2019

# Pathways for Cyprus to reach zero-carbon electricity system

## Deep decarbonization to 2050

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# Executive summary

This report's main objective is to create a roadmap for the country of Cyprus to achieve zero carbon to its electricity system by the year 2050 and by providing insights into the economic and technical feasibility of such a goal. The report will also identify the value of the proposed interconnection to Israel/Egypt and Crete and its effect on the zero-carbon goals. It becomes apparent in the report that importing natural gas to the island would bring lots of benefits to the grid by reducing the current cost of energy by 30% and emissions by 35%. Also, the integration of renewable energy, both wind and solar, can help reduce the country's cost of generation, emissions, and dependency on imported oil products. This report has shown that a zero-carbon electricity system without interconnection is possible with a lower cost of electricity than the year 2020. It has further demonstrated the potential that a 2000MW interconnection by the year 2031 can bring, where it could convert the country of Cyprus into an energy exporter and attract a lot of new investment in the renewable energy field.

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# 1. Introduction

## 1.1. Background

An islanded power system in the Mediterranean with a high dependency on fossil fuel is what describes the energy system of the Republic of Cyprus. Since the creation of Electricity Authority Cyprus (EAC) in 1952, the vertically integrated utility of the country, the electricity sector has passed through rebellion, war, and occupation of 36% of the island by Turkey.

EAC was formed in 1952 by the British government who was then occupying the island of Cyprus, though the "Electricity Development Law.". With the independence of Cyprus in 1960, EAC saw an impressive pace of electrification on the island, and the number of consumers soared from 80,000 in 1960 to 183,000 in 1973, and the number kept growing until 548,000 in 2012 . Due to the rapid expansion of the Cyprus economy from the late 1980s to the late 2000s, Cyprus saw the biggest increase in energy demand in Europe at a pace of 40%, increasing imports on oil products at a level of 8% of the country's GDP.

This oil dependency has created an extreme electricity price volatility up to 13% from 2017 to 2018 and up to 25% from 2018 to 2019. To reduce this volatility, the Cyprus government has been trying to reduce the country's dependency on fossil fuels through different efforts that include the creation of a wholesale electricity market, which will promote private investment in renewable energy by 2021, renewable PPA schemes, net metering, and net-billing schemes. Despite these efforts, the country is still massively depending on these fuels.

Since 2004 Cyprus is part of the EU, and with the country's entry in the union, it has started following the EU directives to move to a cleaner future and away from fossil fuels. As part of these efforts, the ministry of energy and environment in collaboration with EAC have started and created the national energy and climate plan for the country [4], which shows the roadmap of the country for meeting the 2030 goals that the country have set.

This report inspired by the national energy and climate plan for Cyprus will evaluate ways for the country to reach the EU's ambition to go zero carbon until 2050, considering different economic and technological assumptions as well as different policies.

## 1.2. Current system

Three main pillars are governing and running the electricity system in Cyprus, EAC mentioned above as the vertically owned utility, an independent Transmission system operator (TSO), and the Cyprus energy regulatory authority (CERA). EAC owns 99% of conventional generation on the island, the transmission and distribution (T&D) system, and the metering infrastructure of the island. The TSO was separated as an independent operator in the mid-2000's in efforts to create an electricity market in Cyprus and to operate the transmission of electricity in the island and the creation of CERA was done to regulate the electricity market, EAC and the privately own companies that will enter the market.

According to the EAC's annual report in 2018, the grid in Cyprus is currently serving 576,000 consumers with total electricity sales of 4,568 GWh and a peak load of 928MW. The current generation system relies mostly on fossil fuels that include the use of heavy fuel oil and gas oil. The generation technologies that are currently being used in Cyprus are Combined Cycle Gas Turbines (CCGT), Steam turbines (ST), Gas Turbines (GT) and internal combustion engines (ICE). According to statistics published by the TSO in 2019 these technologies served 90.3% of all load and only 9.7% has been served by renewable energy. The 9.7% of renewable energy penetration contains both wind farms and solar connected to the distribution system both behind and in front of the meter solar (Figure 1). The estimated carbon emissions in 2018 from the electricity system based on the current technology reached 2.70 million tons of Co2, which makes the Co2 intensity of the grid at 530gCo2/kWh. This intensity rate makes it significantly higher than the European average at being at 295gCo2/kWh[2].

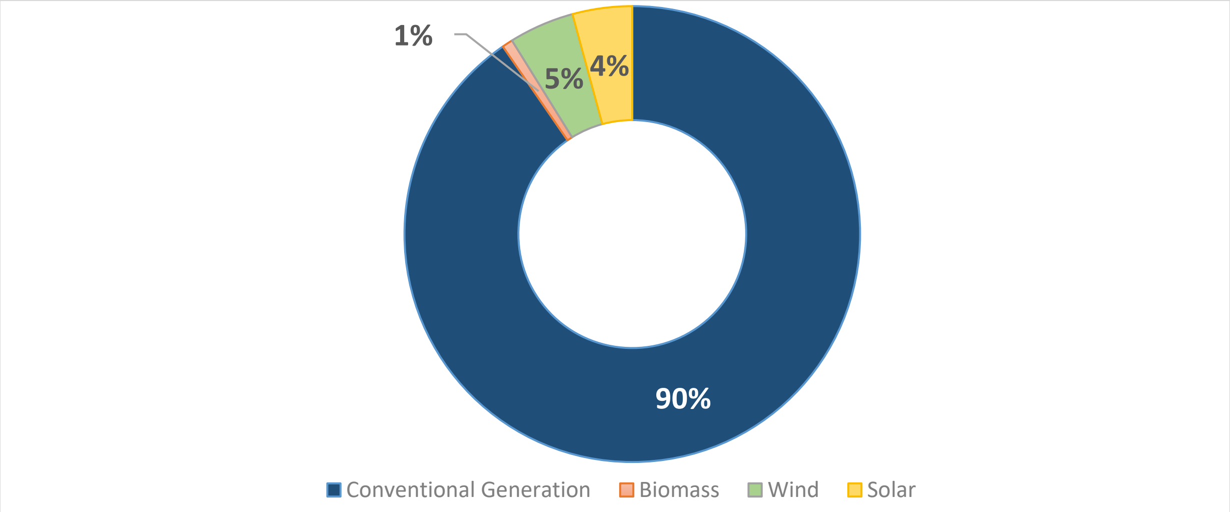

*Figure 1. Generation mix of 2019 [3]*

## 1.3. Policy & Regulation

Current policies and regulations in Cyprus are leading the renewable energy efforts through the goals set by the government and directive guidelines from the EU. The government has set the goal that 13% of the generation mix in Cyprus will be coming from renewable energy by 2020. However it is still unknown if the country will be able to achieve these goals, since in 2019 the generation mix was 9.7%(up 0.7% from 2018 [3]) , and a jump of 3.3% from 2019 to 2020 seems too optimistic. These goals set by the government also include targets for transportation, energy efficiency, and other carbon-emitting sectors that will not be analyzed in this report.

Through the integrated national energy and climate plan of the country [4], the government has set new 2030 goals for the country together with Regulation 2018/842 and the Paris agreement to reduce the country's carbon emission at least to 40% since 2005. These goals include all the carbon-emitting sectors of the economy that participate in the Emission trading system, and this includes at least 32% of renewable energy by 2030.

In March 2020, the European Union proposed an aggressive carbon-neutral goal by the year 2050 through a law that would ensure all countries in Europe emit zero carbon by then. This proposal, also called for the European green deal, that was suggesting the allocation of one trillion Euro in the European investment fund which is dedicated to helping meet these goals. Furthermore, the European climate law [4] has set goals set by the special report created by the Intergovernmental Panel on Climate Change (IPCC), calling for zero carbon goals by all countries until 2050, and the EU wanted to be the first continent following that goal.

## 1.4. Objective

The objective of this report is to provide insights and an indication of the path that Cyprus is currently following with existing policy and how the country can reach goals set by the EU for zero carbon emissions by 2050 in the most cost-effective way. Furthermore, the report will give insights of how an interconnection to a neighboring country can help Cyprus in reaching these goals (as planned by the Euroasia interconnector and Euroafrica interconnector) and will check the effects that these environmental regulations will have to the cost of energy.

The main objective of this report will be to reach these goals most economically, taking into account the climate constraints described below and making sure the system remains reliable to operate.

# 2. Study Scenarios

## 2.1. Overview of Load

This report will try to shed light on a path for the country of Cyprus to reach zero carbon by the year 2050, and this will be done firstly by identifying the future energy and peak load needs of the country and the resources that will be needed to be incorporated in the system to keep it running reliably. For each scenario that will be described below, the system was modeled for three different periods, 2030, 2040, and 2050 with a different set of constraints and objectives for each year in each scenario.

To identify the future energy and peak load needs of the country, historical data until 1994 were retrieved. These data included historical energy needs, peak load needs, the population of the country, Gross domestic product (GDP), and cooling degree days. These variables were chosen based on work done by other similar papers by utilities in different regions, and the reasoning behind these variable can be found in the methodology section of the report.

