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Cyprus' Energy Systems & Pathways to 2020 and 2025

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Abstract

The Republic of Cyprus, an isolated energy system, generated approximately 5TWh of electricity in 2017, 91.6% of which was generated from oil-fired turbines, the large majority of which utilising heavy fuel oil.

The National Energy Strategy (NES) of Cyprus, with which the country aims to meet its EU-2020 targets, compares the increase of renewables to a forecasted demand that is no longer binding; being recently invalidated with new forecasts showing an increase by at least 10% from the Transmission System Operator. The updated forecasts are corrected, and a scenario is developed and modelled using the renewable capacity desired by the national strategy.

This study presents a holistic analysis of the energy systems, highlighting the concerns of relying exclusively on oil-fired turbines, with negative implications on all three elements of the energy trilemma. A business-as-usual model for 2020 shows the country not on course for meeting the 13% required target of renewable electricity generation.

The study suggests a corrected pathway to 2020 from the national energy strategy, resulting to a more cost-effective system that meets the EU-2020 targets. Furthermore, a pathway to 2025 is designed and analysed, to include the gasification of power stations, the implementation of an interconnector that is currently under construction, and to integrate IRENA’s forecasted prices for renewable technologies. The suggested pathway converts Cyprus to a net exporter, bringing down the levelized cost of electricity by 7% compared to the values modelled for 2017, but also outputs a renewable annual share of 26.5%.

Acknowledgements

I would like to take this opportunity to extend my gratitude further than this thesis' timeframe, to the programme director of this course Dr Paul Tuohy, for supporting me whenever in need, but most importantly for being an inspiration for myself and others throughout this last year.

I also want to thank my supervisor, Mr Cameron Johnstone, for guiding me through the early stages of this project and pointing out some fundamental elements for investigating an energy system, sharing his personal experience and knowledge with me.

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This study would have not been possible without the transparency and information access from the numerous national bodies of Cyprus, allowing this research to materialise in its desired forms. I am also very grateful for the open-access EU-funded PVGIS system, from which I was able to extract crucial data to use in constructing required parameters to this study.

Finally, and most importantly, I want to express my gratitude to my family for their never-ending support. My partner Nannie, my parents Eleni and Vassilis, my siblings and closest friends – thank you.

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Glossary

RoC	Republic of Cyprus
TSO	Transmission System Operator
DSO	Distribution System Operator
EAC	Electricity Authority of Cyprus
RES	Renewable Energy Sources
VRE	Variable Renewable Technology
EEZ	Exclusive Economic Zone
VEC	Vassilikos Energy Centre
DEFA	Natural Gas Public Company (known as DEFA from the Greek abbreviation)
NPC	Net Present Cost
LCOE	Levelized Cost of Electricity

1. Introduction

The Republic of Cyprus, denoted in this report as RoC, is the largest island country in the Mediterranean Sea, and one of the smallest EU Member States. With a rising population, the RoC recorded 864,236 usual residents in January 2018 (Eurostat, 2018), with more than 3.6 million tourists arriving per annum (Ministry of Finance, Statistical Service, 2018). Located in between Europe, Asia and Africa, its unique geographical position together with its very resourceful climate, carries a great potential for researching and integrating different renewable energy technologies.

Today, the RoC only controls 59% of the island, with a state currently only recognised by Turkey occupying 36% in the north, a UN buffer zone that is in between at 4%, and the remaining ~1% is from the two British sovereign bases located on the island.

Its electricity generation is largely centralised and energy isolated, relying on oil-fired thermal power stations for more than 90% of total annual generation; resulting in a highly polluting, inefficient and expensive energy system; creating a hostile environment for one of Europe's hotspots of biodiversity. Currently, no energy storage solutions connect to the electricity grid, and there are no published plans of such developments, forcing a high running reserve always sourced from oil-fired thermal power stations. Being the last remaining energy-isolated European Member State, efforts are underway to break this isolation through the interconnector 'EuroAsia', and the gas-pipeline 'EastMed', following recent discoveries of natural gas fields south of the island.

In the face of European energy targets, namely the 2020 target for 13% renewable electricity generation, and the ambitious 2050 target of cutting CO_2 emissions by at least 80% in reference to 1990 values, have raised questions around whether the RoC is developing responsible and sustainable plans for matching the Commission's targets.

This report aims to identify and quantify the current energy system that is in place, and through an analytical and scenario-based approach, to develop suggested pathways that the RoC could follow in diversifying and decentralising its energy generation. All energy pathways are built around the energy trilemma of cost of electricity, environmental sustainability, and security of supply – all of which will constitute a high degree of renewable penetration.

2. Literature Review

This literature review will be an academic overview of the three building blocks of this thesis – the electrical energy systems currently in place, the hydrocarbon resources that have been discovered and which are awaiting exploitation, and the soon-to-be ended energy isolation of the island.

Each of these topics will be explored, and their implications will be analysed through a holistic approach to understanding Cyprus' energy systems. The literature review will be the foundation to then propose various future energy scenarios that the island could follow through the integration of more renewables, but also the potential gasification of the now oil-fired thermal power stations.

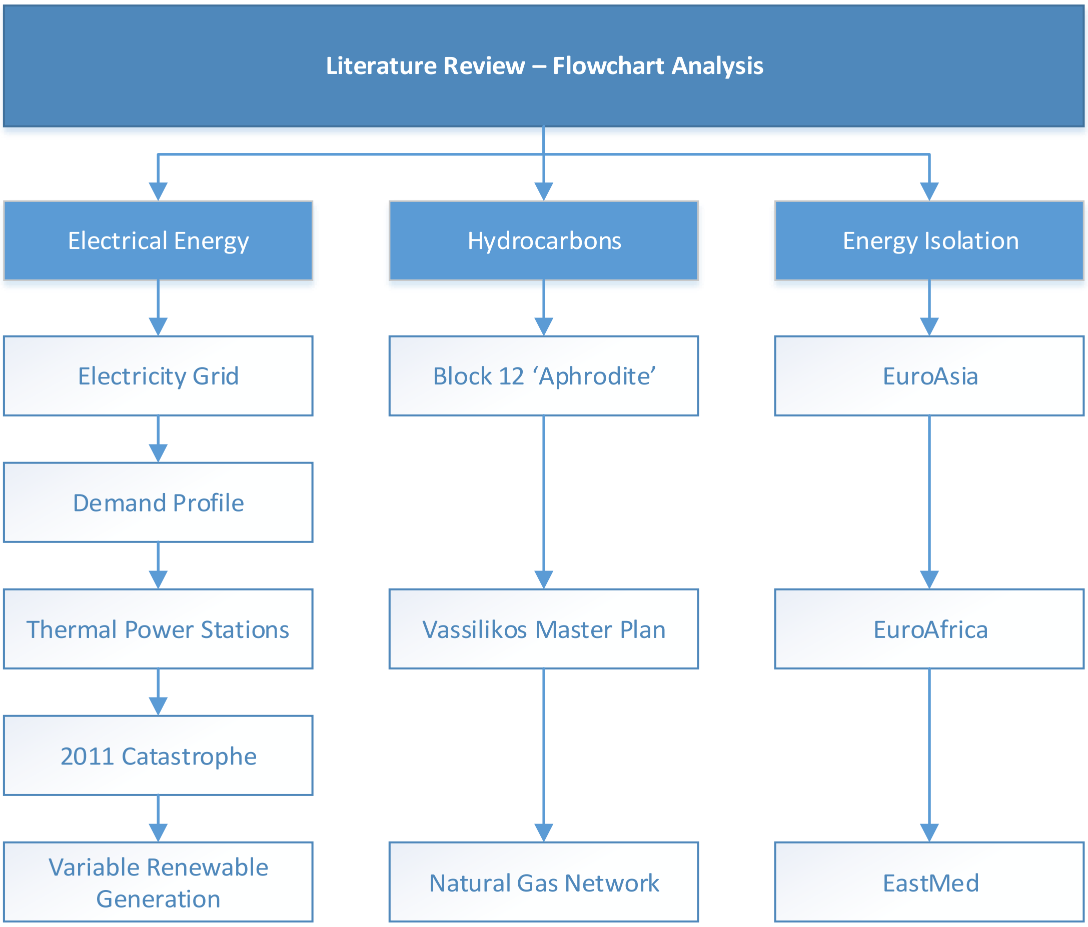

Figure 1 - Literature Review flowchart

2.1. Electrical Energy in Cyprus

Electricity in Cyprus relies mostly on heavy fuel oil, with oil-fired thermal power stations having generated 91.65% of total electricity in 2017. While this percentage remains very high, it is important to note that from 2011 to 2017, generation from renewable energy sources more than doubled from 164.2GWh to 415.3GWh (Transmission System Operator - Cyprus, 2018). Having said that however, Cyprus has one of the biggest solar radiation exposures in Europe, giving the island great conditions for photovoltaics and biomass, as well as significant exploitable energy levels in-directly through wind.

Electricity Grid

Electricity in Cyprus is extremely centralised, with one thermal power station having produced 64.5% of all generation in 2016 (Electricity Authority Cyprus, 2018).

The electricity grid, which is comprised of two public bodies, the Transmission System Operator (TSO) and Distribution System Operator (DSO), operates at relatively low voltage levels compared to other countries. At 66kV and 132kV, electricity is transmitted from power stations to grid supply points, where the DSO transmits electricity from 11kV to the distribution substations at 415V, 50Hz (Transmission System Operator - Cyprus, 2018).

Currently, the electricity grid is operated by only one TSO and DSO, with Cyprus being one of six EU member states where a DSO does not exercise control of high-voltage lines (Eurelectric, 2013).

Demand Profile

In 2016, the annual electricity production in Cyprus was 4.9TWh – in relation to the 3603.9TWh of the EU-28 bloc, standing at 0.13% (Eurostat, 2017). Even with the country's relatively small consumption, Cyprus still must meet EU, national and international targets for reducing its carbon dioxide emissions and its sole dependency on heavy oil.

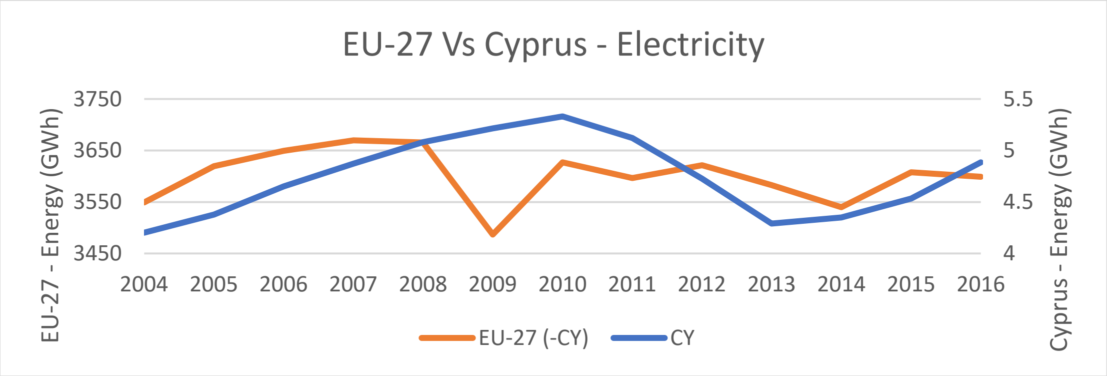

Figure 2 - Energy generation EU-27 Vs Cyprus (Eurostat, 2017)

Peak demand always occurs in the summer, since Cyprus is a popular tourist destination, giving a positive correlation between electricity generation and arrival of tourists, which peak at half the island's population in July and August (Ministry of Finance, Statistical Service, 2018).

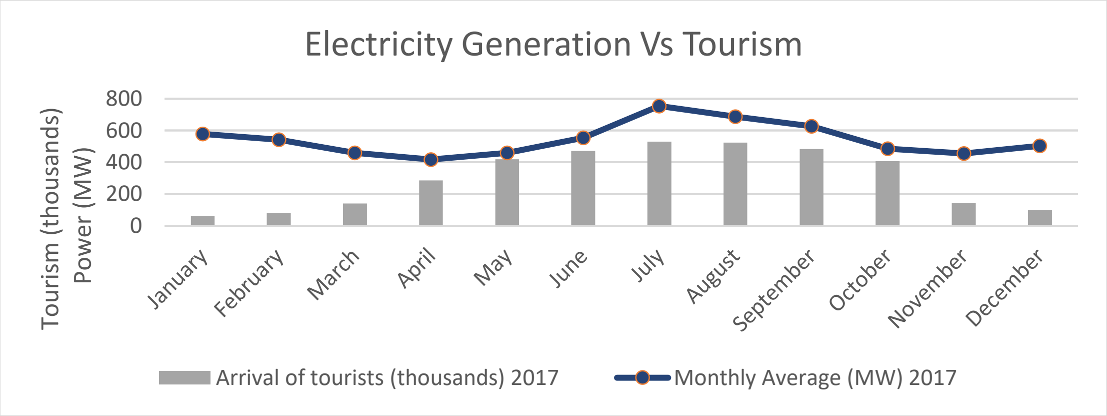

Figure 3 - Relationship between electricity generation and arrival of tourists (Ministry of Finance, Statistical Service, 2018)

Cyprus' peak demand as documented in the latest national annual energy report is approximately 1GW, and the highest was recorded on the 2nd August 2016 at 14:30, with a generation of 996MW (Cyprus Energy Regulatory Authority, 2017). As expected, demand grew in 2017 and after analysing non-published generation data from the TSO, a new peak demand was found on the 3rd July 2017 at 15:00 with a generation of 1023.78MW. Consequently, the days of 3rd and 4th July 2017 were the most energy-hungry of 2017, as shown in Figure 4.

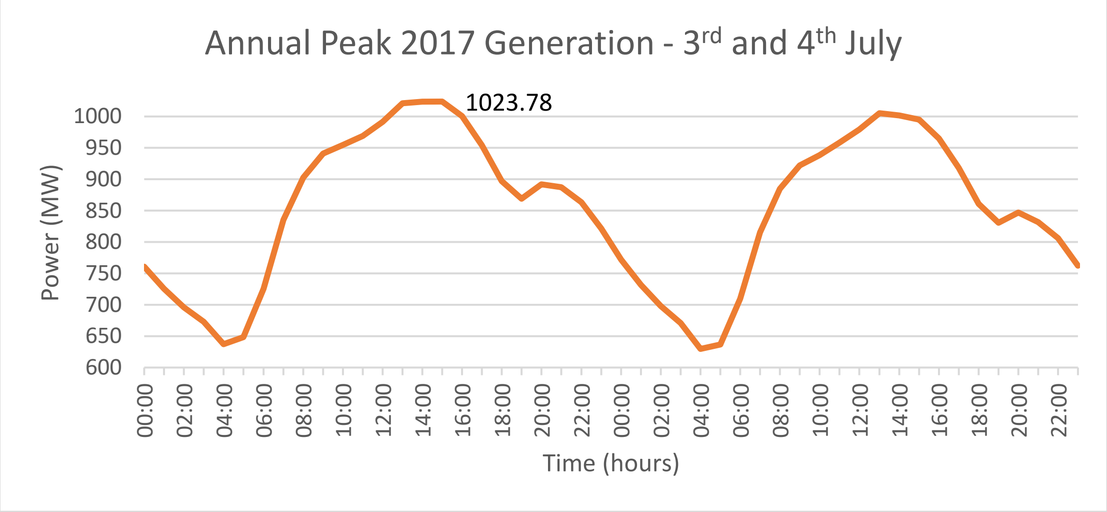

Figure 4 - Annual peak generation, 3rd and 4th July 2017 (Transmission System Operator - Cyprus, 2018)

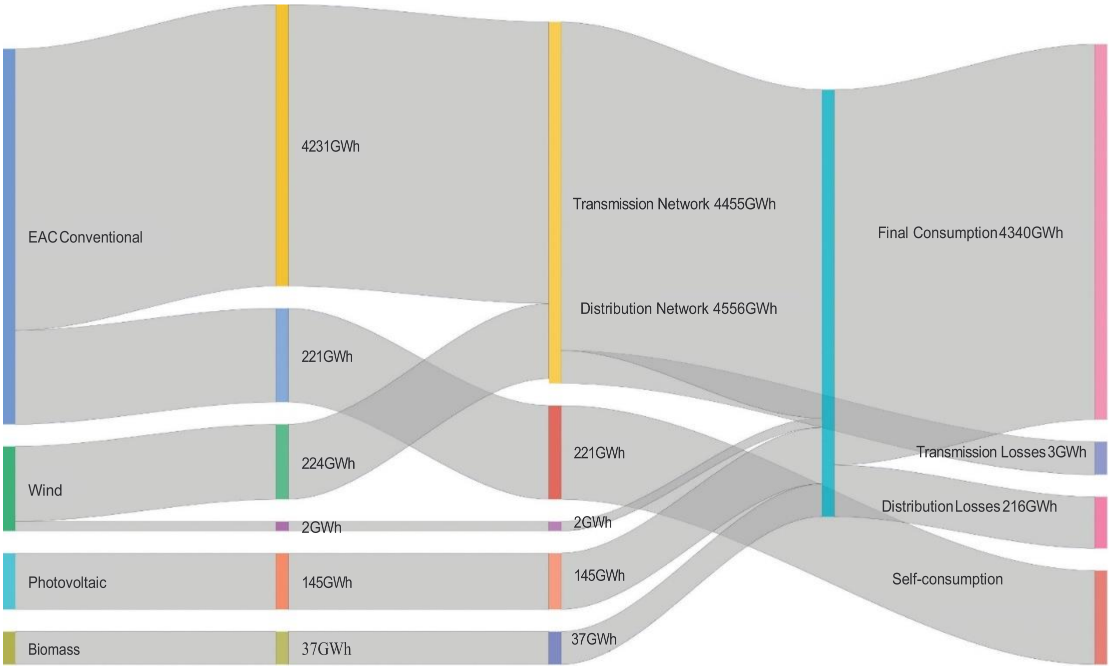

Figure 5 - Energy flow 2016 - Sankey diagram (Cyprus Energy Regulatory Authority, 2017)

Generation varies greatly from hour to hour, with peak demand in the summer occurring always around 14:00-15:00, and in the winter time around 19:00-20:00. The global minimum appears to be around 04:00 for both winter and summer, with summer typically being shifted up by 200MW compared to winter. Summer peaks occur mostly from the contribution of air conditioning units cooling all sectors buildings, with the increase of tourism adding extra pressure. In the winter time, peak demand occurs after working hours, from the extra lighting demand and immersion heaters – even though Cyprus has a high-penetration of solar thermal, hot water storage is often poor resulting in high electricity demand of immersion heating in the winter time.

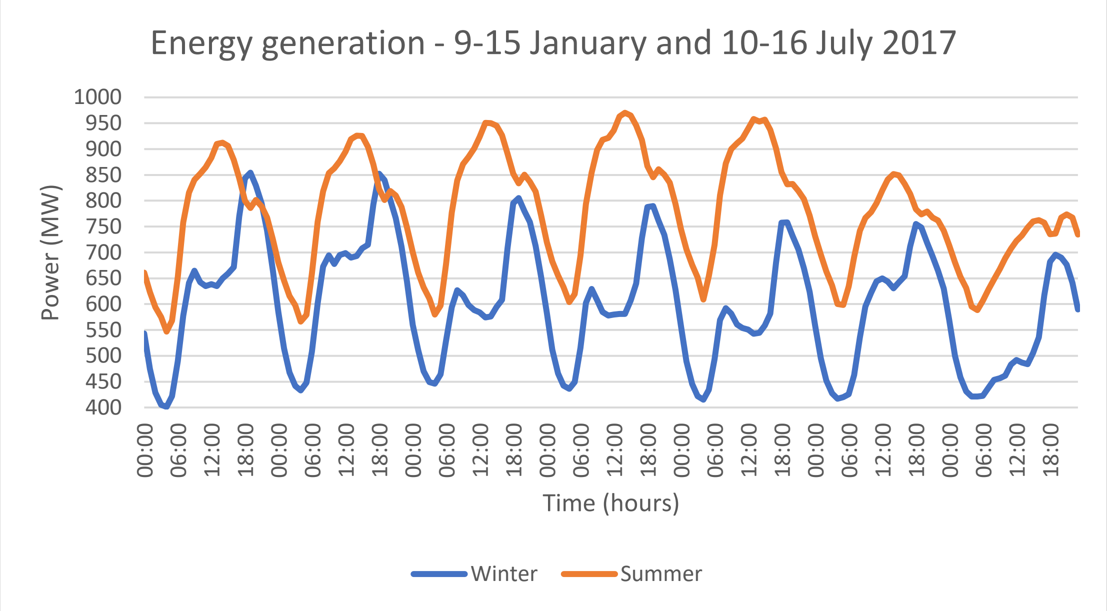

Figure 6 - Electricity generation comparison of winter and summer (Transmission System Operator - Cyprus, 2018)

Another important aspect of the generation profile is one regarding areas north of the ceasefire, where the RoC does not exercise effective control. For reasons not disclosed to the public, the electricity generated and distributed there is not and never have been metered and billed, with speculations pointing to that the RoC did not want to bill a body they did not recognise, in fear that it would legitimise the annexed state that is currently only recognised by Turkey. Data acquired from the TSO, shows typical days of summer, winter and mid-year, as in Figure 7, through a 66kV transmission line (Transmission System Operator - Cyprus, 2017). Further analysis shows that an annual 4.38GWh is transmitted from the RoC, although this number fluctuates every year, and is said to be decreasing – in their latest annual report, the DSO documented a transmission of only 2.9GWh (Electricity Authority of Cyprus, 2017).

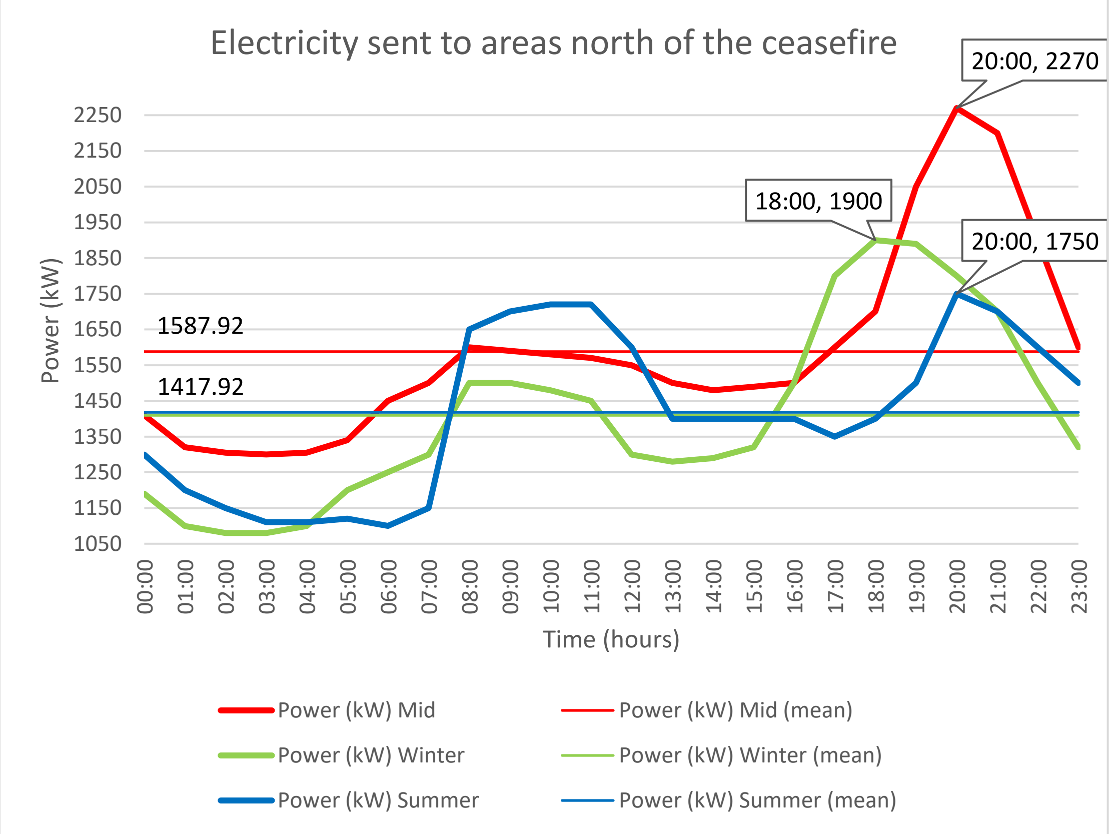

Figure 7 - Electricity sent to areas north of the ceasefire (Transmission System Operator - Cyprus, 2017)

Thermal Power Stations

Cyprus has three thermal power stations that are owned and operated by the Electricity Authority of Cyprus (EAC), which acts as the distribution system owner, and the distribution network operator, with a combined capacity of 1477.5MW.

Table 1 - Thermal Power Stations (Transmission System Operator - Cyprus, 2018), (Electricity Authority of Cyprus, 2017)

Installed capacity of thermal power stations (MW)					
Power Station	**Combined Cycle**	**Steam Turbines**	**Gas Turbines**	**Internal Combustion Engine**	**Total Generation Capacity**
Moni	-	-	4x 37.5	-	150
Dhekelia	-	6x 60	-	100	460
Vassilikos	2x 220	3x 130	1x 37.5	-	868
Thermal Efficiency	**45.67%**	**33.89%**	**24.33%**	**41.58%**	**36.3%**
Fuel Used	Diesel	Heavy fuel	Diesel	Heavy fuel	
Total Generation Capacity	440	750	187.5	100	**1477.5**

As seen from Table 1, turbines are undergoing an upgrade process, being prepared for gas-fired operations. However, the five open cycle gas turbines in *Moni* and *Vassilikos,* at a combined capacity of 187.5MW, currently operate with diesel oil fuel. The 100MW internal combustion engine at *Dhekelia*, and one of the steam turbines at *Vassilikos,* are currently only utilised in emergencies (Transmission System Operator - Cyprus, 2018).

At *Vassilikos,* the largest power station on the island, 440MW capacity of combined cycle gas turbines that offer theoretical efficiencies up to double the ones of traditional open cycle thermal stations, pave the way for what other power stations will naturally follow. Unfortunately, with a gas terminal not yet implemented in any power stations, they also operate with diesel oil fuel (Electricity Authority Cyprus, 2018).

2011 Catastrophe

In the early hours of July 11th 2011, one of the largest non-nuclear, human-induced explosions took place in the naval base ‘Evangelos Florakis’, 500m away from the largest power station, *Vassilikos*, setting it non-operational. This catastrophe required the fastest route to restoring energy generation levels, with generators rented from neighbouring countries at a total capacity of 165MW and installed temporarily in all three power stations (Electriciy Authority of Cyprus, 2012). The DSO, with continuous cooperation from the TSO, were able to supply uninterrupted electricity 30 days after the explosion, after a very aggressive demand-side management process of avoiding high-peaks and scheduling periodical electricity cuts (General Electric, 2017). Finally, the power station of *Vassilikos* was fully restored in 2013, reaching today’s capacity levels of 868MW (Electricity Authority of Cyprus, 2014).

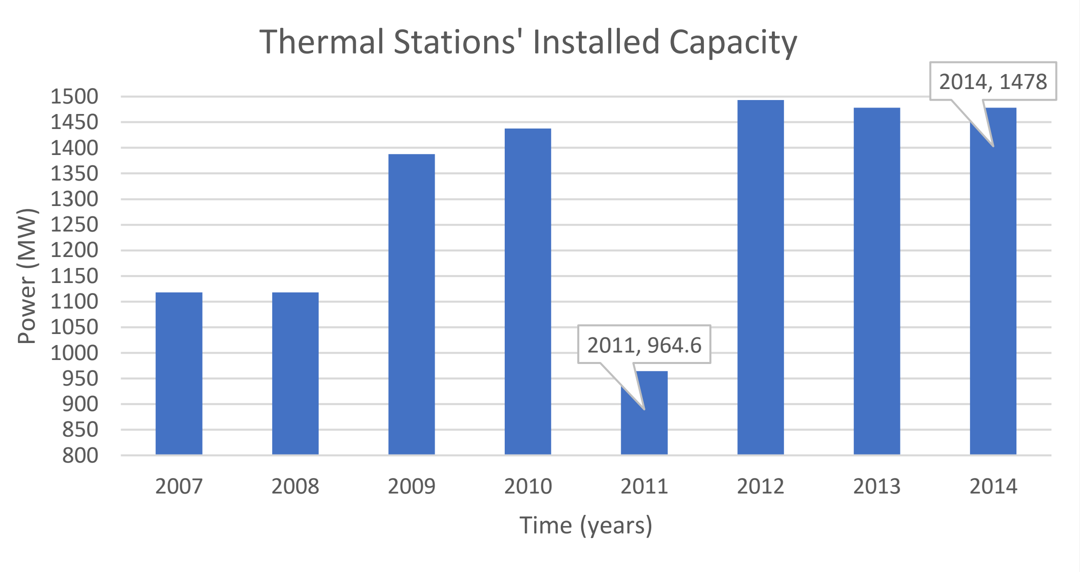

Figure 8 - Thermal Power Stations' Installed Capacity

The unexpected event that took place in July 2011, is reflected in all statements and graphs about the RoC, from electricity generation, to imports/exports, energy forecasts, and important financial elements of the country; rendering void in extent numerous national reports and strategies that the RoC had to then re-calibrate.

Renewable Energy Sources (RES)

As previously mentioned, Cyprus' renewable generation has more than doubled from 2011 to 2017, having generated 8.4% of total consumption in 2017, from a mere 3.3% in 2011. Out of the 415.295GWh renewable energy generation in 2017, wind energy supplied 51% at 211.007GWh, while photovoltaics stood at 40% with 167.792GWh, and lastly biomass at 9% with 36.496GWh.

Table 2 - Renewable Energy Systems (Transmission System Operator - Cyprus, 2018)

Renewable Sources 2017	**Installed Capacity (MW)**	**Generation (GWh)**	**Capacity Factor (%)**
Wind Turbines[1]	155.1	208.65	15.36
Wind Turbines	2.4	2.36	11.21
Photovoltaic Panels	112.1	167.79	17.09
Biomass	9.7	36.49	42.95
Total	**279.3**	**415.29**	**16.97**

Prior to 2010, there was no wind energy on the island. However, the 'Orites' wind farm of 82MW installed capacity was introduced and directly connected to the transmission network, marking the beginning of wind energy in the RoC. Today, there are several wind farms directly connected to the transmission network, with an installed capacity of 155.1MW, and a small number of 2.4MW that is connected to the distribution network.

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[1] Wind turbines connected to the transmission network

Renewable energy share saw an accelerated penetration after 2011, although it was later adversely affected from the Cypriot financial crisis in 2013 (European Commission, 2013). In order to achieve the electricity target of 13% by 2020, the RoC will have to replicate similar penetration rates, as further observed through Figure 9.

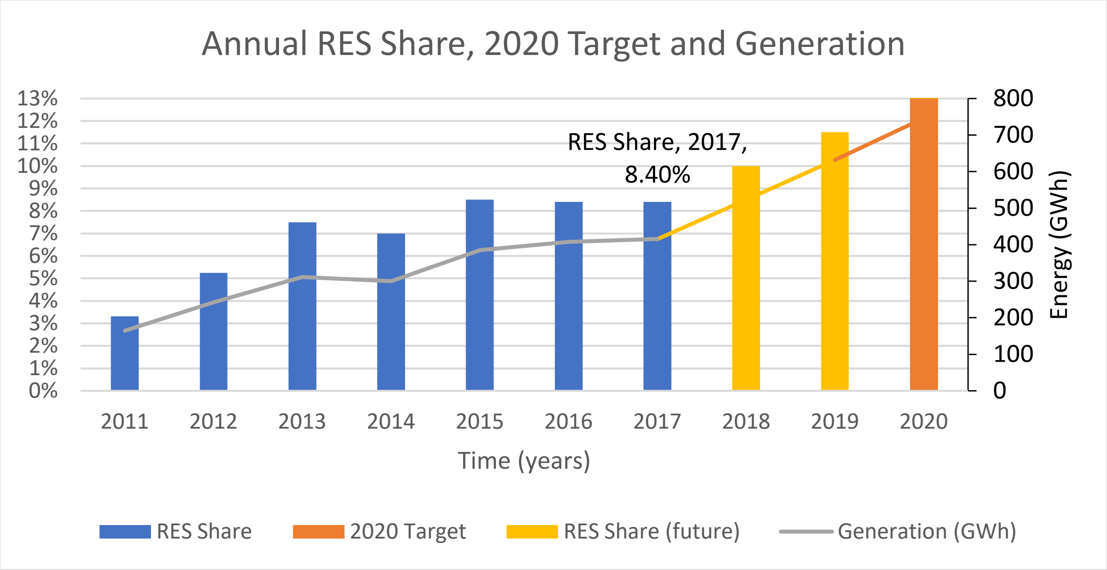

Figure 9 – Annual RES Share, 2020 Target and Generation (Transmission System Operator - Cyprus, 2018)

Moreover, wind energy is underperforming on the island, with a total capacity of 157.5MW and annual generation of 211GWh in 2017, giving an average capacity factor of 15.29%, a value well-below the global average (World Energy Council, 2016). Photovoltaics have demonstrated a slightly higher capacity factor, at 17.9%, although this also falls in the lower region of average values. Photovoltaics have a generally low capacity factor, since the majority of photovoltaic panels are placed on household roofs and thus not optimally commissioned, with technologies such as solar tracking being very rarely utilised.

Biomass-generated electricity was introduced to the energy mix in 2007 with an installed capacity of 250kW, increasing by a factor of 13 in the year after, reaching 3310kW. In 2008, there was no wind energy connected, and photovoltaics stood at 1586kW, 32.39% of the total RES installed by the end of 2008. Despite of biomass leading the renewable generation, it did not follow the rapid uptake of wind turbines and solar photovoltaics. The 82MW wind farm changed drastically the national renewable mix, and photovoltaics have been increasing in greater numbers, with a continuous small-scale uptake after 2012. Furthermore, 2014 was the most accelerated year with 26.1MW of capacity commissioned, which constitutes to 23% of today's photovoltaic capacity.

