used for district domestic hot water. There are multiple controllers that monitors and operate the system through various thermocouples and flow rate sensors. This model successfully meets the cooling demand of the buildings; however, it requires further optimisation to increase system efficiency.

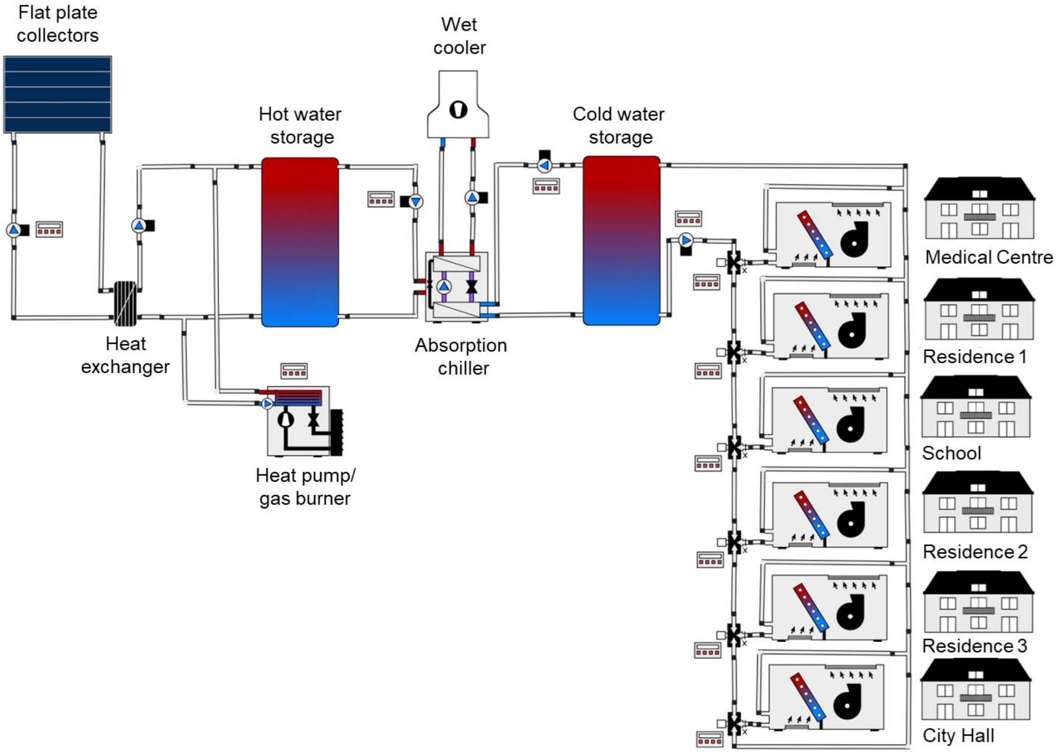

Figure 17: Proposed solar cooling system layout designed in Polysun

Cooling demand estimation

The information supplied by Halki includes the number of air-conditioning units currently installed in each building and their associated capacities, summarised in Table 3. These capacities are then used to estimate the cooling demand by considering various seasonal, population and usage fluctuations, which are discussed below.

Table 3: Current cooling capacity

Building Type	Number of air-conditioning units	Total capacity of air-conditioning units (kW_{heat})
Medical centre	7	21.10
School	13	39.57
City Hall	6	26.38
Residences	20	133.00
Total:	**46**	**220.05**

Using climate data retrieved from Meteonorm, which provides a Typical Metrological Year (TMY), the total number of cooling days was determined in each month of the year, see Table 4. This was done by assuming that if the average temperature in a day was below 16˚C, no cooling would be required at all for that day. It was also estimated through the climate data that on average, cooling would only be required between 08:00 and 19:00.

Table 4: Number of cooling days required

Month	Cooling days required
January	1
February	1
March	6
April	18
May	31
June	30
July	31
August	31
September	30
October	31
November	20
December	6
Total:	**236**

The island has quite a large fluctuation in population over the year due to tourism, which affects the cooling demand. To quantify this, the electrical demand throughout the year was used as an indicator of variance due to population fluctuation. For buildings unaffected by tourism, such as the school, residences and the City Hall, the temperature variance throughout the year was assumed to be a more accurate indicator of cooling demand fluctuation. The electrical demand and temperature variance throughout the year are illustrated in Figure 18.

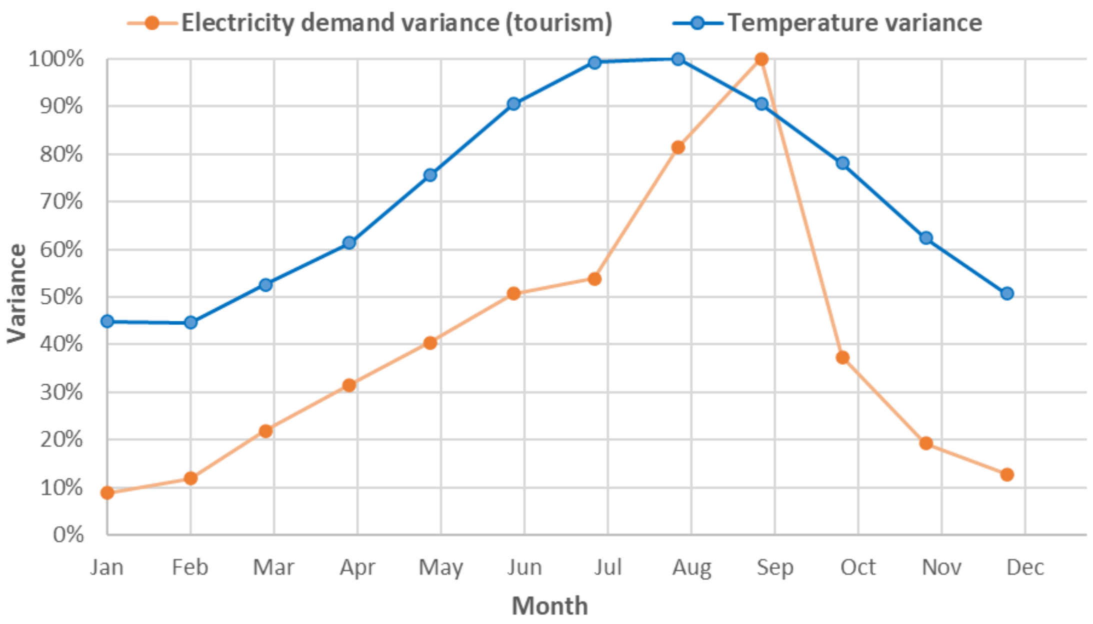

Figure 18: Electrical demand and temperature variance throughout a typical year

Additional cooling demand factors include public holidays, school vacations and weekends, which effect each building differently. A summary of these day factors for each building is given in Table 5. The resulting monthly cooling demand is summarised in Table 6 and illustrated in Figure 19. Now that the cooling demand is estimated for the island, the feasibility of the project with said demand can be considered in the following section.