The peak load in Cyprus has seen rapid growth from the late 1990s to mid-2000 due to the booming economy of the country. The country entering the European Union and subsequently opening its gate to foreign investment is the main reason for that growth. However, after 2010, the country started feeling the ripple effects of the US recession of 2008 with the country's lowest point being in 2013. Furthermore, the Mari in 2013 explosion destroyed the largest power plant in the country, making around 30% of the countries power production unusable. It is fascinating seeing how all these events affected the peak load demand and energy usage of the country.

In Figure 2, the forecasted demand growth of the system can be seen until 2050. The current dispatchable capacity of the system is 1489 MW plus another 268MW of non-dispatchable generation. Important milestones that can be viewed in Figure 2 are the following. The 2021 switch in fuel of a large proportion of the generating capacity to natural gas, In 2023 due to large retirement of power plants projected load will surpass the dispatchable capacity and there will be a need for new generating capacity Another important milestone is in 2038, were all current dispatchable generation will retire and the need to replace the whole generating fleet will be required. In Table 1 below, the deficit that would exist for the three-time periods that were modeled is shown. By the year 2040, all the current power plants will retire, which will force decision-makers to make some serious decision regarding the future electricity grid in Cyprus.

| YEAR | 2020 | 2030 | 2040 | 2050 |
|---|---|---|---|---|
| **PEAK LOAD (MW)** | 1165 | 1370 | 1560 | 1775 |
| **CAPACITY (MW)** | 1480 | 1120 | 0 | 0 |
| **DEFICIT (MW)** | - | 250 | 1560 | 1775 |

Table 1. The deficit of dispatchable generation

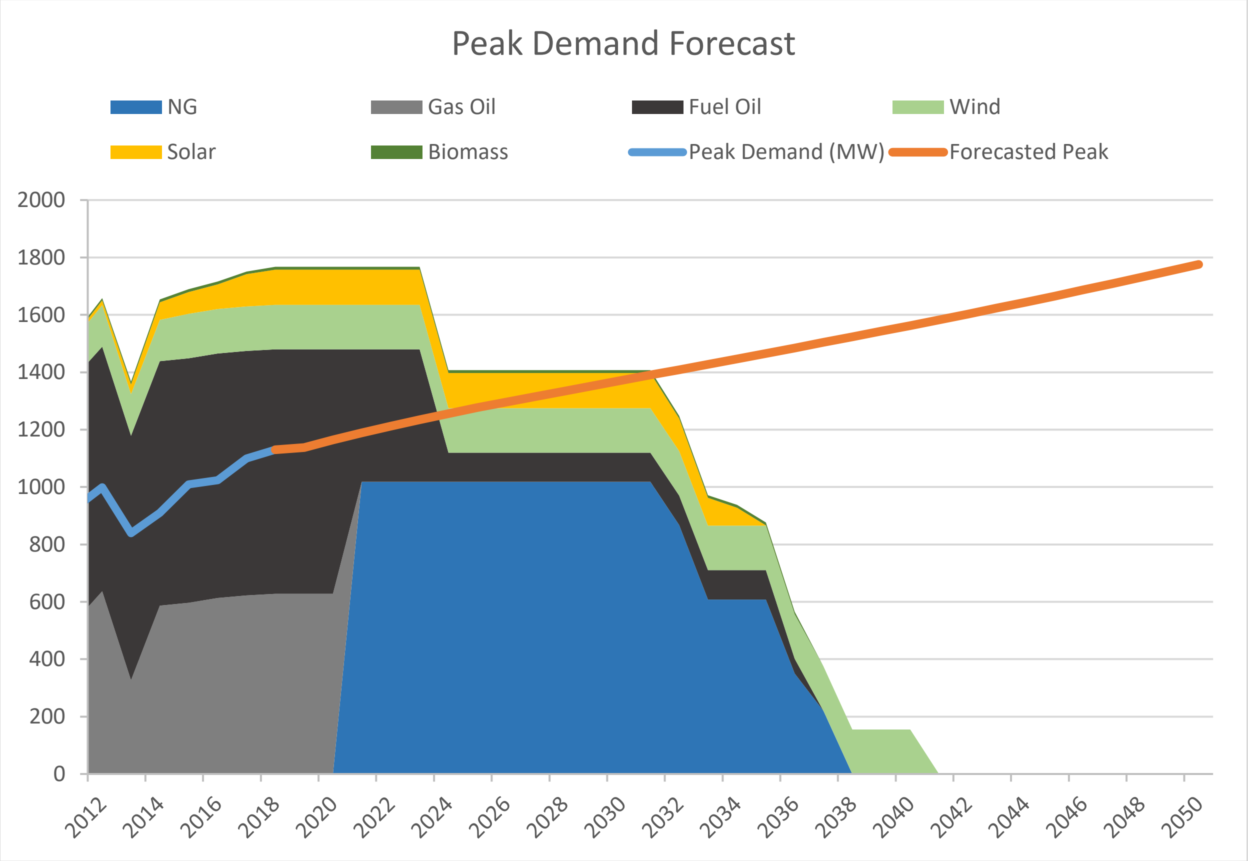

Figure 2 Load forecast until the year 2050 with each generation mix

### 2.2. Scenario overview

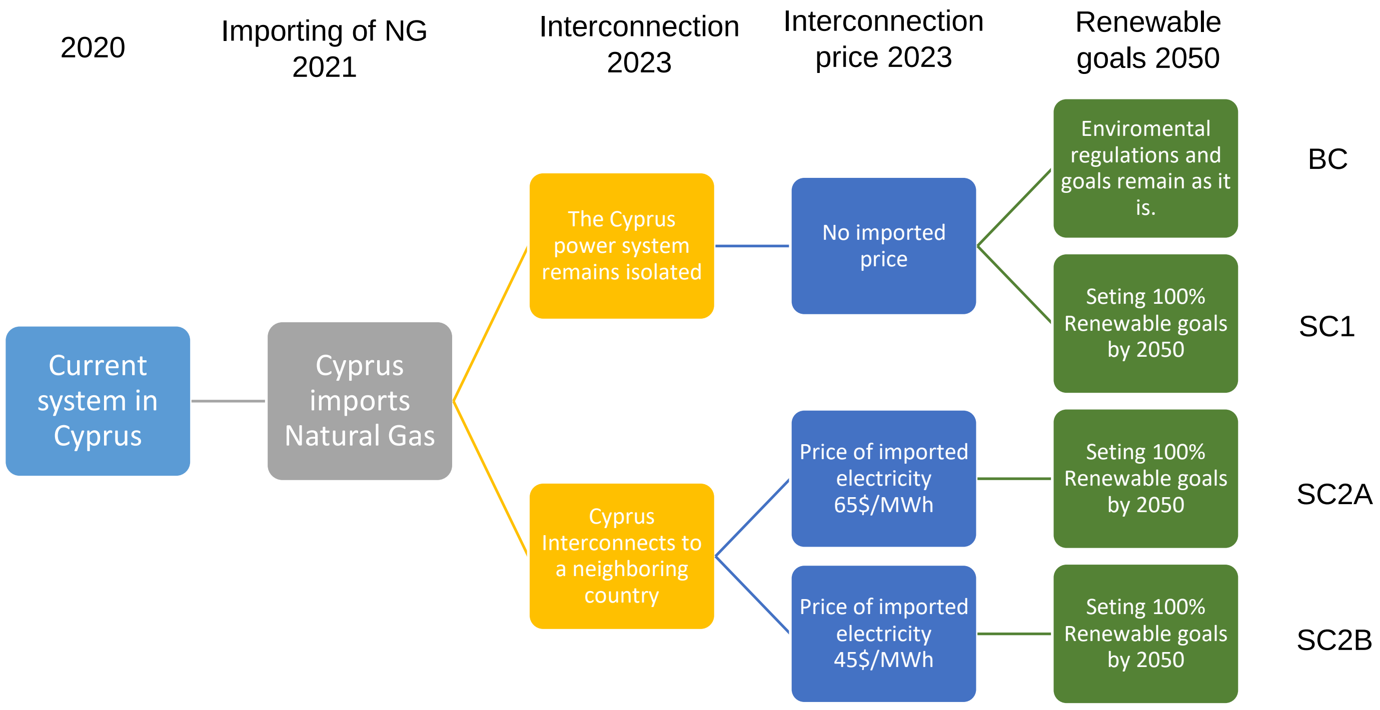

Figure 3. Scenarios

This report will focus mainly on 3+1 scenarios that will take a closer look at the Cyprus grid. These scenarios will try to show how the grid with current regulations and policies will be by the year 2050, also how would the island's grid look like if the country and policy-makers decide to implement zero-carbon goals by 2050 to the electricity sector and finally the report will try to identify and quantify the value that interconnection will be able to bring to the grid itself. Furthermore, the introduction of natural gas to the current generation mix of the country is another aspect that will be analyzed by this report. The introduction of natural gas will not only reduce the price of generation to the current grid but will also reduce the country's emissions to a large extent.

My reference scenario, which will be called the Base case (BC) scenario will show the current path of Cyprus to meet growing load and retiring generation by the year 2050 without additional new environmental policies and regulations in a cost-centric modeling exercise. This scenario will be the business as usual scenario that would follow the mentality that currently exists in Cyprus.