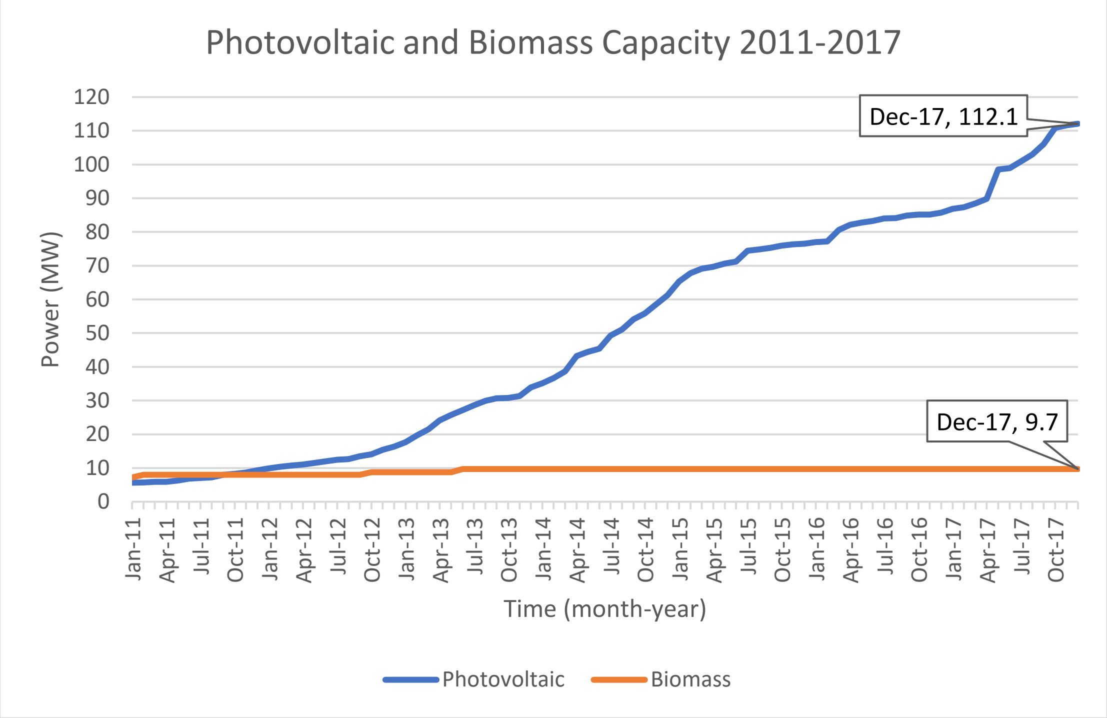

Figure 10 - Photovoltaic and biomass capacity 2011 – 2017 (Transmission System Operator - Cyprus, 2018)

National Energy Strategy

A National Energy Strategy, published by the RoC in 2016 (Ministry of Energy, Commerce, Industry and Tourism, 2016), analyses energy levels both from renewable sources and thermal power stations, and structures the future pathways based on EU-2020 targets. It includes two scenarios with which the targets will be overachieved.

Table 3 - 'Basic Scenario' - National Energy Strategy by the RoC

Year	Forecasted Demand (GWh)	Installed Capacity				Total RES Generation (GWh)	Total RES Share (%)
		Biomass	PV	WTG	CSP		
2015	4,475	10	90	157.5	0	397	9
2016	4,530	15	123.7	157.5	0	473	10
2017	4,670	15	137.2	167.5	0	508	11
2018	4,810	15	170.2	167.5	0	562	12
2019	4,950	New capacities determined by power purchase agreements			≥ 50	743	15
2020	5,100					816	16

Table 4 - 'Scenario without PPAs' - National Energy Strategy by the RoC

Year	Forecasted Demand (GWh)	Installed Capacity				Total RES Generation (GWh)	Total RES Share (%)
		Biomass	PV	WTG	CSP		
2015	4,475	10	90	157.5	0	397	9
2016	4,530	15	123.7	157.5	0	473	10
2017	4,670	15	137.2	167.5	0	508	11
2018	4,810	15	170.2	167.5	0	562	12
2019	4,950	15	204.2	175	50	723	15
2020	5,100	15	288.2	175	50	791	16

The two scenarios published by the RoC seem to be outdated, despite of the most recent version coming into effect on February 16th 2016. The detailed renewable energy penetration report published by the transmission system operator, states the installed capacity of each technology for each month. In December 2015, solar photovoltaic stood at 76.5MW, biomass at 9.7MW and wind turbines at 157.5MW – contradicting the values present in both scenarios of the national energy strategy seen in Table 3 and Table 4. Furthermore, this study assumes that in the national strategy report, all following years after 2015 were estimates or targets of the installed capacity for each technology. As of the end of 2017, solar photovoltaic stood at 112.1MW, biomass at 9.7MW and wind turbines at 157.5MW; the only introduction being the added installed capacity of photovoltaics. According to both scenarios however, the total renewable installed capacity for 2017 should have been 319.7MW, instead of the 279.3MW recorded by the TSO at the end of 2017.

The report also underestimates the increase in demand, forecasting 5.1TWh of energy for 2020, whereas the recently published report by the TSO on future generation places the annual energy levels of 2020 between 5.625 and 5.840 TWh, an increase of at least 10% (Transmission System Operator - Cyprus, 2018).

A correction of the forecasted demand towards 2020 and an analysis of a simulated model of the second scenario projected within the national energy strategy is investigated later in chapter ‘Future Energy Scenarios of Cyprus’.

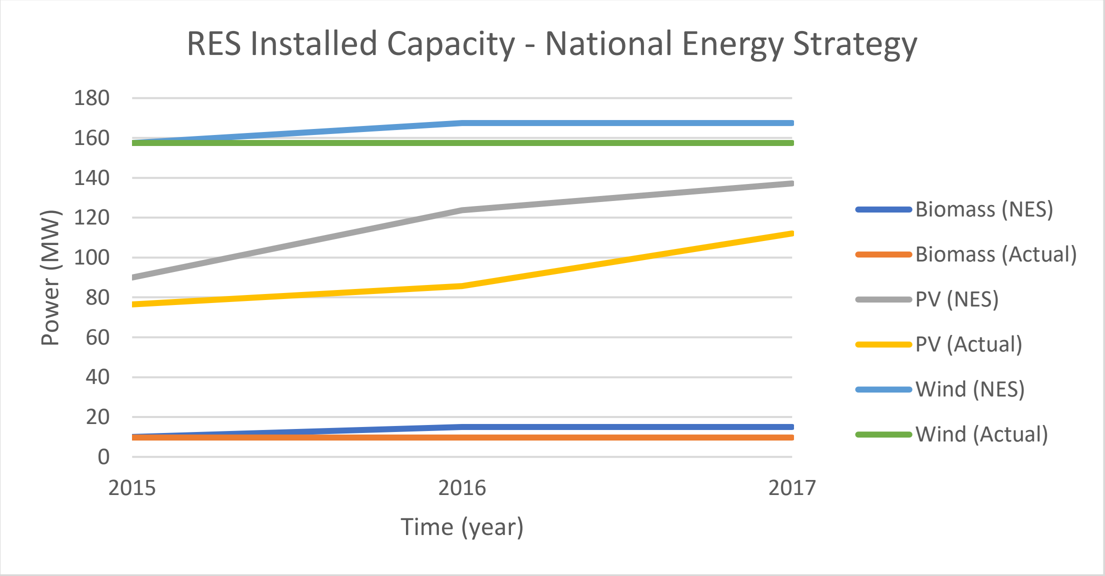

Figure 11 - RES installed capacity - national energy strategy Vs known values

2.2. Hydrocarbon Resources in Cyprus

Hydrocarbon explorations began in 2006 when the RoC started toying with the idea of researching and expanding operations in its Exclusive Economic Zone (EEZ). In doing so, 13 blocks were designed, partitioned and designated for future commercial licences, as shown in Figure 11. In October 2008, the first out of three licencing rounds took place for 11 blocks, excluding blocks 3 and 13.

Block 12 – 'Aphrodite'

Noble Energy, the American petroleum and gas exploration company, was appointed 'Operator' of block 12 after acquiring initially 70% (Cyprus Ministry of Energy, Commerce, Industry and Tourism, 2018). After numerous seismic surveys, significant discoveries were published from the first drilling that took place 20th September 2011, in the namely gas field of 'Aphrodite' in block 12. The original estimates from Noble ranged between 102 and 170 billion cubic metres (bcm), however estimates from partner company Delek Drilling followed a different method and narrowed down its potential to a lower mean value of 129bcm (Delek Drilling, 2018).

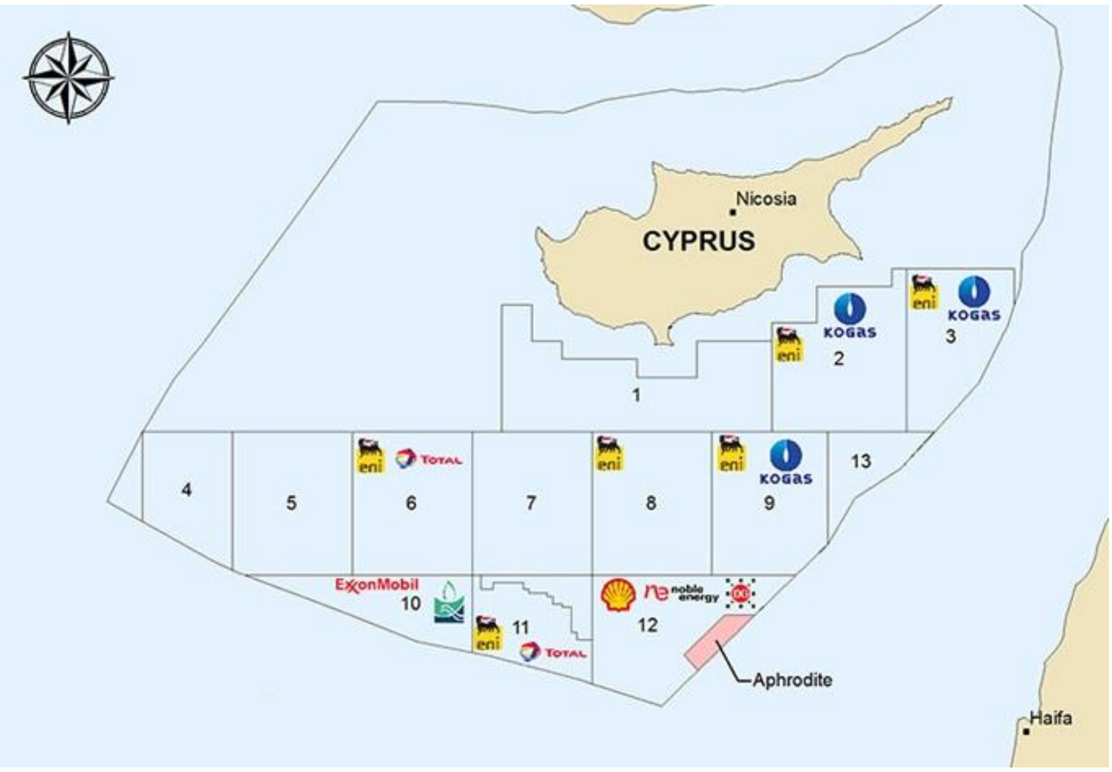

Figure 12 - Activities in the Cypriot EEZ (Cyprus Hydrocarbon Company, 2018)

Vassilikos Master Plan

In 2003, the RoC announced its intentions to construct the Vassilikos Energy Centre (VEC), which would oversee the gasification of its power generation from oil, increase its energy efficiency, and carefully monitor and reduce greenhouse gases. The VEC was originally designed to import natural gas, with in-house storage tanks able to satisfy fuel emergency contingency plans as per the recent directive issued by the European commission, the EU directive 2009/119/EC, which requires fuel emergency stocks of up to ‘90 days of average daily net imports or 61 days of average daily inland consumption, whichever of the two quantities is greater’ (European Union, 2009). The plans for VEC changed however with the discovery of ‘Aphrodite’, and it was put on hold until a final ‘master plan’ could accommodate the new financial dimensions that were unfolding with local natural gas reserves.

Released in 2015, the final ‘master plan’ is now an in-depth report that aims to satisfy the gasification objectives of the initial plan, now including the complex structure of being a natural gas net exporter, instead of importer, to make the extraction of the reserves financially sustainable. The ‘master plan’ aims to integrate natural gas reserves with the only industrial coastal area in Cyprus, Vassilikos, with not only the power station but also its nearby industries, such as ‘Vassilikos Cement Works’ (Poten & Partners, Inc & ALA Planning Partnership Consultancy L.L.C., 2018).

Unfortunately, the plan of constructing an onshore liquefied natural gas (LNG) terminal at the Vassilikos area has been put on hold once again, due to fluctuations in the estimates of the natural gas reserves.

This has compromised the clarity of the financial elements, prolonging once again the development of VEC, the gasification of the thermal power generation plants, and ultimately risking the profitability of extracting natural gas altogether (Cyprus Ministry of Energy, Commerce, Industry and Tourism, 2018).

Natural Gas Network

The idea of importing natural gas and diverting power generation from oil to gas, ultimately converting all conventional generators to combined cycle gas turbine (CCGT) plants, hence achieving higher energy efficiency whilst lowering environmental impacts of oil-fired stations, is now more present than before. With the Cyprus Energy Regulatory Authority (CERA) re-iterating the importance of a natural gas pipeline network in its annual report 2016 (Cyprus Energy Regulatory Authority, 2017), led to initiating a significant project of constructing the first natural gas pipeline network in Cyprus, that will stretch a total of 80km and connect all three conventional power stations owned and operated by EAC.

The rationale is that regardless of how the RoC decides to process local natural gas reserves and, most importantly, the timeframe of that process, a gas network will irrespectively have to be in place. The Cypriot natural gas company, abbreviated DEFA from its Greek name, is the appointed transmission and distribution operator. Their primary responsibilities therefore, include buying, storing and distributing natural gas across Cyprus. The construction of this gas network, overseen by DEFA, has already secured €10m from the European Union, with the project costing roughly €60m. The priorities of DEFA are to connect the three conventional power stations with natural gas, and after to extend their operations inwards to support other sectors, such as domestic uses, businesses, greenhouses, etc. (Natural Gas Public Company (DEFA), 2018).

2.3. Energy Isolation of Cyprus

Cyprus is the last remaining EU member state that is energy isolated; including both electricity and gas. This results to a high dependency on the three thermal power stations, operating on either heavy fuel oil or diesel, forcing amongst other things the running reserve to be constantly sourced from oil-fired turbines. The TSO and DSO have both increased energy efficiencies over the years and have drafted various plans aimed to end this dependency on oil and diversify the energy mix through renewables. Despite these efforts, the island still operates in a highly polluting, isolated and economically volatile energy system.

In 2017, electricity in Cyprus cost €0.1863/kWh, ranking 11th amongst other EU Member States. When comparing it to the purchasing power standard (PPS), an artificial currency that incorporates all prerequisites to allow national comparisons more effectively, Cyprus is placed slightly higher than the European average.

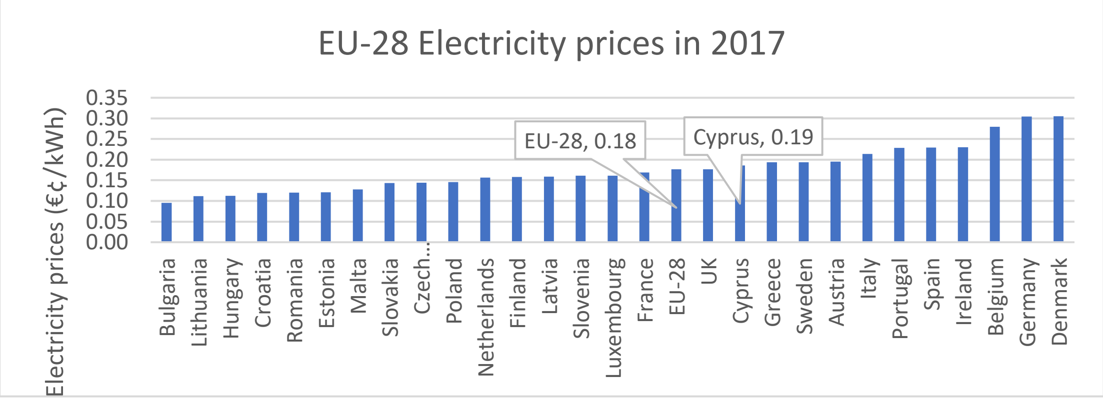

Figure 13 - EU-28 Electricity prices in 2017 (Eurostat, 2018)

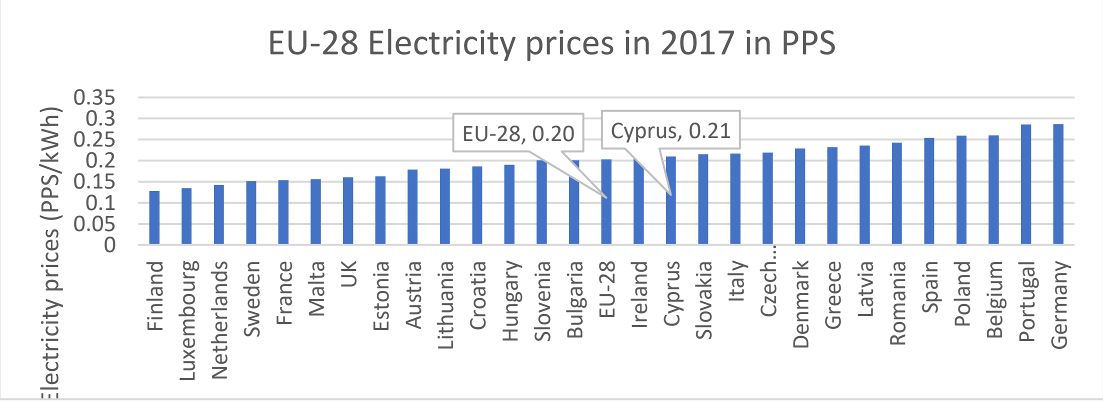

Figure 14 - EU-28 Electricity prices 2017 in PPS (Eurostat, 2018)

Three projects are currently on-course for breaking the energy isolation of the island, EuroAsia, EuroAfrica and EastMed; the first of which has been confirmed and is now under construction.

EuroAsia

A multi-terminal high voltage direct-current (HVDC) subsea cable at ±400kV has been confirmed, and is set out to travel a total 1,518km and carry a capacity of 2GW starting from Israel to Cyprus, from Cyprus to the Greek island of Crete, from Crete to mainland Greece and onto the Pan-European electricity grid. The project is said to be the longest interconnector cable in the world, with its lowest point reaching 3km below sea level.

It will have four converter stations for transforming HVDC to local transmission levels of high voltage alternate-current (HVAC) and vice-versa, in Israel, Cyprus, Crete and mainland Greece (EuroAsia Interconnector, 2018).

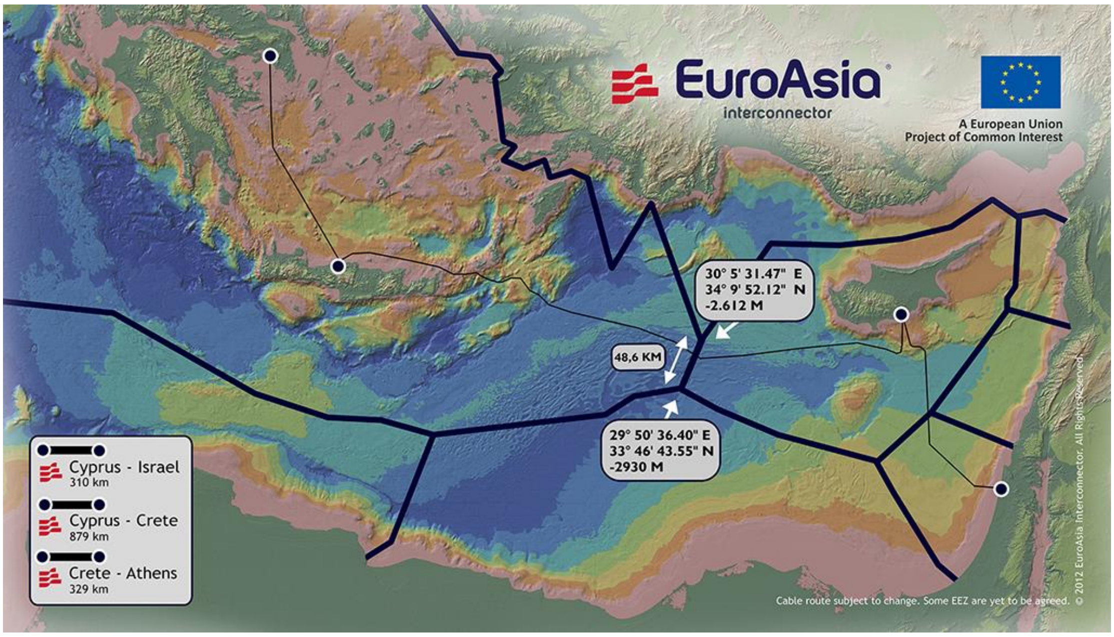

Figure 15 - EuroAsia route (EuroAsia Interconnector, 2018)

The project, which is co-funded by the European Union, is meant to be completed by 2021, with one line commencing earlier in 2020 (EuroAsia Interconnector, 2018).

EuroAfrica

EuroAfrica has the same parent company as EuroAsia, Quantum Energy, and even though the project has not been confirmed, it has received official support from the governments involved. Its characteristics are identical to EuroAsia, being a 2GW multi-terminal VSC-HVDC subsea interconnection, but it begins in Egypt instead of Israel, continuing inwards to Cyprus, Crete and mainland Greece.

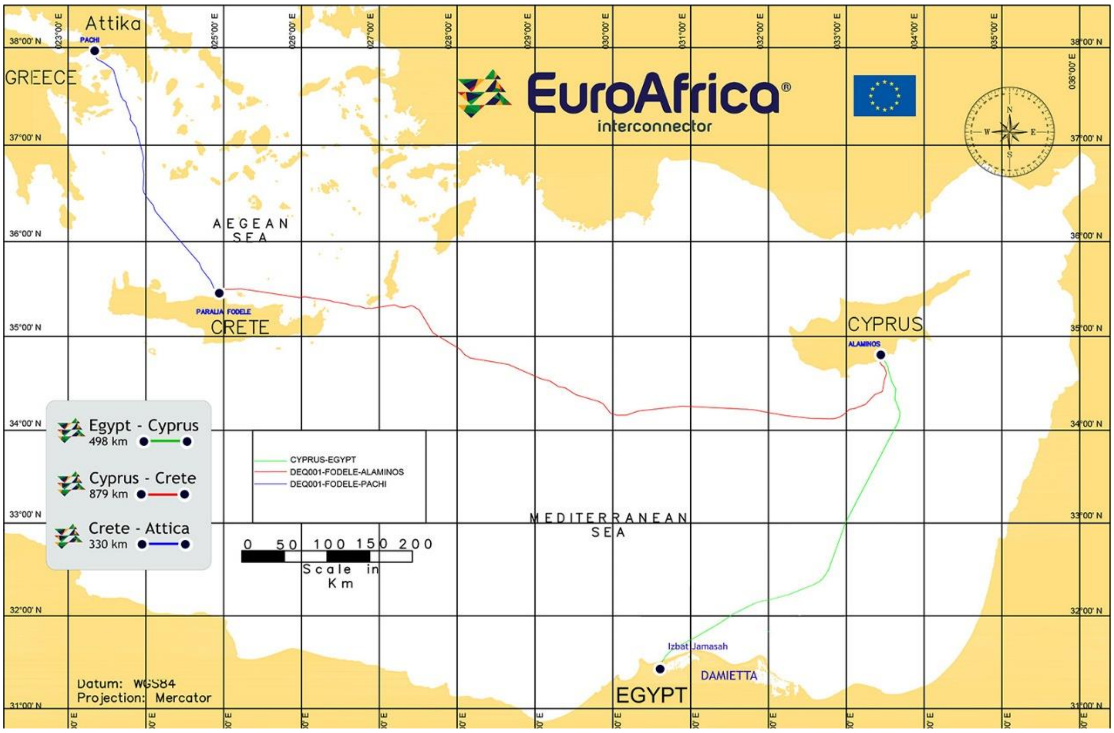

Figure 16 - EuroAfrica route (EuroAfrica Interconnector, 2018)

The two eponymous projects aim to connect Asia and Africa with the European electricity grid mainly for exporting renewable energy to mainland Europe from resourceful environments in its South-Eastern corner, but for also breaking the energy isolation of two islands (Cyprus and Crete). An additional reason for the interconnectors, is said to be the export of the natural gas fields discovered in Cyprus and Israel, but through the form of electricity (EuroAfrica Interconnector, 2018).

EastMed

The Eastern Mediterranean (EastMed) gas pipeline, aims to exploit natural gas resources found in Cyprus and Israel, and incorporate them to the Pan-European gas network. According to the company behind EastMed, IGI Poseidon, the project will start with transporting 10 billion cubic metres of natural gas per year (bcm/y) from Cyprus to Greece, and by utilising the existing connections of IGI Poseidon that connect Greece with Italy, the gas will continue to Italy and from there to the Pan-European gas network. The project is supported by the involved governments of Israel, Cyprus, Greece and Italy, and has already received EU funding under the 'Connecting Europe Facility' Programme (IGI Poseidon, 2018). Currently, EastMed is awaiting deeper seismic surveys along the route, in order to construct the best-case scenario for the pathway. During the pre-front end engineering design (Pre-FEED) phase, the project was deemed technically feasible and economically viable (European Commission, 2016). If EastMed is commissioned, it could enable Cyprus to finance its natural gas industry and allow it to faster replace oil-fired power stations with gas-fired ones.

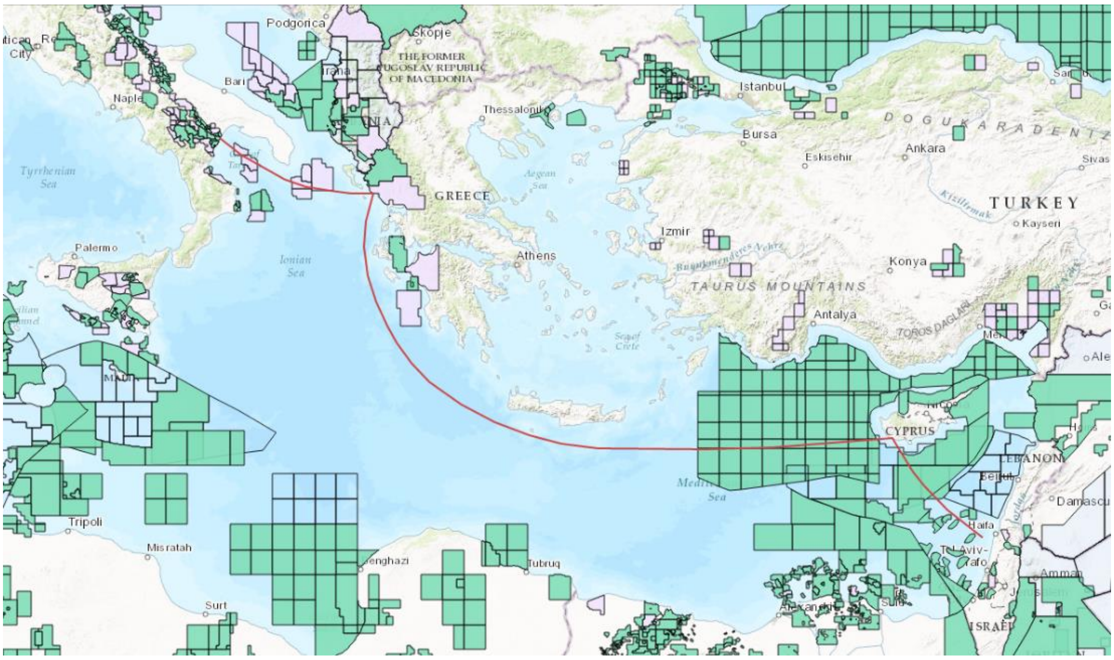

Figure 17 - EastMed gas pipeline map (Haldivor Finance Ltd, 2017)

3. Potential of Renewable Energy Systems

Cyprus is perhaps received with the highest solar radiation in Europe, creating vast opportunities for renewable energy generation directly through photovoltaics, renewable heat through solar thermal, as well as significant energy levels in-directly through biomass and wind energy.

In this section, a breakdown of the resource potential is given, with data obtained from the Photovoltaic Geographical Information System (PVGIS), a programme funded and hosted by the European Commission that outputs a 10-year meteorological average, hourly data on solar radiation, wind speed and direction, bulb temperature values and relative humidity levels (European Commission, 2018).

This section analyses the methodology with which solar radiation is processed on an hourly time-step, and how values will be used in order to construct modelling of solar photovoltaics. Furthermore, wind velocities are analysed on an anemometer height level of 10m, from where values will be interpolated to the corresponding hub height of the wind turbine in interest. In order to capture fully the intensity and direction of wind velocities, wind roses are constructed through MATLAB.

3.1. Solar Radiation

To give a general idea of how solar radiation is distributed throughout the year, the location chosen is the centre of the city of Limassol. The coordinates of the location are: latitude 34.679001, longitude 33.037998 and the elevation is 15m.

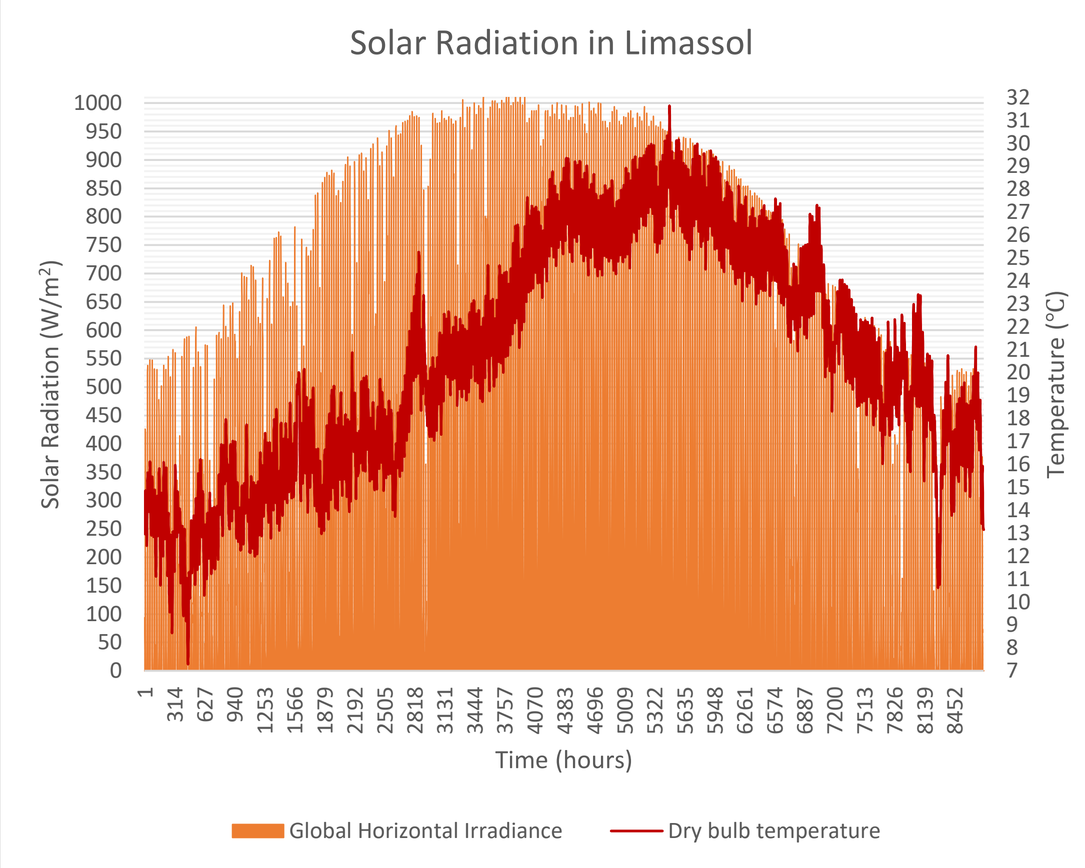

Figure 18 - Solar radiation in Limassol

Solar radiation in the summer peaks over the 1000W/m^2 photovoltaic standard test condition (STC) radiation, with direct irradiance being as high as 88.55% over diffused radiation. The temperature plays a significant part in the performance of solar photovoltaics, with a typical temperature coefficient in the scale of -0.4%/℃. Typical values of dry-bulb temperature were recorded between 10 and 30 ℃.

Global horizontal radiation exceeding 1000W/m^2 is common in summer days, with diffused radiation peaking at around 120W/m^2. Peak values halve during the winter, as seen in Figure 20, with significant exploitable levels present throughout the year.

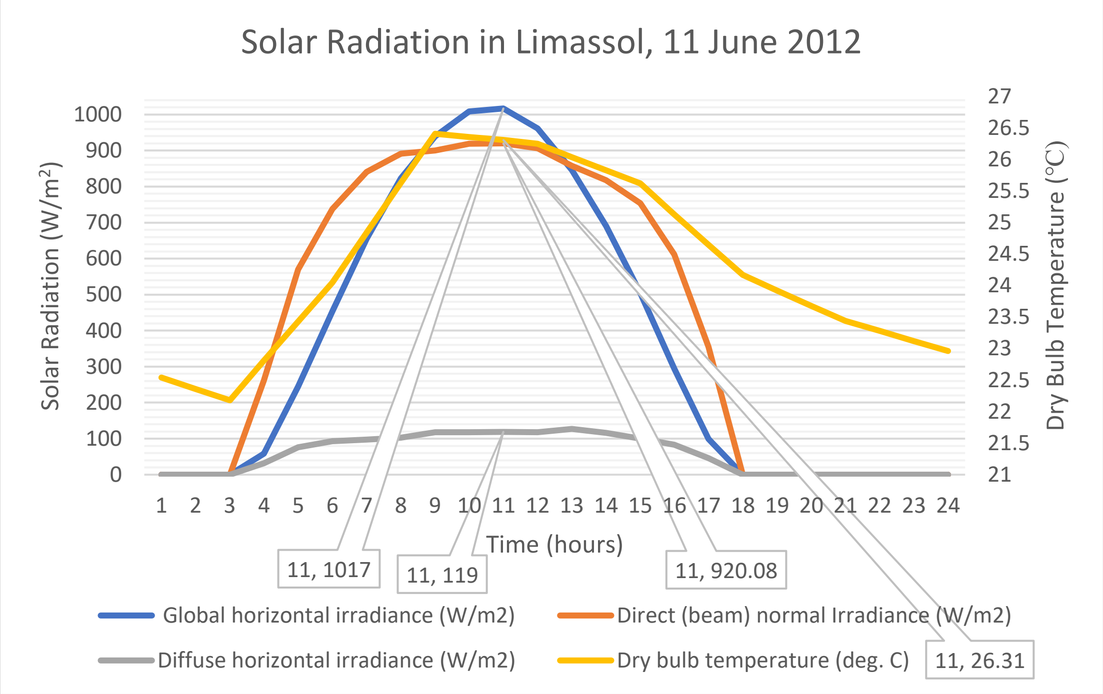

Figure 19 - Solar radiation in Limassol, 11th June 2012

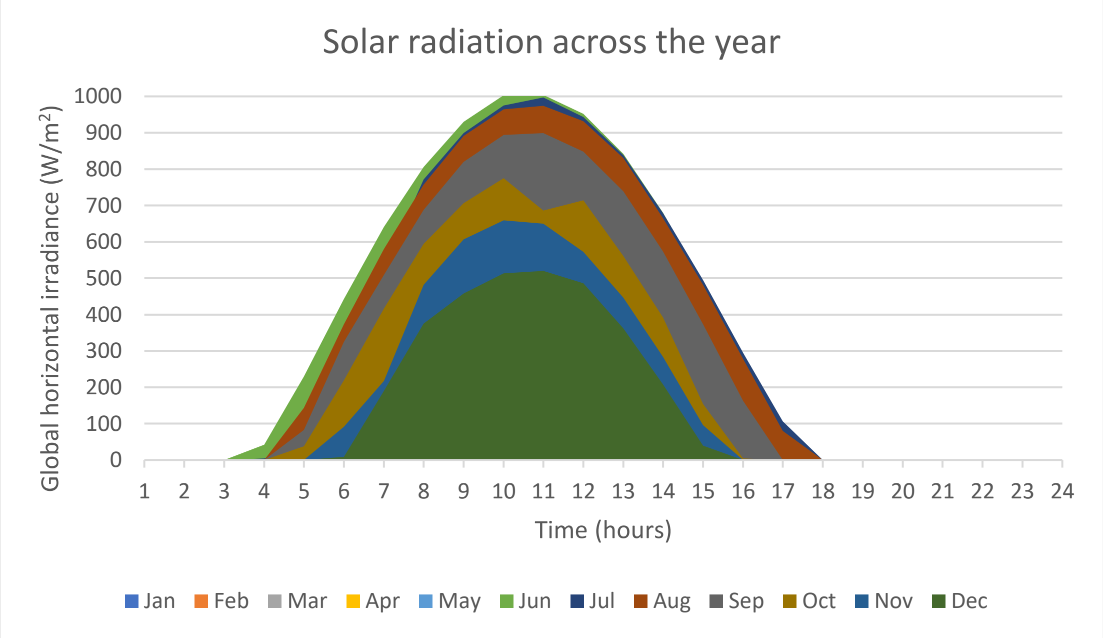

Figure 20 - Solar radiation in Limassol across the year, first day of each month

3.2. Wind Speeds

With wind speeds recorded at the anemometer height, a default height of 10 metres from ground level, wind speeds will need to be interpolated to the hub height of specific turbines. The selected method is simple and widely accepted as it enables calculations to take place for a variation of hub heights.