Table 5: Cooling capacity factors on various day types in the year

Building	Weekday	Weekend	Public holiday	School holiday
Medical Centre	100%	100%	100%	100%
School	100%	0%	0%	0%
City Hall	100%	0%	0%	100%
Residences	80%	100%	100%	80%

Table 6: Monthly cooling capacity estimation for each building in a typical year

Month	Medical centre (kW_{heat})	School (kW_{heat})	City Hall (kW_{heat})	Residences (kW_{heat})	Total monthly cooling demand (kW_{heat})
January	22.22	0.00	0.00	530.48	**552.69**
February	30.11	211.41	140.94	526.16	**908.62**
March	332.46	998.11	665.41	3726.27	**5722.25**
April	1435.83	291.12	2594.74	13970.34	**18292.02**
May	3169.85	7183.74	5265.79	29645.39	**45264.77**
June	3846.54	6147.58	6308.77	34371.46	**50674.35**
July	4223.70	0.00	7660.65	38954.32	**50838.68**
August	6389.49	474.80	7468.05	39240.75	**53573.08**
September	7596.72	9221.37	6759.40	34371.46	**57948.94**
October	2933.36	7957.15	5832.71	30647.89	**47371.10**

November	970.33	4238.85	3107.14	15799.78	**24116.12**
December	194.33	0.00	642.30	3596.89	**4433.53**

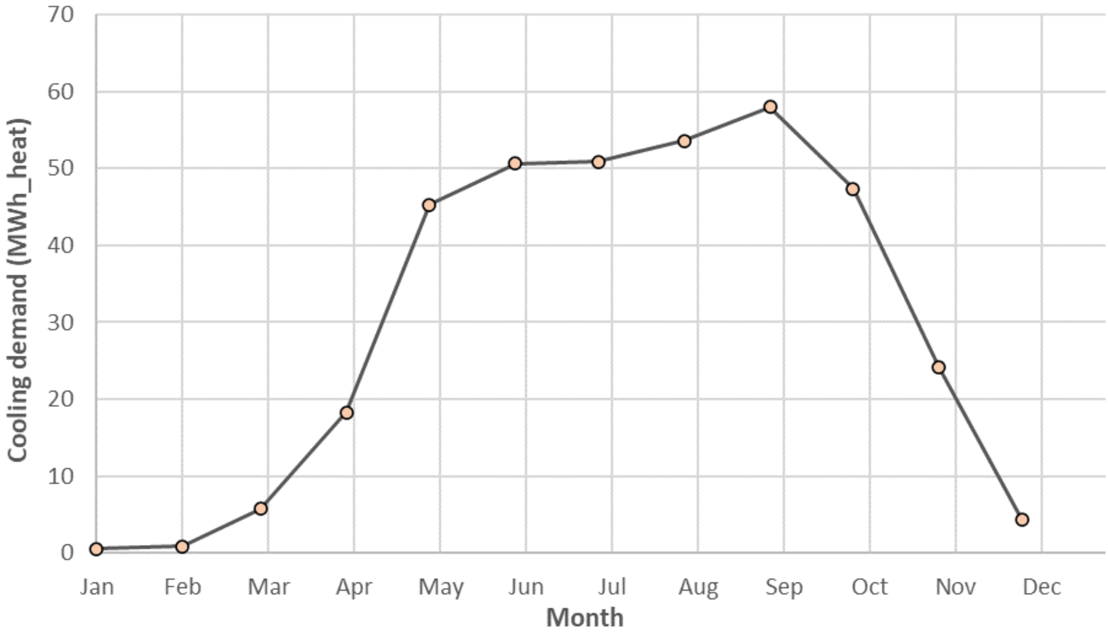

Figure 19: Total monthly cooling demand estimation for the island over a typical year

Feasibility factors

Solar thermal cooling is still a developing technology when compared to other alternative cooling systems such as Vapour Compression Chillers driven by Photovoltaics (PV). Reviewing current literature and case studies shows that appropriate applications and good optimisation are important for increasing the feasibility of solar thermal cooling systems. Considering the application appropriateness is the first step in considering feasibility, as no amount of optimisation can sufficiently improve a system that is inappropriate, due to the high economic competitiveness of alternative technologies. As seen in literature, appropriate applications include:

- Decentralised systems
- Stand-alone buildings (small and large)
- Back-up heat available from non-fossil fuel sources (waste heat or renewable energy)
- Integrated systems that utilise the solar thermal hot water in winter (i.e., domestic hot water)
- Systems implemented in tropical or sub-tropical climates, which have a more consistent climatic behaviour throughout the year

The International Energy Agency developed The Solar Heating and Cooling Technology Collaboration Programme to help grow this industry globally. A key document released through this program is The Solar Cooling Design Guide, in which it has defined 11 key principles for achieving feasible solar cooling systems as well as providing case studies of successful installations (Mugnier et al., 2018). These principles are summarised in

below, as well as if they are achievable for this application.

Table 7: The 11 principals for achieving feasibility in solar cooling designs (Mugnier et al., 2018)

Principal	Description	Achievable
0	Reduce energy demand before applying renewables.	x
1	Choose applications where high annual solar utilisation can be achieved.	x
2	Avoid using fossil fuels as a backup for single-effect ab-/adsorption chillers.	x
3	Design the ab-/adsorption chiller for relatively constant operation at near full load.	x
4	Use wet (or hybrid) cooling towers whenever possible.	✓
5	Design the solar collectors for operation at average (not peak) solar radiation levels.	x
6	Keep the process flowsheet simple and compact.	x
7	Provide thermal storage capacity and hydraulics in a form that matches the thermal requirements of each application.	✓
8	Minimise parasitic power.	x
9	Minimise heat losses.	x
10	Apply appropriate resources to design, monitoring and commissioning.	✓

Considering Table 7 principal 4 is a design factor and can be achieved. Principals 7 and 10 are optimisation and design-based and thus can also be achieved. The remainder of the principals are not achievable by the application considered in this study, which is discussed in further detail.

The first major issue is the centralisation of the district cooling design. This results in extremely long pipelines transporting cold water around the village to many different buildings and will result in high thermal losses as energy is not transported efficiently over long distances using water. The long pipe runs will also need to have many added pumps which will consume additional standby electricity (parasitic power). Typically, a solar cooling system only requires four pumps and a cooling tower fan. This aspect of the application thus fails to meet principals 6, 8 and 9. Due to the number of buildings, that are relatively small, it is not viable to have decentralised systems with large axillary equipment and solar thermal collectors attached to each building.

The climate of Greece is also not ideal for the implementation of solar thermal cooling. Based on the weather data, Greece has a temperate climate which results in large fluctuations between winter and summer temperatures, and solar irradiance when compared to tropical and sub-tropical climates. This results in the system being underutilised in the longer winters. Moreover, it decreases the base load of cooling demand to 0, which is not ideal for solar cooling applications. A base load is typically required to increase utilisation and allow the chiller to operate near full load more often. The chiller has a long start up and shutdown time, which consumes a lot of parasitic power, thus on days where the cooling load is close to 0, the chiller will be fluctuating in operation throughout the day and operating at a small load. This fails to achieve principals 1, 3 and 5.

Another problem encountered with underutilisation in winter is stagnation. If the hot water produced in the solar thermal collectors is not used, they may continue to heat the water and stagnate in the collectors. Therefore, the hot water produced in the winter will need to be continually pumped out of the collectors and possibly cooled, resulting in more parasitic energy. A possible solution to the underutilisation of the system in winter would be to include an application of district domestic hot water (integrated system). This would increase the base load and prevent stagnation problems. However, the hot water would still need to be piped along the same long routes which result in large amounts of thermal losses.