In the first scenario (SC1) of the report due to aggressive environmental goals that were set by the European Union, Cyprus will need to identify and find a way towards their 100% renewable goals. For the average European countries, there are many ways to reach these goals; however, for the island, this is a challenge, and especially if the country would like to keep utility rates low. Therefore, this scenario will provide the cheapest and most effective way for Cyprus to go 100% renewable while keeping the grid reliable.

The second scenario that was modeled for this report was split into two different scenarios SC2A and SC2B. Both these scenarios will show the 2050 grid of Cyprus with 100% renewable energy plus an interconnection. The proposition to interconnect Cyprus and Israel/Egypt and Cyprus and Crete have been in the pipeline for quite some time now, and this interconnection will certainly help the country move to its sustainable goals. The difference between Scenario 2A and scenario 2B will be the importing/exporting price of the electricity. Sensitivity testing was conducted for the different importing and exporting prices because of the variability in electricity prices in Israel and Egypt. The sensitivity test has created 2 different scenarios . In scenario 2A the cost of imported electricity will be 65$/MWh, and for scenario 2B the cost of imported electricity will be 45$/MWh. Dynamic exporting prices were created for these two scenarios, where at peak times (9-5pm) exporting prices were at 25$/MWh and 15$/MWh for scenario 2A and 2B respectively and at off peak times prices of 40$/MWh to 25$/MWh were set. The main reasons that dynamic exporting prices were created was that solar energy in all 4 countries would occur at the same time and all four have excellent solar resource capabilities. The price of electricity in both Egypt and Israel varies and will change in the future due natural gas being extracted by both countries and the further interconnections between them.

All 3+1 scenarios were created to help achieve the project objectives stated above and show the four different paths that the electricity system in Cyprus could take to 2050.

## 2.3. Base case scenario

The Base case scenario in this report is the business as usual case following the current state of the policy and regulation of the country, with the main goal being to drive the cost of electricity as low as possible. The reason the country is trying to reduce the cost of electricity is the fluctuation of oil prices in the past few years and the increase in electricity cost due to these fluctuations. The avoided cost of electricity in Cyprus has surged from 77.12€/MWh in January 2018 to 115.3€/MWh in January 2020. This 50% increase in these two years can all be accounted to the increase in oil prices. This is the reason that the currently policy-makers and regulators have set their goals to drive the cost of electricity as low as possible. This scenario will show which technologies will be needed to be built to meet the 2050 peak load at the lowest cost. The integration of renewable energy in this scenario will not be part of a mandate in this generation mix but rather through the economics of renewable energy, making it cheaper in some cases than conventional generation plants. A healthy reserve margin in generation capacity will be kept at 30%, which is an excellent assumption based on the historical reserve margins, which will be further analyzed in the next chapter.

## 2.4. 100% Renewable scenario 1

According to the European Union's plan for the future of the union for 2050, a 100% renewable scenario is a very plausible scenario coming for all EU member countries. This scenario (SC1) has its difficulties with many people stating that this goal is unreachable, but different integrated resource plans from utilities that have also set the same goals have shown otherwise. These goals will not be easy to reach by the countries, however, with innovative solutions and the right planning, the goals can be reached and will not cost the ratepayers a fortune, which is another argument being stated by critics. As stated, reaching these goals will not be easy for countries, especially countries that are not interconnected and islanded countries such as Cyprus. Being isolated from other grids has been hard on the Cyprus grid for many years forcing EAC to overbuild capacity and marginal planning reserves to extremely high levels of peak demand. Table 2 below shows the planning reserves from 2013 to 2019, and the country has been trying to keep the planning reserves above 30%, which is a healthy margin for an isolated grid.

| *Year* | *Installed Capacity (MW)* | *Peak Load (MW)* | *Reserve (%)* |
|---|---|---|---|
| *2013* | 1448 | 840 | 72% |
| *2014* | 1458 | 910 | 60% |
| *2015* | 1470 | 1009 | 46% |
| *2016* | 1475 | 1016 | 45% |
| *2017* | 1484 | 1100 | 35% |
| *2018* | 1493 | 1070 | 40% |
| *2019* | 1499 | 1074 | 40% |

Table 2. Reserve margins of the Cyprus grid stated by the TSO [6]

For this scenario, the report will try to shed some light on how the country can reach 100% renewable goals with the current state of the grid without interconnections while keeping the planning reserve margin of the system at 30%. The generation technologies that would be reviewed for these scenarios will be current renewable technologies that exist in the system such as Solar, Wind, Biomass and CCGT with renewable gas with the addition of energy storage in the form of Li-ion batteries and pumped storage. In this scenario, energy storage and interruptible load will need to be incorporated in the generation mix to reduce curtailment levels that could reach more than 30% of the system energy generated due to overbuilding in renewable energy to meet demand and the 30% planned reserve. The interruptible load that could be used by the country to mitigate the curtailment of renewable energy is another topic that could be discussed in another report. The interruptible load could be in the form of desalination of water to avoid droughts in the island which happen every few years due to heat waves storming the country in the summer, demand response programs that could be incorporated by EAC, the productions of renewable gas and biofuels, or a combination of the methods mentioned above.

## 2.5. 100% Renewable with Interconnection (Scenario 2)

Interconnection is key to the current EU plan to reach 100% renewable energy and reduction of greenhouse gases (GHG's). The European Commission is currently mandating until 2030 countries to have at least 15% of interconnection to other countries to help reduce their emissions. Cyprus, with the help of European funding, is trying in the next five years to interconnect the island to neighboring countries through undersea cables with Israel and Crete with the Euroasia interconnector and to Egypt through the Euroafrica interconnector. The Euroasia interconnector has started procuring the first connection to Israel, and it is aiming to connect the country and to commission the cable in 2023 with a total capacity of 1000MW of imports and exports. Interconnection will prevent the reserve problems that were stated in SC1, a further interconnection by the year 2031 is expected for another 1000MW. This connection will help prevent the country from overbuilding generation and generate value to better optimize better the new generation mix that will be built to meet the 100% renewable goals of the country. An essential aspect of the interconnection will be the price of electricity imported, and that is why this scenario was split into two parts SC2A and SC2B were developed to test 2 different price points of imported electricity and how these price difference will affect the future generation mix of the country and how much the country rely will on importation of electricity. The two price ranges of the electricity price that were inserted in the model for scenario SC2A and SC2B were 65$/MWh and 45$/MWh, respectively, for each scenario.  Another difference between SC2A and SC2B is the exporting prices. Dynamic exporting was created for the model so that during hours that there is a heavy overproduction of renewables which is usually happening between 9-5pm because of solar then the exporting price would be lower since the other countries that this energy will be exported to will have also production from renewables. These dynamic prices were set as 40$/MWh and 25$/MWh for scenario 2A and 2B respectively during off-peak and 25$/MWh and 15$/MWh during on peak. Extra transmission costs for importing and exporting the energy were considered by the model.

# 3. Analytical Basis

## 3.1. Methodology

To create the conditions for answering the objectives that were set by this report an integrated resource plan (IRP) towards the year 2050 was created to identify gaps between future supply and demand of the load and figure a plausible way to match those two. Utilities all around the world create IRPs to demonstrate their 10-15-year plans for filling missing capacity and their future plans for meeting demand. Figure 4 will demonstrate an overview of my methodology and the modeling practice I used to create this IRP.

The development of this IRP started with load and resource analysis, including finding the power plants that currently exist in the country and analyzing their technical and economical specifications. The load analysis consisted of current and historical load demand data published by EAC and TSO. After the load and resource analysis, load forecasting for the year 2050 was done to identify the load deficit by that year using a multiple regression model. Defining assumptions was a big step for this modeling exercise since these assumptions determine the outcome of the model. Some of these assumptions were the future capital and variable cost for each generating technology and future fuel costs. To ensure the assumptions were reliable, consistent sources such us the International Renewable energy agency (IRENA) and National renewable energy laboratory (NREL) were used. After defining the assumptions of the model, the scenarios were created based on environmental and technological constrains. These scenarios were made considering realistic predictions of how the grid of Cyprus will look at the year 2050. Adding hourly renewable generating data for future wind and solar resources were added through simulated wind and solar data taken from Renewable Ninja. This simulated data was taken from proposed areas where new renewables could be added and were good-quality wind or solar resources exist. All the above-mentioned data were taken and were integrated in a capacity expansion model to find the results.