Equation 1 - Wind speeds interpolation with power law exponent

$$\frac{v_{hub}}{v_{anem}} = \left(\frac{h_{hub}}{h_{anem}}\right)^{a}$$

, with v_{hub} and v_{anem} denoting velocities at the hub's height and anemometer's height respectively, the h_{hub} and h_{anem} denoting heights of the hub and anemometer respectively, and finally a denoting the power law exponent.

According to HOMER Energy's manual, the power law exponent has been optimised at $\frac{1}{7}$, approximating at 0.14 (HOMER Energy, 2018), which is defined as a dimensionless function that incorporates fluid dynamics of surface roughness, stability, and height ranges over which they are determined (The Meteorological Resource Center, 2002).

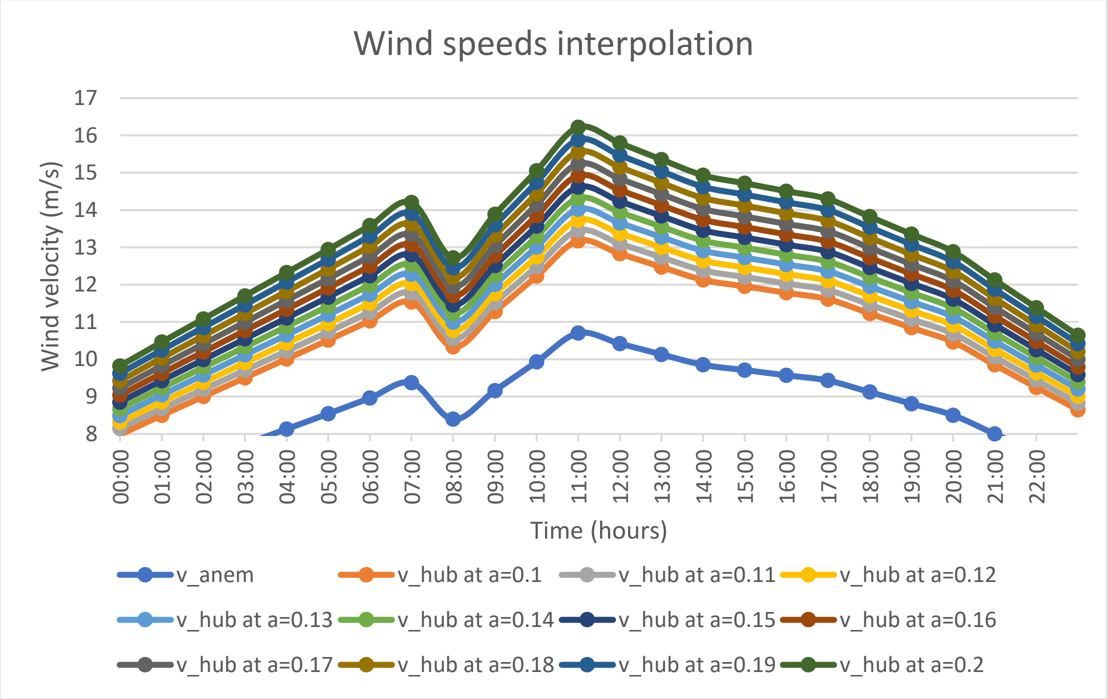

Figure 21 - Wind speeds interpolation with a varying power law exponent

Wind resources exist at relatively high levels, enabling the RoC to invest in both largely available renewable energy systems of wind and solar. At the location chosen previously, the wind speeds averaged over one year, exist at around 5.76m/s – with fluctuations high and low, reaching speeds of up to 20.11m/s.

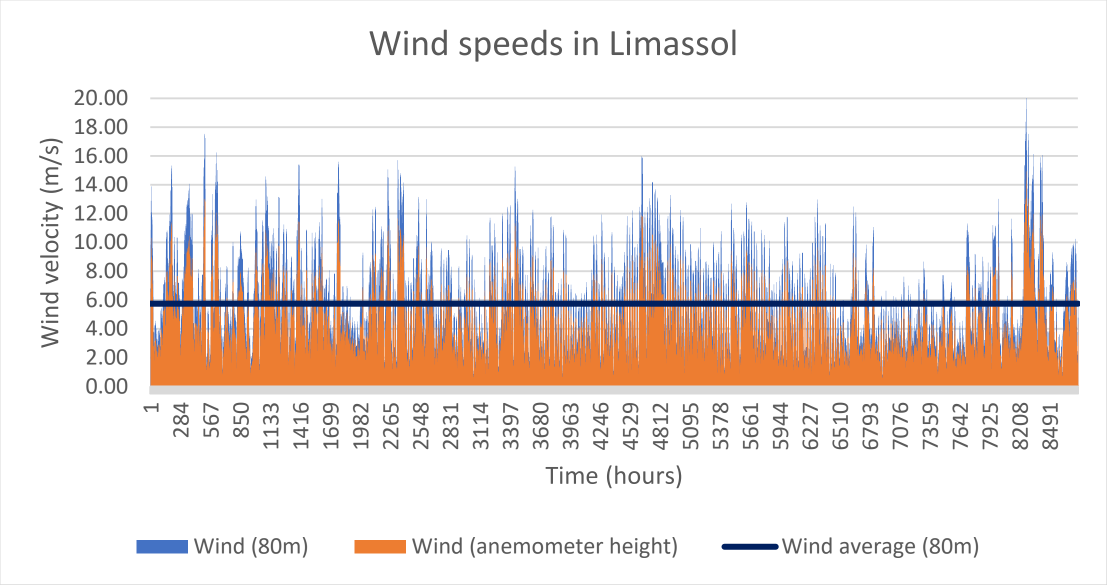

Figure 22 - Wind speeds in Limassol

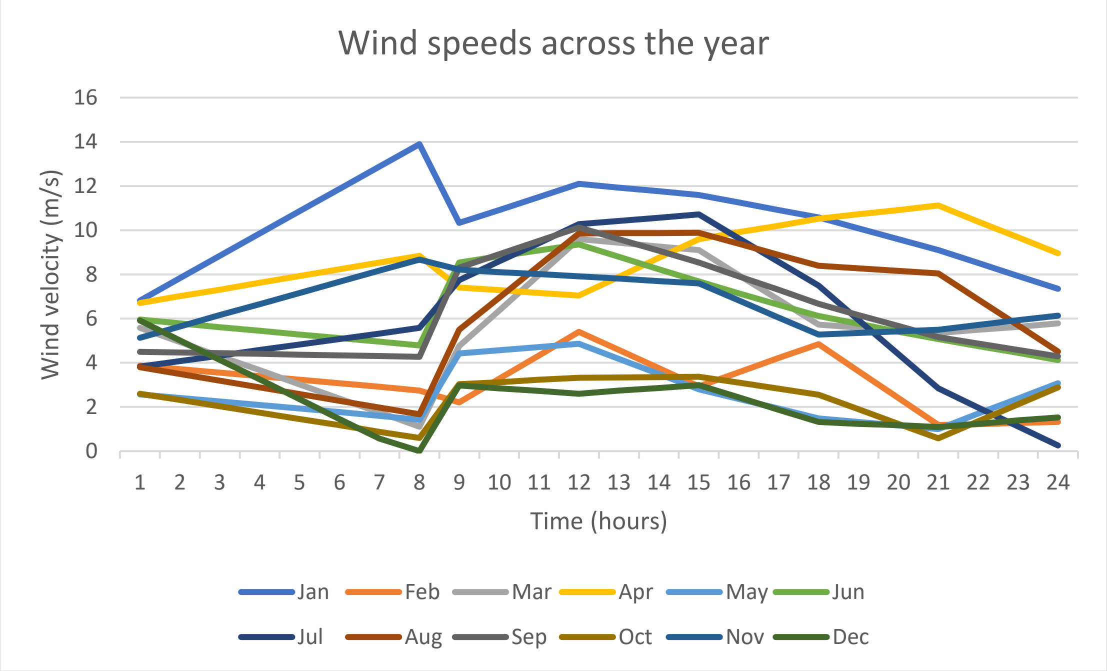

Figure 23 - Wind speeds across the year, first day of each month

MATLAB was utilised in this stage, to process and analyse the wind data to construct a 'wind rose'. Perhaps one of the most powerful charts for wind analysis as it can project not only the typical direction, but also the intensity in each direction. A wind rose therefore is a highly influential graph that is fundamental to determining the success of a site analysis.

At the given location previously mentioned, the wind rose is modelled as shown in Figure 23. The wind resources appear to be mostly directed East, with values between 5 and 10 m/s being the most dominant.

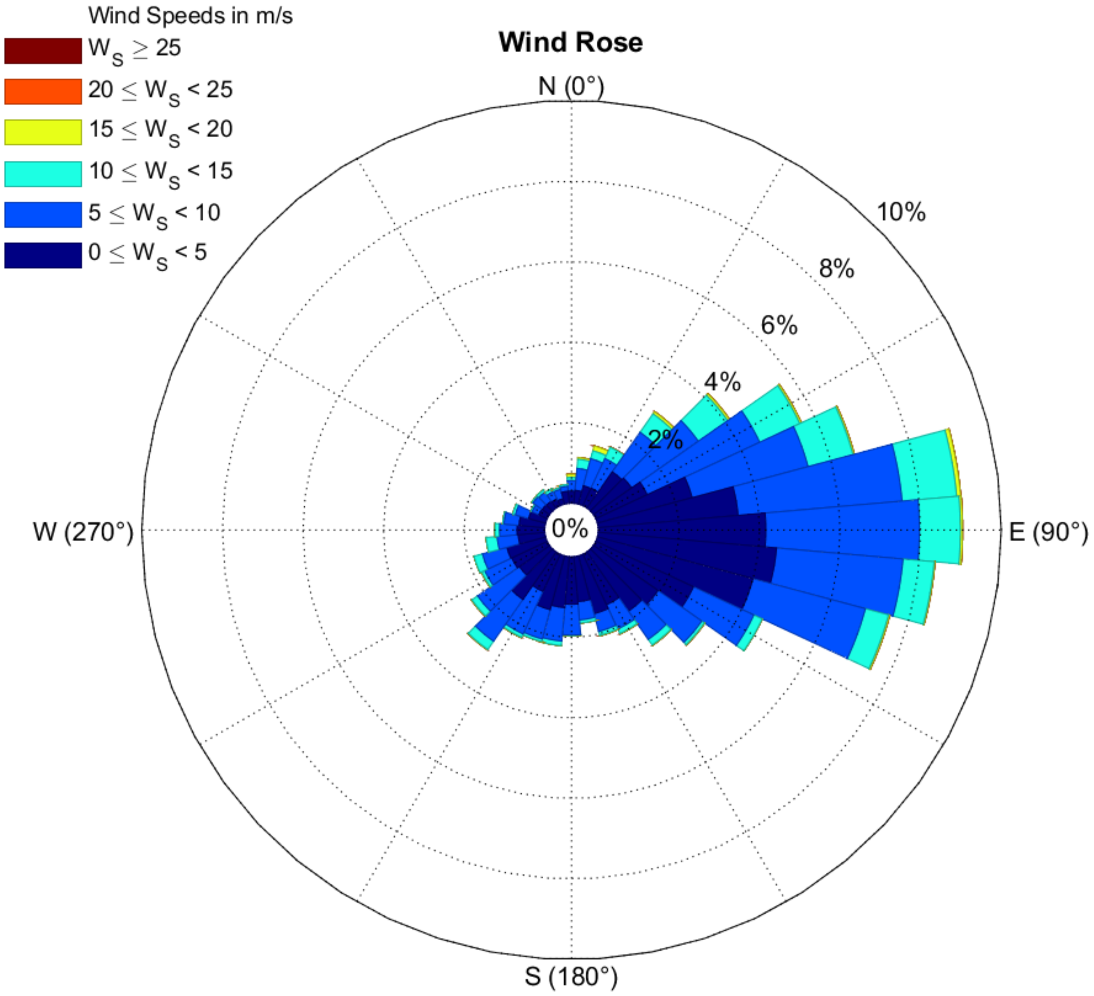

Figure 24 - Wind rose for Limassol (using MATLAB)

4. Energy Systems Analysis

The main software used for energy analysis, is HOMER Energy – a software that models hourly electricity and thermal generation, with integrated economic analysis in-house. Microsoft Excel was always utilised for breaking down the results obtained from HOMER, and developing analysis for extracting the required data.

Renewable generation in 2017 was dominated by wind and solar, and simulations in HOMER Energy allowed an insight in how they relieve and add pressure on the energy system, during their peak and trough times. Curtailment of renewables is a grey zone in terms of data availability, but since the RoC operates in island-mode, with no battery storage solutions, no vehicle-to-grid operations and no smart demand response systems in place, curtailment must be unavoidable with respect to the grid's infrastructure.

In the sections to follow, a detailed methodology of how results are obtained is documented, simulated and compared to the reference numbers that have been already published. The electrical architecture of the systems in place is identified and quantified, followed by the construction of the demand distribution profile. Afterwards, the thermal power stations are separated by technology, to capture each unit's thermal efficiency and fuel usage more accurately.

The days of maximum demand, and maximum renewable penetration, are analysed on an hourly time-step distinctly, so as to understand the boundary conditions of the energy system.

Furthermore, three case-studies at the end of the chapter help understand further how different renewable technologies operate on the island.

Electrical Architecture

As of the end of 2017, the RoC recorded a total capacity of 1757.3MW, 84.2% of which is from the three centralised oil-fired thermal power stations. The final electrical architecture is shown in Table 3, together with energy generation as published for 2017.

Table 5 - Electrical capacity in Cyprus

Technology	**Capacity (MW)**	**Generation 2017 (GWh)**
Biomass	9.7	36.496
Photovoltaics	112.1	167.792
Wind Energy[2]	157.5	211.06
Thermal Power Stations	1477.5	4559.098

Wind energy leads the renewable generation, even though it underperforms relative to photovoltaics. This is expected to change, with the historical trend analysis showing photovoltaics catching up, since they are installed continuously on a small-scale, versus the rather slow and large-scale wind farm installation frequency.

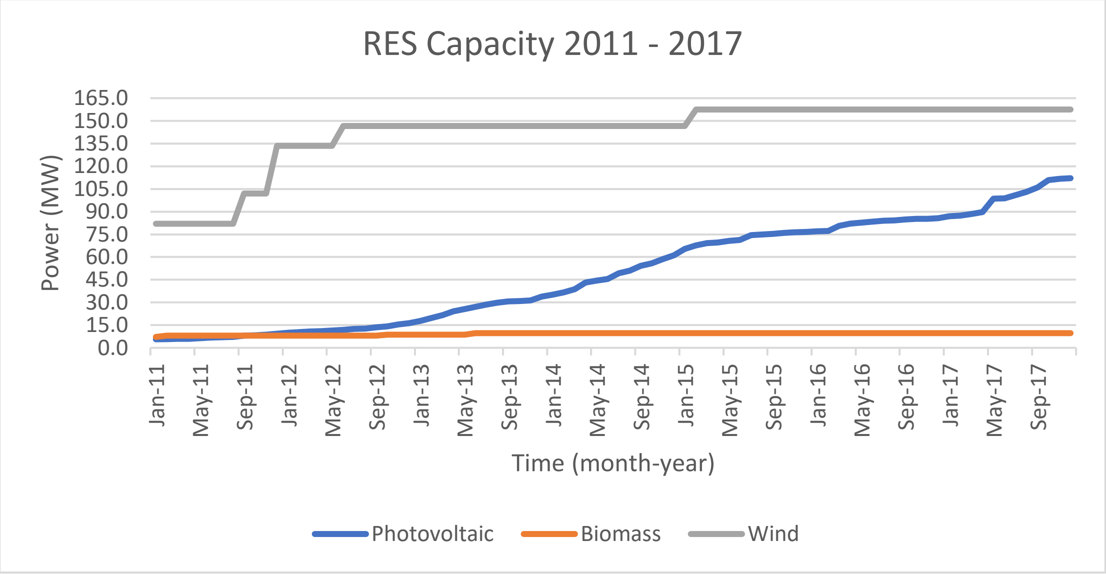

Figure 25 - RES Capacity 2011 - 2017

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[2] Including both distribution and transmission network generation

Demand Profile

The electrical demand, as previously analysed and discussed in section 'Demand Profile', has an annual demand of around 5TWh, with its tourism-driven generation peaking in July. As shown in Figure 25, the global minimum in demand occurs not in January, nor in a typical winter week. A data analysis has shown that April's signature has the lowest values in demand, with the ten lowest values annually recorded in the early hours of the month, at around 300MW.

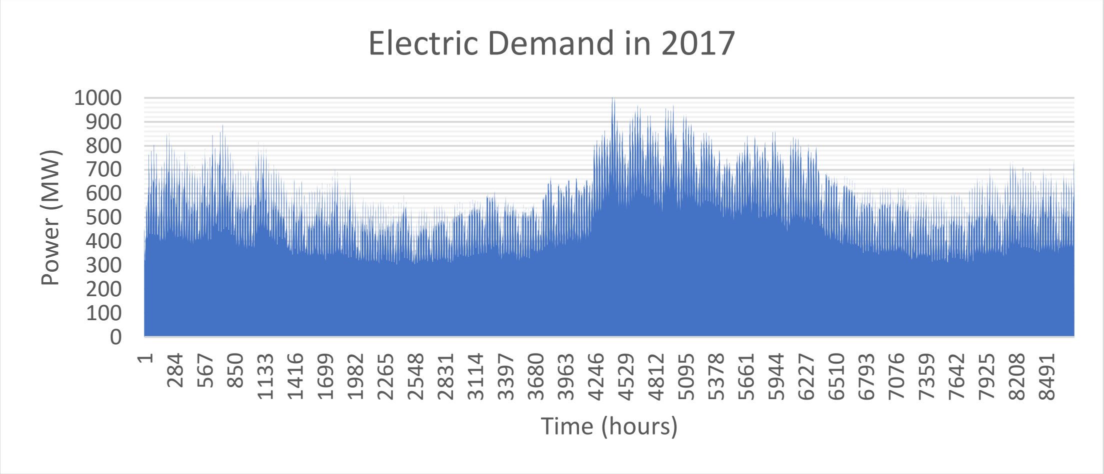


Figure 26 - Electric demand on an hourly basis in 2017

Analysing the maximum and minimum days is fundamental to establishing the boundary conditions of the energy system. As shown in Figure 26, peak values exceeded 1000MW on July 3rd, where minimum values in the range of 300MW were recorded on April 16th.

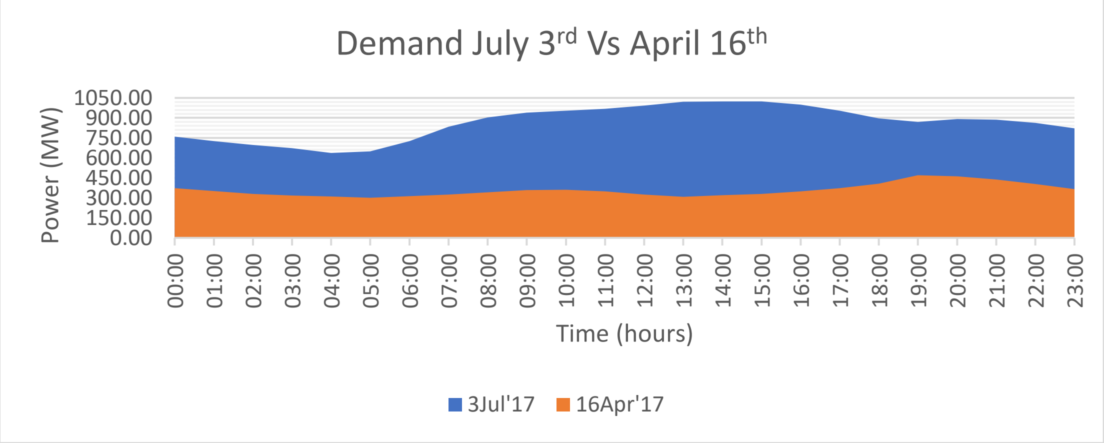


Figure 27 - Maximum Vs Minimum demand in 2017

Thermal Power Plants Generation

The three centralised, oil-fired thermal power stations that constitute 84.2% of installed capacity, also dominate the generation mix, having never fallen below 90% of the annual share. The running reserve is also forced to be sourced from one of the oil-fired turbines, and the inefficient and highly polluting stations depend solely on the volatile prices of oil.

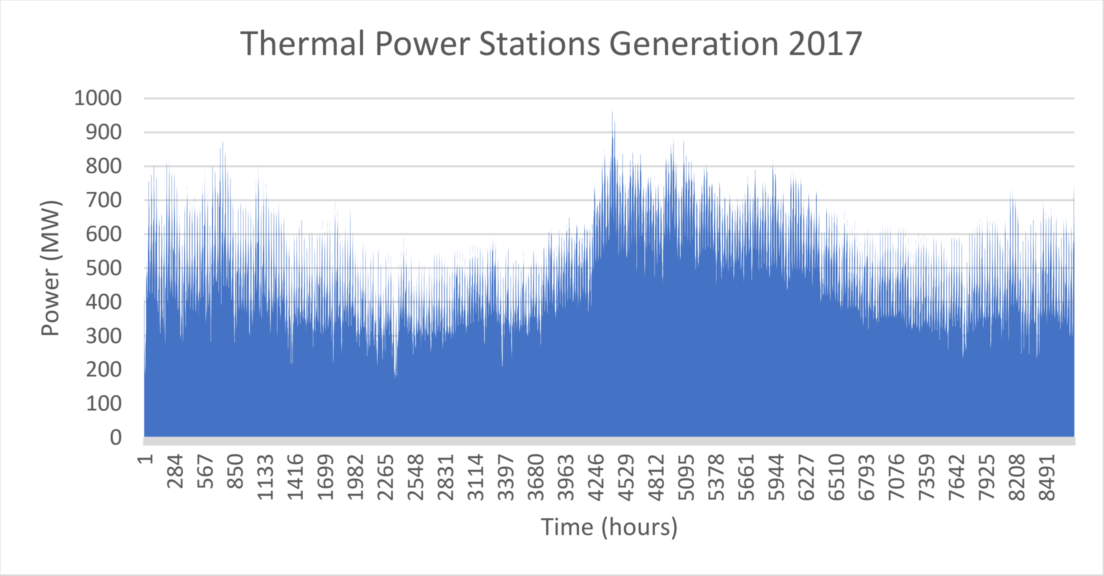


Figure 28 - Energy Analysis 2017 - Thermal stations' generation

All three stations combined, generated a total 4343.51GWh over the year in 2017, with a minimum generation of 171.11MW recorded in April, and a maximum of 965.8MW in July. The stations were thereby utilised at a capacity factor of 33.55%, with recorded greenhouse gas emissions of 6.48Mt of CO_2 equivalent (Eurostat, 2018), placing the RoC 2nd lowest in the EU-28 bloc, but one of the poorest in emission rates per capita, placing the RoC 6th at 4.074 million grams of CO_2 equivalent.

Thermal Power Plants Generation – Modelling

In order to model all thermal stations in HOMER, each technology was designed separately, to capture more accurately the fuel consumption, and most importantly to output a more holistic result of the financial aspects and thermal efficiencies of the overall energy system. With the three technologies of steam, gas and combined cycle gas turbines modelled, heavy fuel oil-fired steam turbines can be seen in Figure 29 to be dominating generation, with diesel-fired gas turbines operating as little as possible due to their inefficiencies and expense of fuel, whereas diesel-fired combined cycle turbines operate at a much higher thermal efficiency; hence prioritised over gas turbines.

Table 6 - Generation units, fuel and thermal efficiencies

Technology	Combined Cycle	Gas Turbines	Steam Turbines	ICEs
Capacity (MW)	440	187.5	750	100
Fuel Type	Diesel	Diesel	HFO	HFO
$\eta_{thermal}$ **(%)**	45.67	24.33	33.89	41.58

The three thermal power stations in the RoC, modelled separately here by the three different technologies, have an annual generation of 4,357,475.351MWh, generating thus 91.45% of annual consumption.

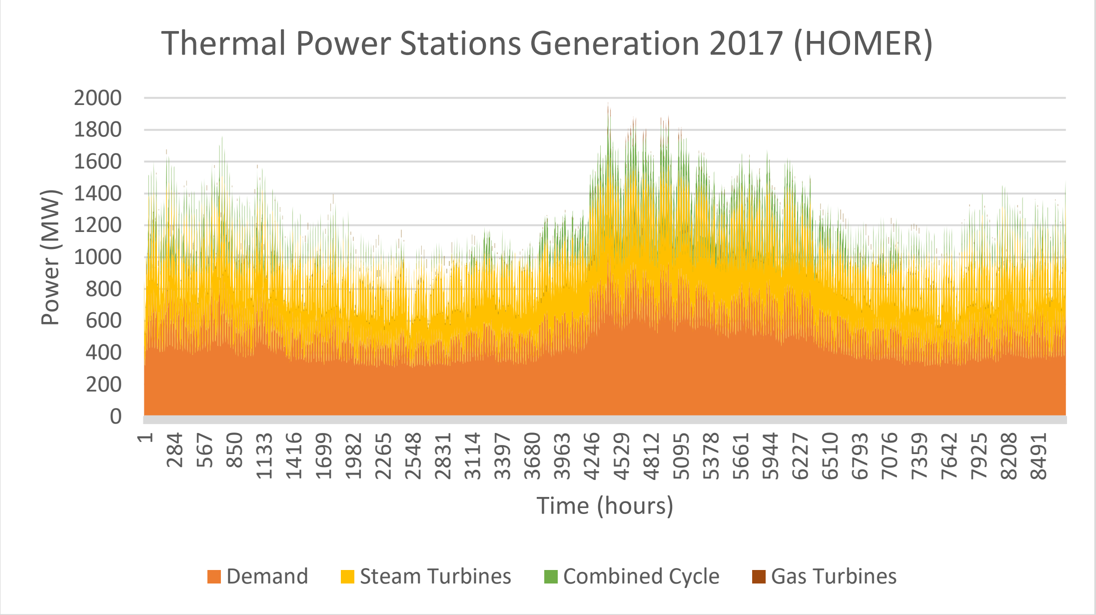


Figure 29 - Thermal power stations generation 2017 as modelled (HOMER)

Fuel Usage – Thermal Power Plants

This section is dedicated in determining the different fuels utilised, through understanding the generation dispatch techniques that the RoC follows. The body responsible for these operations, is namely ‘The National Energy Control Centre of Cyprus’. A continuously manned operation located in the capital, Nicosia, is responsible for monitoring and regulating all generation units in order to maintain the supply of uninterrupted electricity. A brief description of their tasks as outlined on the TSO’s website are (Transmission System Operator - Cyprus, 2018):

- Execute necessary operations to ensure safe, reliable and economic supply
- Ensure that frequency levels and voltages throughout the system are continuously kept within regulated limits
- Facilitate modifications and repairs to the transmission network safe and fast
- Co-ordinate required actions for immediate restoration of supply after unplanned system disturbances
- Generate a reliable forecast for demand, hourly and daily
- Take all necessary actions to achieve operation at minimum cost to consumers

It will also be assumed that, because of the financial dimensions of renewable energy sources, mainly the wind and photovoltaic assets, generation from the units will be taken almost always, avoiding curtailment as much as possible; even though as stipulated previously since the national energy system has no battery solutions nor an interconnector in place, curtailment must be unavoidable.

The annual report published by the DSO, the Electricity Authority of Cyprus, documents the volume of fuel used by all stations, together with heat losses and overall efficiencies of the thermal power plants.

Table 7 - Fuel consumption and efficiencies of the thermal power stations

Period	**2015**	**2016**	**Difference (%)**
Heavy fuel (t)	857,868	882,677	2.89
Diesel fuel (t)	89,358	149,967	67.83
Average calorific value (kJ/kg)	43,017	42,844	-0.4
Average generating efficiency (%)	36.47	36.25	-0.6
Average heat rate (kJ/kWh)	10,429	10,448	0.18

Fuel Usage – Thermal Power Plants – Modelling

Apprehending the fuel distribution in HOMER entails numerous steps, so that overall annual fuel consumption matches similar results to the ones published by the RoC. The import prices, as published by the EAC in their annual report, gave an average price for diesel oil at 384.17 €/t, and heavy fuel oil 224.58 €/t. This was a great decrease from the year before, where in 2015 diesel oil was 22% and heavy fuel oil was 16% more expensive. With a combination of heating values, price of fuel per litre and the thermal efficiency of generation plants, the step of designing the fuel distribution was complete.

Table 8 - Heavy fuel and diesel specifications

	Heavy Fuel Oil	**Diesel Oil**
Density (t/L)	980	846
Lower Heating Value (MJ/kg)	39	45.6
Higher Heating Value (MJ/kg)	41.8	42.6
Consumption 2016 (t)	882,677	149,96
Price 2016 (€/t)	224.58	384.17
Consumption 2016 (L)	865,023,460	126,866,160
Price 2016 (€/L)	0.22	0.32

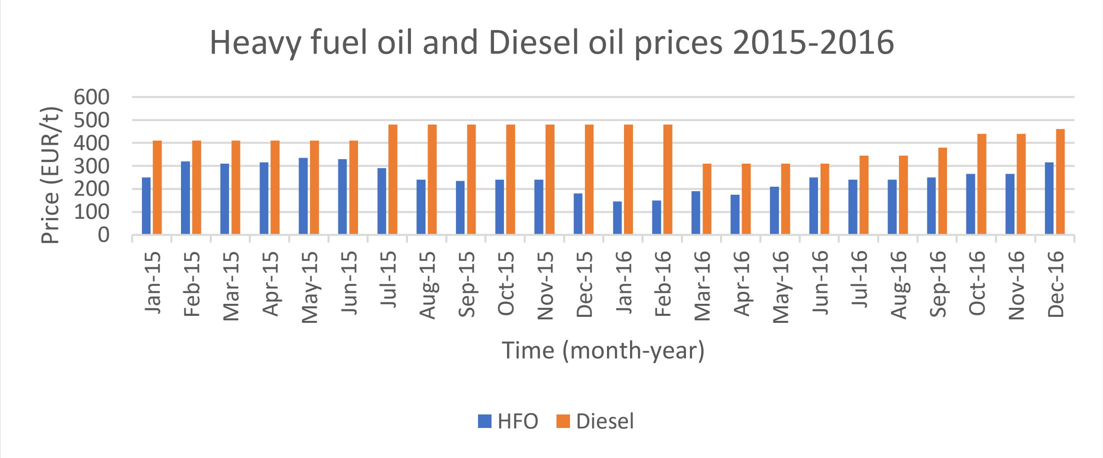


Figure 30 - Heavy fuel and diesel oil prices in 2015-2016 (Electricity Authority of Cyprus, 2017)

The steam turbines were the most utilised, generating a staggering 79.51% of annual demand. This is due to their large installed capacity and cost-effectiveness of fuel, with heavy fuel oil as their primary fuel being considerably cheaper than diesel oil. It was modelled with a mean electrical efficiency of 31.9%, having consumed in total 1.12 million metric tonnes of heavy fuel oil. In practice, steam turbines would operate at a lower rate, but since maintenance schedules are unavailable, the HOMER model can assume a 100% availability, and thus optimise sources based on cost-effectiveness. Furthermore, the RoC in 2016 published a consumption of approximately 1 million litres of oil, 87.21% being heavy fuel oil and 12.79% diesel oil.

In an attempt to assimilate the published ratio in the HOMER model, the combined cycle generators were modelled with a minimum load ratio of 30%. In extent, the fuel ratio as modelled was 88.65% heavy fuel oil and 11.18% diesel oil, bringing the total oil consumed to 1.26 million metric tonnes.

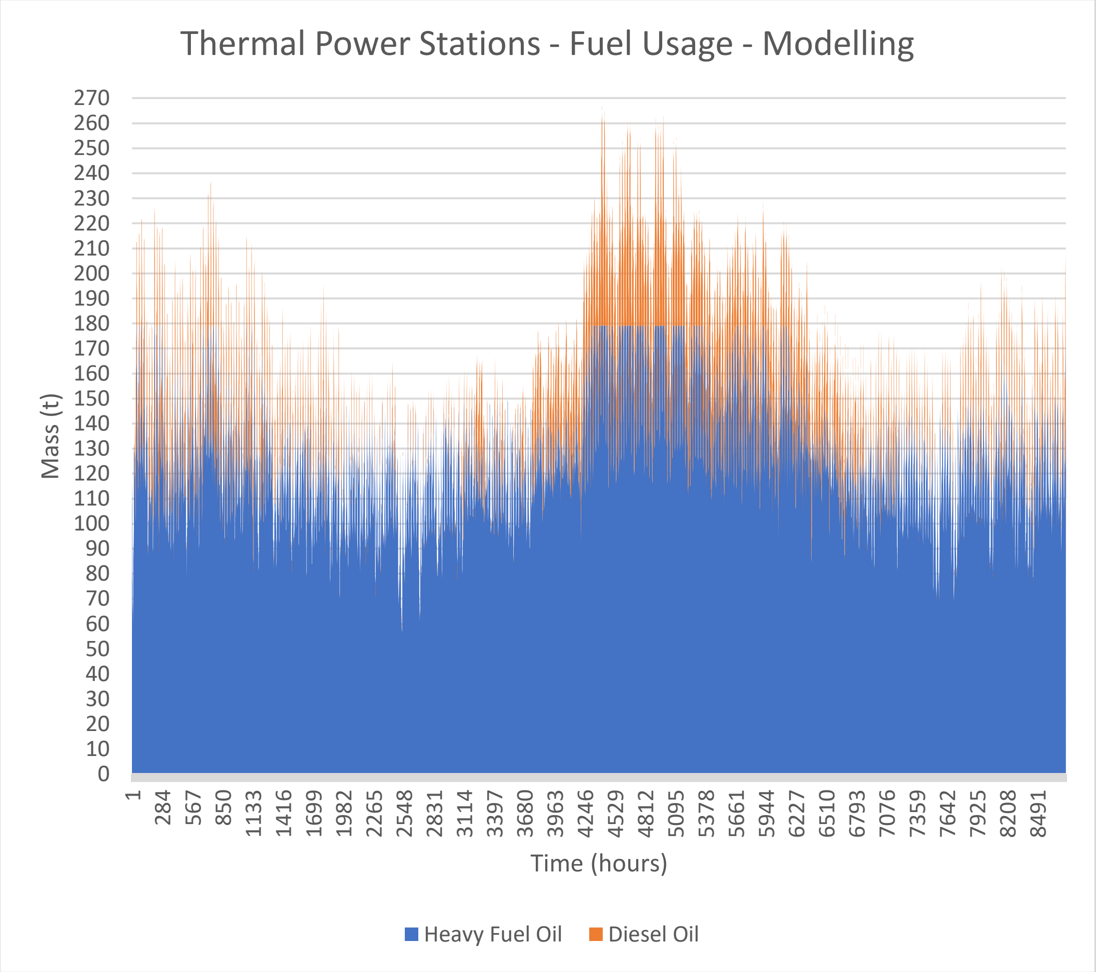


Figure 31 - Thermal power stations fuel usage - modelling

Wind Turbines Generation – Modelling

To capture a more realistic image of how wind turbines are operating, within the limitations of HOMER Energy of not allowing you to simulate more than two components of wind turbines, the location chosen will be the one later analysed for the case-study of ‘Orites’ 82MW wind farm, since they account for more than half of installed capacity by 2017 (52%). Furthermore, a general value for the turbines’ efficiency must be integrated, averaging efficiencies of the actual turbine performance, the electrical transmission efficiency, various environmental factors that affect the units, etc. In addition to that, a fixed scheduled maintenance will be incorporated to account for non-scheduled downtime due to mechanical failures. According to a study on wind turbine failures, geared wind turbines larger than 1MW, have a typical failure rate of 0.52 turbines/year, with 112.67 hours of downtime/failure, whereas direct-drive wind turbines have a failure rate of 0.19 turbines/year, with 34.98 hours of downtime/failure. To avoid modelling all wind turbines experiencing a downtime all at once, a second component of wind turbines will be added to carry out the overall downtime.