The information on cooling demand given by the client revealed that the buildings are currently not used efficiently, with doors and windows being possibly left open during cooling hours. This validates principal 0 and it could result in having to implement an oversized solar cooling system for the application. This can easily be fixed through energy efficiency awareness programmes.

Principal 2 advises that the back-up heat for single-effect absorption chillers (the one appropriate for this study) should not come from fossil fuels. This is because using fossil fuels to produce chilled air through an adsorption chiller is a very inefficient process when compared to vapour compression chillers. Ideally this back-up heat would come from waste heat or a renewable source such as the burning of biogas, both of which are not available in this application. This would require the design to maximise solar fraction, to minimise the need for back-up heat, which in turn violates principal 5.

A further option would be to use vapour compression chillers as the backup for chilled air. In this case vapour compression chillers would not be viable in a centralised cooling setup for similar reasons of large pipe runs; however, decentralised vapour compression chillers units, like the ones currently installed may be the best option, especially if they are driven by PV. If PV is already to be implemented on the island, having PV drive already existing vapour compression chillers units will most likely be far more financially feasible compared to establishing a district-scale centralised ST cooling system in an application that fails so many of the primary design principals.

Model results

The model (developed using the software Polysun) predicts that the system's flat plate collectors will add 585 MWh of heat to the tanks annually. The system will consume a total of 87 MWh of electrical energy annually, through the operation of the heat pump, pumps, and control systems. A factor that must be considered carefully in all solar thermal systems is stagnation of hot water in the collectors during the summer months. Figure 20 shows the temperature of the hot water in the collectors through the year, which doesn't come close to the maximum specified collector temperature of 190˚C. The maximum temperature in the collectors during the summer is 140˚C, which is an indicator that minimal stagnation is occurring.

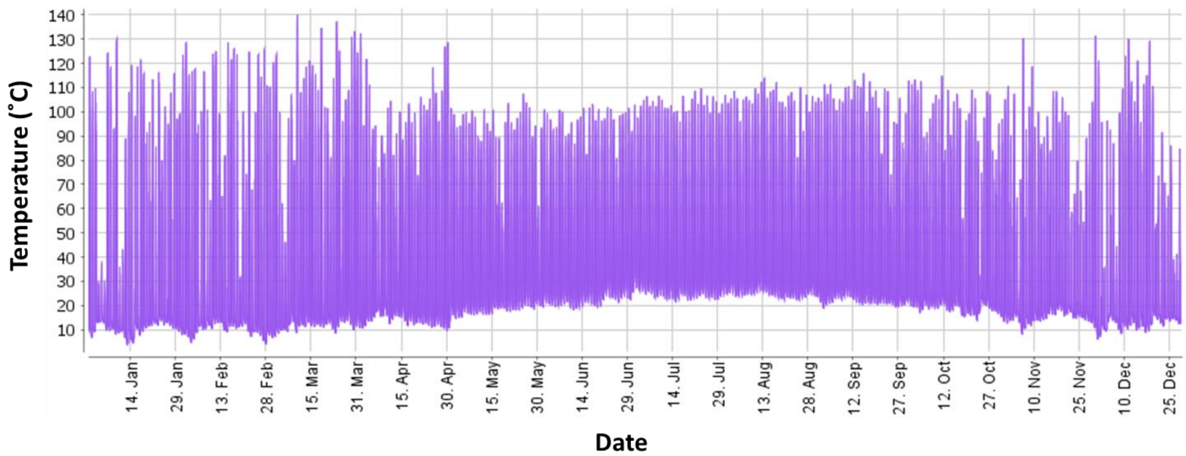

Figure 20: Collector temperature throughout the year (resolution less than 1 minute). Source: Polysun simulation results.

The economic pre-feasibility of the project has been investigated through a financial model simulated in Polysun, that provides a first insight of the project's viability over its lifetime. Input parameters have been chosen by consulting literature, the details of which are given in Table 8**Error! Reference source not found.**. The recent increase in European electricity prices has not been accounted for in the model as it may be a temporary occurrence. The model sets the year-on-year electricity increase equal to the 20-year inflation average. This is a conservative approach as an increase in electricity costs will make a solar thermal system with a high solar fraction more financially attractive.

Table 8: Input parameters of the financial model

Parameter	**Value**	**Reference**
Project lifetime	20 years	37[9]
Effective interest rate	11.13%/year	[8]
Electricity price increase	1.32%/year	[13]
Technology price change	7.10%/year	[12]
Inflation (20-year average)	1.32% /year	[13]
Total equipment costs	€ 586 745	[5][7][6][10]
Design, planning and logistics cost (8% of CAPEX)	€ 46 940	[7]
Site works and installation (10% of CAPEX)	€ 58 675	[7]
Maintenance costs (6.5% of CAPEX)	€ 45 000/year	[11]
Cost of electricity	€ 0.17/kWh	Halki

The results of the financial model are given in Table 9. These initial economic results are indicative of a system that is not feasible, having an unattractive cost of energy—or Levelised Cost of Heat (LCOH)—when compared to current electrical vapor compression chilling and especially when compared to PV coupled with vapour compression chillers. Literature points to similar conclusions when considering these two technologies [5].

The net present value (NPV) for this study is expressed in terms of Net Present Cost (NPC). It must be noted that value is the difference between the benefit and the cost. A benefit analysis, whereby this system is compared to a base case, has not been analysed, as simulations considering energy sales for determining the true benefit falls outside the scope of this study. Therefore, the NPC has been determined and is expected to be negative as the system costs alone have been considered. This NPC represents what the system will cost over its lifetime, which is illustrated in Figure 21.

If we consider the recent large price increase for electricity in Greece, which has gone up to € 0.3/kWh; and we take a worst-case scenario and assume an electricity increase of 15% per year for the next 20 years, the LCOH of the system goes up to € 0.34/kWh. This is still indicative of a system that is not feasible.

Table 9: Financial model results

Parameter	**Value**
Total investment cost in year 1	€ 852 865
Net Present Cost (NPC) of project over its lifetime	€ -1 249 651
Levelised Cost of Heat (LCOH)	€ 0.27/kWh
Total electricity expenditure over project lifetime	€ 184 532

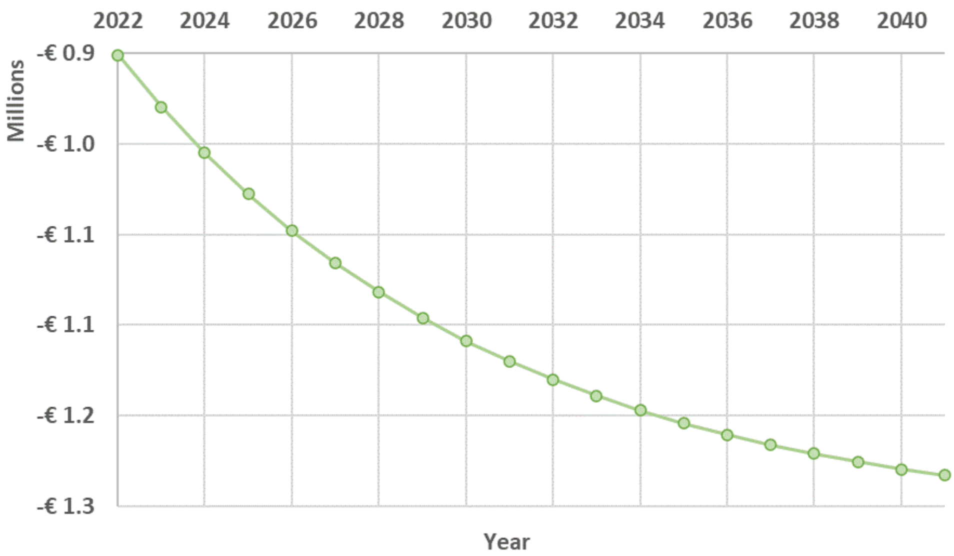

Figure 21: Net Present cost of the system over its 20-year lifetime (Polysun results)