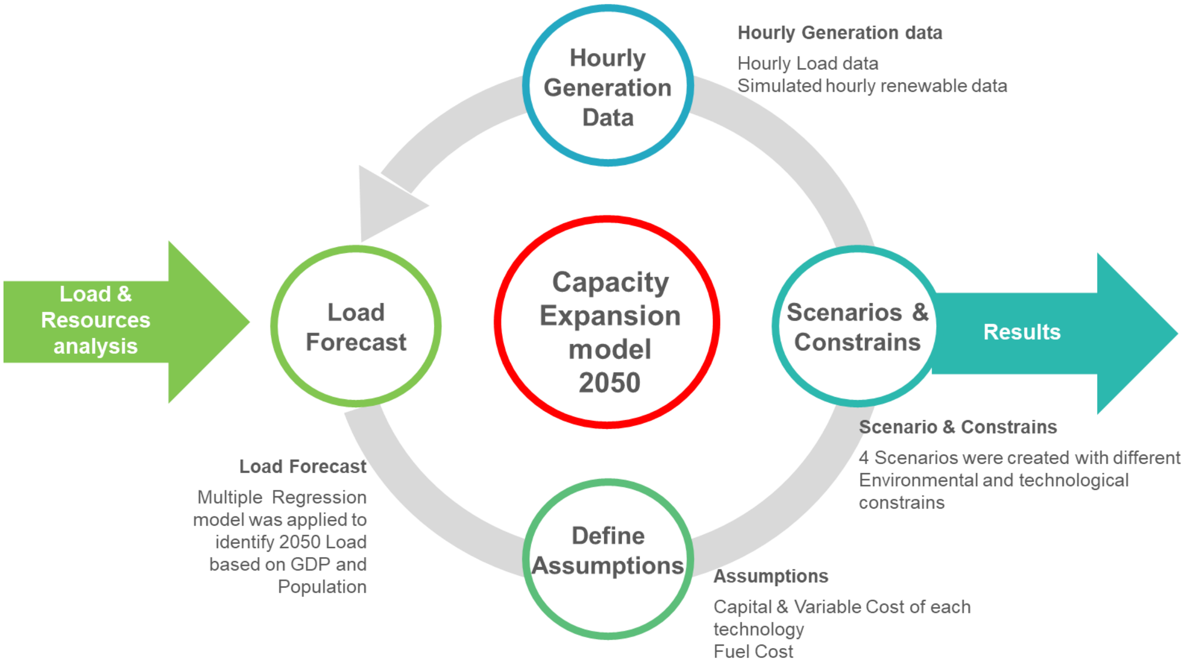

Figure 4. An overview of my methodology to create the IRP

The Capacity expansion model was used to find the results for this report, which is a widely used method by many reports such us Annual Energy Outlook from EIA for 2015 and many IPCC reports.

## 3.2. Loads and resources

One of the IRP's goals is to identify future capacity shortages and energy needs of the country. To best identify the deficits of the system firstly we need to identify the current resources and load. The current resources can be split into two categories, dispatchable capacity and non-dispatchable capacity. Both categories can be used to provide the energy needs of the country's load, however both categories cannot be weighted the same way in meeting capacity needs of the system. Dispatchable generation as the name suggests can be controlled and therefore can be used to cover 1 to 1 the load requirements. Non-dispatchable generation such as Solar and wind, which in the early capacity installation offer value to generation capacity similar to dispatchable generators, however with increasing the megawatts of non-dispatchable generation the value they have in comparison to load capacity decreases. This can be viewed in Figure 5 below you can see the percentage of capacity that each Megawatt of solar and wind will have with increasing the overall capacity. It is clear that by adding more solar more and more it loses the capacity value it can provide to the grid, unlike wind which seems to remain constant until 1500MW where capacity value starts to drop.

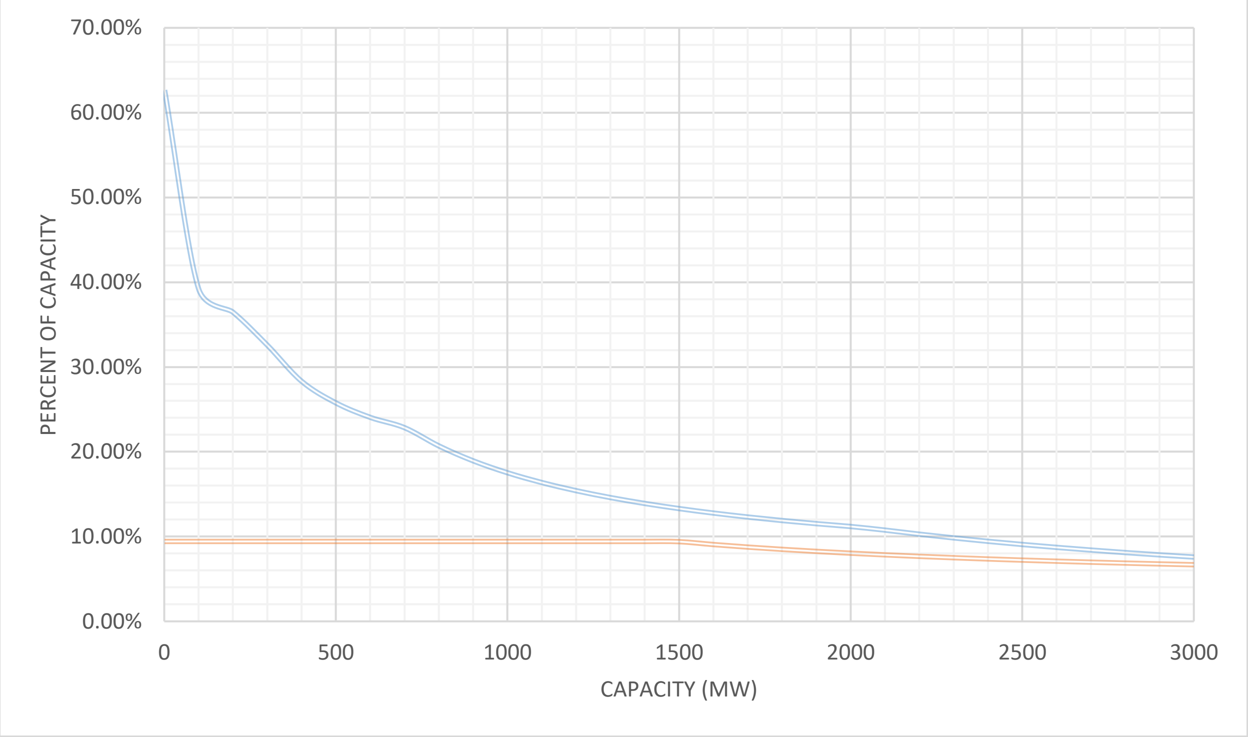

Figure 5. Capacity value based on capacity

## 3.3. Load forecasting

Load Forecast in Integrated resource plans is a way to help provide a link between long term investments and operating needs for the grid This forecast will allow us to see the uncertainty that exists in the current grid, the uncertainty that exists for the future of the country until 2050 and how renewables will affect the grid. Load forecasts in different IRPs have different variables that would affect the future load, such as Historical sales, cooling degree days, heating degree days, population growth, electricity prices, gross domestic product, and many more. The variables that were used to forecast the future load were the ones that have historically affected the Load in Cyprus, which are the historical sales and load, the gross domestic product (GDP) of the country, the population of Cyprus and finally the cooling degree days of the country. These variables were chosen as part of the load forecasting process because of the correlation found between them and the peak load of the country. Historical data were taken into consideration from 1994 regarding the variables used, and a multiple regression model was used to identify the trend of future load growth. Forecasted values for Population, GDP, and cooling degree days were used for the load forecasting based on data gathered from European statistical reports. The method that was used for forecasting the load of Cyprus by 2050 was the top-down method, wherein many utility load forecasts are being used with great success. The actual load forecast has been already demonstrated in figure 2 in the previous chapter.

## 3.4. Assumptions

Assumptions that were included in the model were fuel costs, capital costs for each technology, and variable cost for each technology. All the data regarding cost were acquired by IRENA's renewable energy roadmap for the republic of Cyprus [7], which assumes fuel costs until 2035, and the same assumptions were continued until the year 2050. Fuel costs that were used for each year can be viewed in Table 3 below. Biomass was a fuel cost that was not provided by IRENA's fuel cost projections, but this was calculated based on current biomass prices in Cyprus plus a 0.5% increase per year. The technology to produce biomass and biofuels such us renewable gas is heavily invested nowadays and in the near future, and as a result, there might be a decrease in future biomass and renewable gas prices; however, they were not taken into consideration in this model. Further investigation in Biomass/biofuel prices and land use can be done in another report because these are the fuels that can also be used in a reduction in fuel dependency on transportation. A carbon price was also set due to the cap and trade program that is currently in place in the European Union and projections for the carbon price, and the allowances were set based on EU projections [9] with price in 2020 being 10$/tonCO2 and reaching prices of 70$/tonCO2 in 2050.

| **YEAR** | | **2020** | **2030** | **2040** | **2050** |
|---|---|---|---|---|---|
| **NATURAL GAS** | $/MMBTU | 9.9 | 10.2 | 10.8 | 11.4 |
| **GAS OIL** | $/MMBTU | 17.3 | 18.5 | 20.7 | 22.9 |
| **FUEL OIL** | $/MMBTU | 12.04 | 12.9 | 14.3 | 15.7 |
| **BIOMASS** | $/MMBTU | 25 | 26.3 | 27.6 | 29.0 |

Table 3. Fuel costs used in the model

Cost assumptions for renewables such as Solar, Wind and Biomass were taken from the Techno-economic electricity supply model for Cyprus [8], and assumptions for energy storage (Li-ion) were taken directly from Tesla's new pricing on their utility-scale solutions. Storage solutions will play a huge role in the Base Case and SC1 due to the lack of interconnection; in the other two scenarios, storage is still incorporated in the mix, however, on a much smaller scale due to cost. Below in Figure 6, the projected renewable cost is presented.