Table 9 - Failure rate per wind turbine technology, downtime per failure, and capacity installed per technology (Reder, et al., 2016)

Wind Turbine	Capacity	Failures/Turbine/Year	Downtime/Failure
Direct Drive	82MW	0.52	112.67 hours
Gearbox < 1MW	0	0.46	151.46 hours
Gearbox ≥ 1MW	76MW	0.52	112.67 hours

The ‘Orites’ wind farm, as is later analysed as a case-study, consists of 41 Vestas V90-2.0MW, which are direct-drive wind turbines. That will output an estimated failure rate of 0.19 failure/turbine/year, a total 272.49 hours of downtime per year for the entire 82MW wind farm, translating to just 3.11% of the year as downtime.

Equation 2 - Failure rate of 41 direct drive wind turbines

$$V90_{DD}\ (failure\ rate\ of\ 41\ turbines) = 7.79\,\frac{failures}{year}$$

Equation 3 - Downtime of 41 direct drive wind turbines

$$V90_{DD}(downtime\ of\ 41\ turbines) = 272.49\,\frac{hours}{year}$$

The remaining wind turbines will be assumed as geared wind turbines of rated power 2MW, thus 38 geared turbines of capacity 76MW. For the geared turbines, the estimated failure rate is 0.52 failures/turbine/year, bringing the total to 2,226.36 hours of downtime per year, translating to a significant 25.41% of the year as downtime.

Equation 4 - Failure rate of 38 geared wind turbines

$$WTG_{gearbox} = (failure\ rate\ of\ 38\ turbines) =\ 19.76\,\frac{failures}{year}$$

Equation 5 - Downtime of 38 geared wind turbines

$$WTG_{gearbox} = (downtime\ of\ 38\ turbines) = 2{,}226.36\,\frac{hours}{year}$$

In conclusion, a total of 79 wind turbines with an installed capacity of 158MW will be modelled as the wind capacity installed in the RoC, with an estimated downtime altogether at 2,498.85 hours of downtime per annum, or 28.52% of the annual availability. In order to distribute the downtime, one component will consist of one 2MW wind turbine, that will enter downtime of 48 hours at an interval of approximately 52 hours, summing therefore a total annual downtime of 2498.85 hours. The other component will consist of 78 wind turbines of 2MW, with a continuous operation throughout the year.

Renewable Generation – Modelling

As already documented in section 'Renewable Energy Sources (RES)', renewable sources in 2017 are led by wind turbines' production, with biomass having faded in small numbers since the rapid uptake of wind and solar farms. Simulating a known year has successfully validated the HOMER Energy software, with the total renewable generation in 2017 modelled to be 414.96GWh. The overall capacity factor of renewables was found to be 16.93%, with wind turbines at 15.99%, photovoltaics at 16.02%, and biomass at 42.72% - numbers very similar to the ones published.

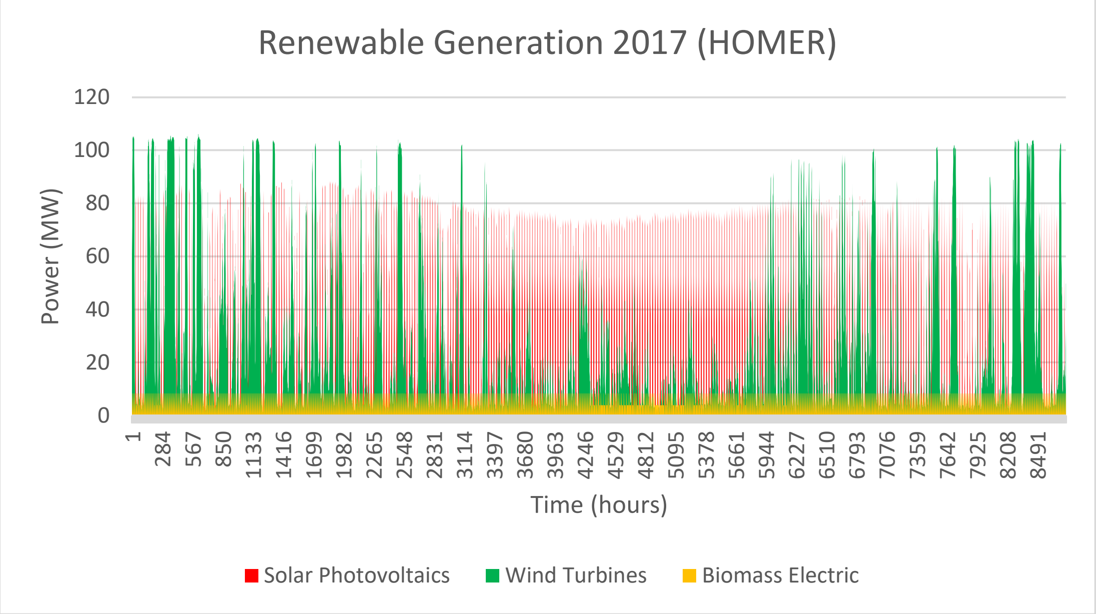


Figure 32 - Energy Analysis 2017 - Renewables generation (HOMER)

To investigate the sustainability of current renewables generation in the energy system, an analysis will be done for the days of maximum demand and maximum renewables penetration, to demonstrate the feasibility of additional renewable capacity. This is fundamental to ensuring the security of supply, as high and rapid increases in generation and/or demand can cause great instabilities to a grid lacking battery solutions and an interconnector; a grid that could be characterised as brittle, once the high running reserve of oil-fired turbines is withdrawn.

Maximum Demand 2017 – July 3rd

Renewable generation pales away during a high-demand day in July, contributing to a maximum of 12.12% at 10:00, which is lower than the annual share the RoC will be required to demonstrate by 2020. The average renewable penetration of that day was modelled to be 5.51%, with photovoltaics having generated 2.49% and wind turbines 3.26%, leaving thermal stations generating 94% (excluding running reserves).

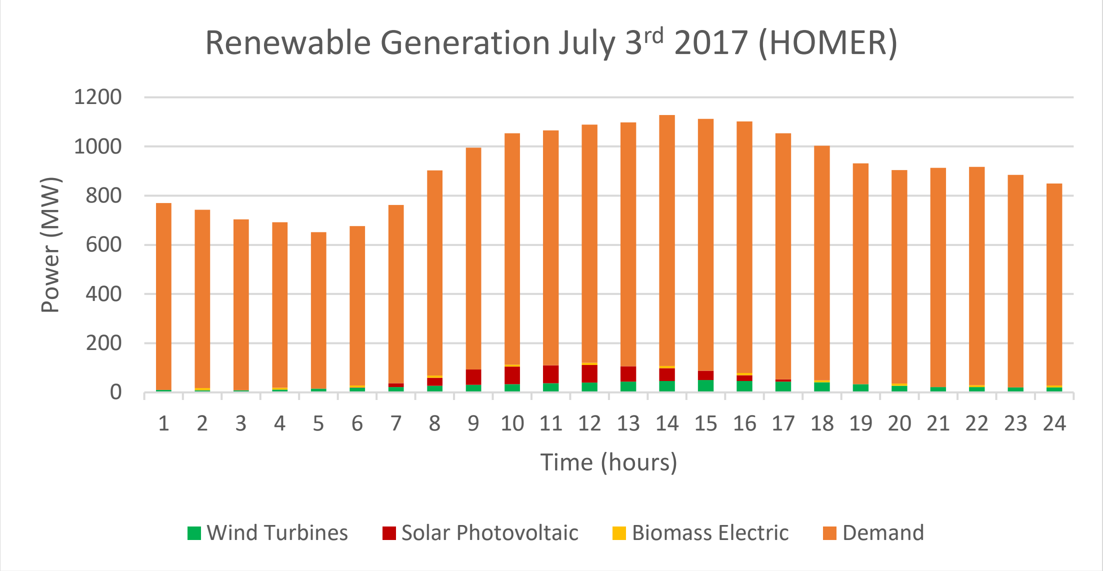


Figure 33 - Energy Analysis 2017 - Renewable generation on July 3rd

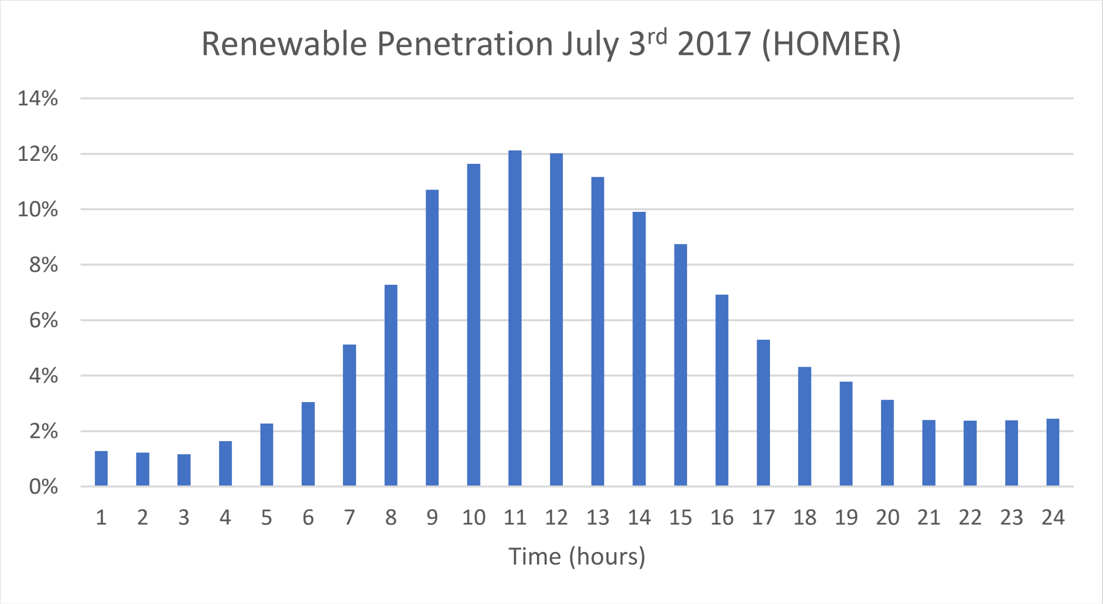


Figure 34 – Energy Analysis 2017 - Renewable penetration levels on July 3rd

Maximum RES Penetration 2017 – April 16th

On April 16th, one of the lowest days in demand but highest in weather resources, found renewables generating as much as 51.35% at 09:00. The overall renewable share of the day was modelled to be 26.62%, reducing oil-fired generation units to 74%. Solar photovoltaics recorded a share of 5.34% and wind turbines 19.75%.

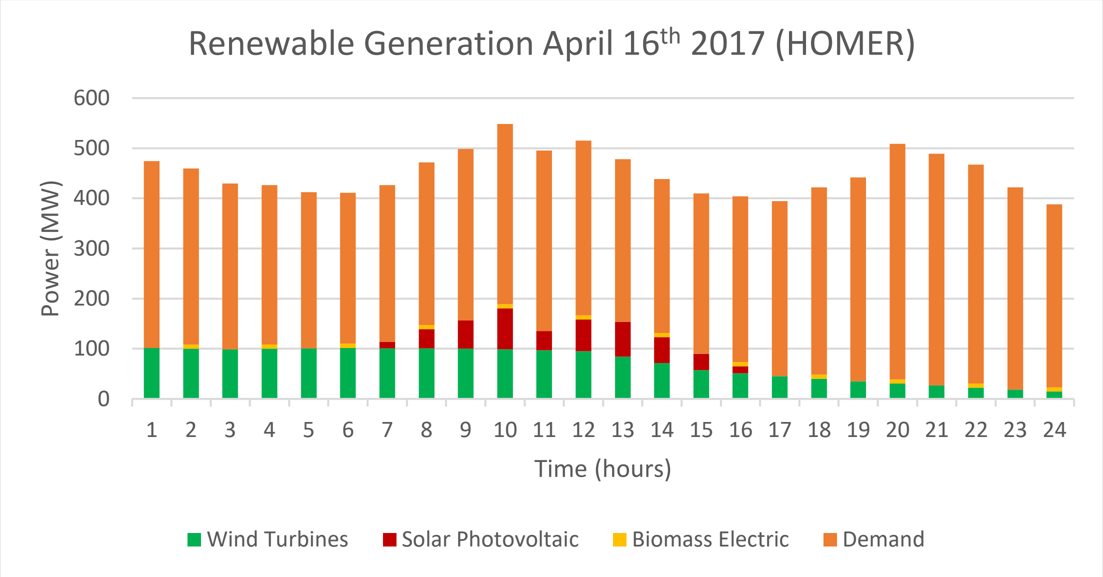


Figure 35 - Energy Analysis 2017 - Renewable generation on April 16th (HOMER)

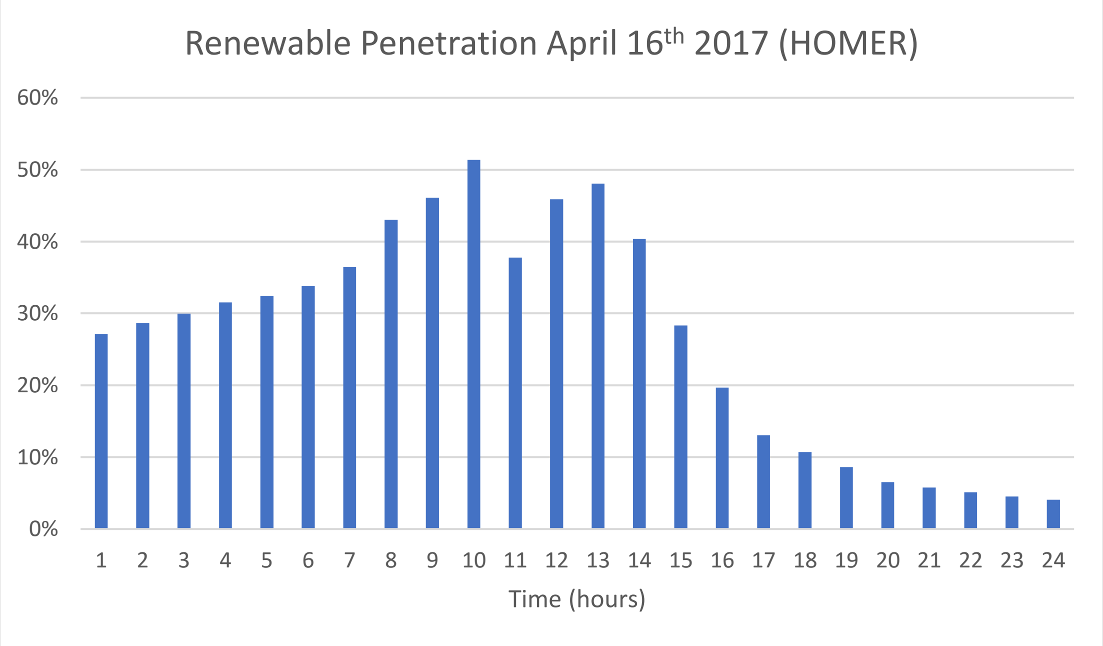


Figure 36 - Energy Analysis 2017 - Renewable penetration on April 16th (HOMER)

Biomass Generation – Modelling

As of the end of 2017, the RoC recorded 14 biomass units at a total electrical capacity of 9.7MWe. The annual report from the TSO, published the summed generation from all 14 units on a monthly basis, giving an annual capacity factor of 42.95% in 2017 (Transmission System Operator - Cyprus, 2018). However, with no transparency on each unit, and no low-level details on biomass resources and fuel distributions, this forces the simulation to a rather high-level analysis. Since the capacity is not large enough to interfere at any point in the security of supply throughout the year, the simulation will assume a similar capacity factor of 42.95% and thereby a constant generation at 4.17MWe. Calculating the lowest value in demand recorded in 2017 to be around 300MW, as well as that each biomass unit will be less than 1MWe in capacity, it is very unlikely that a constant generation would cause issues to the energy system of a real-life scenario.

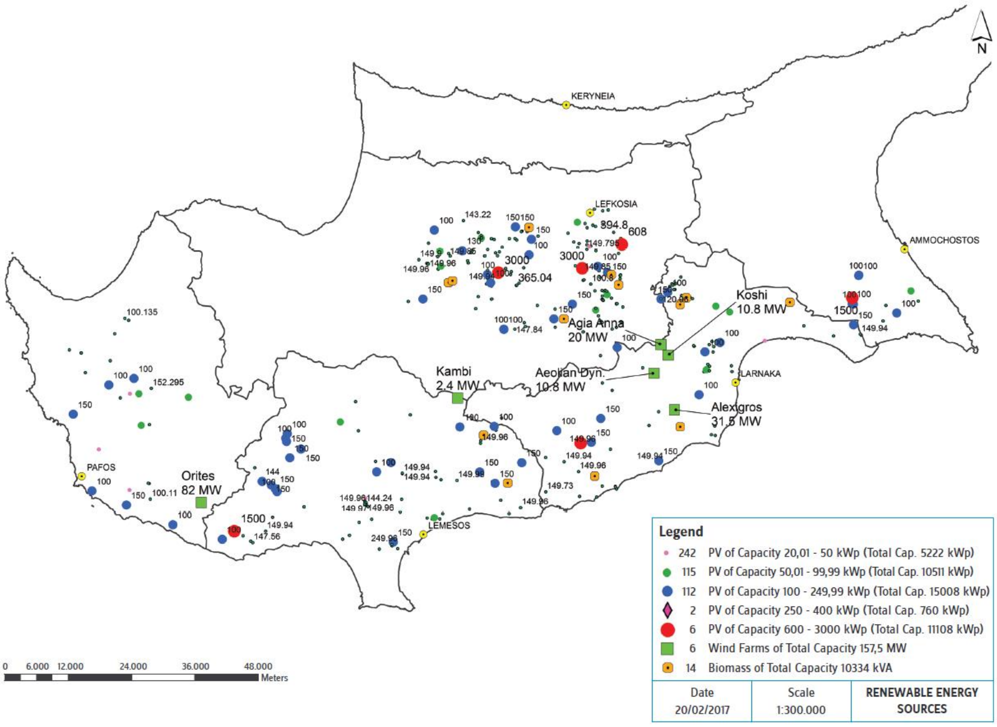


Figure 37 - Cyprus renewable generation units map (Cyprus Energy Regulatory Authority, 2017)

4.1. Case-Study: ‘Orites’ Wind Farm

The first wind farm in the RoC, namely ‘Orites’ from the region’s name, was installed in 2010 by local-based company DK Wind Supply, reaching an installed capacity of 82MW. It is comprised of 41 Vestas V90-2.0MW, with the wind farm directly installed in the transmission network.

With a capacity of 82MW, the group estimated an annual production of 128GWh, approximating that to an annual usage of 25,000 households. As analysis has shown from published generation records, the total installed capacity of wind farms on the transmission network, 155.1MW, generated 208.6GWh in 2017.

Located in the south-west of the island, the area’s coordinates are: latitude 34.73700, longitude 32.657001 and the elevation is 447m. Utilising the European-funded and hosted PVGIS system, 10-year meteorological hourly data were downloaded for that area.

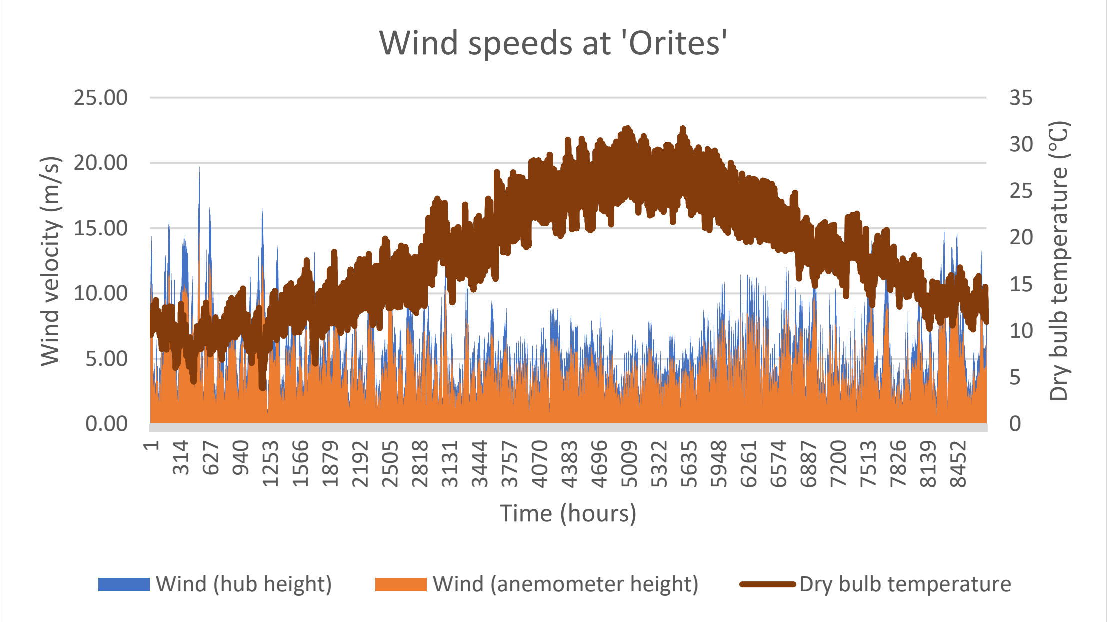


Figure 38 - Wind resources and temperature at 'Orites' wind farm

From a brief analysis of the data, the wind velocities have an average of 5.77m/s, with as high as 19.71m/s and temperatures varying from a maximum of 31.72 and a minimum of 3.83 °C.

The wind turbines installed, namely the V90-2.0MW, have a rated power of 2MW at rated wind velocity 13.5m/s, a cut-in speed of 4m/s, cut-out speed of 25m/s and a re-cut-in speed of 23m/s. Their standard operating temperatures are from -20 to 40 °C, with a hub height of 80m, and blades 44m long. The wind rose generated through MATLAB, shows the direction to be mainly directed East as expected, with a great frequency of wind speeds above 8m/s.

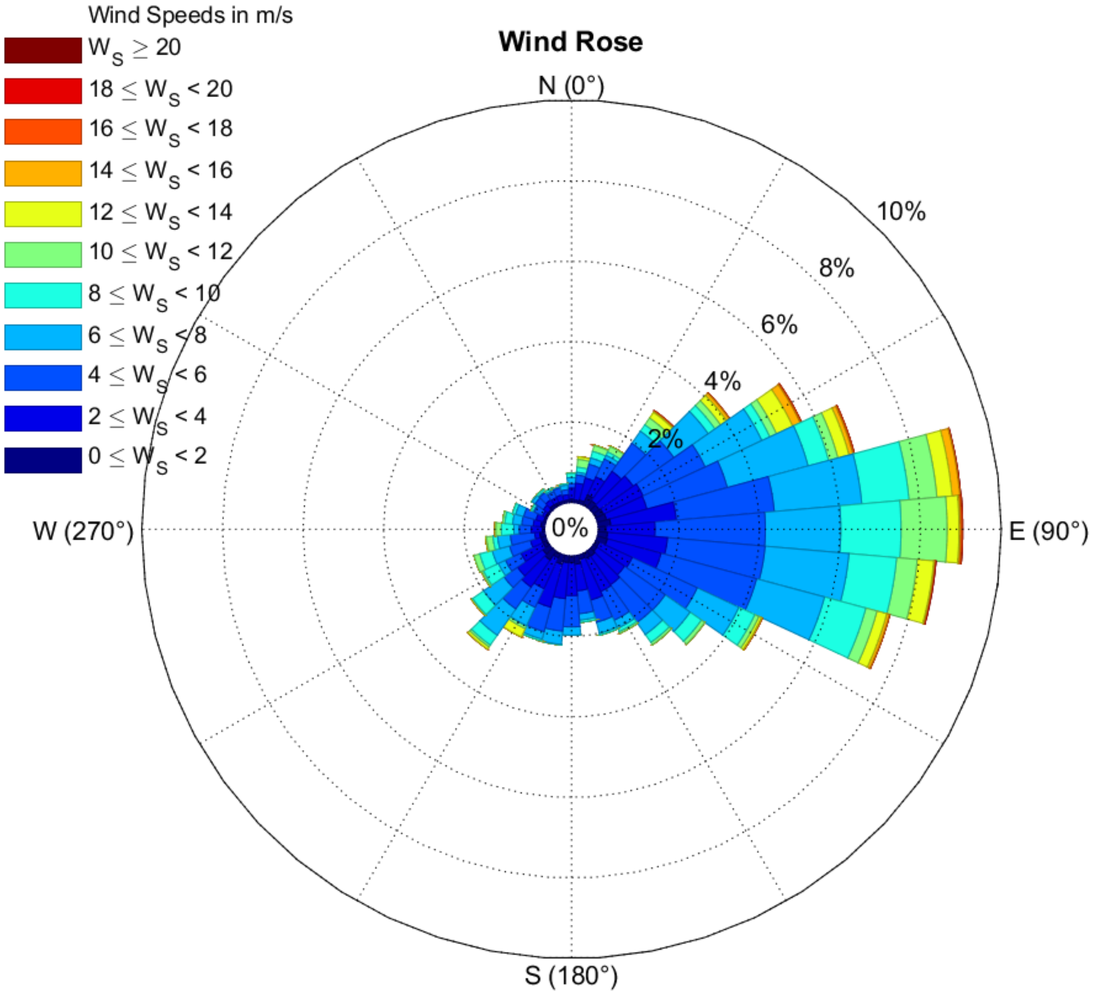


Figure 39 - Wind rose for 'Orites' wind farm (using MATLAB)

The power curve of the turbine, as extracted from the company's technical datasheet, is as shown in Figure 36, with the wind velocity exceedance curve shown in Figure 37.

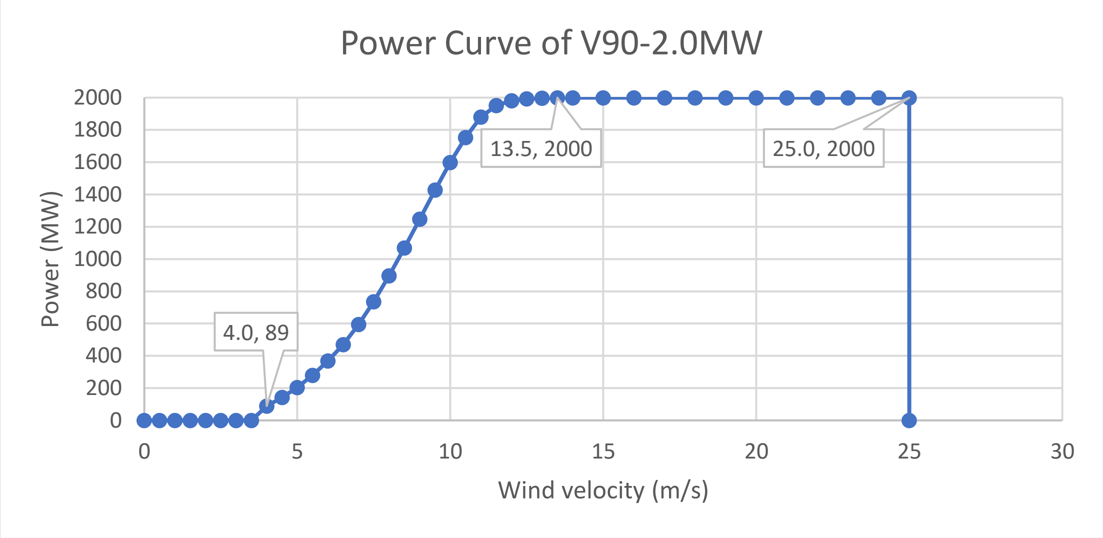


Figure 40 - Power curve of V90-2.0MW (Vestas, 2010)

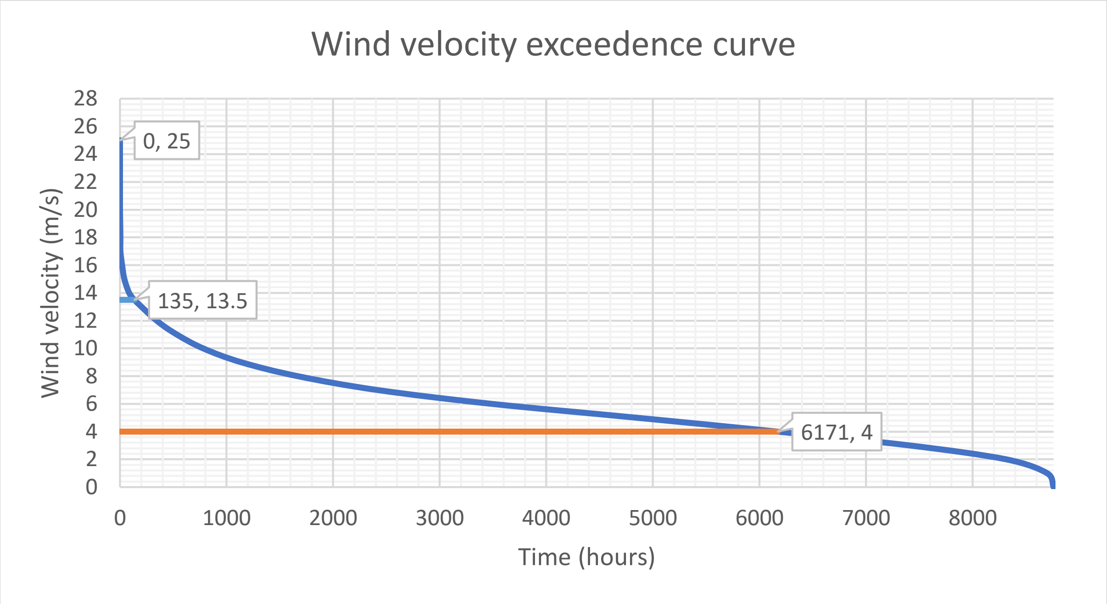


Figure 41 - Wind velocity exceedance curve at 'Orites'

By fusing the analysis of the wind velocity exceedance curve and the turbine's power curve, a reliable modelling can take place in HOMER Energy, assuming 100% availability of the units in terms of maintenance and curtailment.

The 41 turbines were modelled in HOMER, after interpolating the wind velocities for the hub's height correction and inputting the power curve of the selected turbine.

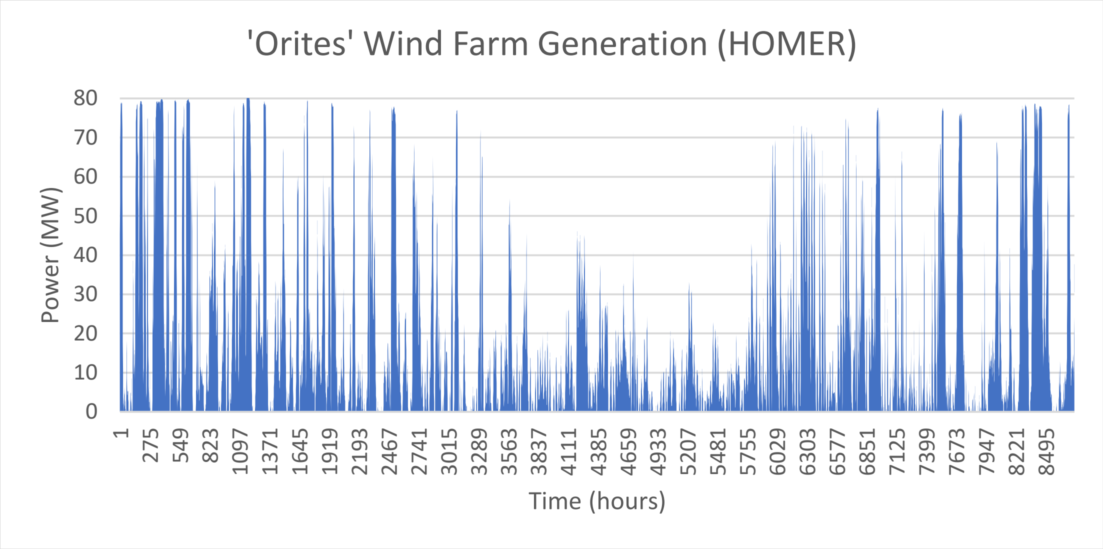


Figure 42 - 'Orites' wind farm generation (HOMER)

The total production of the wind farm was modelled at 163.86GWh, reaching a capacity factor of 22.8% - a 28% increase from the group's estimated generation, assuming that the units have 100% availability and that no curtailment takes place. Furthermore, analysis has shown that the units selected were not appropriate for the area, with a mere 2% of wind velocities existing above the rated 13.5m/s.

The turbine selected is a wind class IEC IIIA, meaning that it is a wind turbine appropriate for low wind, defined to have an average wind velocity of 7.5m/s, and an area of high turbulence intensity (International Electrotechnical Commission, 2005).

To further demonstrate that the selected turbines are inappropriate for the area, a HOMER model was built on top of the first one to compare how different models would operate, at a replicated environment. To maintain the exact environment previously used, the selected wind turbine must be again at a hub height of 80m but in order to maximise power extraction at lower wind velocities, the turbine needs to be of a lower rated power, with a power curve optimised at lower velocities.

The chosen wind turbine, Leitwind LTW80-1.0MW, has a rated power of 1MW at rated wind velocity 11m/s, a cut-in speed of 3m/s and a cut-out speed of 25m/s. The hub height is 80m, with a rotor diameter of 80.3m.

The power curve of the LTW80-1.0MW, as extracted from the company's technical datasheet, is shown in Figure 39.