Conclusions on solar thermal cooling

This study performed a pre-feasibility investigation of a centralised district solar thermal cooling system for the island of Halki in Greece. The cooling demand of the district was estimated by considering the medical centre, school, City Hall and 20 residential homes, given the capacity of existing cooling infrastructure. The estimated demand considers seasonal variation, annual temperature fluctuation, tourism, and day types such as holidays. A solar cooling system layout was proposed and developed in simulation to indicate proof of concept. The initial observations of long pipe runs were noted, which could lead to large thermal losses.

Feasibility factors were investigated by considering design principals defined by The Solar Heating and Cooling Technology Collaboration Programme. Out of the 11 principles considered, three of them could be met as they are design and optimisation factors. The remainder of the principals are failed to be met by the considered application. This will likely make this project infeasible when compared to alternative technologies.

In summary solar thermal cooling will likely not suit this application, mainly due to:

- The heat losses in long pipe runs with distribution to many different buildings
- Large parasitic power required
- Stagnation of the system for extended periods
- Low utilisation and base load due to climate fluctuation
- Inefficient fossil fuel back-up (no waste heat re-use or biogas available)

The pre-feasibility results point toward considering a PV driven system architecture over solar thermal. Additionally, buildings already have existing vapour compression chillers air-conditioning units installed, saving on initial capital. Investigations are also already underway regarding the implementation of a large-scale PV field, which would allow for economies of scale when compared to a standalone solar thermal installation. Further engineering design and optimisation for the centralised solar thermal cooling system considered in this study would most likely not yield fruitful insights.

Energy System Modelling

Halki plans to develop decentralised renewable energy systems such as a 1 MWp solar PV plant and the vertical axis wind turbines investigated in the first part of this report. The electricity consumed on the island is currently provided by the undersea cable to Rhodes; hence, the introduction of intermittent renewable energy production onto the grid could affect its functioning. As part of this work, Halki therefore requested to model the energy system to study the impact of these renewables and to determine their feasibility.

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, that is used and input for the model, was estimated based on the available data. Thereafter, the various renewable technology components included in the model have been identified. Finally, the general assumptions of the model are explained.

Electricity demand

The annual electricity consumption on Halki is 1 586 MWh, as estimated by the island representatives based on the number of houses and businesses. However, the variation of the electricity consumption is not known as a metering device is only planned to be installed in the near future. The load profile on the island is thus not available: this profile displays the electrical consumption for each hour of the day for the entire year. Therefore, based on assumptions, a synthetic load profile has been estimated as an approximation of the actual load profile on the island.

First, the synthetic load profile is based on the monthly electricity consumption of the water desalination unit, which is known. As indicated by the island representatives, it is safe to presume that the overall electricity consumption will follow a similar distribution as the water desalination unit is a good indicator of the seasonal variation due to tourism. Applying this distribution to the total energy consumption, the estimation of the monthly energy consumption was derived, as illustrated in Figure 22Figure 22: Estimated monthly electricity consumption on Halki. The figure clearly shows an increased electricity consumption in the summer months due to tourism.

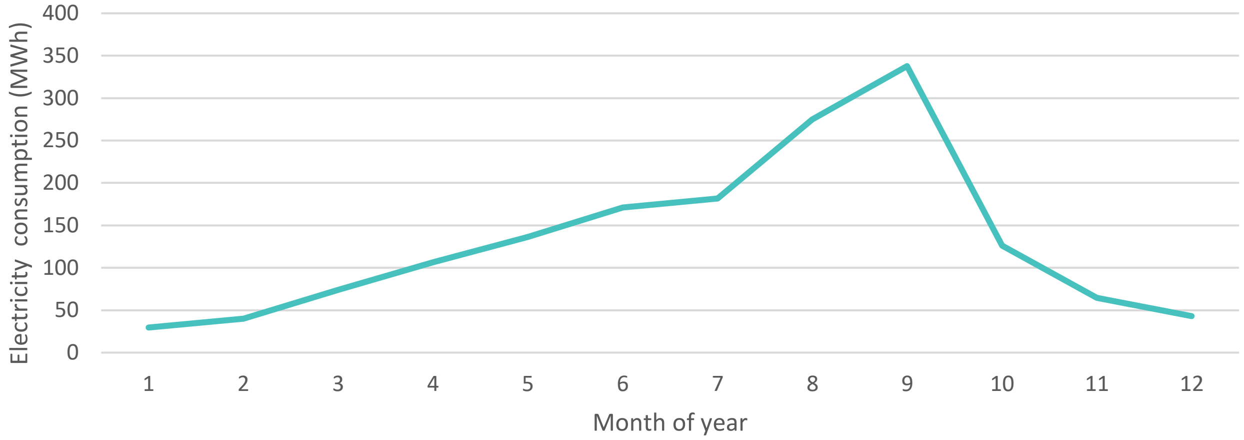

Figure 22: Estimated monthly electricity consumption on Halki

Secondly, these monthly figures were converted into an hourly load profile through load distributions present in the Homer modelling software. Figure 23 illustrates a typical July weekday and weekend day of the synthetic load profile for Halki.