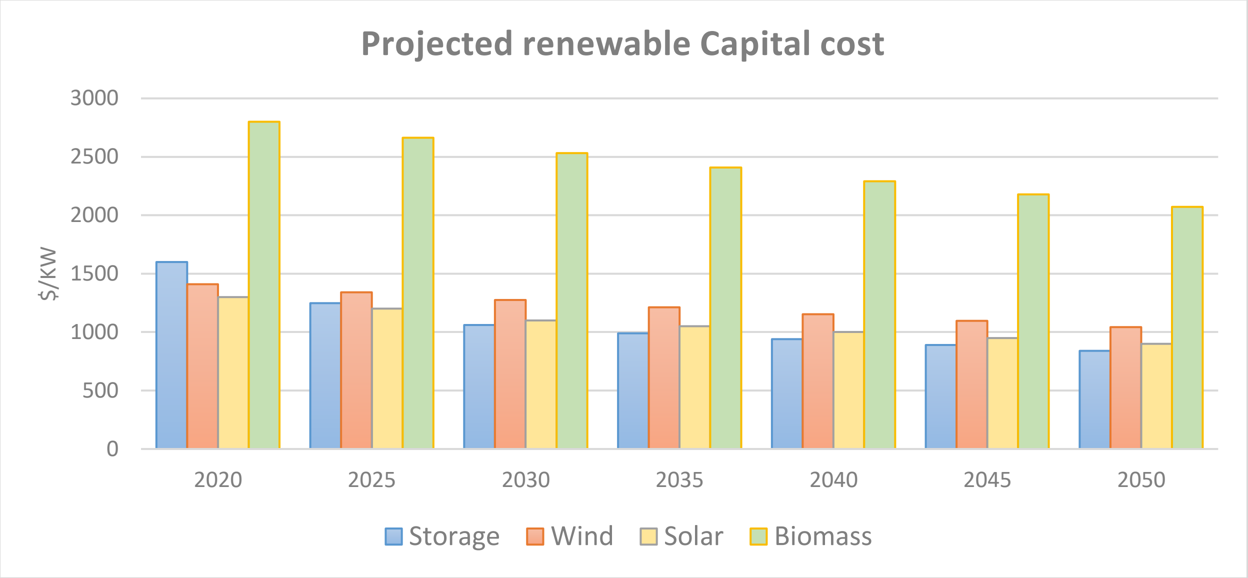

Figure 6. Projected renewable capital cost

As can be seen from Figure 6, significant breakthroughs in capital cost are not expected in the future except for some reduction in energy storage, where 4-hour battery storage has seen massive cost reductions due to economies of scale and ramping up production for Electric vehicles. Battery storage in the model is only assumed as 4-hour storage. Pump hydro is also incorporated in the model based on Poullikkas 2013 [9], and it is incorporated only in SC1 due to again the lack of interconnection and the need for long term storage and higher levels of dispatchable load. In other scenarios, pump storage due to the low capacity factors described by the Poullikkas paper and the high cost, it was not economical in the mix.

# 4. Study Results

## 4.1. Overview

Staring with an overview of my results can be seen in Table 4 seen below that shows an overview of the capacity that is proposed to be built by the year 2050.

| Scenario | 2020 | BC 2050 | SC1 2050 | SC2A 2050 | SC2B 2050 |
|---|---|---|---|---|---|
| CCGT (GW)<br>*Uses renewable gas | **0.4** | **1.1** | **1.1*** | **-** | **-** |
| GT (GW) | **0.3** | **0.8** | **0.6** | **-** | **-** |
| ST (GW) | **0.75** | **-** | **-** | **-** | **-** |
| ICE (GW) | **0.1** | **-** | **-** | **-** | **-** |
| SOLAR (GW) | **0.1** | **1.7** | **3.9** | **2.2** | **2** |
| WIND (GW) | **0.15** | **2** | **1.6** | **5.1** | **3.6** |
| STORAGE (GW) | **-** | **0.3** | **2.3** | **-** | **-** |
| BIOMASS (GW) | **0.01** | **-** | **0.1** | **-** | **-** |
| PUMP HYDRO (GW) | **-** | **-** | **0.13** | **-** | **-** |
| IMPORT (GW) | **-** | **-** | **-** | **2** | **2** |

Table 4 Overview of the generation capacity for the year 2050

As we can see from the Table the current capacity mix in 2020 consist of a combination of Combine cycle gas turbine (CCGT), Gas turbines (GT), steam turbines (ST), internal combustion engine (ICE), solar, wind and biomass. As we saw from the load forecast in chapter 2 the projected load deficit for the year 2050 will be 1775 MW and this capacity deficit will be fulfilled by the Base case through 1.1GW of CCGT installation, almost triple the current capacity replacing the 750 MW of Steam turbines that currently exist, also the addition of 0.8GW of Gas turbine will be needed as Peaker plants to cover reserves and peaks. A more than tenfold increase in the current solar and wind capacity will help supply large part of the energy needed to the system without any environmental mandates only taking into account the cost benefits that this technology will bring to the system.

Looking at Scenario 1 in 2050 we can see that 1.1GW CCGT that will be built after the year 2020 would need to be supplied with renewable gas (synthetic natural gas or substitute natural gas) to avoid having stranded assets into the system. This renewable gas can be synthesized through curtailed energy or excess energy that the massive amounts of renewables will have through the 3.9GW of solar and 1.6GW of wind. In this scenario 1 the 100% renewable scenario we can see that there is a big need for solar and it is the scenario with the highest capacity of solar, this is because the solar can synergize very well with the 2.3GW of 4 hour storage that will be installed to cover part of the reserve and supply the system with cheap solar energy. This scenario as mentioned above has also a 130MW installed of Pump hydro, that will be used as seasonal storage.

Moving on to Scenario 2A and 2B it is clear in both scenarios that conventional generators will be replaced by the interconnection that will happen that will be able to provide up to 2000MW after the year 2031 and a large portion of the generation will be from renewable energy since it will be cheaper to produce some of the energy in Cyprus. In both scenarios Cyprus will export heavily to the interconnected areas the extra renewables and it will be able to supply part of energy needs from them and from imports also.

In Figure 7 below we can see the capacity mix for all 3 test years of 2030, 2040 and 2050. This graph shows a great representation of generation mix that will be needed to meet all constrains and scenario requirements. As we can see in the Base case a steady investment in the 4 main technologies is seen of CCGT, GT, Solar and Wind is the right mix that would provide the cheapest electricity to the ratepayers. Something very interesting that can be viewed here is that Scenario 1 and the Base Case show great similarities until the year 2040 with the capacity mix for both scenarios. In scenario 1 we can see that reaching the 60% 1990s Co2 levels by the year 2040 seem like a very plausible scenario and that would be the optimal, however moving from the 2040 environmental goal to the 2050 goal of zero carbon emissions we can see there is a big leap of technologies that would be added to the mix to help reach these goals. In that last decade for scenario 1 there will be a need for heavily investment in renewable gas that will be able to supply the 1.1GW of CCGT that would be online at the time and heavy investment in energy storage will be needed. Another thing we can see in 2050 for SC1 is the heavy overbuild of renewable to cover part of that capacity that will be needed with the 30% reserve margin that was added as part of the constrains. The reason for overbuilding capacity was also seen in further detail in Figure 5 that shows the capacity value that renewables bring on the capacity mix.

Scenario 2a and 2b do not differ from the results shown in table 4 with steady increase in the capacity of renewables over time setting Cyprus as a net exporter.