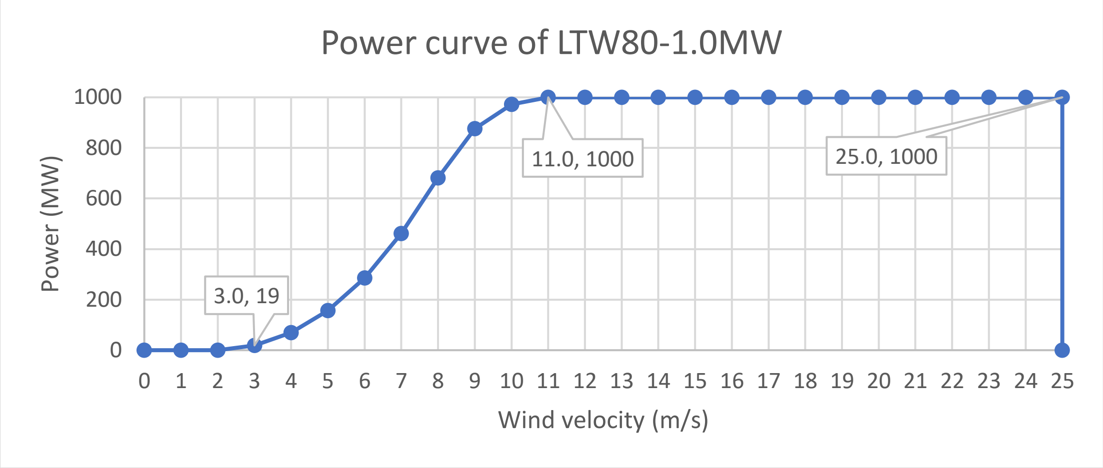


Figure 43 - Power curve of LTW80-1.0MW (Leitwind, 2014)

It can be observed directly from comparing generation graphs shown in Figure 40 and Figure 44, how the LTW80-1.0MW function adequately better during the warmer months, generating annually 219.81GWh and delivering a capacity factor of 30.6% - thus generating 34.2% more energy. The additional effective area utilised by 82 turbines instead of 41 is absent from this comparison, even though wind-rich environments are not common in the RoC, with the argument extending only for the engineering design of the wind farm.

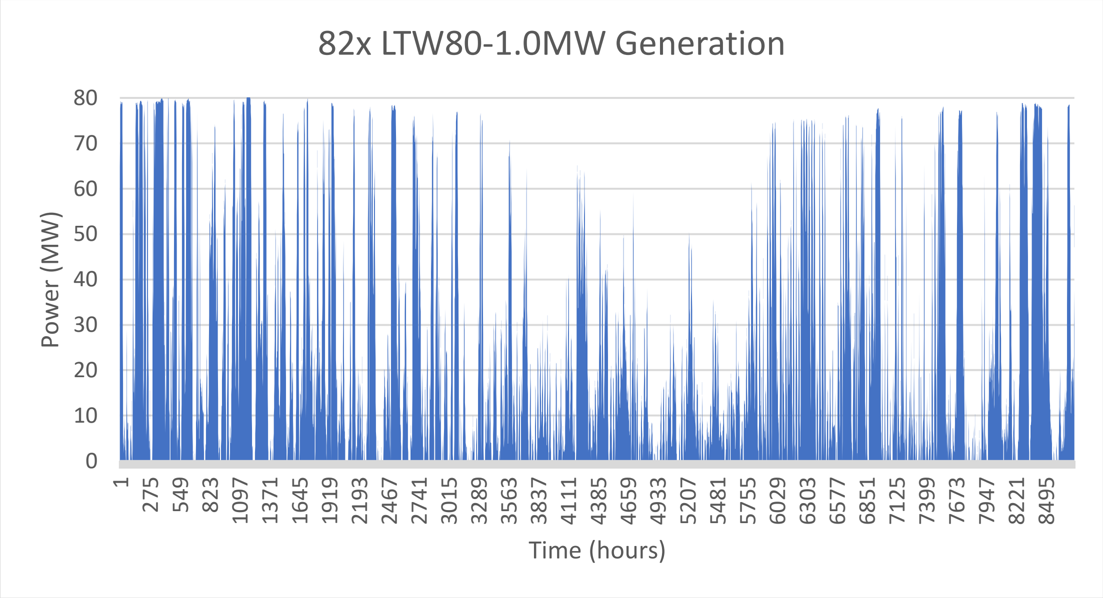


Figure 44 – LTW80-1.0MW x81 wind farm generation (HOMER)

4.2. Case-Study: 'Frenaros' Solar Photovoltaic Farm

The largest solar photovoltaic farm in Cyprus, namely 'Frenaros' from the region's name, is a 4.4MW photovoltaic farm installed in 2017. It is located south-east of the island, and the area's coordinates are: latitude 35.053001, longitude 33.877998 and the elevation is 38m. After utilising the PVGIS database, data for the location were extracted and analysed, as shown in Figure 45 and Figure 46.

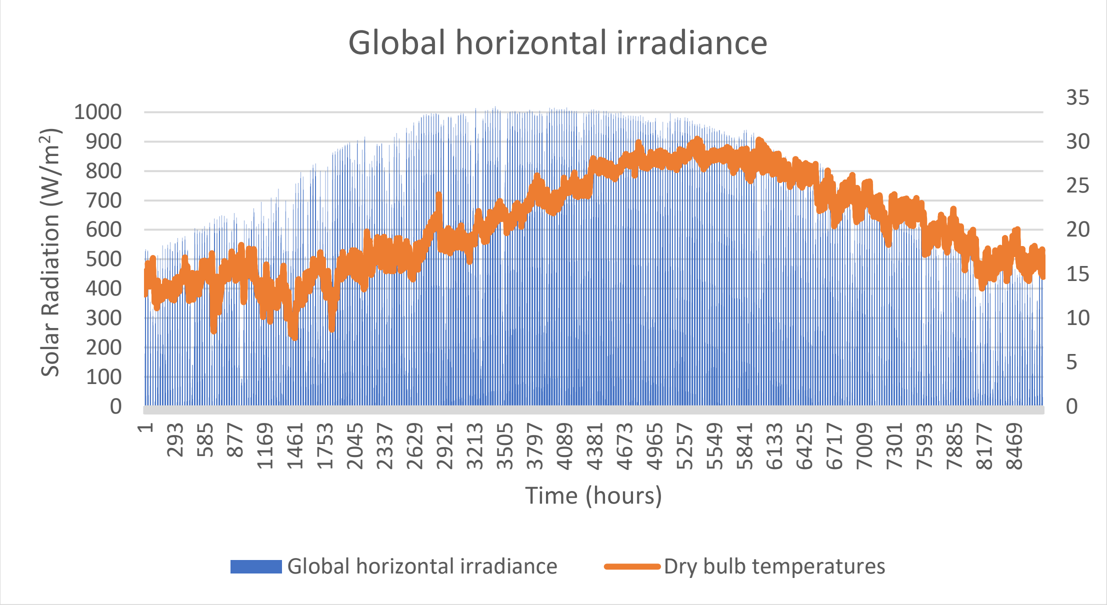


Figure 45 - Solar radiation at 'Frenaros' photovoltaic farm

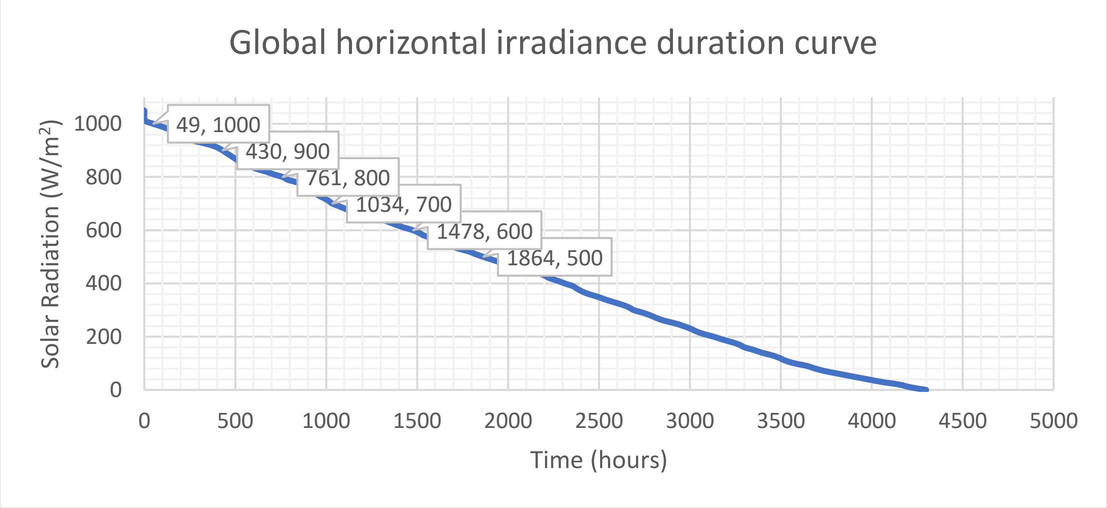


Figure 46 - Global horizontal irradiance duration curve at 'Frenaros' photovoltaic farm

The modules installed at ‘Frenaros’, fabricated by company RECOM, are mono crystalline modules with a rated power 345W at standard test conditions. The module’s characteristics, as taken from the company’s datasheet are as follows (RECOM, 2018):

Table 10 – Electrical characteristics of photovoltaic module RCM-345-6MA

Electrical Characteristics – RECOM – RCM-345-6MA	
Rated Power	345W
Power Tolerance	0 ~ +5W
Maximum Power Voltage (V_{mp})	38.41V
Maximum Power Current (I_{mp})	8.91A
Open Circuit Voltage (V_{oc})	46.88V
Short Circuit Current (I_{sc})	9.42A
Module Efficiency	17.76%
Maximum Series Fuse	15A

Table 11 - Temperature characteristics of photovoltaic module RCM-345-6MA

Temperature Characteristics – RECOM – RCM-345-6MA	
Pmax Temperature Coefficient	-0.40%/°C
V_{oc} Temperature Coefficient	-0.32%/°C
I_{sc} Temperature Coefficient	+0.048%/°C
Operating Temperatures	-40 ~ +85 °C
Nominal Operating Cell Temperature (NOCT)	45 ± 2°C

Table 12 - Mechanical characteristics of photovoltaic module RCM-345-6MA

Mechanical Data – RECOM – RCM-345-6MA	
Dimensions	1956mm x 992mm x 40mm
Weight	24.0kg

A HOMER model of the photovoltaic farm ‘Frenaros’, sheds light to an in-depth understanding of the hourly operation and performance of photovoltaic panels on the island. Using reliable meteorological data from PVGIS, a model was created incorporating the local dry bulb temperatures and global horizontal irradiance. After introducing the photovoltaic module to HOMER and integrating local parameters, the annual production of the 4.4MW farm was modelled at 6,455.849MWh, standing at 0.135% of the demand in 2017. The capacity factor was relatively low however, modelled at 16.7%.

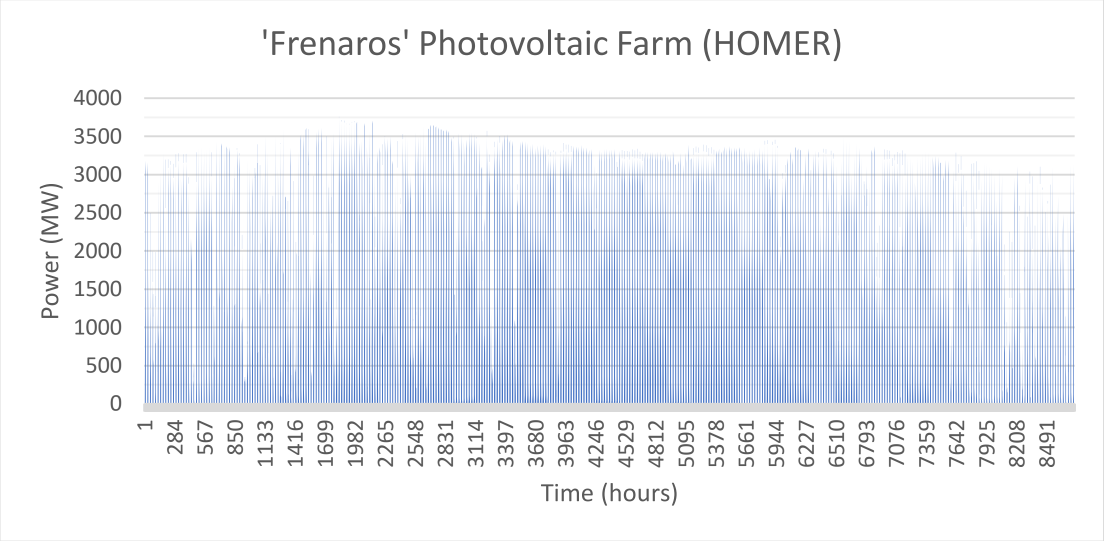


Figure 47 - 'Frenaros' photovoltaic farm generation (HOMER)

One of the reasons for the low performance, could be the high temperature coefficient of maximum power output, currently at -0.4%/°C. It could also be the uncertainty of the site’s solar radiation data, even though the dataset point to a high degree of radiation, as well as 430 recorded hours with radiation exceeding 900W/m^2, 49 of which are higher than 1000W/m^2, as also observed in Figure 46.

The clearness index, the dimensionless unit that indicates the ratio of solar radiation that penetrates through the atmosphere to the surface, is calculated within HOMER based on monthly averages of global horizontal irradiance, latitude and time of the year. At the selected area, the clearness index had an annual average of 62.3%, a maximum value of 72% and as low as 46.4%.

4.3. Case-Study: ‘Alassa’ Concentrated Solar Power Plant

A 50MWe concentrated solar power (CSP) plant, proposed initially in 2013, is due to enter the electricity network on June 30th 2020 and operate thus for half of 2020 (assuming no delays).

It consists of 300 low-height solar thermal receivers (STRs), with integrated graphite-based thermal storage. The 2x 25MWe steam turbines are said to operate at an efficiency of approximately 38% (Department of Environment, 2015). The continuous operation promised by the CSP plant, assuming a daily average 6.12kWh/m^2 of direct normal irradiance, has an estimated 171.4GWh of annual generation – a capacity factor of 39.13% (Solastor, 2017).

The software used for energy analysis, HOMER, has restrictions on modelling CSP plants. Specifically, the model cannot simulate thermal storage and generation after sunset, rendering the case study incomplete. However, as it is a substantial renewable energy source entering the market in 2020, the CSP plant could be a catalyst in meeting the 2020 targets of 13% renewable generation.

To integrate the CSP plant in the energy systems analysis, this study accepts the estimates at 171.4GWh per annum, and assumes a stable, continuous operation all year round. The disadvantages of doing this are clear when analysing hourly time-steps of the power flow, but such operation is not impossible by a CSP plant with thermal storage and 24/7 operation capabilities; it is however unlikely.

In conclusion, this generation unit will enter all future energy scenarios starting July 1st 2020, at a continuous generation level of approximately 19.5MW. The economics of the technology, along with forecasted investment costs up to 2025 are discussed in the next section.

4.4. Generation Economics

This section investigates one of the three elements of the energy trilemma, to determine that cost-effectiveness of different generation technologies, and in extend the build the foundation to the pathways of different future energy scenarios.

The existing energy systems in the RoC, mainly of the three centralised oil-fired power stations, are difficult to calculate due to the lack of transparency of the capital repayment status. Therefore, the analysis will assume that all stations start from day 0, with no capital having been paid off. Numerous studies were taken into account for this section, but the primary ones are the ‘EIA – Capital Cost Estimates for Utility Scale Electricity Generating Plants’ (EIA, 2016) for thermal power stations and biomass, and the ‘IRENA - The Power To Change: Solar and Wind Cost Reduction Potential to 2025’ (IRENA, 2016) for wind turbines and solar energy (CSP and PV).

The values in interest are the overnight capital cost and the annual operation and maintenance (O&M) for each technology. Each one derives from the global weighted average of projects around the world.

The concentrated solar power plant ‘Alassa’, is said to cost €175 million, with operation and maintenance not yet fully defined. The price documented in IRENA’s global weighted average costs places CSP plants much higher, at 5700 \$/MW, whilst the confirmed project results to a lower rate of 3500 €/MW, or approximately 4000 \$/MW. Both are correct, as per their definition, and IRENA’s operation and maintenance costs will be taken as is, published at 0.03 – 0.04 \$/kWh. Adjusting a linear calculation to modelling the CSP plant in ‘Alassa’, O&M have a predicted range of 5,142,000 to 6,856,000 \$/year, assuming a 171.4GWh annual generation. This study will assume the mid-value for O&M, placing it at around \$6 million per annum.

Due to lack of data, the operation and maintenance cost of biomass power units have integrated associated costs of fuel, being modelled in HOMER as a fixed \$12.56 per operation hour. Since generation is also fixed to output the desired capacity factor, O&M costs are calculated at 110\$/kW including biomass fuel.

The results extracted from the studies, are outlined in Table 13 and Table 14.

Table 13 - Generation economics of different technologies in 2015

Unit Technology	**2015**	
	Capital ($/MW)	**O&M ($/kW)**
Wind Turbine (onshore)	1,560,000	60
Solar Photovoltaic	1,810,000	18
Combined Cycle Gas Turbine	978,000	11
Combustion Turbine	1,101,000	17.5
Biomass	4,985,000	110
Concentrated Solar Power (ST)	3,500,000	102.84

Table 14 - Generation economics of wind and solar PV in 2025

Unit Technology	**2025**	
	Capital ($/MW)	**O&M ($/kW)**
Wind Turbine (onshore)	1,370,000	*60*
Solar Photovoltaic	790,000	*18*
Concentrated Solar Power (ST)	3,325,000	*102.84*

The report by IRENA, included an analytical forecast of how the prices for wind and solar photovoltaic will progress to 2025, showing a sharp decrease of the global weighted average for solar photovoltaic, specifically a 56.35% reduction in the overnight capital cost in just 10 years. The operation and maintenance, even though it is expected to drop, has no specified values within the report due to the underlying complexities and are therefore kept in this analysis as they were reported in 2015. According to the study from IRENA, CSP plants' investment costs will reduce by -37% from 2015 to 2025. This ratio applied to the cost of the CSP plant in 'Alassa' will mean CSP plants could be as low as 2,205,000 $/MW by 2025. However, this 37% is more likely to reflect on less expensive projects, thus bringing down the global weighted average. Therefore, the 2025 investment costs for a CSP plant will be reduced by 5% of the reported project in 'Alassa', bringing the rate down to 3,325,000 $/MW. The operation and maintenance costs, as well as the ones for wind and solar photovoltaic, remain unchanged to 2025.

The figures taken from IRENA and EIA, were used directly to develop the economic model for the Cyprus' energy systems. With the installed capacities of each technology defined, together with rates per unit of power and operation and maintenance, a linear calculation is performed that shows an economic analysis of the energy system, as shown in Figure 48.

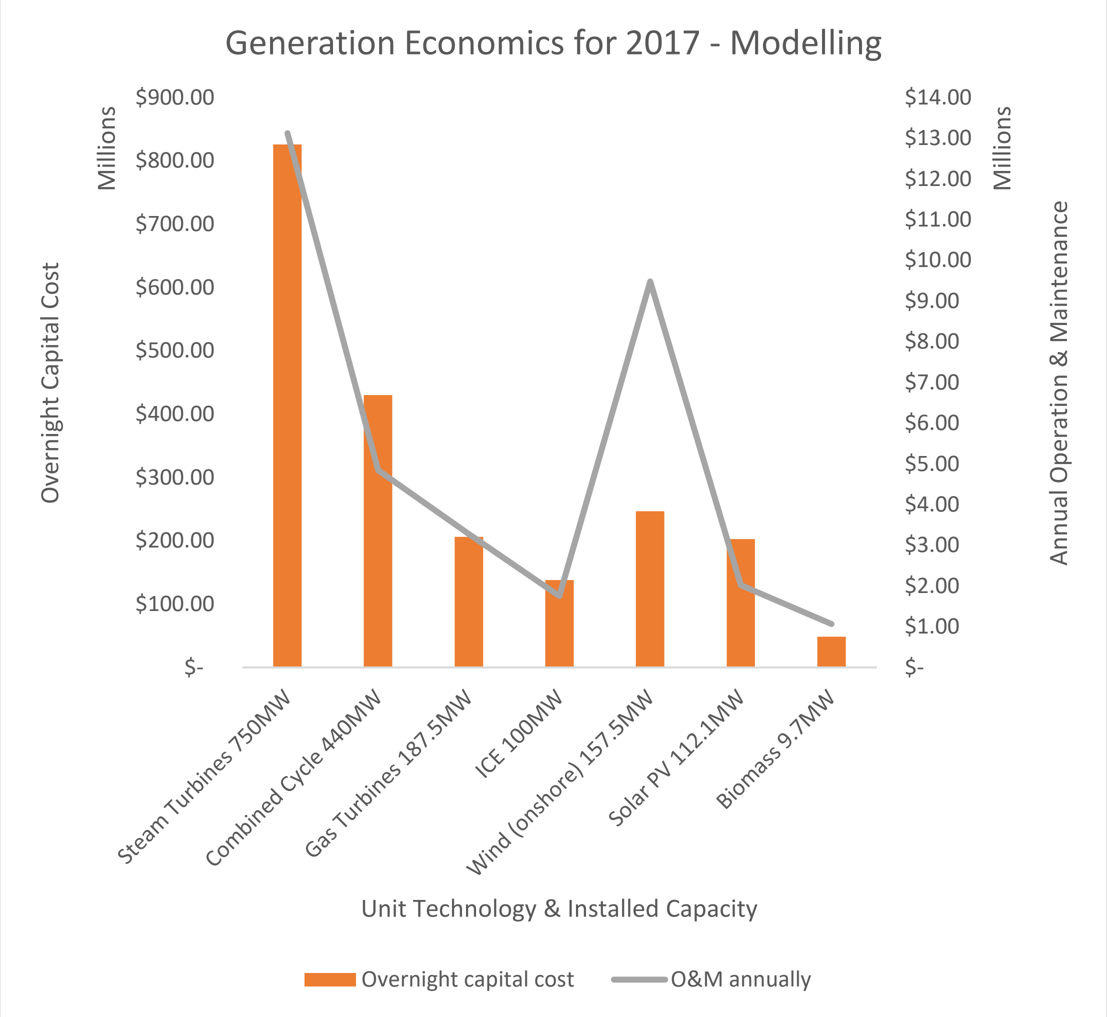


Figure 48 - Generation economics for 2017 - Modelling

HOMER carries built-in capabilities for generating a financial breakdown, by analysing the values of capital, operating and replacement costs, fuel and potential salvage from remaining values on projects that have ended. By introducing to the model the capital, operation and maintenance, replacement costs of components and finally the fuel prices analysed previously in page 50, HOMER can then generate a Net Present Cost (NPC) that includes all costs associated with the energy system throughout its life-cycle. After calculating the NPC, HOMER is then able to project a levelized cost of electricity (LCOE) for each component, and finally for the energy system.

As this study is ultimately interested in optimising energy scenarios that the RoC could follow, the NPC serves as a primary element to comparing different scenarios, followed by the LCOE.

The calculated levelized cost of electricity from this energy system, is 101.9$/MWh.

Table 15 - Cost summary of energy system for 2017 (HOMER)

Unit	Capital ($)	Fuel ($)	O&M ($)	NPC ($)
Steam Turbines	682,620,000.00	3,245,589,259	140,263,554	4,068,472,813
Combined Cycle	430,320,000.00	700,378,254	29,298,947	1,120,763,751
Gas Turbines	206,437,500.00	10,630,186	450,332	173,077,781
Wind Turbines	243,360,000	N/A	121,001,554	394,098,333
Solar Photovoltaic	202,901,000	N/A	26,085,142	228,986,142
Biomass	48,354,500	N/A	7,295,208	51,270,733
Wind Turbine (downtime)	3,120,000.00	N/A	1,551,301	5,052,542
Steam Turbine (Backup)	143,130,000	0	0	112,766,042
ICE (Backup)	137,900,000	0	0	114,543,109
Total	2,108,142,999	3,956,597,700	325,946,042	6,279,031,251

The generation results of the energy system designed to reflect 2017, are detailed in Table 16, with the corresponding fuel consumption in Table 17. The system in general mirrors the published results for 2017, with renewables optimised to include the symmetry of the conditions that are present in the RoC. That includes parameters unknown, such as unscheduled/scheduled maintenance, electrical faults, or other unexpected events that terminate generation from wind, solar photovoltaic or biomass units.

Table 16 - Energy generation as modelled in HOMER, for 2017

<table>
<tr><th>Technology</th><th>Capacity (MW)</th><th>Generation (MWh)</th><th colspan="2">Generation (%)</th></tr>
<tr><td colspan="5">Thermal Power Stations</td></tr>
<tr><td>Steam Turbines</td><td>620</td><td>3,788,580.538</td><td colspan="2">79.51</td></tr>
<tr><td>Combined Cycle</td><td>440</td><td>564,668.928</td><td colspan="2">11.85</td></tr>
<tr><td>Gas Turbines</td><td>187.5</td><td>4,359.375</td><td colspan="2">0.09</td></tr>
<tr><td colspan="5">Renewable Energy Sources</td></tr>
<tr><td>Wind Turbines</td><td>158</td><td>221,376.263</td><td>4.65</td><td rowspan="3">RES
8.71%</td></tr>
<tr><td>Photovoltaics</td><td>112.1</td><td>157,282.233</td><td>3.30</td></tr>
<tr><td>Biomass Electric</td><td>9.7</td><td>36,300.054</td><td>0.76</td></tr>
<tr><td colspan="5">Reserved for emergency use, limited working hours</td></tr>
<tr><td>Steam Turbine</td><td>130</td><td>0</td><td colspan="2">0</td></tr>
<tr><td>ICE</td><td>100</td><td>0</td><td colspan="2">0</td></tr>
</table>

Table 17 - Fuel consumption as modelled in HOMER, for 2017

Fuel	**Fuel Consumption (t)**	**Fuel Consumption ($)**
Heavy Fuel Oil	1,117,896.454	3,245,589,259.27
Diesel Oil	143,165.903	711,008,441.16
Total	**1,261,062.357**	**3,956,597,700.43**

5. Future Energy Scenarios of Cyprus

In this chapter, the future energy scenarios will be defined and analysed, with data extracted from HOMER Energy and further analysed to support hypotheses.

The year of 2017 has been successfully modelled, validating the energy software that is to be used for this study, HOMER Energy.

A crucial point is the business as usual scenario, which sets the reference point for all other scenarios, for comparison of results and further validation of the software used.

After analysing the recently published forecasts of the transmission operator on annual generation and peak demand for the years 2018 to 2025, the years in interest were generated on an hourly basis, giving the backbone for future scenarios to be investigated. With just the peak and total demand published in the report for the years 2018 to 2025, the distribution profile of 2017 was adapted and thus their symmetries are identical. Furthermore, the analytical forecasts include low, mid and high values.

The first scenario to be investigated, is the business-as-usual trend for 2020, that exists to portray the potential problems in delaying acting, but also as a standard comparison scenario for contemplating advantages and disadvantages of different pathways proposed.

The second scenario will be the system proposed by the RoC for 2020, analysed previously in this study, with however a correction in the forecasted demand. Finally, the third and last scenario of pathways to 2020 will be the suggested pathway to 2020 for the RoC, aiming at enhancing the balance of the energy trilemma and optimising between cost, renewable generation and security of supply. At the same time, a more realistic growth will be applied, since development has not been as expected.

Lastly, the suggested pathway to 2025 is introduced, designing the potential future energy system that will integrate the gasification of the power stations, the implementation of the interconnector EuroAsia, using the synergy of the two elements to increase renewables penetration without violating in any way the energy trilemma.

Time is a crucial component in designing an energy system. With the RoC having 157.5MW of wind capacity as of the end of 2017, the time needed to design, conduct necessary environmental studies, receive appropriate licenses and commission a wind farm becomes a fundamental constrain to future energy scenarios.

According to a report issued by Vestas, there are six key aspects to designing and commissioning a wind farm. The first one, site analysis, is essentially a feasibility study to determine whether the site in interest is sufficiently resourceful or not. Installing an anemometer in the area to record and structure a comprehensive wind velocity analysis, as previously done for the 'Case-Study: 'Orites' Wind Farm', takes at least 12 months (Vestas, n.d.). The legal aspect, electrical connection, choosing the turbine technology, agreeing to the financial dimensions of the project, and finally delivering and commissioning the wind farm, are the remaining five aspects. These can easily take another 12 months, bringing the total to at least two years from perceiving the idea to commissioning and operating.

Another source places the timeframe to two years, but for a single 500kW wind turbine. For a larger project, of numerous wind turbines with rated power higher than 1MW, the duration expands due to the rise in complexities (Renewables First, 2015).

With the above timeframes in mind, a wind farm project could not initiate and enter the electricity network prior 2020. For a best-case scenario however, this study will assume that various projects have been already initiated, with them finishing the 12-month long wind data monitoring at the end of year 2018. This allows for some wind farms to come into operation within 2020, however a limited number. Generation from solar photovoltaic parks takes significantly less time, with site analysis being substantially shorter than for wind. After analysing numerous reports, solar photovoltaic projects take approximately 4 to 5 months from perceiving the idea to commissioning and operating (Solect Energy, 2016) (Sunlight Solar, 2014) (Santhanam, 2015).

5.1. Forecasting Energy Demand

The forecasted energy demand as seen in Figure 41 and Figure 42, show a steady increase from the annual 4.765TWh in 2017, up to 5.856TWh in 2020. The sensitivity degree of taking low, mid and high values aims at generating a reliable dataset, from which the future energy scenarios can be materialised.

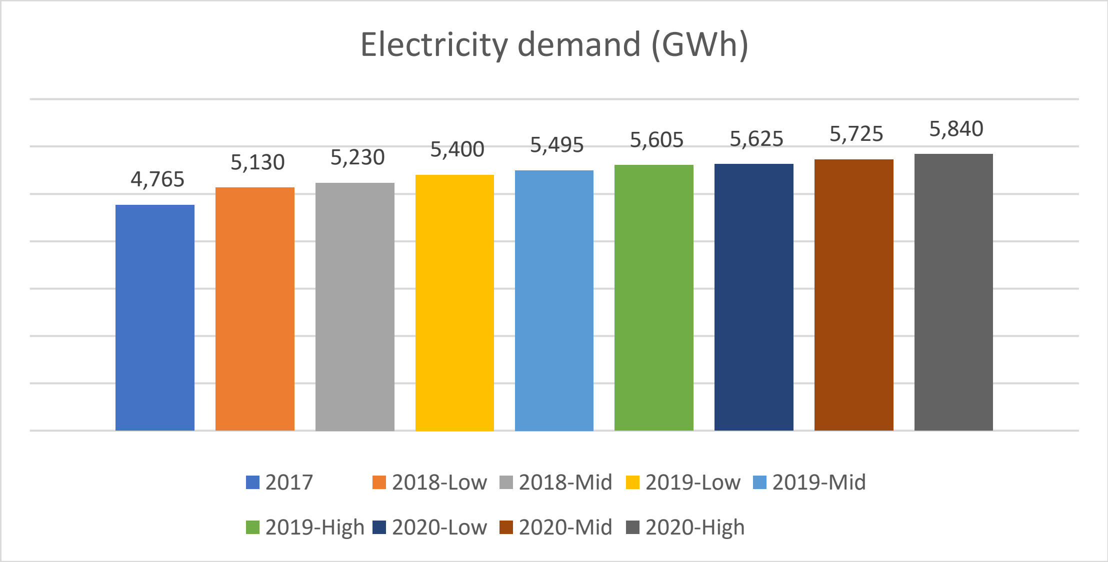
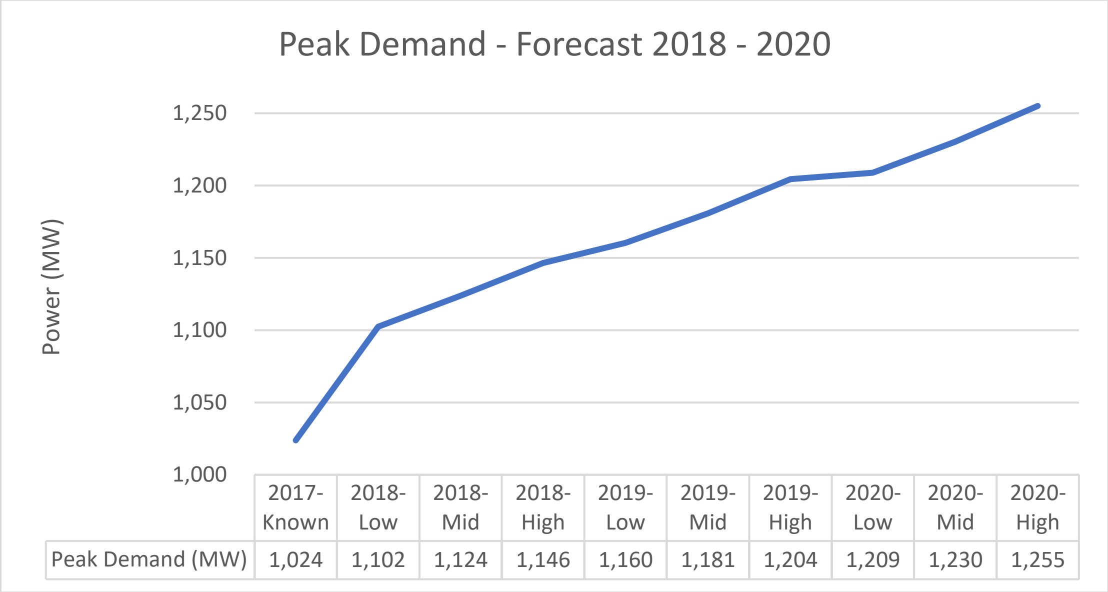


Figure 49 - Forecasted electricity demand until 2020



	2017-Known	2018-Low	2018-Mid	2018-High	2019-Low	2019-Mid	2019-High	2020-Low	2020-Mid	2020-High
Peak Demand (MW)	1,024	1,102	1,124	1,146	1,160	1,181	1,204	1,209	1,230	1,255

Figure 50 - Forecasted electricity peak demand until 2020

5.2. Pathway to 2020: Business as Usual (BaU)

A business-as-usual trend for 2020

This scenario is developed for the year of 2020; to support the arguments raised later in future energy scenarios. By incorporating the forecasted energy demand and the expected business-as-usual trend of the increase in renewables capacity, the model can then be simulated using the methods seen throughout the section '**Error! Reference source not found.**'.

Electricity generation from renewables is expected to rise, especially with the introduction of the concentrated solar power plant on July 1st 2020, but as seen in Figure 9 it is currently not on course for meeting the 2020 target.

Assuming that the load in the year 2020 is the one reflected by the 2020-Mid values, as seen in Figures Figure 49, Figure 50 and Figure 51, the renewable share drops from 8.55% to 7.10% assuming no further renewable capacity is installed. This section will incorporate the business-as-usual trend in renewables penetration, and model how they stand with 2020 demand forecasts.

A limitation introduced to the system, is that HOMER cannot process a leap year, being restricted to 8760 hours for an annual analysis. Therefore, February 29th is omitted from the hourly analysis of 2020.