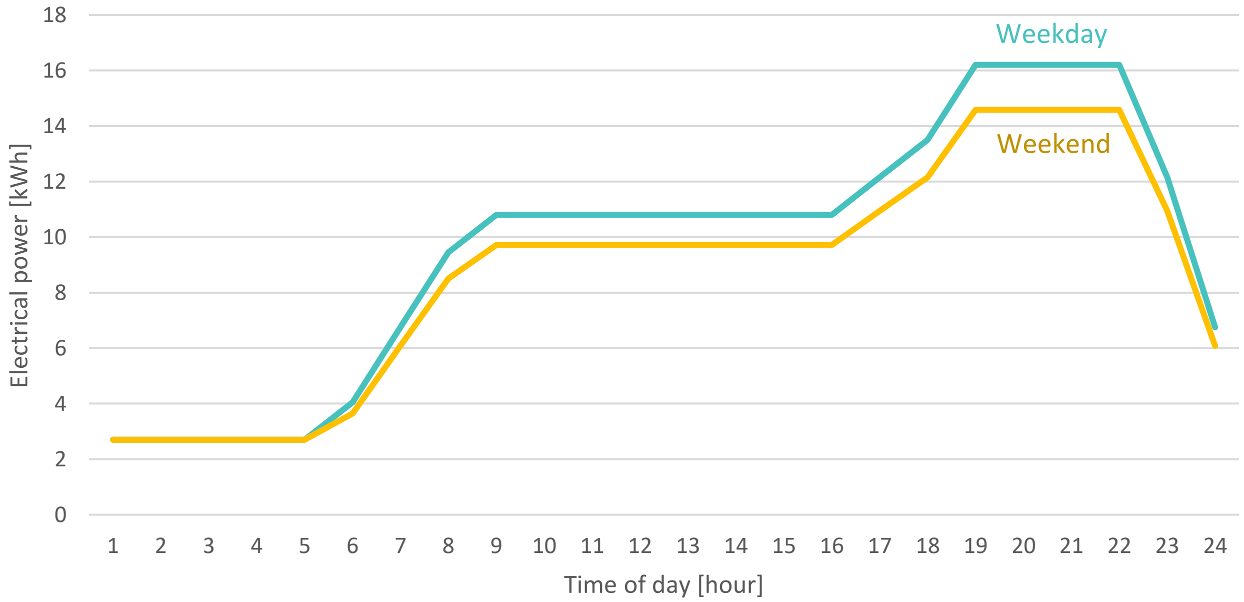

Figure 23 Typical hourly demand profiles for a Weekday and a Weekend in July in Halki

Components

The electrical components that are included in the model are:

Wind turbines: The Fairwind F180-50 50 kW, with a hub height of 32 m, is the vertical axis wind turbine used in the first part of the report for the resource maps. It has a limited environmental impact due to its smaller size and therefore poses less visual obstruction. These turbines can be installed without a crane and are hence ideal for more remote locations. The capital cost was given by a Fairwind sales representative and equals €215 000 for the turbine itself, the installation, and the additional civil and electrical works, while the O&M cost are about €1 800 per year. The expected lifetime of the wind turbine is 20 years.

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 with the wholesale price having quintupled over the last six months. 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 €0.04 /kWh via the submarine cables. Both of these prices are still speculative; therefore, a sensitivity analysis will be carried out to study whether changing these prices upwards or downwards has 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 as part of the Dodecanese Islands [14], see Figure 24. 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.

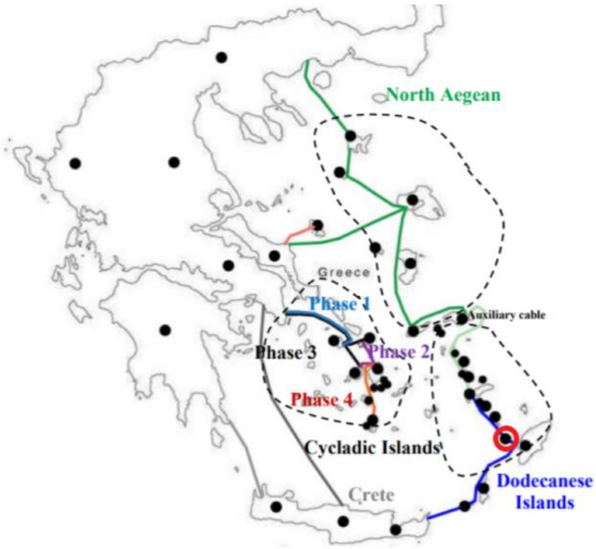

Figure 24: Greek islands grid extensions plan

The battery: A generic Li-ion battery of 100 kWh 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 2020 IRENA report and equals €25 000 for a 100 kWh battery while the O&M cost are about €1 000 per year [15]. The expected lifetime is 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 [16].
- Inflation: The average expected inflation rate in Greece is 1.36%, based on the projections of 2022 to 2026 [17].
- Cost reflectivity: There are no recoverable costs at the end of the lifespan of the system.
- Price of electricity: For the purposes of this study, it is assumed that the electricity produced by the existing 1 MWp solar farm is sold to the island citizens at a price of €0.15 /kWh. The excess of electricity production from this solar plant is sold to Rhodes at a price of €0.04 /kWh. At the time of writing of this study, the energy community works as a non-profit organisation though: energy produced from the PV plant, either as a surplus or a regular supply to the grid, is not sold and no profit is made. The produced energy is measured and is distributed to the community's members' energy bills, through net-metering procedures. The character of the energy community could change in the future to a profit-making organisation, in which case the scenarios and prices indicated in this study would provide guidance on the feasibility of the technologies.

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, the production from the already existing 1 MWp solar PV plant, the researched vertical axis wind turbines from the first part of this report, and possibly a battery storage system.

From a financial point of view, the optimal solution is the status quo: taking electricity from the grid in combination with the existing solar PV plant. This section describes this scenario, but also analyses at scenarios when placing wind turbines, when placing battery storage and when placing both. The impact of the grid electricity price is studied to determine when wind turbines and battery storage become financially interesting. Furthermore, the impact of these components on the renewable fraction is calculated, as well as their levelised cost of energy.

The optimal solution

The HOMER model revealed that the lowest cost energy solution for Halki is to rely on the planned solar PV plant supplemented with grid power. This solution offers a renewable fraction—the percentage of load covered by renewable energy—of 53% 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 existing solar PV plant, see Figure 25.

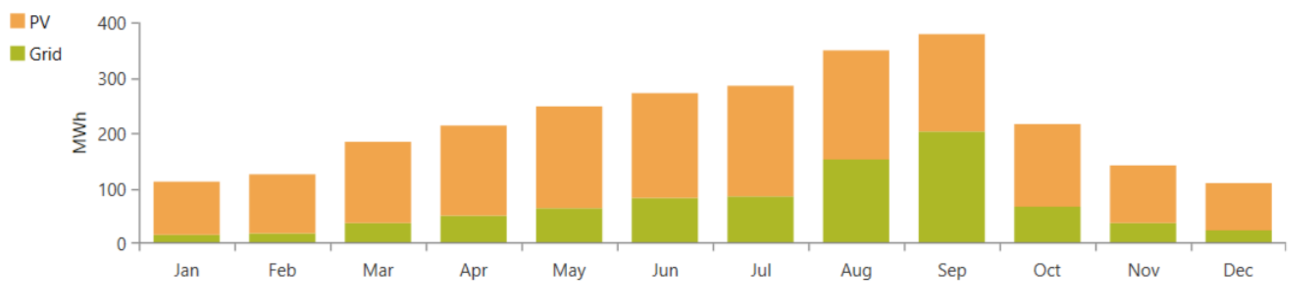

Figure 25:Monthly electricity production for a PV and grid-connected system

Looking at the daily variation throughout the year, Figure 26 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 €0.04 /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.

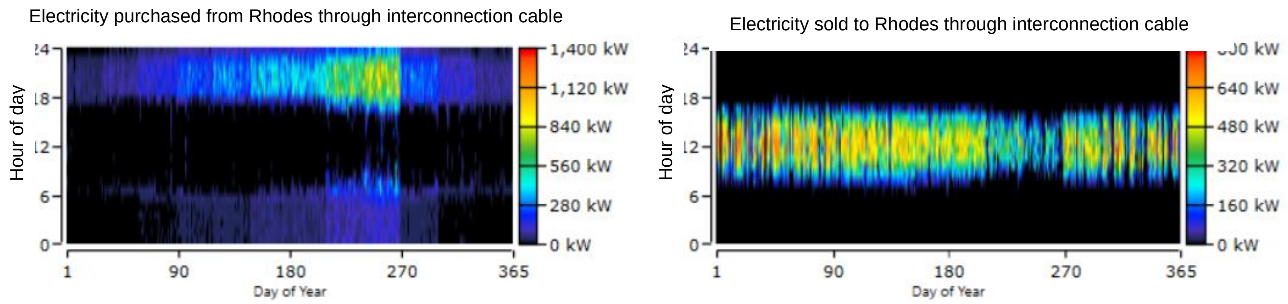

Figure 26: Grid purchases and sales throughout the year

Table 10 gives and overview of the annual energy balance for the base case energy system in Halki.