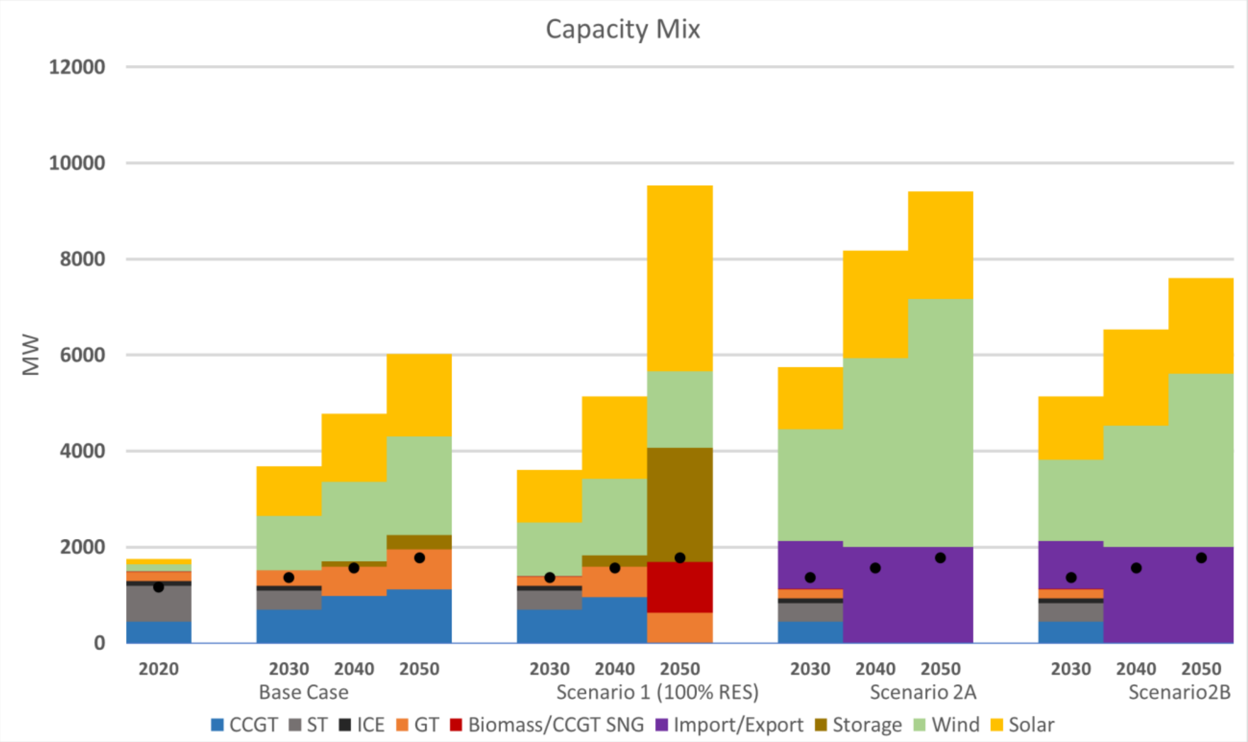

Figure 7 Capacity mix for all three test years

The generation mix seen in Figure 8 below will shed some more light to the way each generator is dispatched and the influence each generator will have in the system.

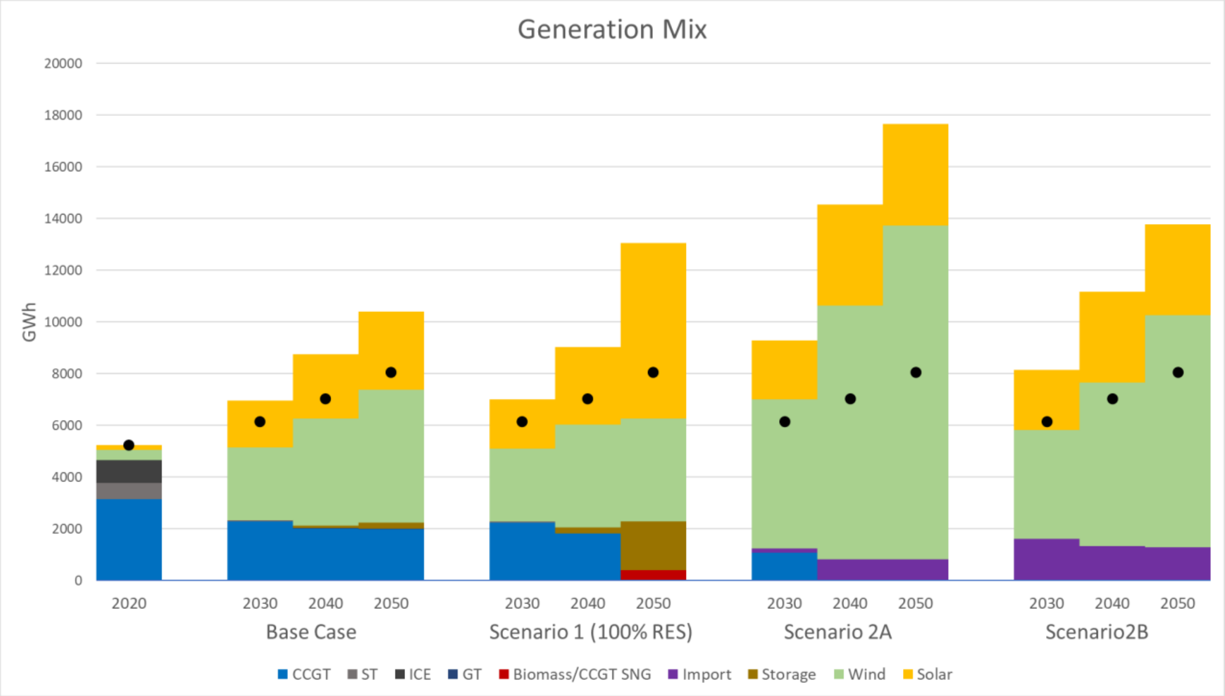

Figure 8 Generation mix for all scenarios

The generation mix in Figure 8 shows a different story from the capacity mix that we saw above. If we start from the Base case a mix of Combine cycle power plant solar and wind are the main generators that can be seen with wind increasing the generation percentage it occupies slightly every 10 years and the addition of small amounts of storage can be seen from 2040 and even more significant in 2050. As it was noticed also in the capacity mix SC1 and BC are following again the same pattern until the year 2040 and by the year 2050 we can see that solar increases by lot to supply the energy for the energy storage that has replaced large parts of the energy provided by the CCGTs and the CCGT with the renewable gas are dispatched in very few occasions. In scenario 2A and 2B it is visible that in both scenarios due to the volatility of renewable energy importing parts of the energy needed will be essential for the reliability of the grid even with massive overbuild of renewables. In this figure exports are not visible and they will be presented further into the report. The black dot again represents the energy needed in GWh for these test years and it is obvious in the graph that overproduction of renewables is happening in all scenarios and especially in Scenario 1, were curtailment of energy in massive amounts is to be expected due to the lack of interconnection. In scenario 2A and 2B curtailment is not visible due to a large part of the overproduction that is happening being exported.

## 4.2. Scenario Results

A great way of understanding the variability of each generating technology though the year based on each month is with hour-month graph. This graph will show a better representation of the generation mix shown above with the variability of the months. Below hour-month graphs will be presented for the year of 2050 that will help shed light and help understand the way that different generators will be dispatched in each month of the year and show the variability of renewable energy during the different months.

### 4.2.1. Base Case

Figure 9 below shows the hour-month graph for the Base case. The base case is as described above the business as usual scenario following current environmental regulations that exist today and optimizing generation based on cost-centric approach. In this scenario a combination of CCGT, wind, solar and small amounts of storage are being dispatched. This figure confirms the results we have identified in the previous 2 figures by showing solar and wind fulfilling most of the load with high penetration of combine cycle power plant filling gaps that exist and the small amounts of storage fulfilling peaks and ramps that happen after 3 in the afternoon were the sun goes down and solar production is reduced substantially. Due to extreme variability in wind energy in the winter it is clear that peaks in the winter sometimes require CCGT and storage to fill the average load shown in the graph and sometimes the wind energy is adequate for it. Summer load as we can see are due to reduction in wind energy especially in August and September being filled with CCGT and storage.