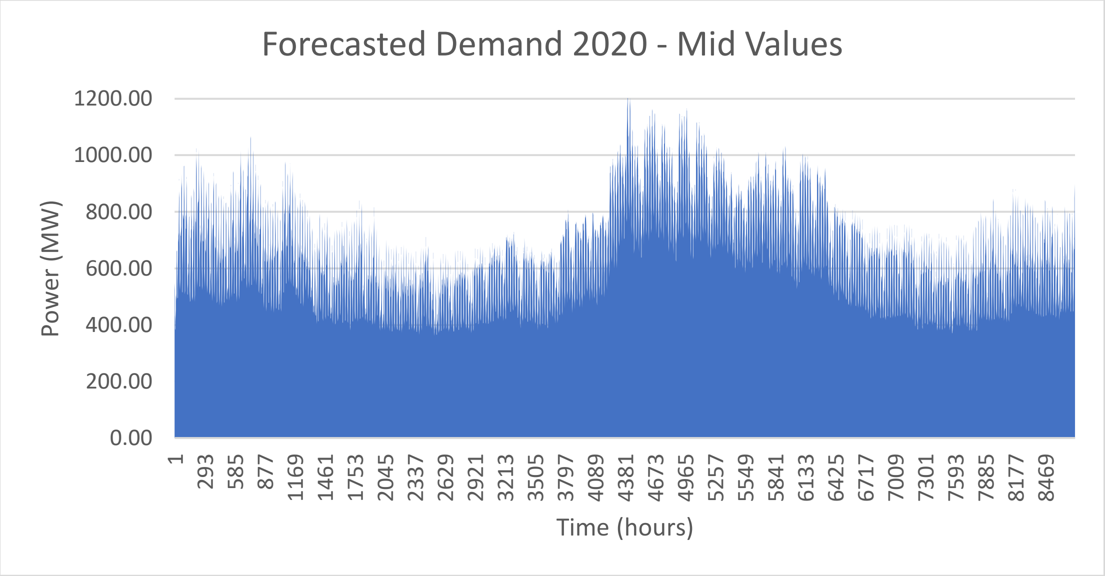
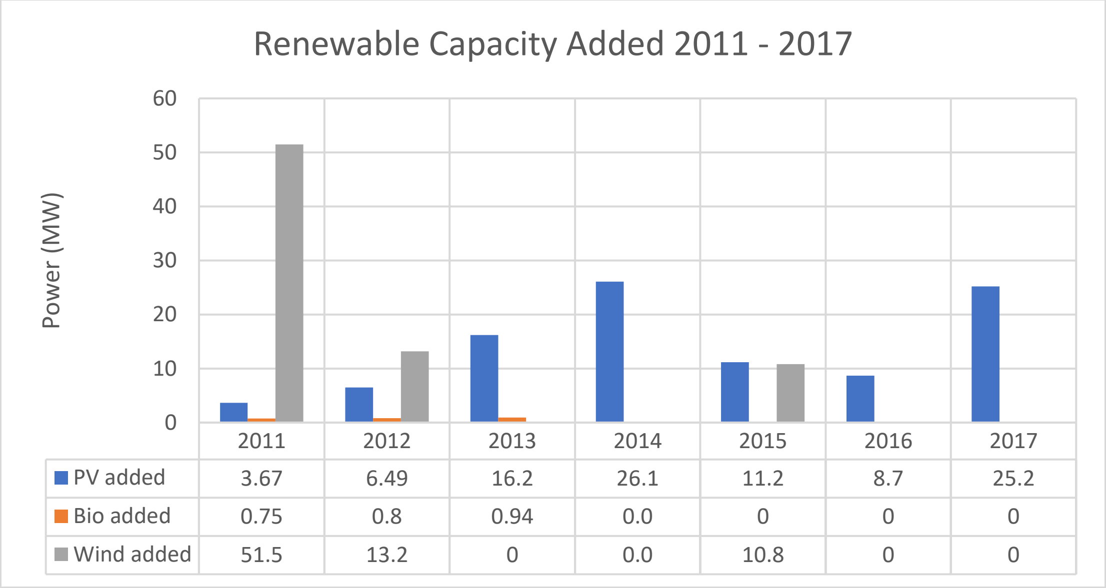


Figure 51 - Forecasted demand for 2020 (mid values) – February 29th omitted

Electrical Architecture

Determining the increase in renewable capacity involved analysing the historic trend between 2011 and 2017. An interesting find was that solar photovoltaic, however fluctuating, always had an annual increase of over 3MW. Wind energy, being a more large-scale investment, recorded a typical installation frequency of three years with at least 10MW. Lastly biomass, had no new investments since 2013, after reaching 9.7MWe in June 2013.



	2011	2012	2013	2014	2015	2016	2017
🟦 PV added	3.67	6.49	16.2	26.1	11.2	8.7	25.2
🟧 Bio added	0.75	0.8	0.94	0.0	0	0	0
⬜ Wind added	51.5	13.2	0	0.0	10.8	0	0

Figure 52 - Renewable capacity installed 2011 - 2017

A weighted average of the annual increase showed solar photovoltaics at 1.28, biomass at 0.03 and wind turbines at 0.91 MW installed per annum. It would have been wrong to apply that linearly to analyse wind turbines annually, so a single installation was introduced on January 1st, 2020 of an 18MW wind farm, reaching therefore a wind turbines' capacity of 176MW. Similarly, biomass was modelled as a single unit at 1.3MWe, entering the energy mix on January 1st, 2020.

As seen in Figure 53, the final capacity in 2020 includes wind turbines at 175MW, solar photovoltaic at 158.3MW, biomass at 11MW, and lastly the concentrated solar power plant at 50MWe entering July 1st, 2020.

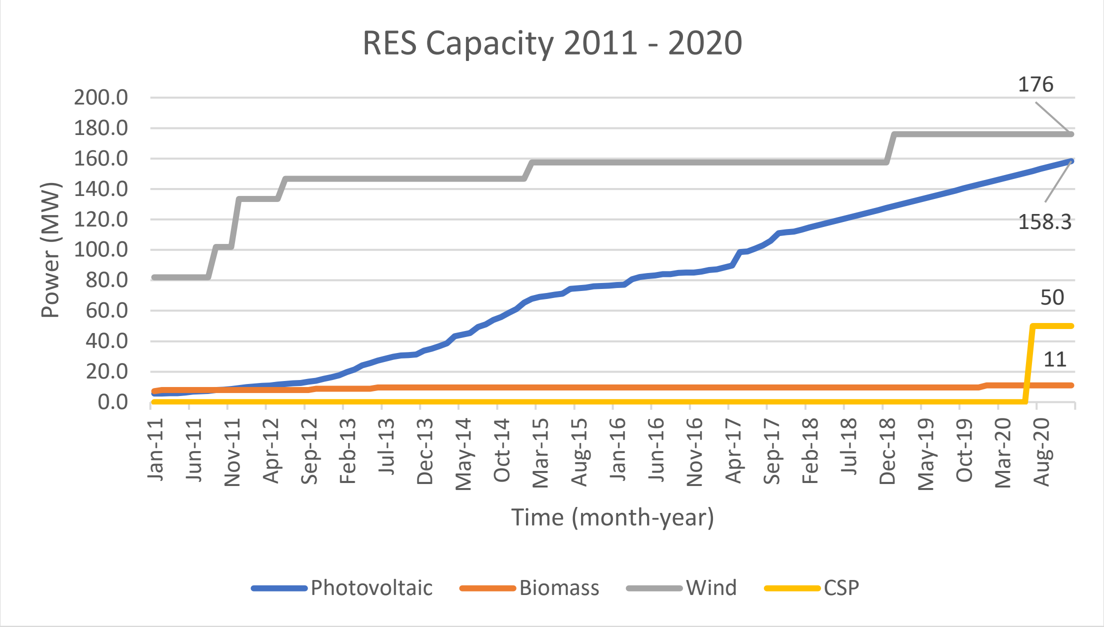


Figure 53 - Renewable capacity forecast for 2020 business-as-usual

Assuming the thermal power stations remain identical as of 2017, the electrical architecture of the 2020 business-as-usual model is as shown in Figure 54.

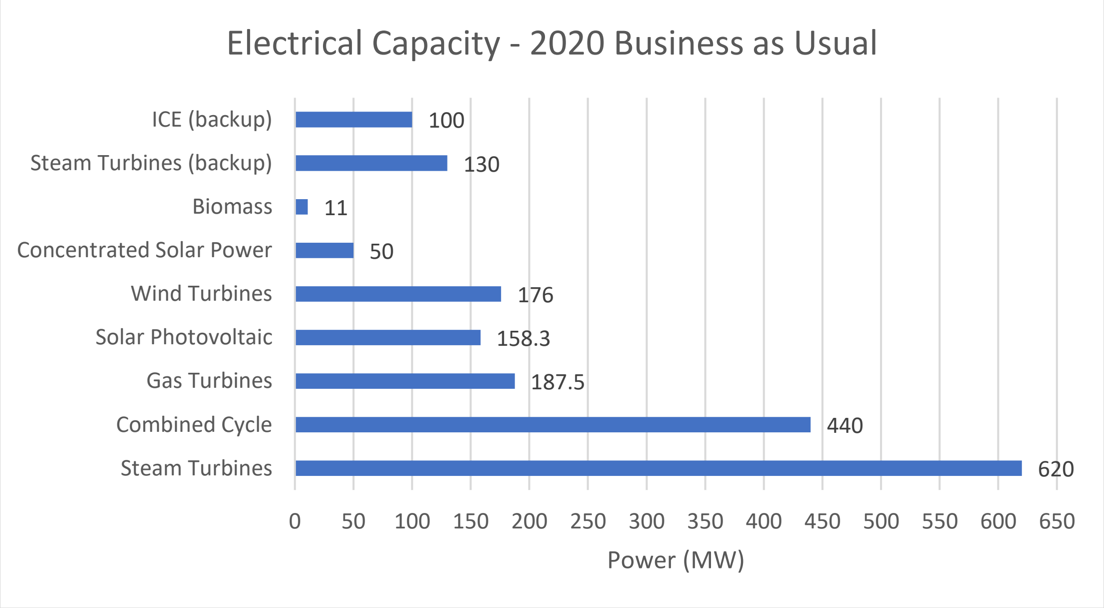


Figure 54 - Electrical architecture of scenario 2020 business-as-usual

Generation Results

The energy output from both renewable and conventional sources are outlined in this section, with the CSP vividly coming in operation on July 1st.

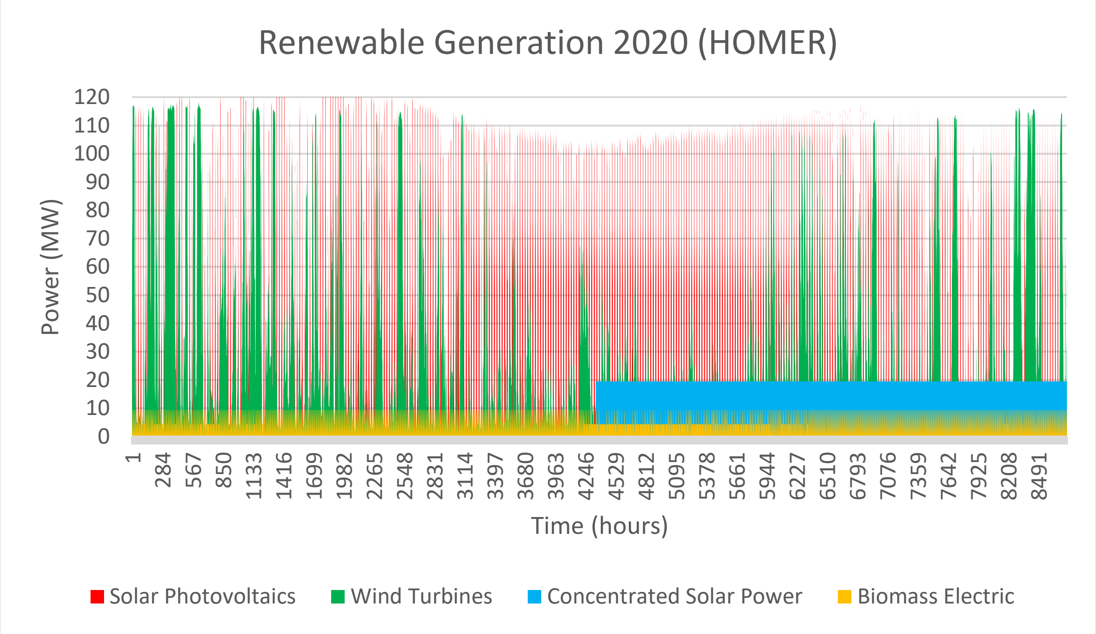


Figure 55 - Renewable results for pathway to 2020: business-as-usual

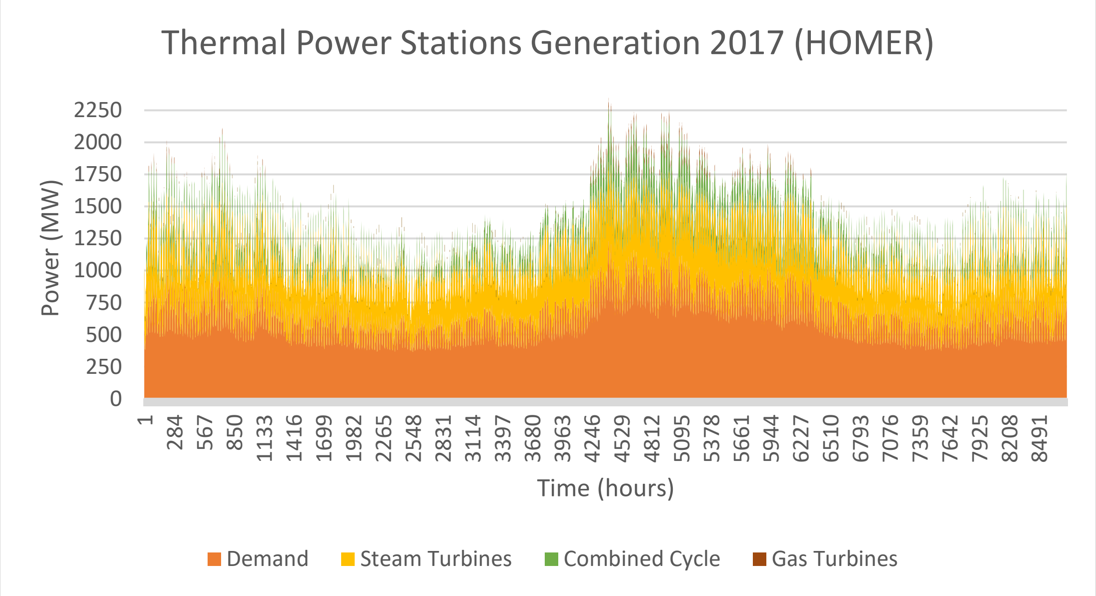


Figure 56 - Thermal power stations results for pathway to 2020: business-as-usual

A post-simulation analysis shows the energy system in 2020 to have a renewable share of 10.43%, a small fraction of increase from the 2017 energy model. This is due to the demand rising proportionally to the renewable capacity installation, proving that the RoC is forced to introduce renewables at a much higher rate to meet 2020 targets.

Table 18 – Energy generation results from 2020 business-as-usual scenario

Technology	**Capacity (MW)**	**Generation (MWh)**	**Generation (%)**	
Thermal Power Stations				
Steam Turbines	620	4,147,882.047	72.64	
Combined Cycle	440	947,484,599	16.59	
Gas Turbines	187.5	34,898,635	0.61	
Renewable Energy Sources				
Wind Turbines	176	246,890.035	4.32	**RES** **10.43%**
Photovoltaics	158.3	222,103.278	3.89	
CSP Plant	50[3]	86,404.384	1.51	
Biomass Electric	11	40,259,235	0.71	
Reserved for emergency use, limited working hours				
Steam Turbine	130	0	0	
ICE	100	0	0	

Table 19 – Fuel usage results from 2020 business-as-usual scenario

Fuel	**Fuel Consumption (t)**	**Fuel Consumption ($)**
Heavy Fuel Oil	1,216,704.364	3,532,463,565.06
Diesel Oil	249,726.565	1,240,222,288.03
Total	**1,466,430.929**	**4,772,685,853.10**

---

[3] Operation from July 1st, 2020

Cost Summary

The life-cycle cost of the energy system in this scenario is approximately $7.45B, with the levelized cost of electricity at 100.9$/MWh.

Table 20 - Cost summary of 2020 business-as-usual scenario

Unit	Capital ($)	Fuel ($)	O&M ($)	NPC ($)
Steam Turbines	682,620,000	3,532,463,565	140,263,554	4,355,347,119
Combined Cycle	430,320,000	1,155,129,811	44,476,973	1,608,591,806
Gas Turbines	206,437,500	85,092,476	3,602,659	254,030,415
Wind Turbines	271,440,000	N/A	134,963,272	439,571,218
Solar Photovoltaic	286,523,000	N/A	36,835,665	323,358,665
Concentrated Solar Power	100,000,000	N/A	38,776,085	164,607,676
Biomass	54,835,000	N/A	9,097,887	59,522,944
Wind Turbine (downtime)	3,120,000.00	N/A	1,551,301	5,052,542
Steam Turbine (Backup)	143,130,000	0	N/A	112,766,042
ICE (Backup)	137,900,000	0	N/A	114,543,109
Total	2,326,325,499	4,772,685,853	409,567,401	7,447,391,541

Additionally, the business-as-usual model on HOMER presented a potential breach of the security of supply. During the day of maximum demand, July 3rd, peak demand was approximately 1.2GW, violating the defined operation reserve by a small margin. However, the two backup generators, with a total capacity of 230MW, are configured on HOMER to be always off, and in practice, they would power on to ensure a match of supply and demand, respecting therefore the pre-defined operation reserve.

In conclusion, the business-as-usual model serves a fundamental purpose of projecting vividly the problem that the RoC faces in meeting EU-2020 targets.

5.3. Pathway to 2020: National Energy Strategy

The future energy scenario that encompasses the targets of the RoC in their national energy strategy for meeting 2020 targets of 13% renewable electricity

As discussed in section ‘National Energy Strategy’, the RoC has a slightly outdated energy strategy, projecting at least 10% less demand in 2020 than most recent forecasts. This scenario therefore investigates the results of such pathway, but instead chooses the corrected forecasted demand.

The electrical architecture of this scenario will be the one projected by the RoC, even though their estimates proved higher than real values. The electrical architecture is documented in Figure 57.

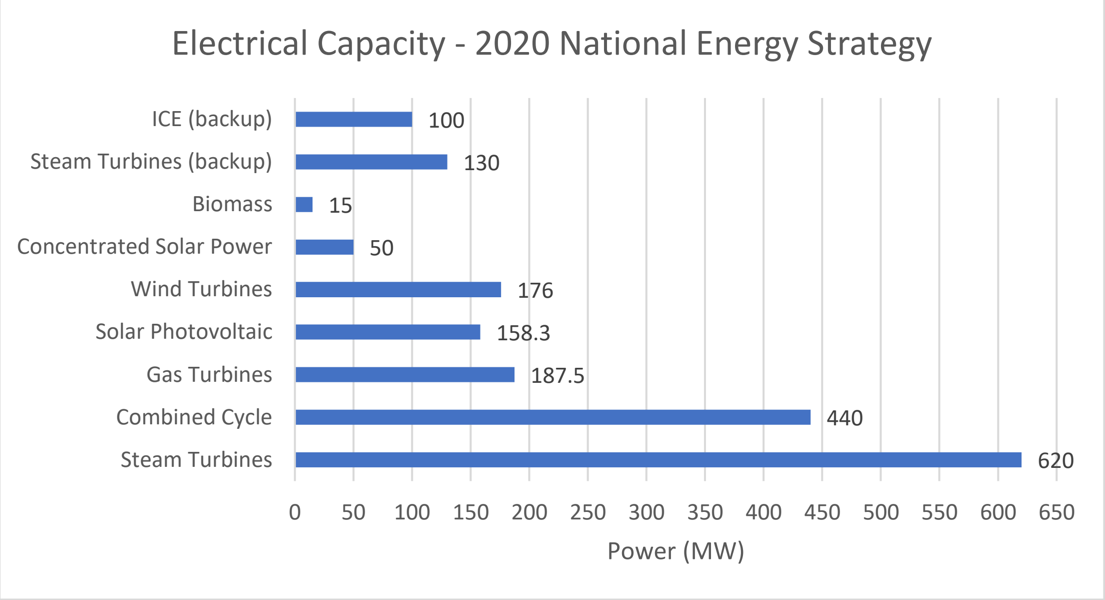


Figure 57 - Electrical architecture of 2020 national energy strategy

Energy Generation Results

This scenario marks the first time that a single renewable energy source exceeds a thermal power source, solar photovoltaics to gas turbines. Being substantially larger than other renewable sources, it dominates the generation mix with 7.08% share.

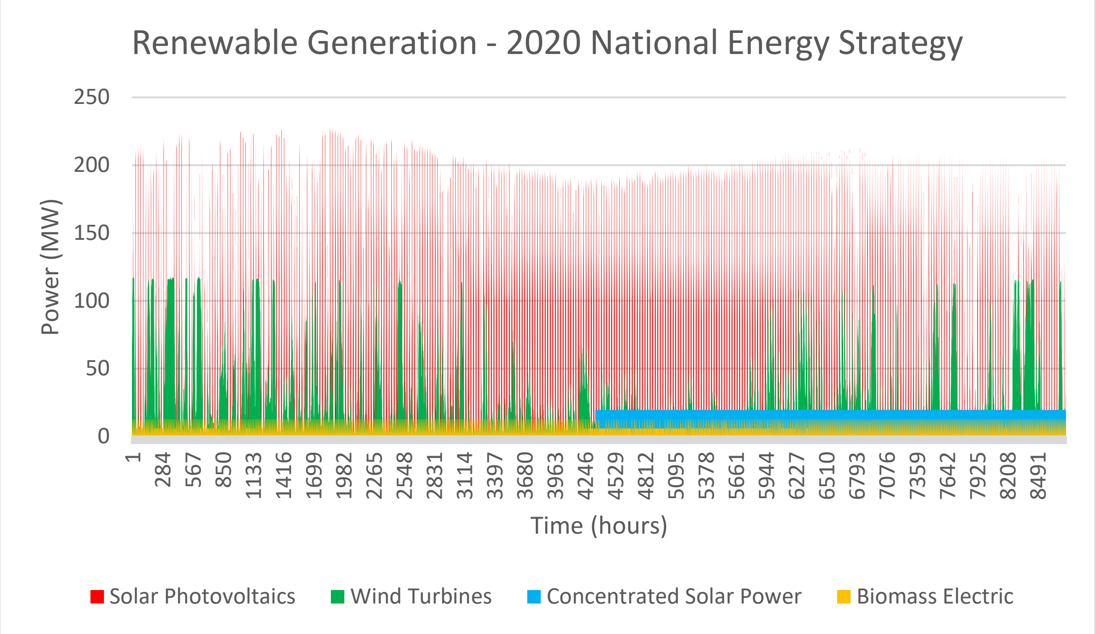


Figure 58 - Renewable energy results of 2020 national energy strategy

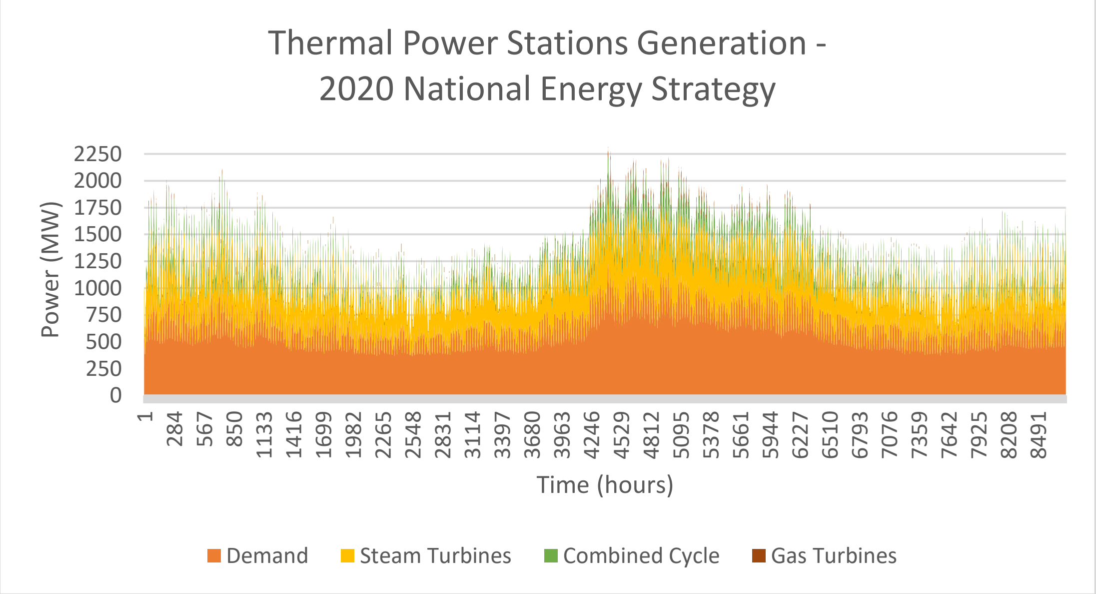


Figure 59 - Thermal power stations energy results of 2020 national energy strategy

The national energy strategy, even with an outdated forecasted demand, successfully meets the 2020 target in modelling a 13.88% annual renewable share. The concentrated solar power plant of 50MWe that comes in the mix in the second half of 2020, generates 1.51% of the forecasted demand, which without the renewable share would have dropped below the 2020 targets.

Table 21 - Energy generation results of 2020 national energy strategy

Technology	**Capacity (MW)**	**Generation (MWh)**	**Generation (%)**	
Thermal Power Stations				
Steam Turbines	620	4,003,177.538	70.1	
Combined Cycle	440	906,836.100	15.88	
Gas Turbines	187.5	32,390.625	0.57	
Renewable Energy Sources				
Wind Turbines	176	246,890.035	4.32	**RES 13.88%**
Photovoltaics	228.2	404,359.852	7.08	
CSP Plant	50[4]	86,404.384	1.51	
Biomass Electric	15	54,976.501	0.96	
Reserved for emergency use, limited working hours				
Steam Turbine	130	0	0	
ICE	100	0	0	

Table 22 - Fuel usage results of 2020 national energy strategy

Fuel	**Fuel Consumption (t)**	**Fuel Consumption ($)**
Heavy Fuel Oil	1,176,910.619	3,416,930,205
Diesel Oil	239,288.794	1,188,384,967
Total	**1,416,199.413**	**4,605,315,172**

---

[4] Operation from July 1st, 2020

Cost Summary

The projected life-cycle cost of this energy system is approximately $7.56B, with a levelized cost of electricity at 102.5$/MWh. This is a difference of +1.5% from the business-as-usual model in the net present cost and levelized cost of electricity.

Note, the associated costs with the CSP plant have been halved, to reflect the technology going online in the second half of 2020.

Table 23 - Cost summary of 2020 national energy strategy

Unit	Capital ($)	Fuel ($)	O&M ($)	NPC ($)
Steam Turbines	682,620,000	3,416,930,205	140,263,554	4,239,813,759
Combined Cycle	430,320,000	1,109,401,607	43,462,723	1,560,653,313
Gas Turbines	206,437,500	78,983,359	3,346,018	247,392,899
Wind Turbines	271,440,000	N/A	134,963,272	439,571,218
Solar Photovoltaic	521,642,000	N/A	67,062,784	588,704,784
Concentrated Solar Power	100,000,000	N/A	38,776,085	164,607,676
Biomass	74,775,000	N/A	12,189,497	80,804,906
Wind Turbine (downtime)	3,120,000.00	N/A	1,551,301	5,052,542
Steam Turbine (Backup)	143,130,000	0	N/A	112,766,042
ICE (Backup)	137,900,000	0	N/A	114,543,109
Total	2,581,384,499	4,605,315,172	441,615,239	7,563,910,253

5.4. Pathway to 2020: Suggested

2020 13% RES electricity share

In this scenario, a modification of the BaU scenario will be generated to investigate the required capacity of renewable sources needed to reach 13% of renewable electricity share. Focusing the energy analysis through the lenses of the energy trilemma, this scenario's electrical architecture is presented in Figure 60.

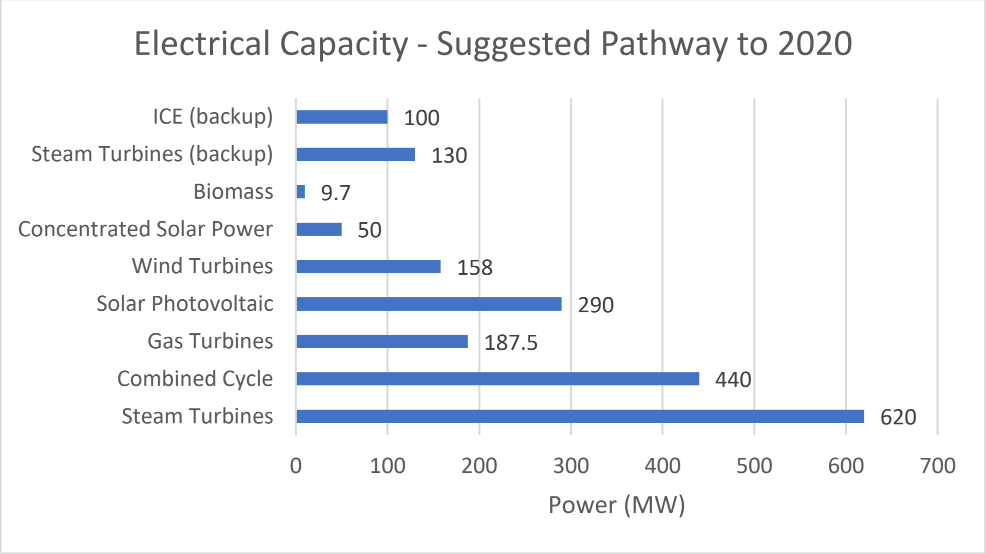


Figure 60 - Electrical architecture of the suggested pathway to 2020

The generation economics shows that the most cost-effective renewable energy source in the RoC, is solar photovoltaic – thus increasing in this scenario only that, leaving biomass at 9.7MWe, wind turbines at 158MW and the CSP plant at 50MWe.

Energy Generation Results

The energy results show how disproportional solar photovoltaics' output becomes, in relation to the remaining renewable sources.

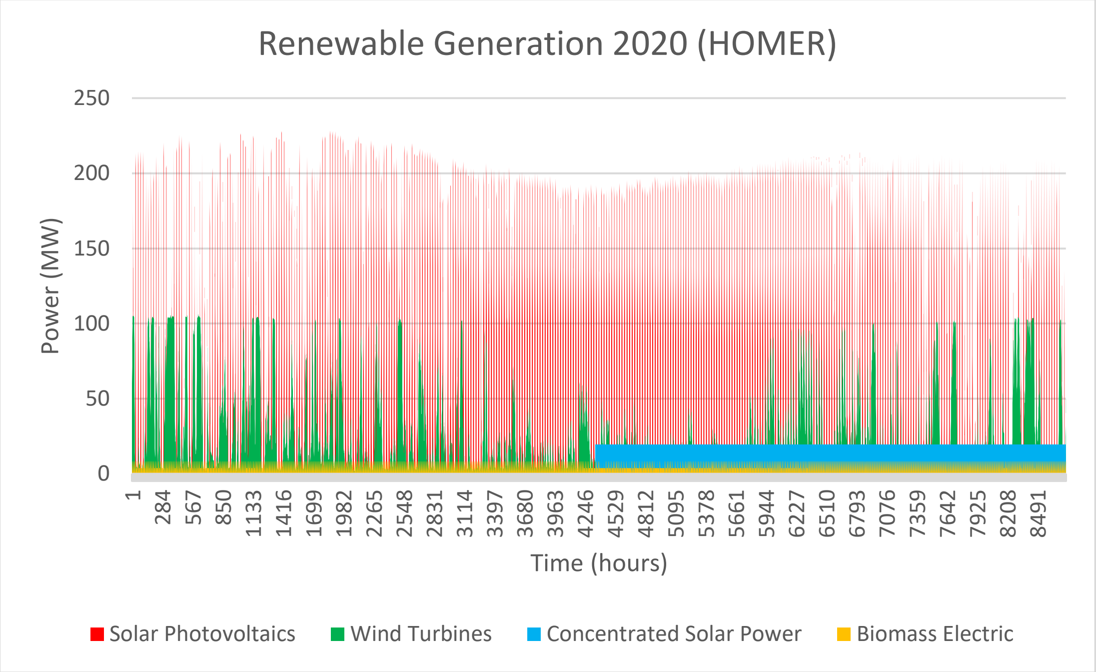


Figure 61 - Renewable generation results of 2020 best-case scenario

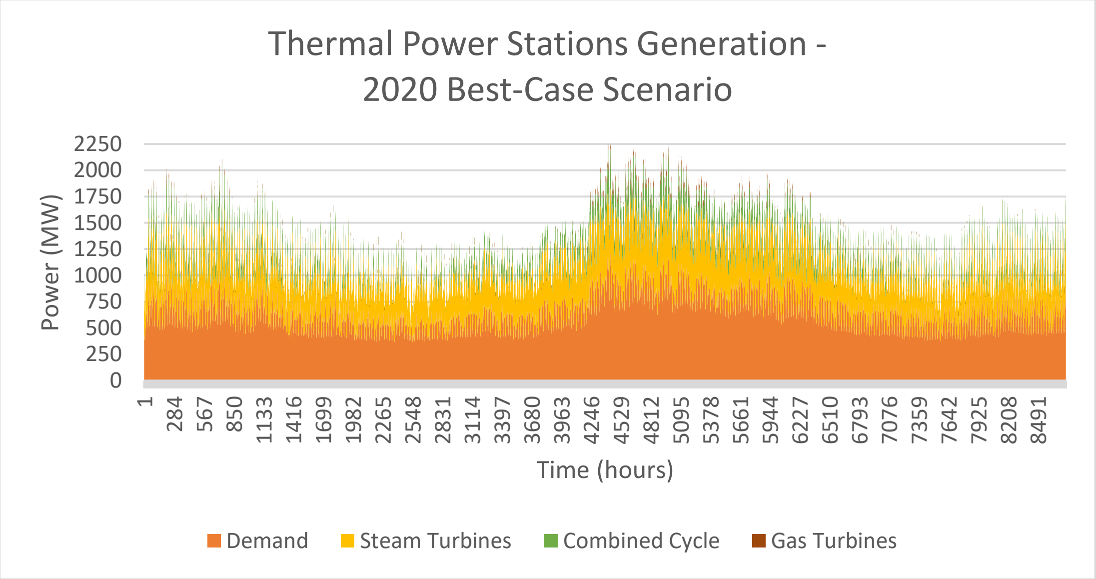


Figure 62 - Thermal power stations generation of 2020 best-case scenario

This scenario is suggested as a pathway to 2020, as it gives the most realistic energy system that can be attained for 2020, since these capacities are assumed to be online and in operation from January 1st 2020, except the CSP plant, and result in a 13.15% renewable electricity share in domestic consumption.