Table 10 Annual energy balance of lowest cost system

Description	Annual electricity input/output [kWh]
Total electricity production	**2,638,813**
PV energy production	1,802,212
Grid energy Purchased	836,602
Total electricity consumption	**2,548,703**
Electricity demand	1,598,998
Grid energy sold	962,705
Excess electricity	**90,110**

Source: Consultant analysis using Homer Pro results

Adding wind turbines

Wind turbines could try to fill the remaining gap when solar is not producing in the evening. A disadvantage for wind in Halki is that it blows mostly during the winter, when there is no tourism and therefore the demand is low. Figure 27 illustrates that when adding one wind turbine (shown as RPS), the demand in winter is met by renewable energy (PV plus wind) while the demand in summer is still largely catered by the grid.

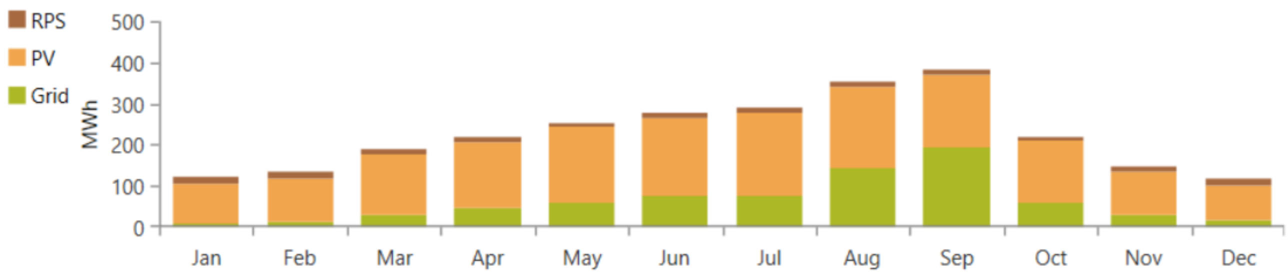

Figure 27: Monthly electricity production for a PV, wind turbine (RPS) and grid-connected system

In the base-case scenario, the installation of wind turbines is not economically viable. This base-case scenario is composed of the planned solar PV plant with an electricity price on the island of €0.15 /kWh and a selling price to Rhodes of excess electricity of €0.04 /kWh.

Adding wind turbines to the electricity mix becomes economically viable only if the electricity price on the island increases and/or the price of excess of electricity sold to Rhodes increases with respect to the base case scenario. This is illustrated in Figure 28, which shows the limit for wind feasibility as a white corrugated line, drawn from a price on the island of 0.21 €/kWh and 0.1 €/kWh injection remuneration to 0.28 €/kWh island price and zero injection price. All situations left of this line have as a financial optimum to not install wind turbines on top of the existing solar PV plant. On the other hand, situations right of this line have as a financial optimum the inclusion of wind turbines and the grid as a back-up. One can also see that the optimal number of wind turbines increases in size when going to the top-right corner of the graph (increasing power price and increasing injection price).

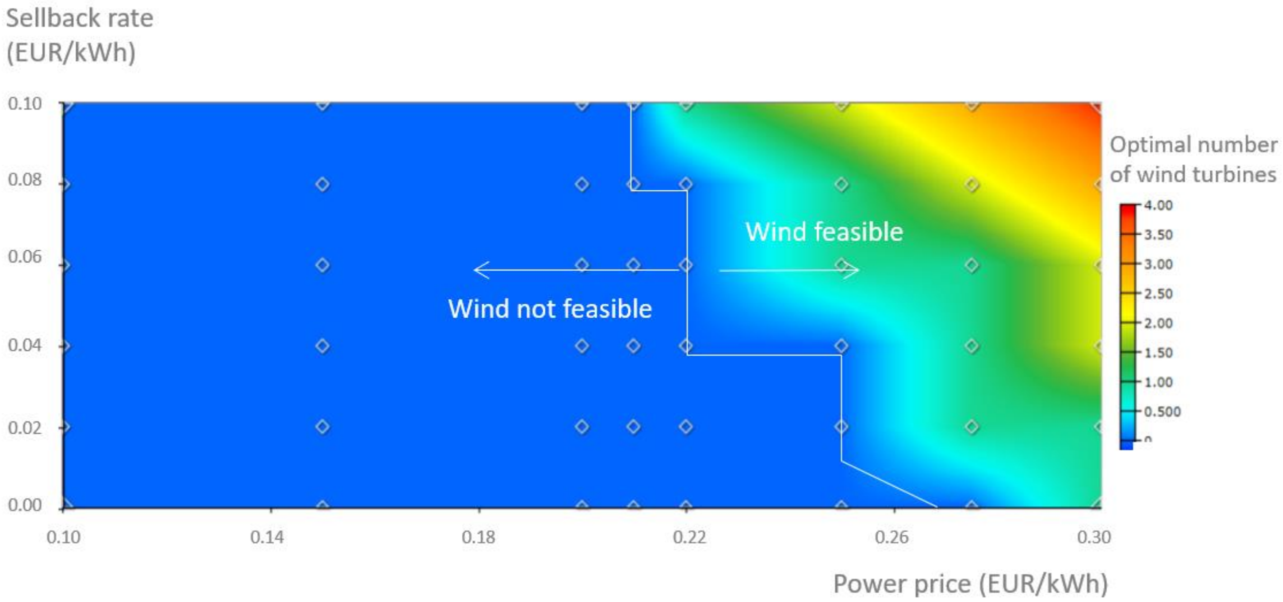

Figure 28: Impact of grid injection and consumption price on the wind turbine capacity

Regardless of their viability, wind turbines have the potential for significantly increasing the renewable fraction, see Figure 29. The addition of one vertical axis wind turbine increases this renewable fraction by 6%, from 53% up to 59%. In turn, the more wind turbines, the higher the percentage of wind energy sold to Rhodes. With four wind turbines, more 51% of wind production is sold to Rhodes, resulting in a staggering 72% renewable fraction.

Assuming that the injection price for excess electricity to Rhodes remains at 0.04 €/kWh the price for wind energy on the island for the technology to be viable, would be €0.22 /kWh. In order for wind energy to become more financially interesting than importing electricity from Rhodes, the price on wind on the island would need to increase to 0.265 €/kWh, as indicated in Figure 28. Each additional wind turbine will have diminishing returns though: the higher wind installed capacity, the more excess of wind that would need to be sold to Rhodes at a lower price than self-consumption.

The total cost of energy is calculated as the cost of energy of the grid and wind combined. This cost increases with the number of vertical axis wind turbines installed: starting at a price of €0.15 /kWh for the base-case scenario and rising to €0.27 /kWh for six installed wind turbines, as shown in Figure 29.