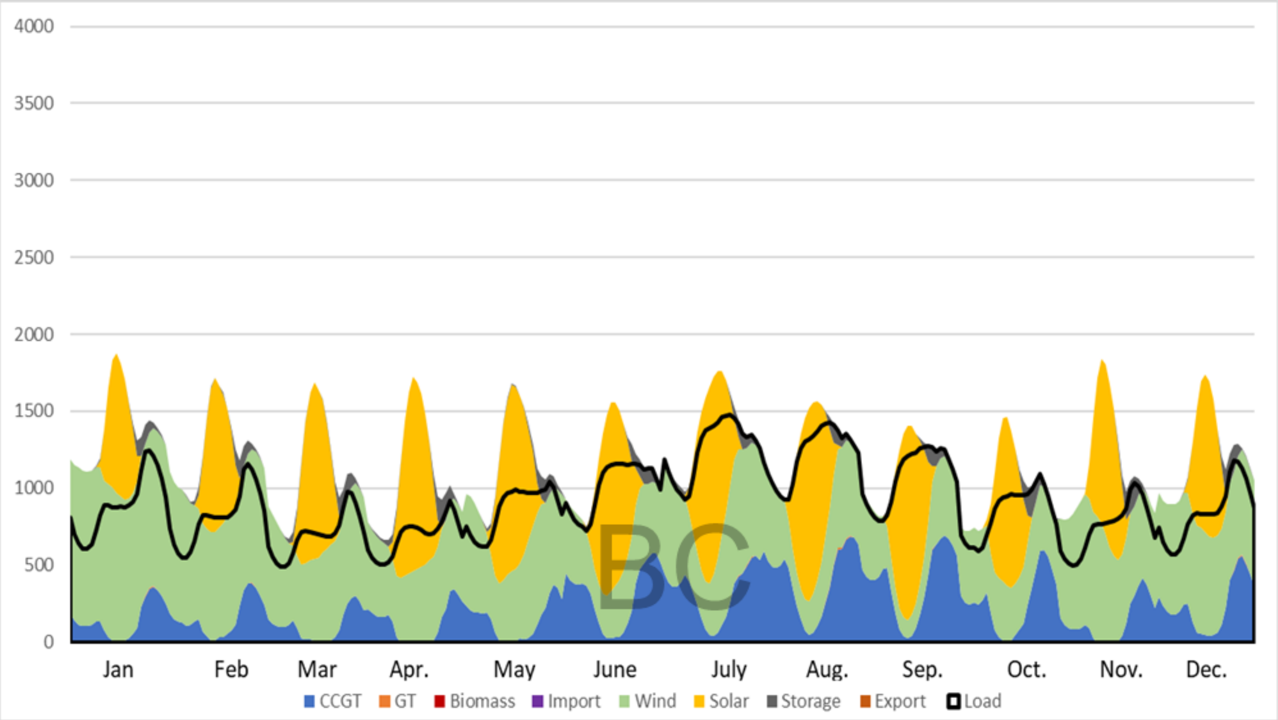

Figure 9 Hour-month graph for the Base Case scenario

### 4.2.2. Scenario 1

In Scenario 1 Figure 10 will show the hour-month graph and present the variability between the months with the pure renewable scenario. In this figure Solar and storage dominate the generating capacity for the whole year with small variability between summer and winter. Wind again acts as the base load of the country's generation and peaks are being met through the combine cycle power plant that would run on renewable gas. Due to the higher prices of renewable gas that come closer to biomass the CCGT are being dispatched only when needed and allow solar plus storage to fill the rest. The spring and fall months that have higher amounts of wind and solar together rather than the summer and winter show that the CCGT with renewable gas is rarely used those months, however the CCGT is  required to fulfill part of the reserves of the country.

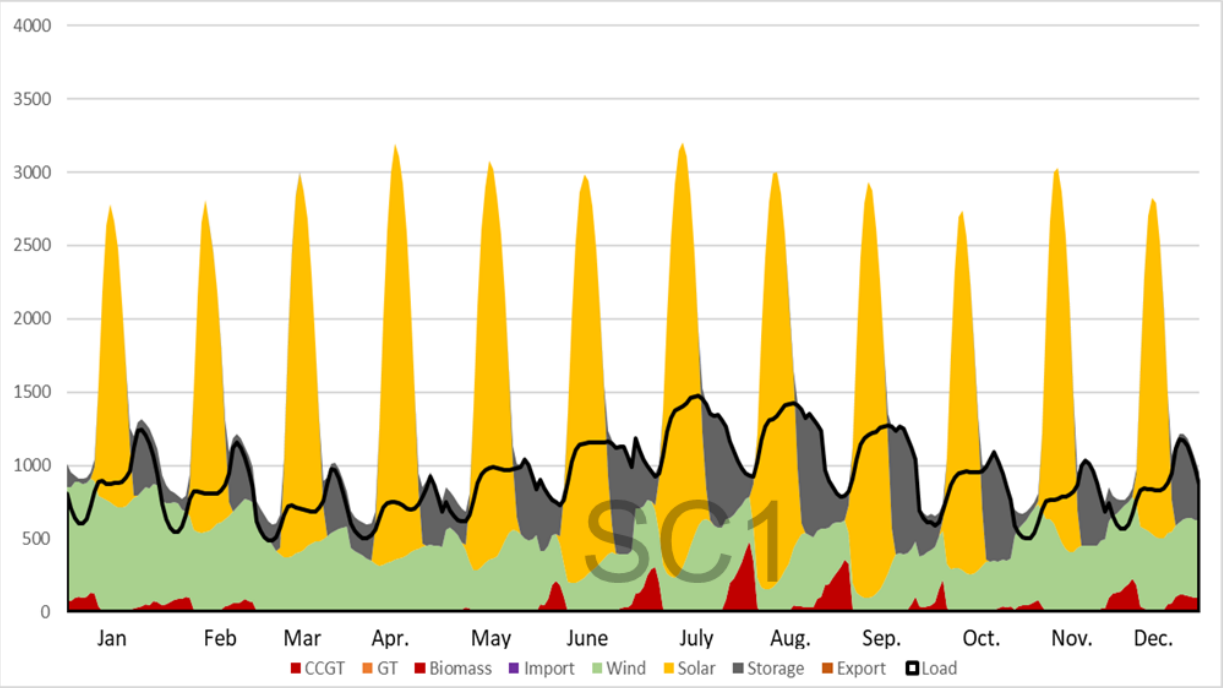

Figure 10. Hour-month graph for Scenario 1`

### 4.2.3. Scenario 2A

In Scenario 2A importing prices were set 65$/MWh 20$ higher than Scenario 2B and it is expected a higher percentage of exports since importing and exporting prices are more expensive. Figure 11 confirms the theory with the generating mix oversupplied by renewables mostly wind energy because of the higher premiums that are paid exporting at off-peak times. Due to variability of renewables and cost effectiveness of importing energy it is necessary sometimes and especially were peaks occur. The ability to import and export provides also great reliability to the system and as can be seen in the figure below can make the country into a net exporter of energy to the large energy markets that the country will interconnect to. Israel and Egypt have peak load of 11.5GW and 29.4GW respectively and can easily absorb such small amounts renewable energy that could be supplied to these countries. In this scenario import percentages reach 10% due to the higher prices; export levels reach 95% and curtailment 12%. These levels indicate the country depending very little on importing energy but heavily depending on lower electricity prices by exporting excess electricity.

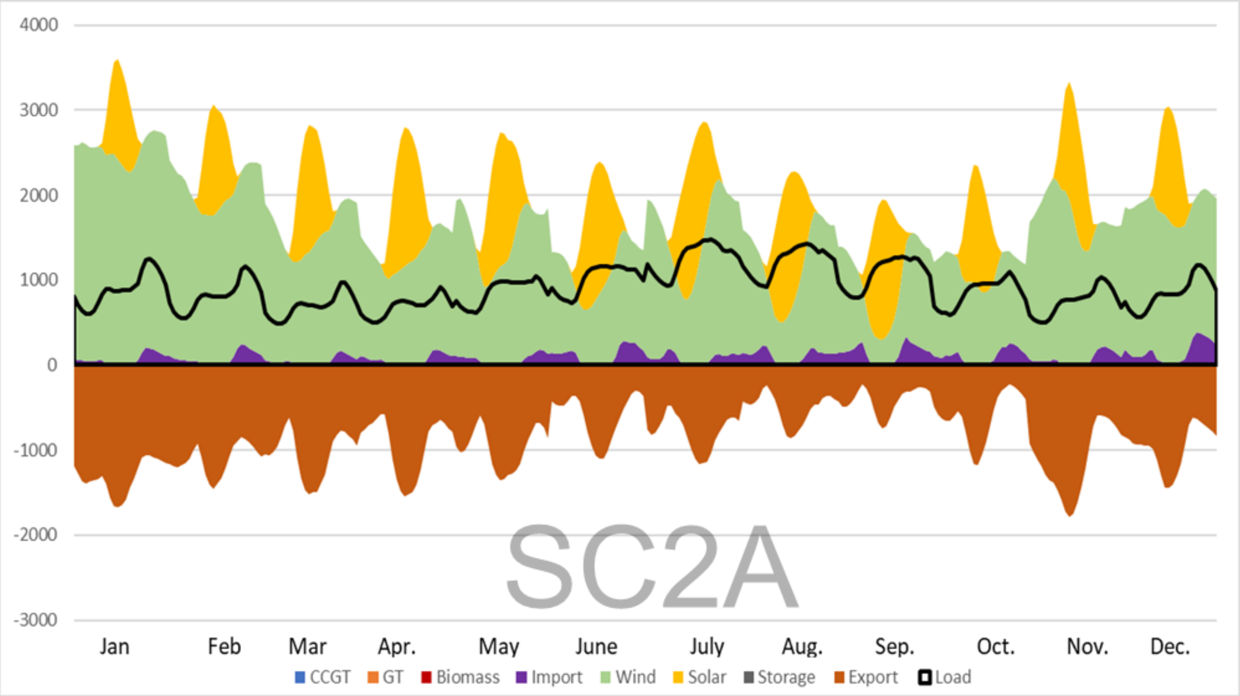

Figure 11. Hour-month graph for Scenario 2A

### 4.2.4. Scenario 2B

In Scenario 2B in Figure 12 the graph seems remarkably similar to scenario 2A, which was expected. The main differences are the dependency of the system more to imports since importing prices are lower than the previous scenario lowering also exports due to the lower prices making overbuilding for renewables less expensive. The same pattern of a combination of solar and wind fills the base load of the country with peaks being met again by imports. In this scenario consist of 16% of total generation of the system and exports can reach up to 65% and curtailment can reach 4%. These numbers represent again that Cyprus will become a net exporter of energy and curtailment is kept at exceptionally low levels due to the dynamic export prices. Overbuilding solar in this case and wind that would increase also exporting in off-peak price but will also increase on-peak production becomes uneconomical after this point.