Table 24 - Energy generation results of the suggested pathway to 2020

Technology	**Capacity (MW)**	**Generation (MWh)**	**Generation (%)**	
Thermal Power Stations				
Steam Turbines	620	4,029,174.194	70.56	
Combined Cycle	440	921,772.411	16.14	
Gas Turbines	187.5	33,472.878	0.59	
Renewable Energy Sources				
Wind Turbines	176	221,376.263	3.88	**RES** **13.15%**
Photovoltaics	228.2	406,885.348	7.13	
CSP Plant	50[5]	86,404.384	1.51	
Biomass Electric	15	36,075.841	0.63	
Reserved for emergency use, limited working hours				
Steam Turbine	130	0	0	
ICE	100	0	0	

Table 25 - Fuel usage results of 2020 best-case scenario

Fuel	**Fuel Consumption (t)**	**Fuel Consumption ($)**
Heavy Fuel Oil	1,184,059.706	3,437,686,164.44
Diesel Oil	243,362.372	1,208,615,664.21
Total	**1,427,422.078**	**4,646,301,828.65**

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[5] Operation from July 1st, 2020

Cost Summary

The system analysed is produced with a net present cost of approximately $7.53B, with a levelized cost of electricity at 102.1$/MWh.

Table 26 - Cost summary of 2020 best-case scenario

Unit	Capital ($)	Fuel ($)	O&M ($)	NPC ($)
Steam Turbines	682,620,000	3,437,686,164	140,263,554	4,260,569,718
Combined Cycle	430,320,000	1,126,994,418	44,019,846	1,579,460,227
Gas Turbines	206,437,500	81,621,245	3,457,391	250,260,090
Wind Turbines	$243,360,000	N/A	121,001,554	394,098,333
Solar Photovoltaic	524,900,000	N/A	67,481,636	592,381,636
Concentrated Solar Power	100,000,000	N/A	38,776,085	164,607,676
Biomass	48,354,500	N/A	7,906,160	52,293,374
Wind Turbine (downtime)	3,120,000.00	N/A	1,551,301	5,052,542
Steam Turbine (Backup)	143,130,000	0	N/A	112,766,042
ICE (Backup)	137,900,000	0	N/A	114,543,109
Total	2,530,141,999	4,646,301,828	424,457,532	7,536,032,752

5.5. Pathway to 2025: EuroAsia

2025 pathway, with interconnector

In this scenario, the feasibility of the interconnector EuroAsia is analysed, whilst taking advantage of the forecasted prices of renewable energy sources in 2025 by IRENA. According to the recently published forecasts in demand, there will be an increase of 40% compared to 2017, with the peak demand at ~1.4GW and the annual generation at ~6.7TWh. This scenario documents a scaled-up version of the generation in 2017 and investigates how the energy system can cope with a 40% increase, without a growth in thermal power stations.

In determining the electrical architecture of this scenario, since the interconnector boosts the security of supply, the two remaining elements of the energy trilemma are prioritised. Therefore, this scenario investigates the pathway towards a strong balance between an increased renewable penetration and the levelized cost of electricity. Numerous scenarios were taken into consideration, since an interconnector gives space for a higher energy complexity bearing benefits not yet unlocked in the RoC. However, with the assumed tariffs of importing and exporting energy through the interconnector, problems arise when attempting to export renewable electricity generated at a lower cost than the selling point; forcing thus curtailment of the units, or selling at a higher rate, both of which increases its levelized cost of electricity. Thereby, a battery energy solution is integrated with a 2MWh capacity, to demonstrate how the flexibility and dispatchability provided by a battery energy unit, could provide benefits over the fluctuating parameters of an interconnector.

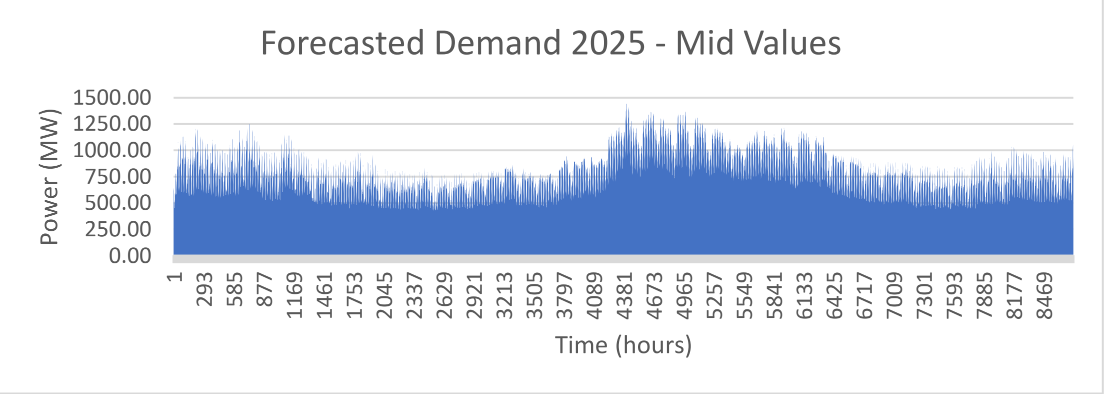


Figure 63 - Forecasted demand for 2025

Interconnector EuroAsia

The 2.0GW sub-sea HVDC interconnector, EuroAsia, introduces a large financial uncertainty, as it is yet unclear how much each involved country will be responsible for paying. In extend, the available margin is also unclear, and a bi-directional 500MW of shared capacity is taken as an assumption. Additionally, the model after a sensitivity analysis of the tariffs, introduces four variations throughout the year. Since peak demand occurs always in the summer, it will most likely be more expensive during summer days, whereas in the early hours of winter the associated demand of electricity will be significantly less, and therefore have a reduction in tariffs. The default cost of importing electricity is set at 104$/MWh, with exporting at 50$/MWh.

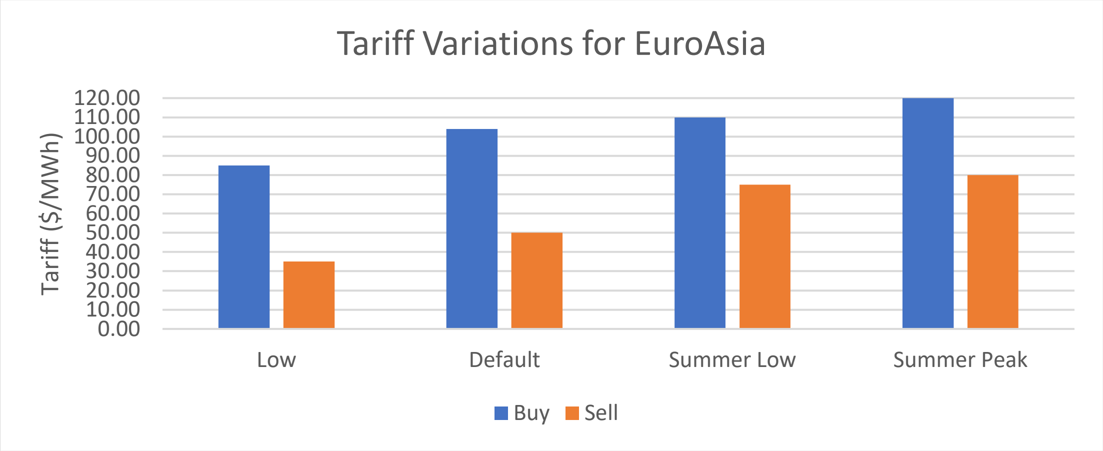


Figure 64 - Tariff variations for EuroAsia

The interconnector is estimated at a total cost of $3.78B, with four projects awaiting construction (EuroAsia Interconnector, 2018):

- Four VSC HVDC converters at each involved country, at a total $1.18B
- Cable L1: Israel ←→ Cyprus, $509M running for 310km
- Cable L2: Cyprus ←→ Crete, $1.47B running for 879km
- Cable L3: Crete ←→ Attica, $619M running for 329km.

The 2.0GW HVDC bi-directional sub-sea interconnector, at a total length of 1,518km, is modelled in HOMER with a capital cost rate of 622,200.26$/km – assuming the total capital cost is divided equally between the four partner countries.

Electrical Architecture

The electrical architecture of this scenario is built from the suggested pathway to 2020, with all new technologies installed using IRENA's 2025 forecasted costs. Combined cycle gas turbines and gas turbines now operate with natural gas instead of diesel, and thus utilise a higher thermal efficiency operating at a lower levelized cost of electricity. This had a result in demoting the use of the 400MW heavy fuel oil-fired steam turbines, increasing heavily the dependency on combined cycle gas turbines.

From 2017 to 2020, the best-case development for meeting the 2020 targets was, amongst other, a 177.9MW new capacity of solar photovoltaic. Applying that linearly, gives a range of a potential increase from 0 to 296.5 MW of new solar photovoltaic from 2020 to 2025; assuming therefore a 59.3MW installed capacity per annum. Adapting this relationship to other renewables sources, gives a total renewable capacity range of 0 to 406.5MW until 2025. However, with the increase in demand at around 6.7TWh, the renewable capacity increase will be insufficient with keeping in line with the renewable share uptake from 2017 to 2020.

This scenario will assume that a higher penetration rate can be achieved between 2020 and 2025, thus bringing the renewable annual share over 25% in 2025. A battery energy unit, and the ability to export excess renewable energy from the interconnector, allows for this scenario to unfold higher numbers of solar photovoltaic, being the technology with the lowest levelized cost of electricity.

The electrical architecture of the pathway to 2025, including the interconnector EuroAsia, is presented in Figure 65.

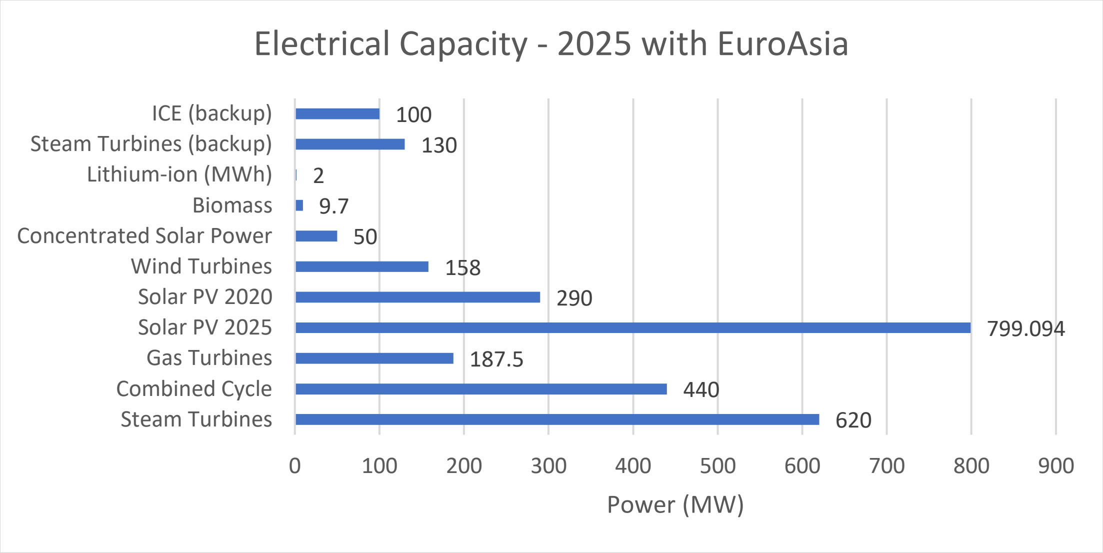


Figure 65 - Electrical architecture of the pathway to 2025: EuroAsia

The increase in solar photovoltaics was carefully assessed by determining the size with which the maximum penetration does not exceed demand by what is economically unfeasible, therefore having the ability to export to a profitable extend, whilst providing a high renewable penetration to domestic consumption. The remaining energy units, both conventional stations and renewable sources, remain static as of the suggested pathway to 2020.

Solar photovoltaics therefore become the single highest energy system source per capacity, at a total 1,089.094MW. The 799.094MW installed for 2025, are utilising the new forecasted prices, while the rest remain as modelled with the quoted prices for 2015.

Energy Generation Results

The figures Figure 66 and Figure 67 present the hourly time-step of electricity generation from both renewable sources and conventional power stations.

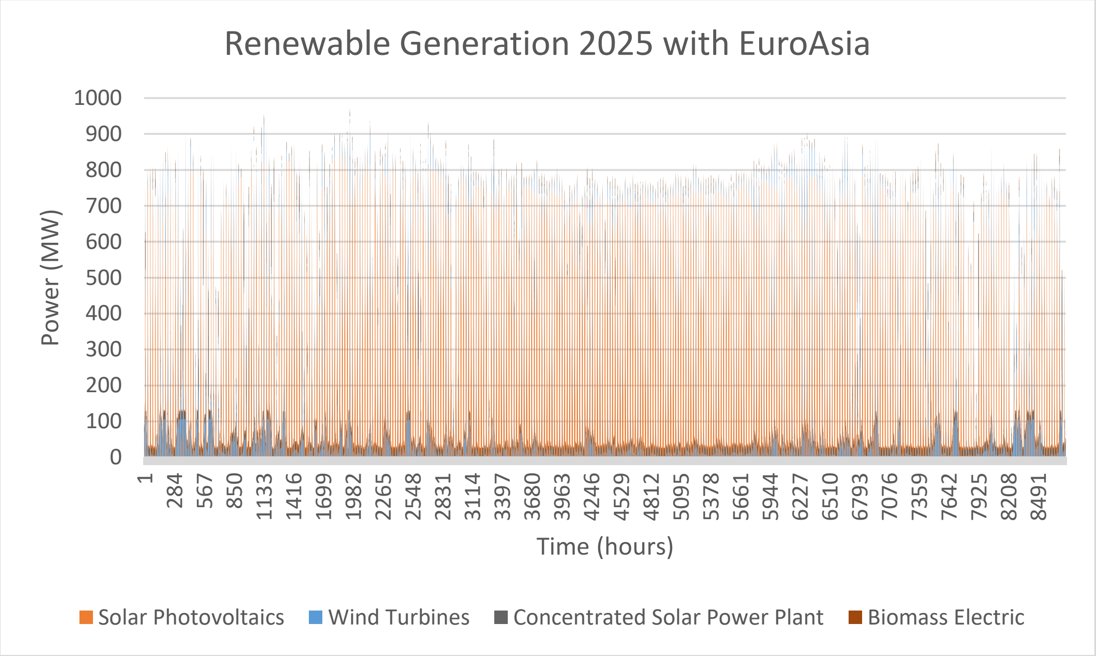


Figure 66 - Renewable energy generation results for the pathway to 2025: EuroAsia

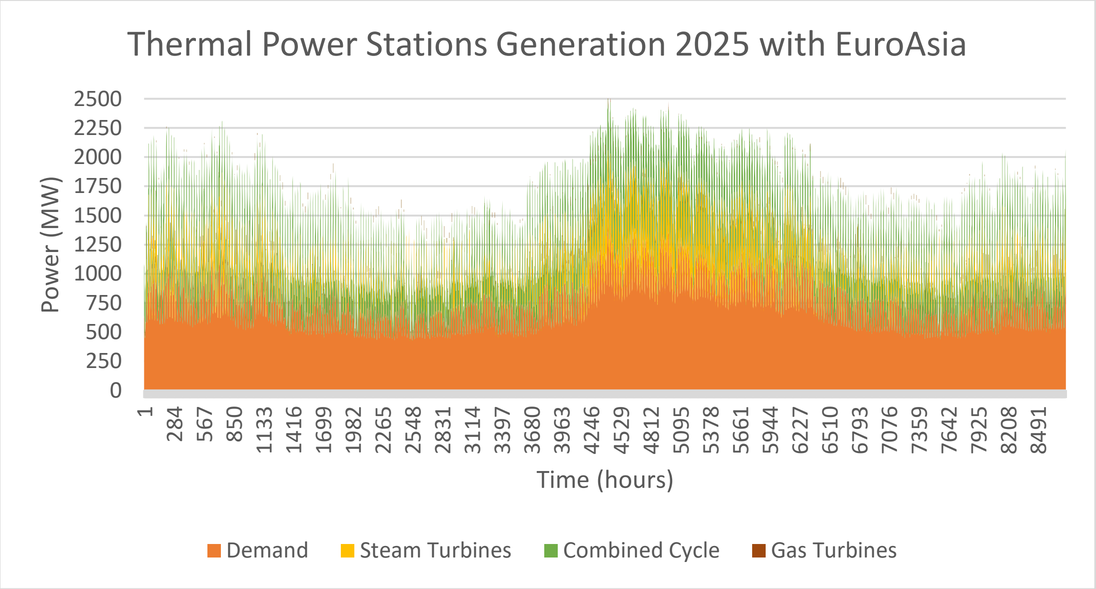


Figure 67 - Thermal power stations energy generation results for the pathway to 2025: EuroAsia

This scenario presents a renewable generation share of 29.17%, 22.74% of which derives from solar photovoltaics. However, a portion of that generation is exported via the interconnector EuroAsia, with the renewable consumption within the RoC reducing to 26.5%. Furthermore, the energy system appears to have no violations or risks associated with the security of supply, with a much more diverse network than the 2017 energy mix – with the most dominant source being combined cycle gas turbines at 45.59%.

Table 27 - Energy generation results for the pathway to 2025: EuroAsia

<table>
<tr><th>Technology</th><th>Capacity (MW)</th><th>Generation (MWh)</th><th colspan="2">Generation (%)</th></tr>
<tr><td colspan="5">Thermal Power Stations</td></tr>
<tr><td>Steam Turbines</td><td>620</td><td>1,968,452.234</td><td colspan="2">29.36</td></tr>
<tr><td>Combined Cycle</td><td>440</td><td>3,056,567.589</td><td colspan="2">45.59</td></tr>
<tr><td>Gas Turbines</td><td>187.5</td><td>2,798.450</td><td colspan="2">0.04</td></tr>
<tr><td colspan="5">Renewable Energy Sources</td></tr>
<tr><td>Wind Turbines</td><td>176</td><td>223,954.215</td><td>3.34</td><td rowspan="4">RES
26.5%</td></tr>
<tr><td>Photovoltaics</td><td>1,089.094</td><td>1,524,400.130</td><td>22.74</td></tr>
<tr><td>CSP Plant</td><td>50</td><td>171,399.999</td><td>2.56</td></tr>
<tr><td>Biomass Electric</td><td>9.7</td><td>35,896.700</td><td>0.54</td></tr>
<tr><td colspan="5">Reserved for emergency use, limited working hours</td></tr>
<tr><td>Steam Turbine</td><td>130</td><td>0</td><td colspan="2">0</td></tr>
<tr><td>ICE</td><td>100</td><td>0</td><td colspan="2">0</td></tr>
<tr><td colspan="5">Battery Energy Units</td></tr>
<tr><td>Technology</td><td>Capacity (MWh)</td><td>Throughput (MWh)</td><td colspan="2">COE_{avg}($/MWh)</td></tr>
<tr><td>Lithium-ion LFP</td><td>2</td><td>1,601,892</td><td colspan="2">83.1</td></tr>
</table>

Table 28 - Fuel usage results for the pathway to 2025: EuroAsia

Fuel	Fuel Consumption (t)	Fuel Consumption ($)
Heavy Fuel Oil	580,636.082	1,685,763,506
Fuel	**Fuel Consumption (m^3)**	**Fuel Consumption ($)**
Natural Gas	676,395,851.700	2,378,400,250

Maximum Demand – July 3rd

The day of maximum demand, July 3rd, is investigated for this scenario for demonstrating the usability of the battery unit and the robustness of the energy system.

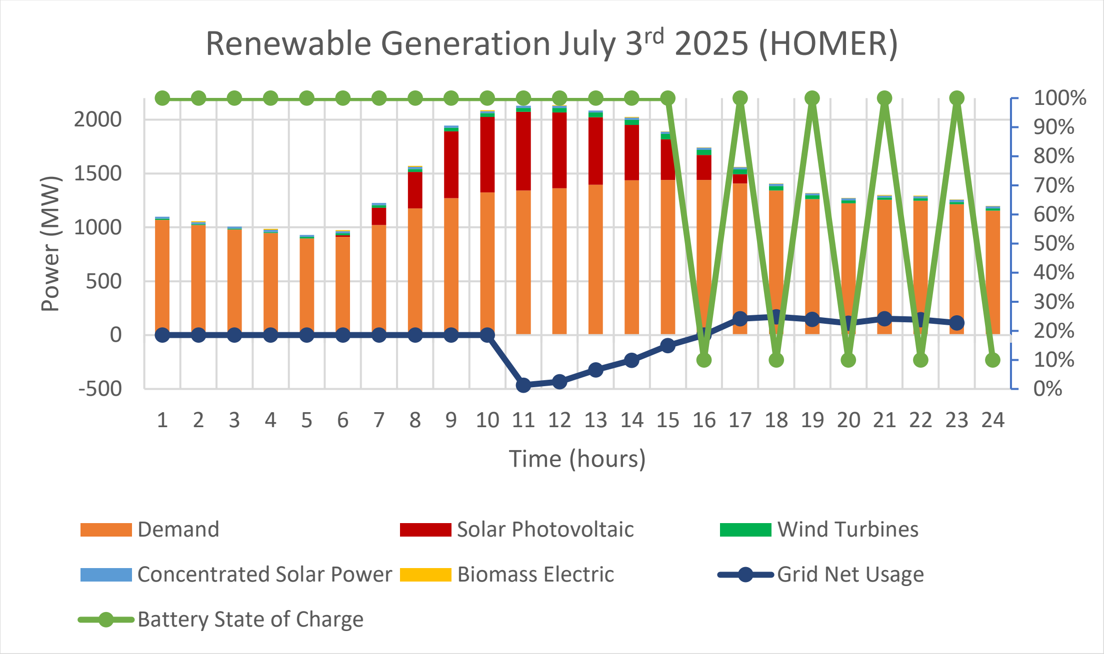


Figure 68 - Renewable generation on July 3rd, 2025

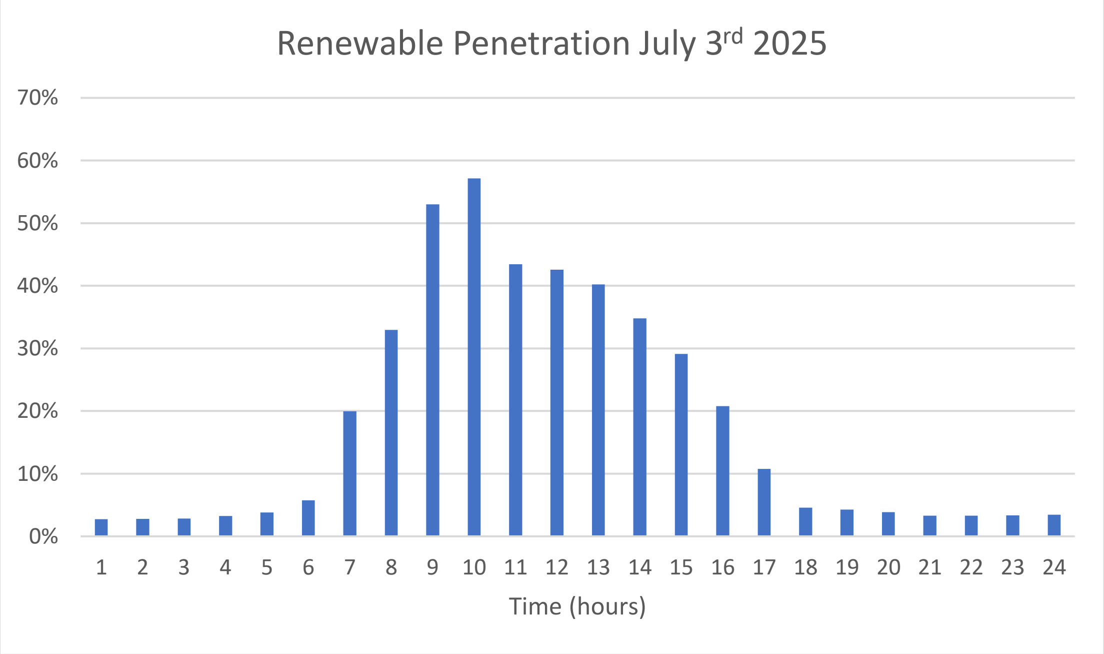


Figure 69 - Renewable penetration on July 3rd, 2025

Maximum RES Penetration – April 9th

On April 9th, renewables generated 36.48% of consumed energy, with solar photovoltaics at 39.07%, having exported energy through the interconnector.

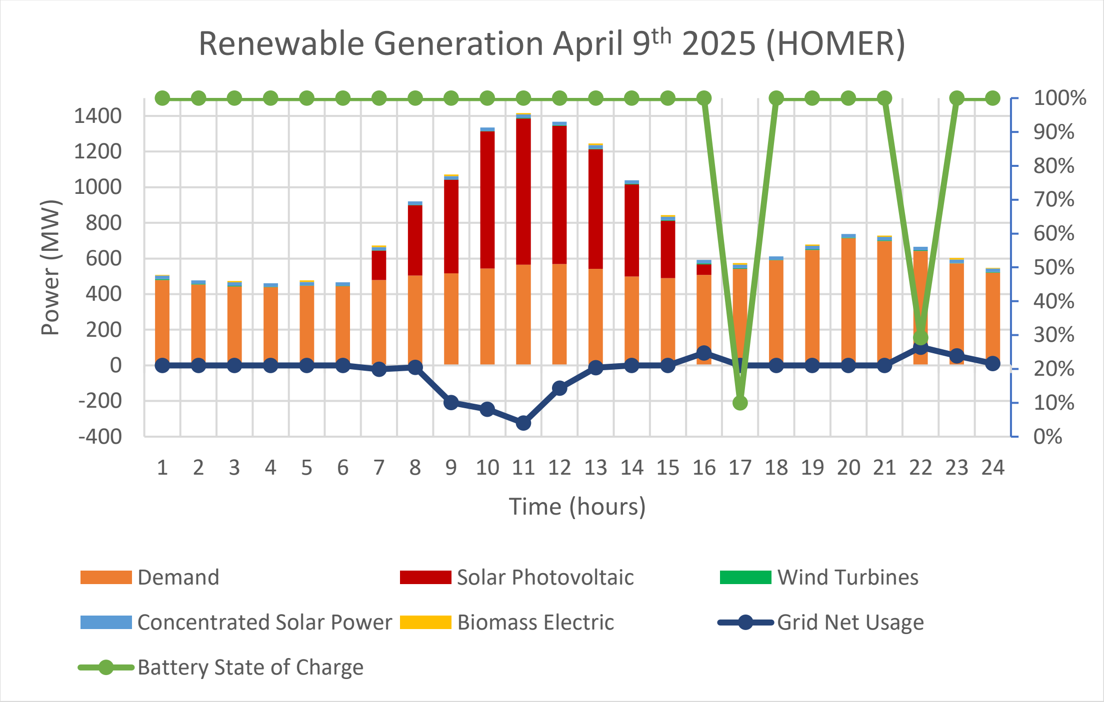


Figure 70 - Renewable generation on April 9th, 2025

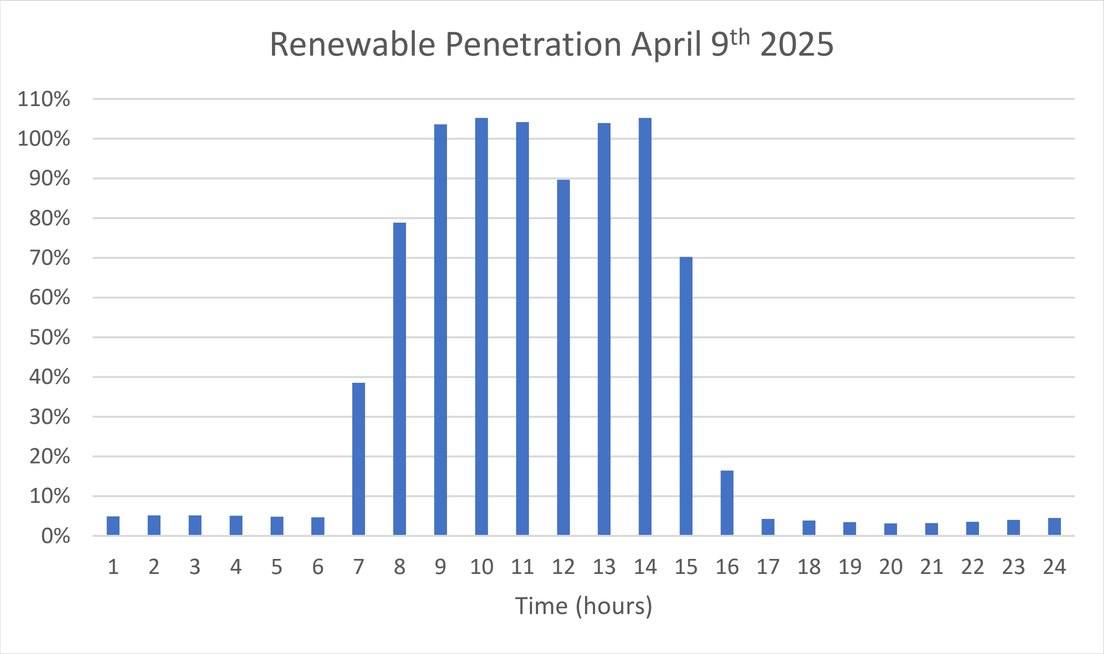


Figure 71 - Renewable penetration for April 9th, 2025

Battery Energy Unit

The battery modelled in this scenario, is a HOMER generic 1MWh lithium-ion battery, with a nominal voltage 600V at a 1.67kAh capacity, a 90% roundtrip efficiency and a deep discharge of 90%. The economics of the battery were extracted from IRENA's forecasted costs on energy storage for 2025 (IRENA, 2017) for a lithium iron phosphate battery, as shown in Table 29.

The values for this analysis were the ones indicated by *Reference.*

Table 29 - Lithium Iron Phosphate (LFP) forecasted costs (IRENA, 2017)

Energy Storage Unit	**2025**		
Lithium Iron Phosphate (LFP)	**Best**	**Worst**	**Reference**
Cycle Life (full-cycles)	15,157.3	1,515.7	3,789.3
Calendar Life (years)	26.3	6.6	15.8
Depth of discharge (%)	100.0	84.0	90.0
Round-trip efficiency (%)	95.1	82.0	93.1
Self-discharge (%/day)	0.1	0.4	0.1
Energy Installation cost ($/kWh)	108.6	457.1	314.2

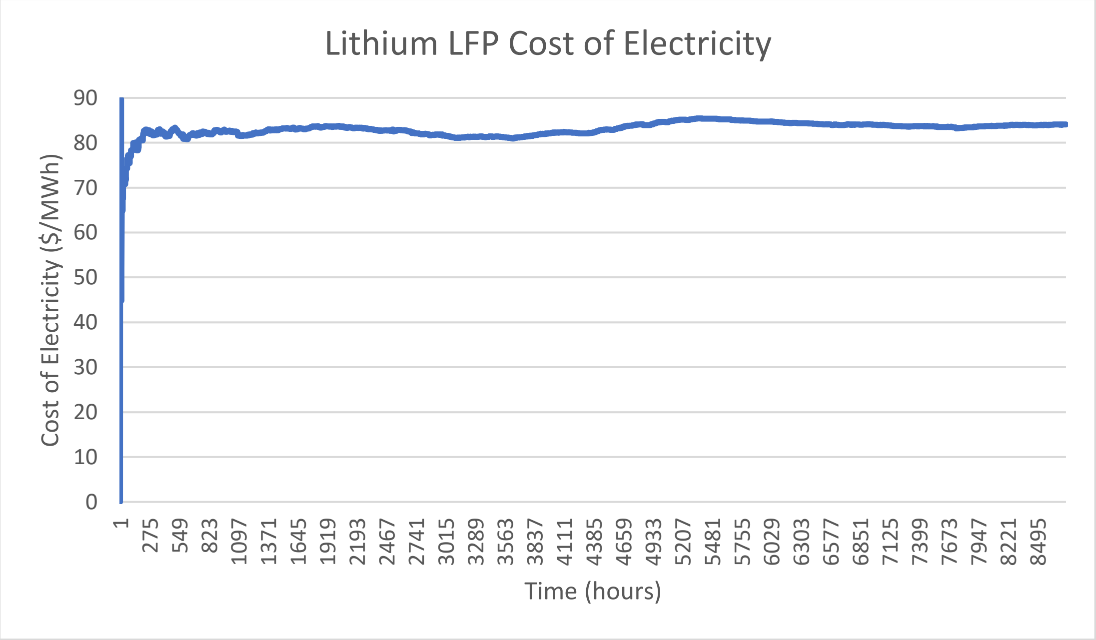


Figure 72 - Lithium LFP cost of electricity analysis for pathway to 2025: EuroAsia

Cost Summary

The energy system has a net present cost of approximately $8.65B and a levelized cost of electricity at 94.8$/MWh, with the breakdown documented in This scenario for 2025, has a net present cost of approximately $8.65B, and a levelized cost of electricity at 94.8$/MWh.

Table 30. Solar photovoltaics in 2025 recorded the most cost-effective energy source, surpassing conventional power stations and noting a levelized cost of electricity at 56.38$/MWh.

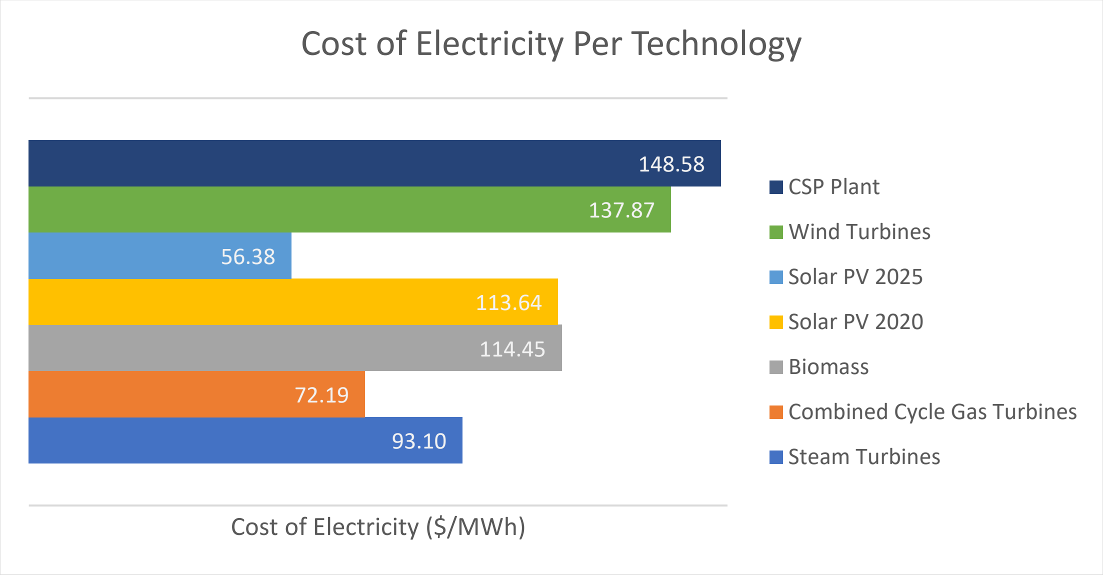


Figure 73 - Cost of electricity per technology for pathway to 2025: EuroAsia

Additionally, the RoC through this scenario becomes a net exporter, with imports being less than half of exports as observed in Figure 74 and reflected by the negative operation and maintenance cost in This scenario for 2025, has a net present cost of approximately $8.65B, and a levelized cost of electricity at 94.8$/MWh.

Table 30.