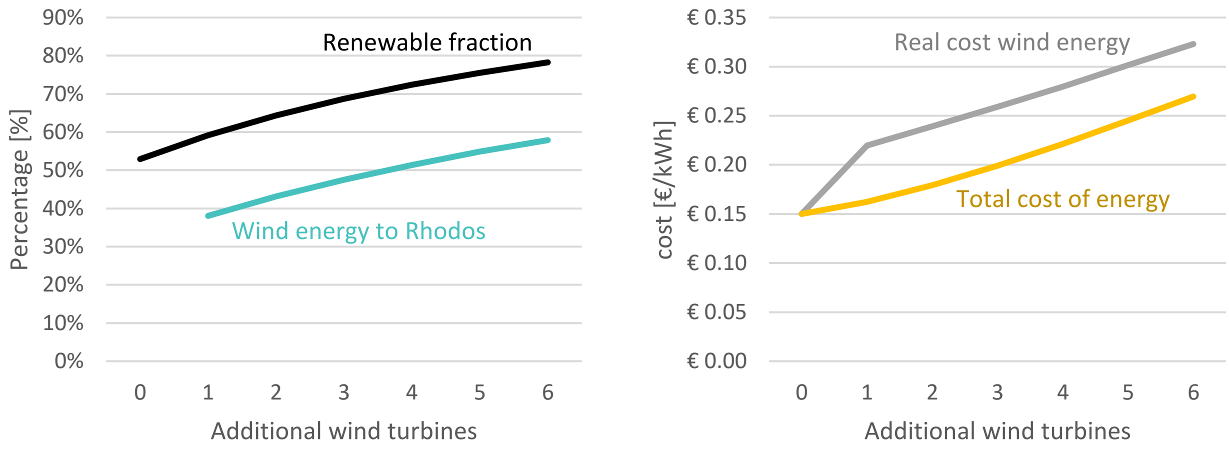

Figure 29: Impact of placing wind turbines

Adding battery storage

A battery storage solution could use the excess electricity produced by the existing solar PV plant 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/or lower injection prices. This is indicated in Figure 30 which shows that a linear line can be drawn from a power price of €0.21 /kWh and zero injection remuneration to €0.30 /kWh power price and €0.09 /kWh injection price (simply stated, the difference in both prices should be €0.21 /kWh). All situations left of this line have as a financial optimum to use solely the grid as a back-up for the existing solar PV plant. Situations right of this line on the other hand have as a financial optimum the inclusion of a battery storage system and the grid as a back-up. One can also see that the optimum battery capacity increases in size when going to the bottom-right corner of the graph (increasing power price and decreasing injection price).

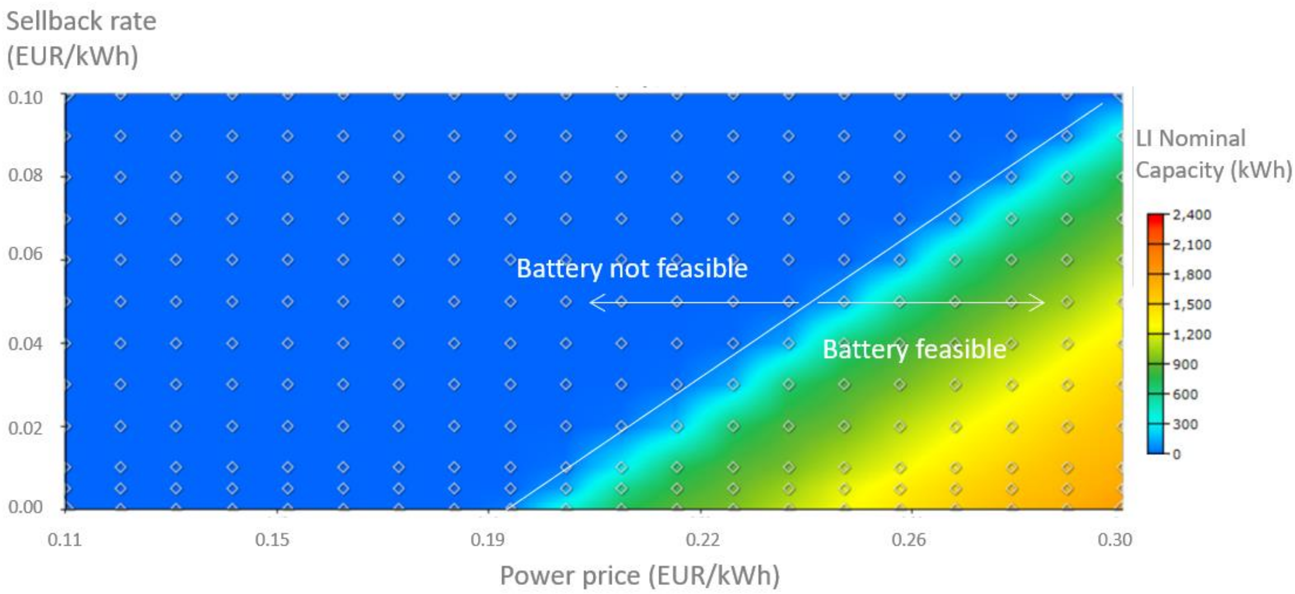

Figure 30: Impact of grid injection and consumption price on the battery capacity

Adding a battery significantly increases the renewable fraction, as shown in Figure 31. For example, battery of 1 MWh could increase the renewable fraction from 53% to 69%. The additional benefit gained from larger storage systems does decrease – because the battery will no longer be able to discharge fully in the evening as shown in Figure 32– but this penalty is less severe as was the case for wind turbines. The levelised cost of storage for a 1 MWh battery is €0.223 /kWh and increases with extra capacity due to the aforementioned diminishing returns, as shown in Figure 31.

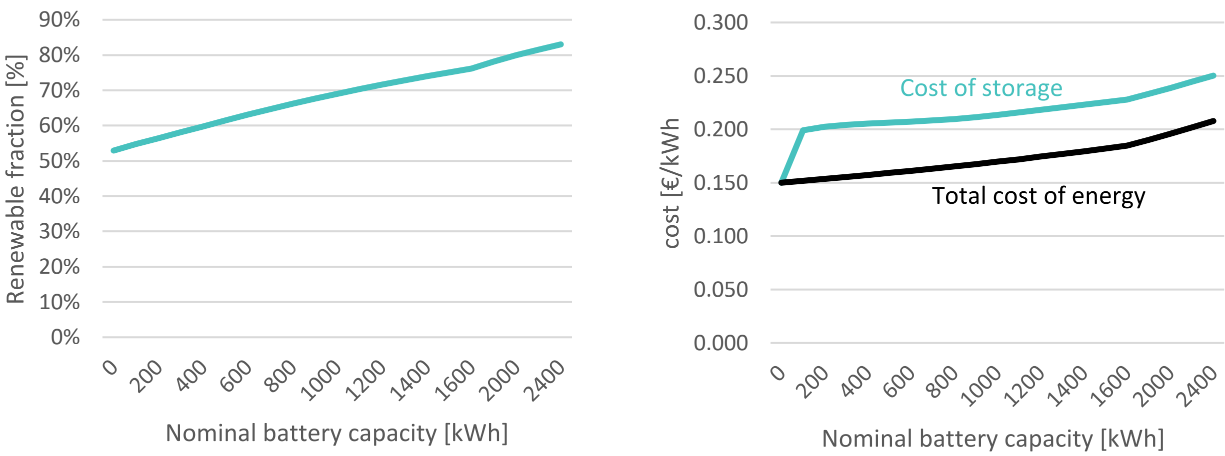

Figure 31 Impact of placing battery storage

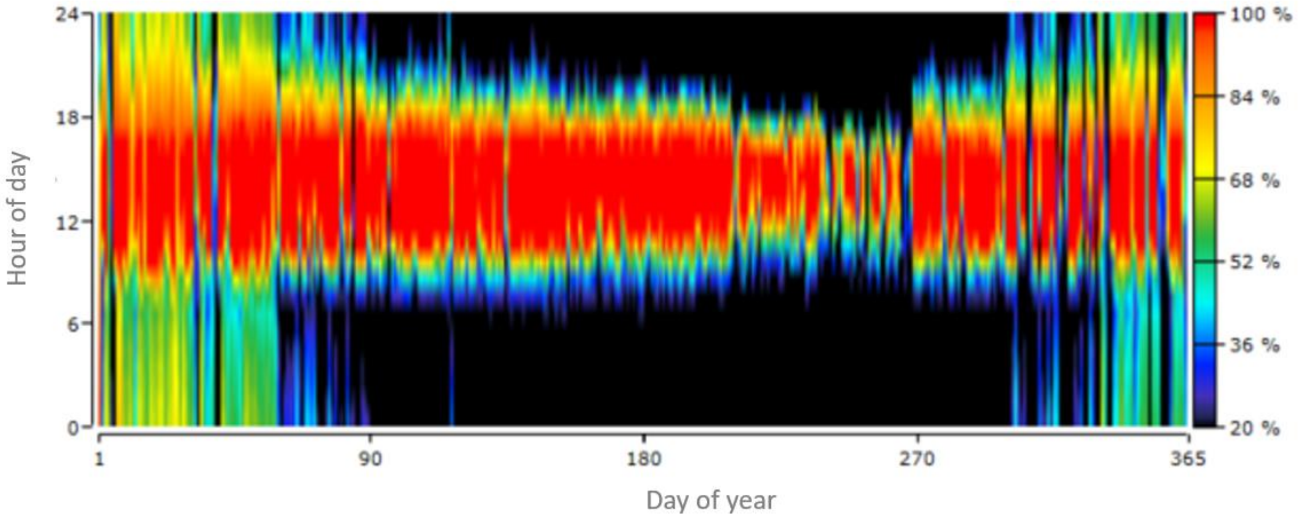

Figure 32: State of charge of 1.5 MWh battery throughout the year

As a comparison, to reach a renewable fraction of 75%, five wind turbines had to be installed at a total cost of energy of €0.245 /kWh[2] to break-even while 1 500 kWh of storage could be installed at a total cost of energy of only €0.182 /kWh. Investing in battery storage is thus a cheaper alternative to ramp up the renewable energy fraction than installing wind turbines[3]. Depending on the power price and the injection price, investing in a battery storage solution can even become a better alternative than the base case of solely using a grid connection, as indicated in Figure 30.

Adding wind turbines and battery storage

The previous two sections looked at wind turbines and battery storage independently. This section looks at the possibility of placing both battery storage and wind turbines. Figure 33 illustrates the combined effect of both wind turbines and battery storage with the base-case scenario. If the grid price is sufficiently high, adding either wind or storage (or both) becomes interesting. The actual combination of technologies would eventually depend on the sellback rate: for low injection prices, excess wind production has no value and therefore battery storage is the best solution. On the other hand, if the injection price is high, wind turbines become more lucrative as excess energy is sold to the grid at a premium. There also exists a combined optimum for both wind turbines and battery storage for grid prices from €0.24 /kWh and sellback rates between €0.03 /kWh and €0.08 /kWh.

[2] This total cost of energy only applies to the electricity on top of the one produced by the existing solar PV plant. It thus serves as a comparison against the base case of utilizing the grid for load that is not met by the solar PV plant.

[3] Considering a grid price of €0.15 /kWh and an injection price of €0.04 /kWh

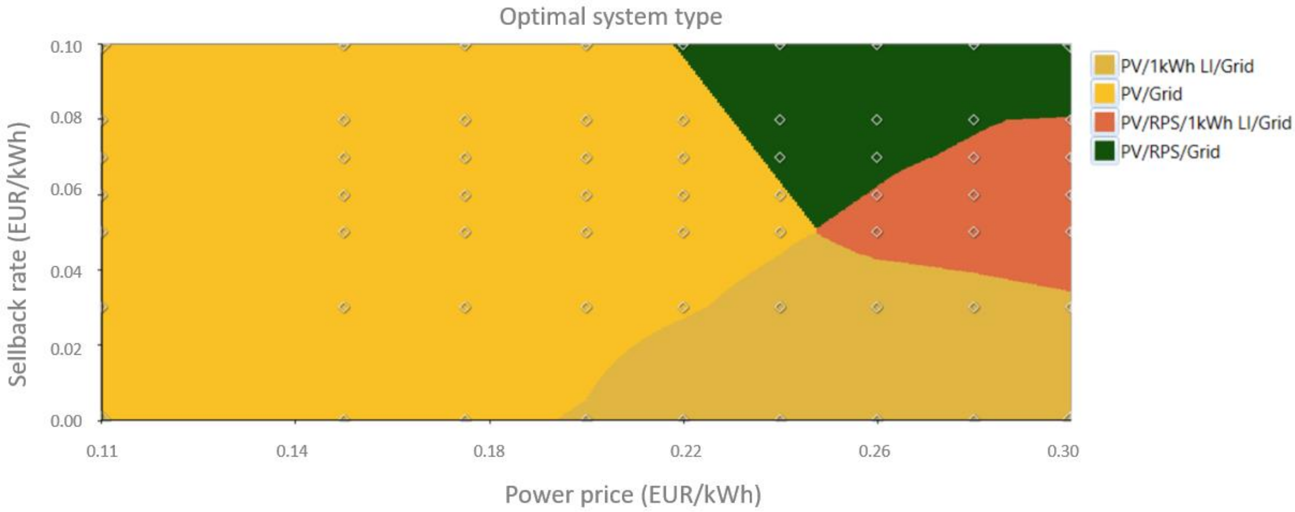

Figure 33: Impact of grid injection and consumption price on the battery capacity and wind turbines

Conclusions on system modelling

In this section, a model of Halki in HOMER Pro is presented to determine the viability of different energy mixes on the island. 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, without taking into account possible subsidies, the base-case scenario is the financial optimum. Adding wind energy and a Li- ion battery increases the renewable-fraction consumed on the island. The more wind energy capacity installed on the island, the more excess electricity that needs to be sold to Rhodes, at a much lower price (€0.04 /kWh) than self-consumption (€0.15 /kWh). Wind energy becomes viable at higher electricity prices on the island and higher sellback rates.

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 with higher island electricity prices and lower sellback rates. To increase the renewable fraction on the island, installing a battery is more competitive in the current scenario than installing wind energy though. As a final conclusion, a graph-matrix has been designed that provides the feasible electricity mix depending on the price combinations.

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