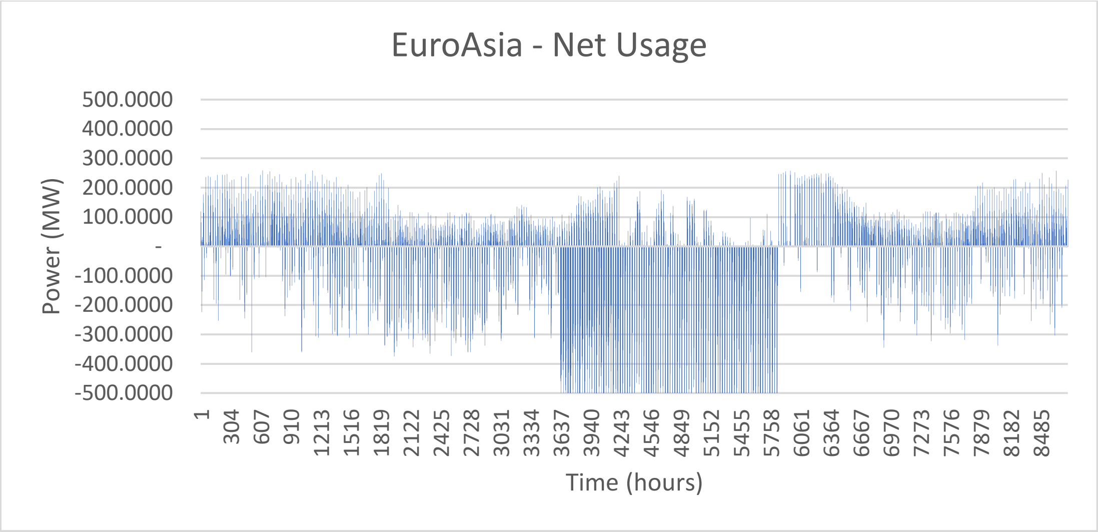


Figure 74 - Interconnector EuroAsia net usage for pathway to 2025: EuroAsia

This scenario for 2025, has a net present cost of approximately $8.65B, and a levelized cost of electricity at 94.8$/MWh.

Table 30 - Cost summary for the pathway to 2025: EuroAsia

Unit	Capital ($)	Fuel ($)	O&M ($)	NPC ($)
Steam Turbines	682,620,000	1,685,763,506	72,517,538	2,369,164,407
Combined Cycle	430,320,000	2,373,584,431	56,155,124	2,852,495,873
Gas Turbines	206,437,500	4,815,818	280,852	166,914,470
Wind Turbines	246,480,000	N/A	122,552,856	399,150,876
2020 Solar Photovoltaic	524,900,000	N/A	67,481,636	592,381,636
2025 Solar Photovoltaic	631,284,260	N/A	185,945,416	817,229,676
Concentrated Solar Power	200,000,000	N/A	77,552,171	329,215,353
Biomass Electric	48,354,500	N/A	8,394,292	53,110,433
Battery Lithium-ion	628,400	N/A	1,292,751	2,137,585
Grid EuroAsia	944,500,000	N/A	-114,185,818	830,314,181
Steam Turbine (Backup)	143,130,000	0	N/A	112,766,042
ICE (Backup)	137,900,000	0	N/A	114,543,109
Total	4,206,554,659	4,064,163,756	477,986,822	8,649,423,646

6. Discussion

The RoC is a small economy, and thus cannot persuade prices and create a competitive market by promoting an interest for specific technologies. The pathway to 2025 was designed, knowing that prices of renewables are due to drop significantly in the next 10 years, as seen from IRENA's reports on forecasted costs. A prime example of that is battery energy units and concentrated solar power plants, whose costs are expected to change by -48% and -37% respectively. These technologies hold the key to developing a more sustainable energy system, providing the dispatchability and flexibility needed from high-penetration renewable systems.

An isolated energy system of a relatively large-scale consumption, such as Cyprus, with a current peak demand of 1GW and an expected 3.5% increase per annum, a high renewable penetration would undermine the network that is currently characterised as brittle. To tackle the stochastic nature of renewables and ensure a security of supply, will add a growing pressure on the financial elements – hence the trilemma of energy. To avoid trading one element for another and pave the way for a more fruitful energy system, Cyprus needs to carefully craft its national energy strategy well into the following decades, incorporating forecasted costs of variable renewable energies.

The suggested pathway to 2020 therefore, includes the minimum required solar capacity for meeting the EU-2020 targets of renewable generation, whilst keeping maximum marginal renewable penetration infrequent over 50%, as seen in Figure 75 – with just 9 time-steps exceeding 65% of renewable generation.

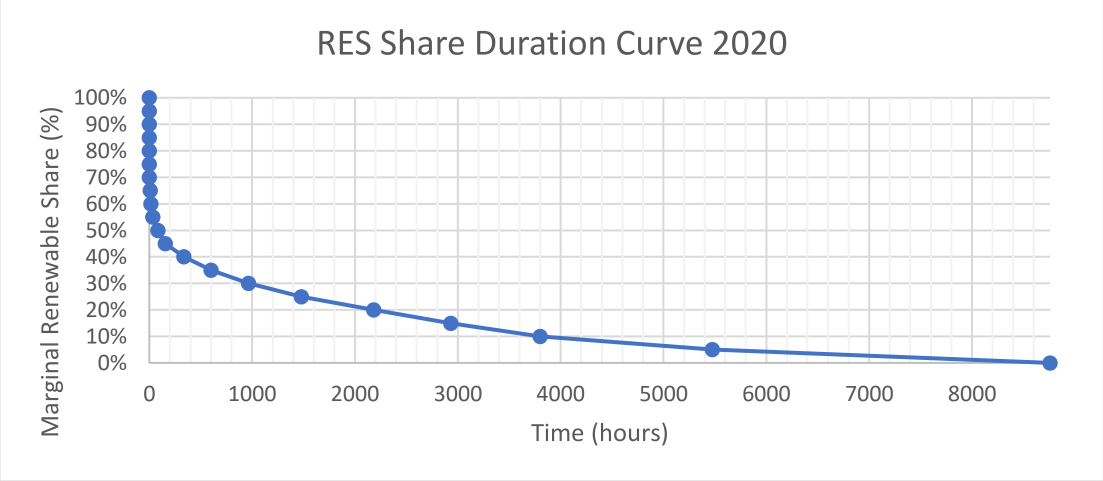


Figure 75 - Renewable share for the suggested pathway to 2020 (duration curve)

The following, Figure 76, sheds some light on how different scenarios stand against each other. The suggested pathway for 2025, is comprised of predominantly the increase in solar photovoltaics. The capital investment for the additional 799MW of photovoltaics, is $631.28M, with its total net present cost being under 10% of the system's total net present cost, at $817,229,676.

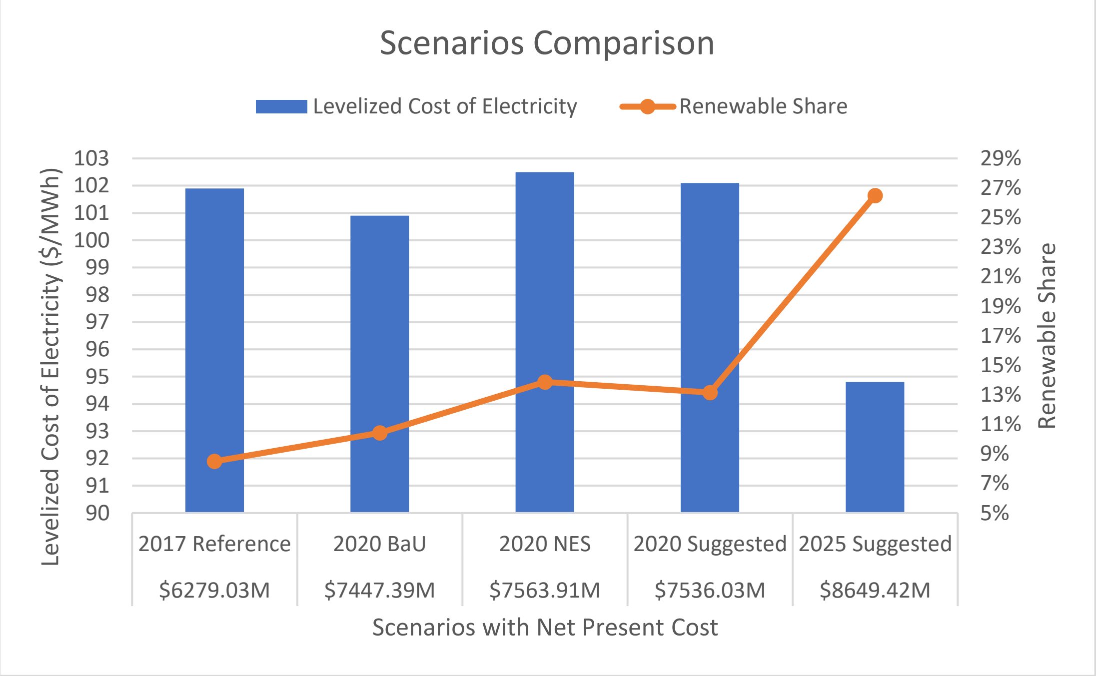


Figure 76 - Scenarios comparison, NPC, LCOE and RES share

The net present cost for 2025, being significantly higher than the 2020 scenarios, has a levelized cost of electricity substantially less than the rest, being reduced by almost 7% from the 2017 reference scenario, from 101.9 to 94.8 $/MWh.

A worrying element of the 2020 scenario for meeting the EU targets, is the possible delay of the concentrated solar power plant. With a capacity of 50MWe, it has the potential to swing the renewable share below the desired 13%.

Transitioning towards 2025, the implementation of the interconnector EuroAsia will most likely be a game-changer for the energy architecture of the RoC. The shared capacity, fluctuating or fixed, will give a breathing space for imports during peak loads, and exports during high renewable energy generation. The very existence of the interconnector will pave way for renewable projects more frequently than before, although numerous implications remain unknown.

The tariff variation on imports and exports, is an element that should have been analysed and published at a higher transparency, with the sole information published being the total capacity of the bi-directional sub-sea cable. The unwanted scenario here will be an export tariff significantly less than the levelized cost of electricity of say, solar photovoltaics, resulting to curtailment or exporting at a lower price, whichever is less economically damaging.

Furthermore, the project of EuroAsia has not released any in-depth environmental impact assessment, only a very brief non-technical summary of the areas within the territories of Cyprus (Atlantis Consulting, 2016), but not to the full extent of the project. It is however confirmed and reported to be under construction at the time of this writing.

The gasification of the thermal power stations, either through Cyprus' own reserves or through imports of natural gas, is due to be in operation before 2025. With an onshore gas-pipeline underway to connect the three centralised power stations, there are questions regarding whether or not EuroAsia will replace the unconfirmed project of EastMed, the gas-pipeline project aimed at connecting Cyprus to mainland Europe. Perhaps this would lead to the RoC becoming a generation hub, exporting vast quantities of energy from their natural gas reserves.

6.1. Further Research

The concentrated solar power plant, at an electrical capacity of 50MW, was restricted from the modelling resources and was simulated at a constant generation of a lower capacity factor, thus not utilising the time-step thermal storage that it integrates in practice. Further research would be greatly beneficial in order to provide a detailed modelling for finding the optimal balance between generating and storing, as a function of the next day's forecasted consumption. The ability to throttle the renewable generation up and down, could impact the system's overall levelized cost of electricity, especially with the added capabilities of exporting that energy.

As time progresses, the infrastructure should be investigated for required upgrades in bringing the system in line with EU-2050 targets of drastically reducing carbon dioxide emissions. The introduction of electric vehicles is estimated to take a big role in designing the energy systems of tomorrow, and further research of how vehicle-to-grid operations could be integrated on an hourly basis will be highly beneficial.

Running reserves are traditionally sourced from highly-dispatchable sources, in the case of the RoC this would be gas turbines or combined cycle gas turbines, since they deliver a much lower time response. With weather forecasts advancing, the ability to predict, within a safe range, the renewable energy output of wind and solar, will allow for renewables to perform as running reserves.

Finally, Cyprus has no offshore renewable technologies in operation, and a feasibility study to determine and develop technologies that could be benefited from that would be highly influential, again, in light of the presence of an interconnector, sustaining the estimated net export status that the RoC could attain.

7. Conclusions

This report documents the academic analysis of Cyprus' energy systems, including energy flowing to and from the occupied area north of the ceasefire line. After an in-depth literature review of the energy systems, the case-studies conducted for solar photovoltaic, wind turbines and concentrated solar power, the report investigated the feasibility of the business-as-usual trend for meeting the EU-2020 targets for 13% renewable electricity generation. After demonstrating the lack of development for increasing renewables' capacity, which according to the business-as-usual trend will only reach 10.43% of renewable generation by 2020, two more scenarios were quantified and simulated.

The first pathway to 2020, is the one projected by the national energy strategy of the RoC. However, it seems to be outdated, using invalidated forecasted demand for 2020, but it appears to be matching the 2020 target regardless, at 13.88%, since initially the report was aiming for 16%.

The suggested pathway for 2020, includes only an increase in solar photovoltaics, being the most cost-effective component, and simulates a pathway where renewable generation stands at 13.13% by 2020. Development has been slow in the previous years, forcing the suggested pathway at a more realistic pace, but also a more cost-effective one; resulting in a lower net present cost and levelized cost of electricity than the national energy strategy's scenario.

The next pathway, aims at generating a fruitful transition towards 2025, adding three elements to the system: interconnector EuroAsia, IRENA's forecasted costs for renewable technologies, and the gasification of the thermal power stations. The pathway, including costs for the interconnector and the development of a 26.5% renewable share in domestic electricity consumption, has a net present cost 14.77% higher than the suggested pathway to 2020, but delivers a much lower levelized cost of electricity.

In conclusion, the national energy strategy should be re-drafted, prioritising the analysis of how EuroAsia will be utilised, and preparing the infrastructure for a higher distribution generation and ultimately vehicle-to-grid operations.

8. References

1) Atlantis Consulting, 2016. *Environmental Impact Assessment for the construction and operation of EuroAsia Interconnector: Cyprus Area,* Nicosia: Atlantis Consulting Ltd.

2) Cyprus Civil Defence Department, Ministry of Interior, 2016. *2nd Report on the national risk assessment of the Republic of Cyprus*, Nicosia: Republic of Cyprus.

3) Cyprus Energy Regulatory Authority, 2017. *Annual Report 2016*, Nicosia: CERA.

4) Cyprus Hydrocarbon Company, 2018. *Activities - Block 12.* [Online]
Available at: http://chc.com.cy/activities/block-12/
[Accessed 27 June 2018].

5) Cyprus Ministry of Energy, Commerce, Industry and Tourism, 2018. *Hydrocarbon Service - Granted Licenses.* [Online]
Available at:
http://www.mcit.gov.cy/mcit/hydrocarbon.nsf/page16_en/page16_en?OpenDocument
[Accessed 27 June 2018].

6) Cyprus Ministry of Energy, Commerce, Industry and Tourism, 2018. *Hydrocarbon Service - LNG Terminal.* [Online]
Available at:
http://www.mcit.gov.cy/mcit/hydrocarbon.nsf/page19_en/page19_en?OpenDocument
[Accessed 27 June 2018].

7) Delek Drilling, 2018. *Aphrodite Gas Field.* [Online] Available at: https://www.delekdrilling.co.il/en/project/aphrodite-gas-field [Accessed 27 June 2018].

8) Department of Environment, 2015. *EOS Project | Alassa Cyprus,* Nicosia: Cyprus Ministry of Agriculture, Rural Development And Environment.

9) EIA, 2016. *Capital Cost Estimates for Utility Scale Electricty Generating Plants,* Washington DC: EIA.

10) Electricity Authority Cyprus, 2018. *Generation.* [Online] Available at: https://www.eac.com.cy/EN/EAC/Operations/Pages/Generation.aspx [Accessed 19 June 2018].

11) Electricity Authority of Cyprus, 2014. *Annual Report 2013,* Nicosia: Electricity Authority of Cyprus.

12) Electricity Authority of Cyprus, 2017. *Annual Report 2016,* Nicosia: EAC.

13) Electriciy Authority of Cyprus, 2012. *Annual Report 2011*, Nicosia: Electricity Authority of Cyprus.

14) Eurelectric, 2013. *Power Distribution in Europe,* Brussels: EURELECTRIC.

15) EuroAfrica Interconnector, 2018. *EuroAfrica Interconnector route.* [Online] Available at: https://www.euroafrica-interconnector.com/at-glance/the-route/ [Accessed 13 July 2018].

16) EuroAsia Interconnector, 2018. *Contract Notice - Utilities,* Nicosia: Quantum Corporation.

17) EuroAsia Interconnector, 2018. *EuroAsia construction.* [Online] Available at: https://www.euroasia-interconnector.com/cable-construction/ [Accessed 13 July 2018].

18) EuroAsia Interconnector, 2018. *EuroAsia project schedule.* [Online] Available at: https://www.euroasia-interconnector.com/at-glance/project-timeline/ [Accessed 13 July 2018].

19) European Commission, 2013. *European Economy | The Economic Adjustment Programme for Cyprus,* Brussels: European Commission.

20) European Commission, 2016. *Eastern Mediterranean Natural Gas Pipeline – Pre-FEED Studies,* Brussels: EC.

21) European Commission, 2018. *European Gas Markets | Quarterly Report,* Brussels: European Commission.

22) European Commission, 2018. *Photovoltaic Geographical Information System.* [Online] Available at: http://re.jrc.ec.europa.eu/pvg_tools/en/tools.html#TMY [Accessed 17 July 2018].

23) European Union, 2009. Council Directive 2009/119/EC. *Official Journal of the European Union*, Volume 52.

24) Eurostat, 2017. *Energy balance flow for CY 2016.* [Online] Available at: http://ec.europa.eu/eurostat/cache/sankey/sankey.html?geos=CY&year=2016&unit=GWh&fuels=0000&highlight=&nodeDisagg=1111111111&flowDisagg=true&translateX=18.69040917734378&translateY=151.81998308459947

&scale=0.5&language=EN

[Accessed 15 June 2018].

25) Eurostat, 2017. *Energy balance flow for European Union.* [Online]

Available at:

http://ec.europa.eu/eurostat/cache/sankey/sankey.html?geos=EU28&year=2016&unit=GWh&fuels=6000&highlight=&nodeDisagg=1111111111&flowDisagg=true&translateX=-607.6313606428744&translateY=145.67619032048685&scale=0.8705505632961241&language=EN

[Accessed 11 July 2018].

26) Eurostat, 2018. *Emissions of greenhouse gases and other pollutants.* [Online]

Available at: http://ec.europa.eu/eurostat/data/database

[Accessed 10 August 2018].

27) Eurostat, 2018. *Energy.* [Online]

Available at: http://ec.europa.eu/eurostat/web/energy/data/main-tables

[Accessed 13 July 2018].

28) Eurostat, 2018. *Population Data.* [Online]

Available at: http://ec.europa.eu/eurostat/web/population-demography-migration-projections/population-data/main-tables

[Accessed 25 July 2018].

29) Eurostat, 2018. *Purhcasing power parities.* [Online]

Available at: http://ec.europa.eu/eurostat/web/purchasing-power-parities/data/main-tables

[Accessed 16 July 2018].

30) General Electric, 2017. *A Rapid Recovery | How EAC Restored Power in Record Time.* [Online]

Available at: https://www.ge.com/power/case-studies/eac

[Accessed 2 August 2018].

31) Haldivor Finance Ltd, 2017. *EastMed Pipeline Project: East Mediterranean region turns into Energy Hub.* [Online]

Available at: https://www.haldivor.com/news-and-publications/36-eastmed-pipeline-project-east-mediterranean-region-turns-into-energy-hub

[Accessed 2 August 2018].

32) HOMER Energy Support, 2016. *Marginal diesel generation cost.* [Online]

Available at:

http://usersupport.homerenergy.com/customer/en/portal/articles/2188636-marginal-diesel-generation-cost

[Accessed 19 August 2018].

33) HOMER Energy, 2018. *Wind Resource Variation with Height.* [Online]

Available at:

https://www.homerenergy.com/products/pro/docs/3.11/wind_resource_variation_with_height.html

[Accessed 7 August 2018].

34) IGI Poseidon, 2018. *Eastmed.* [Online]

Available at: http://www.igi-poseidon.com/en/eastmed

[Accessed 16 July 2018].

35) International Electrotechnical Commission, 2005. *IEC Classification of Wind Turbines*, s.l.: IEC.

36) IRENA, 2016. *The Power To Change: Solar and wind reduction potential to 2025*, s.l.: IRENA.

37) IRENA, 2017. *Electricity Storage and Renewables*, Abu Dhabi: IRENA.

38) IRENA, 2017. *Electricity storage and renewables: Cost-of-service tool*, Abu Dhabi: IRENA.

39) Leitwind, 2014. *LTW80*, Sterzing/Vipiteno: Leitner AG / SPA.

40) Ministry of Energy, Commerce, Industry and Tourism, 2016. *National Energy Strategy 2015-2020*, Nicosia: Republic of Cyprus.

41) Ministry of Finance, Statistical Service, 2018. *Tourism.* [Online]
Available at:
http://www.cystat.gov.cy/mof/cystat/statistics.nsf/services_71main_en/services_71main_en?OpenForm&sub=1&sel=2
[Accessed 11 July 2018].

42) Natural Gas Public Company (DEFA), 2018. *Projects.* [Online]
Available at: https://www.defa.com.cy/en/projects
[Accessed 27 June 2018].

43) P. &. P. I. & A. P. P. C. L., 2018. *Master Plan of the Vasilikos Area Update - Executive Summary*, Nicosia: Republic of Cyprus.

44) Pereira, D., 2015. *MathWorks | MATLAB Wind Rose.* [Online]
Available at: https://uk.mathworks.com/matlabcentral/fileexchange/47248-wind-rose
[Accessed 6 August 2018].

45) RECOM, 2018. *Mono Crystalline Module | Black Panther*, s.l.: RECOM.

46) Reder, M. D., Gonzalez, E. & Melero, J. J., 2016. *Wind Turbine Failures - Tackling current Problems in Failure Data Analysis.* s.l., Journal of Physics: Conference Series 753 (2016) 072027.

47) Renewables First, 2015. *What is a wind turbine project timeline?.* [Online]
Available at: http://www.renewablesfirst.co.uk/windpower/windpower-learning-centre/how-long-will-the-whole-project-take/
[Accessed 17 August 2018].

48) Santhanam, N., 2015. *Timelines of a MW Solar Project Installation in India.* [Online]
Available at: http://www.solarmango.com/2015/12/14/timelines-of-a-mw-solar-project-installation-in-india/
[Accessed 17 August 2018].

49) Solastor, 2017. *The EOS CSP Green Energy project in Cyprus,* s.l.: EOS Project.

50) Solect Energy, 2016. *TAKING THE FIRST STEP: UNDERSTANDING THE SOLAR TIMELINE.* [Online]
Available at: https://solect.com/taking-the-first-step-understanding-the-solar-timeline/
[Accessed 17 August 2018].

51) Sunlight Solar, 2014. *Solar Project Steps and Timeline.* [Online]
Available at: http://sunlightsolar.com/residential/solar-project-steps-and-timeline/
[Accessed 17 August 2018].

52) The Meteorological Resource Center, 2002. *Wind Speed Profiles.* [Online] Available at: http://www.webmet.com/met_monitoring/625.HTML [Accessed 7 August 2018].

53) Transmission System Operator - Cyprus, 2014. *Cyprus Generation and Transmission System December 2014,* Nicosia: Transmission System Operator - Cyprus.

54) Transmission System Operator - Cyprus, 2017. *Daily Load Curves by Consumer Class.* [Online] Available at: https://www.dsm.org.cy/en/cyprus-electrical-system/electrical-energy-generation/energy-generation-records/daily-load-curves-by-consumer-class [Accessed 12 July 2018].

55) Transmission System Operator - Cyprus, 2018. *Brief Description of the Transmission System.* [Online] Available at: https://www.dsm.org.cy/en/cyprus-electrical-system/the-cyprus-transmission-system-greek-version/brief-description-of-the-transmission-system [Accessed 19 June 2018].

56) Transmission System Operator - Cyprus, 2018. *Electrical Energy Generation.* [Online] Available at: https://www.dsm.org.cy/en/cyprus-electrical-system/electrical-energy-generation [Accessed 15 June 2018].

57) Transmission System Operator - Cyprus, 2018. *Long Term Forecast.* [Online] Available at: https://www.dsm.org.cy/en/cyprus-electrical-system/electrical-energy-generation/long-term-forecast [Accessed 18 August 2018].

58) Transmission System Operator - Cyprus, 2018. *PENETRATION OF RENEWABLE ENERGY SOURCES (RES) INTO THE CYPRUS ELECTRICAL SYSTEM,* Nicosia: Transmission System Operator - Cyprus.

59) Transmission System Operator - Cyprus, 2018. *The National Energy Control Centre of Cyprus.* [Online] Available at: https://www.dsm.org.cy/en//cyprus-electrical-system/national-energy-control-centre/the-national-energy-control-centre-of-cyprus [Accessed 6 August 2018].

60) Transmission System Operator - Cyprus, 2018. *Yearly Record of Total Generation.* [Online] Available at: https://www.dsm.org.cy/en/cyprus-electrical-system/electrical-energy-generation/energy-generation-records/yearly/2000-2017 [Accessed 11 July 2018].

61) Vestas, 2010. *General Specification | V90-1.8/2.0 MW 50Hz VCS,* Randers: Vestas Wind Systems | Technology R&D.

62) Vestas, n.d. *Key Aspects in Developing a Wind Power Project,* North Palm Springs: Vestas - American Wind Technology, Inc..

63) World Energy Council, 2016. *World Energy Resources - Wind,* s.l.: World Energy Council.

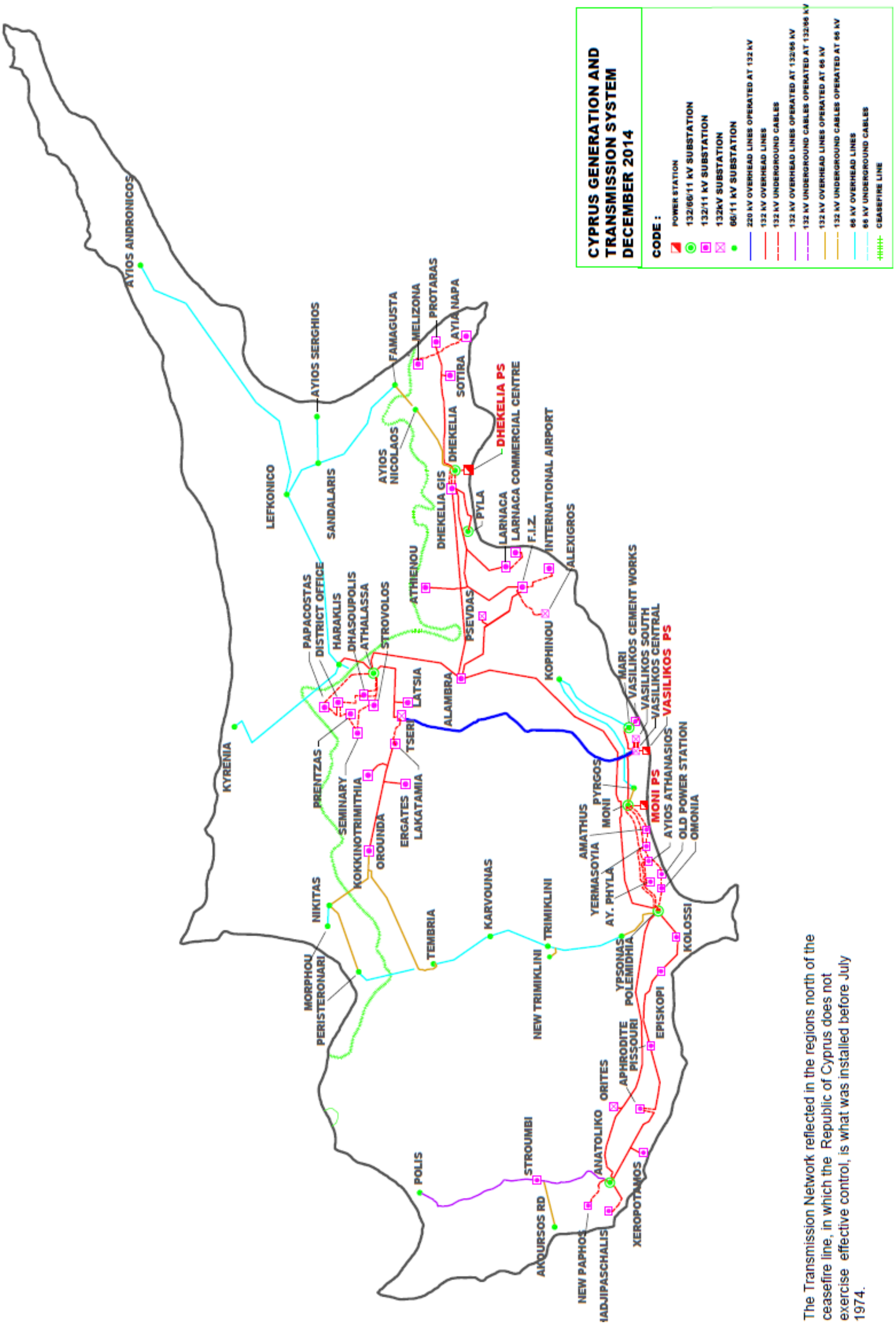
9. Appendices

9.1. Transmission Network

Table 31 - Transmission Network (Transmission System Operator - Cyprus, 2018)

Description	**Unit**	**In Commission 31/12/2012**
220kV overhead (OH) operated at 132kV	km	45.4
132kV OH	km	465.93
132kV underground (UG)	km	154.27
132kV UG operated at 66kV	km	8.12
66kV UG	km	2.35
132kV OH operated at 66kV	km	136.89
66kV OH	km	262.7
132/66kV Inter-bus transformers	No.	13
Apparent power rating	MVA	648
132/11kV Step-down transformers	No.	94
Apparent power rating	MVA	3152
66/11kV Step-down transformers	No.	56
Apparent power rating	MVA	588
Substations	No.	64

9.2. Generation and transmission system



The Transmission Network reflected in the regions north of the ceasefire line, in which the Republic of Cyprus does not exercise effective control, is what was installed before July 1974.

Figure 77 - Generation and transmission system (Transmission System Operator - Cyprus, 2014)

9.3. MATLAB source code for WindRose

Source code for analysing and generating a wind rose in MATLAB (Pereira, 2015).

```
clc; clear all; close all;

%% Check that excel.exe is not running

[~,result] = system('tasklist /FI "imagename eq excel.exe" /fo table /nh'); %Check
if the process excel.exe is running (taks manager process list)
while ~isempty(strfind(result,'EXCEL.EXE')) % If excel.exe is there, display
message
    PosibAnswers   = {'I have saved my work and manually closed excel','I cannot
close excel, kill the process'};
    Seleccion    = questdlg({'Excel is running.';'Save your work, close excel and
choose one of the following options.'},'EXCEL IS
RUNNING!',PosibAnswers{1},PosibAnswers{2},PosibAnswers{1});
    switch Seleccion
        case PosibAnswers{2} % If user wants to kill the process
            system('taskkill /IM "Excel.exe" /F /T'); % Kill the process, force
termination
    end
    [~,result]   = system('tasklist /FI "imagename eq excel.exe" /fo table /nh'); % Re
check that excel is not running.
end

%% Reading data, creating windrose, writing output table and saving image into
file.
% Read the excel spreadsheet data
ExcelName   = [pwd filesep 'wind data.xlsx'];          % Full path to Excel input file
e.g.: 'C:\Users\User1\Desktop\Wind data.xlsx'
OutputExcel = [pwd filesep 'wind data outputs.xlsx'];  % Full path to Excel output
file e.g.: 'C:\Users\User1\Desktop\Wind data.xlsx'
if exist(OutputExcel,'file'); delete(OutputExcel); end % Delete the output excel if it
exists, as a new one will be created.
[data]      = xlsread(ExcelName,'Data');

% Assign direction and speed
direction = data(:,1); % Directions are in the first column
speed = data(:,2);     % Speeds are in the second column

% Define options for the wind rose
Options = {'anglenorth',0,... 'The angle in the north is 0 deg (this is the reference
from our data, but can be any other)
           'angleeast',90,... 'The angle in the east is 90 deg
           'labels',{'N (0)','S (180)','E (90)','W (270)'},... 'If you change the reference
angles, do not forget to change the labels.
```

```
         'freqlabelangle',45};

% Launch the windrose with necessary output arguments.
[figure_handle,count,speeds,directions,Table] =
WindRose(direction,speed,Options);

% Write the output table into same excel, new worksheet
% Change OutputExcel to ExcelName if you want the outputs to be created in the
input excel.
xlswrite(OutputExcel,Table,1,'A1'); % Write into the ExcelFile the table data in
sheet 1 (you can specify a name), starting at cell A1.

% Save the figure into an image file
ImageName = ['WindRose_' datestr(now,'yymmdd_HHMMSS') '.png']; % Save
the image into WindRose_date_time.png
print('-dpng',ImageName,'-painters'); % Print = save
delete(figure_handle); % Close the widnrose figure
clear figure_handle;   % Clear the figure handle variable

%% Writing the image into excel (tricky part)
% Retrieve image dimensions
a      = size(imread(ImageName));
width  = a(2);
height = a(1);
clear a;

% Open the excel file for internal modifications
Excel = actxserver ('Excel.Application'); % handle to excel application
try
   ExcelWorkbook = Excel.workbooks.Open(OutputExcel); % Excel 2010+
catch exc
   try
      ExcelWorkbook = invoke(Excel.workbooks,'Open',OutputExcel); % Previous
versions
   catch exc2
      disp(exc.message);disp(exc2.message);throw(exc2); % didn't work. could not
open excel file for modifications.
   end
end

% Get the sheet name
Sheets  = Excel.ActiveWorkBook.Sheets;
ActSht = Sheets.Item(1); % If you specified a name for the output sheet, specify it
here again, insetad of 1.

% Convert the pixels into points
auxfig = figure('units','pixels','position',[0 0 width height]); % auxiliary figure with
dimensions in pixels
```

```
set(auxfig,'units','points'); % convert dimensions into points
p = get(auxfig,'position');   % Get the position in points
delete(auxfig);               % close the auxiliary figure
clear auxfig;
p      = p * 0.75;            % Scale factor for image in excel, change as needed.
width  = p(3);                % Width in points
height = p(4);                % heihgt in points

% Add the picture inside the excel
ActSht.Shapes.AddPicture([pwd filesep
ImageName],0,1,ActSht.Range('B1').Left,ActSht.Range(['A'
num2str(size(Table,1)+2)]).Top,width,height);  % VBA reference:
.AddPicture(Filename, LinkToFile, SaveWithDocument, Left, Top, Width,
Height)

% Close the excel file
[~,~,Ext]  = fileparts(OutputExcel);
if strcmpi(Ext,'.xlsx') % If xlsx file
    ExcelWorkbook.Save  % Save the workbook
    ExcelWorkbook.Close(false) % Close Excel workbook.
    Excel.Quit;         % Quit excel application
    delete(Excel);      % Delete the handle to the application
elseif strcmpi(Ext,'.xls') % If old format
    invoke(Excel.ActiveWorkbook,'Save'); % Save
    Excel.Quit          % Quit Excel application
    Excel.delete        % Delete the handle to the application.
end
```