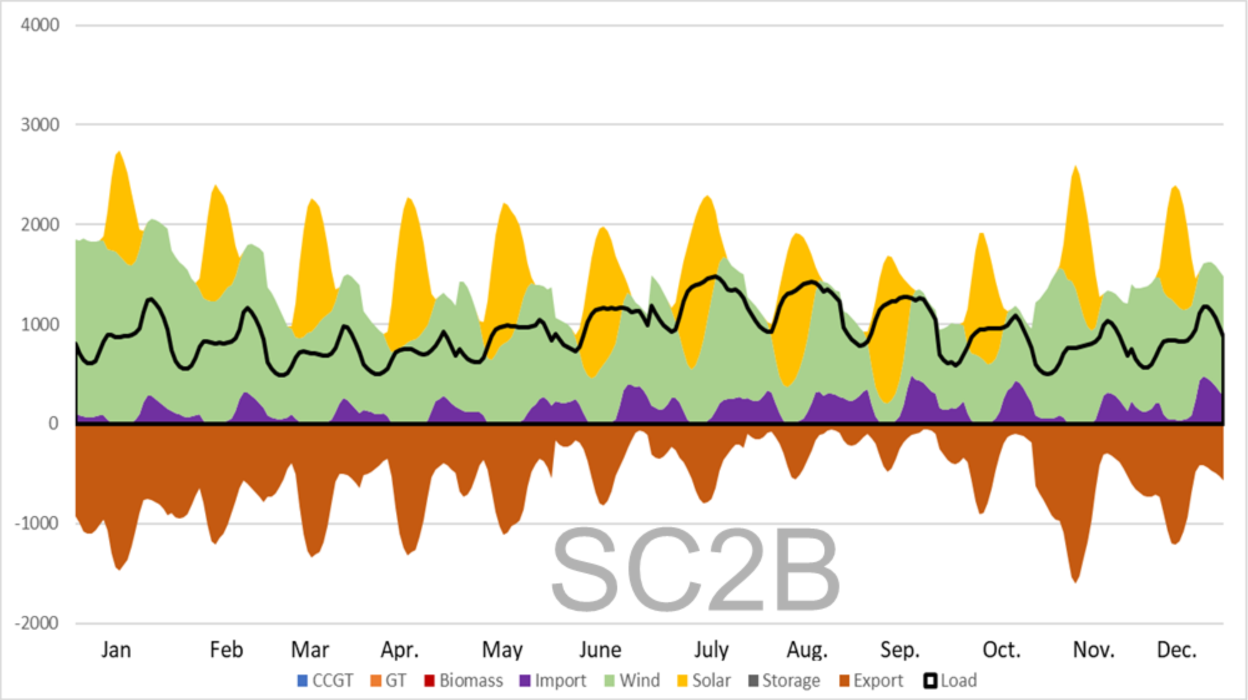

Figure 12. Hour-month graph for Scenario 2B

## 4.3. Cost & Economical Analysis

Part of the project objective was to compare the scenarios based on the cost that all these scenarios and the effect this changes to the grid will have on the country and the cost of energy. Therefore, in this chapter a detailed analysis of the cost of all the systems and the investment cost will be checked.

### 4.3.1. Cost Analysis

Taking firstly the cost of the system in each scenario a great representation for that can be seen in Figure 13. Some very obvious results that can be viewed in the figure below are the 2021 milestone, were natural Gas is introduced to the island. With the fuel change there is a reduction of 30% in the cost of energy from 142$/MWh to 98$/MWh due to the Combine cycle power plants working with greater efficiency due to the new fuel and the lower fuel cost that natural gas will have over gas oil from 17.4$/MMBTU in 2021 to the 9.9$/MMBTU. This reduction will come at millions of dollars of investment cost to create the infrastructure that include the Floating Storage Regasification Unit (FSRU) to import the natural gas to the country and the pipelines that will connect the power plants to the FSRU.

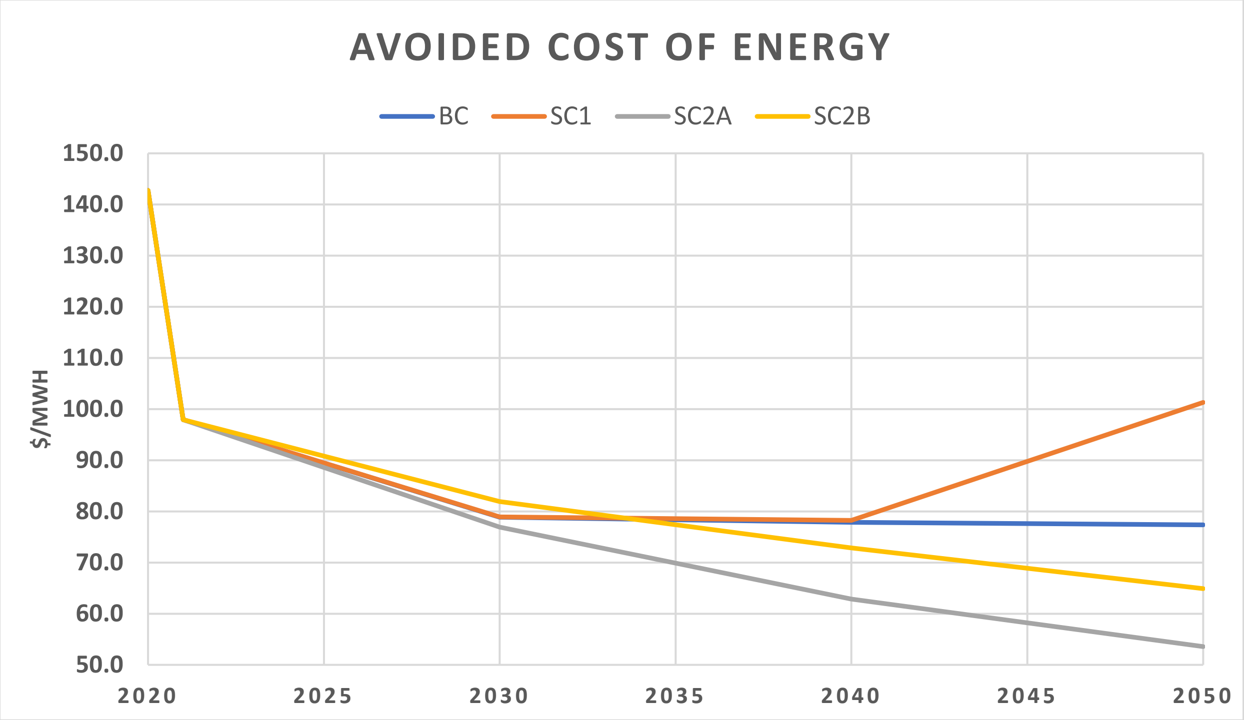

Figure 13 Avoided cost of energy for each scenario.

If the year 2030 is taken under the microscope it is visible that all 4 scenarios will reduce even further the cost of energy due to optimizing generation and based on the new fuel that will join the energy mix of Cyprus with the Base case scenario and Scenario 1 having exactly the same cost and continuing that trend until the year 2040. This is because the goals set in Scenario 1 with 32% RES by the year 2030 will provide the most economical solution for the country by that year and again with the environmental goal of reducing the country's emissions by 60% from the 1990s lever by the year 2040. This means that by continuing the current mentality of choosing the most cost-effective generating technologies to be deployed in the grid of Cyprus the country can reach its environmental goals. BC and SC1 starting at 2040 start changing values since with current technologies completely decarbonizing the country comes at the cost. The Base case avoided cost continues to drop even after the year 2040 reaching its lowest point at 2050 at 77.4$/MWh. This number is almost half of the current cost of electricity and can be achieved in the next 30 years. Scenario 1 as we saw in the previous part of the report due to the rapid increase of energy storage in system's mix and the conversion of part of the combine cycle plants to using more expensive renewable gas to fulfill capacity and reserve the cost of energy increases by the year 2050 to 101.3$/MWh. This number is lower than today's number by 28% even with the added environmental constrains. Scenario 2A can be seen starting from 2030 having lower cost than all the other scenarios and the reason is the 65$/MWh that converts to 103$/MWh marginal cost for importing the energy by the year 2030 will still be lower marginal cost than the existing Steam turbines, Gas turbines and Internal combustion engines that will still be operational by the year 2030. Scenario 2A combines the cheap prices that the CCGT with natural gas will bring in the system which will have marginal cost of around 80$/MWh and the importing energy replacing the inefficient power plants that run with other fuels and because of exporting excess renewables that will be built by the year 2030. Continuing down the timeline for SC2A building more and more cheaper renewable and exporting this energy out of the country helps reduce the cost even further reaching the avoided cost of energy 53.5$/MWh by the year 2050. In Scenario 2B the mix mostly shows that the lower importing prices replace completely all generation including CCGT completely from the mix due to lower marginal cost reaching 79$/MWh for importing the energy which will be lower than the CCGT, and this increased avoided cost of energy that is seen in the figure is because exporting the energy has a lower price than in SC2A. Moving to the year 2050 the avoided cost line of SC2B follows the decline SC2A follows due to the same reasons, retirement of the current generating capacity and reduced cost of building renewable without overproduction problems and curtailment problems the exist in Scenario 1.

### 4.3.2. Economic Impact

In this part of the report the economic impact of these scenarios to the country and EAC will be analyzed. The investment graph below in Figure 14 will provide some insights to these economic impacts.

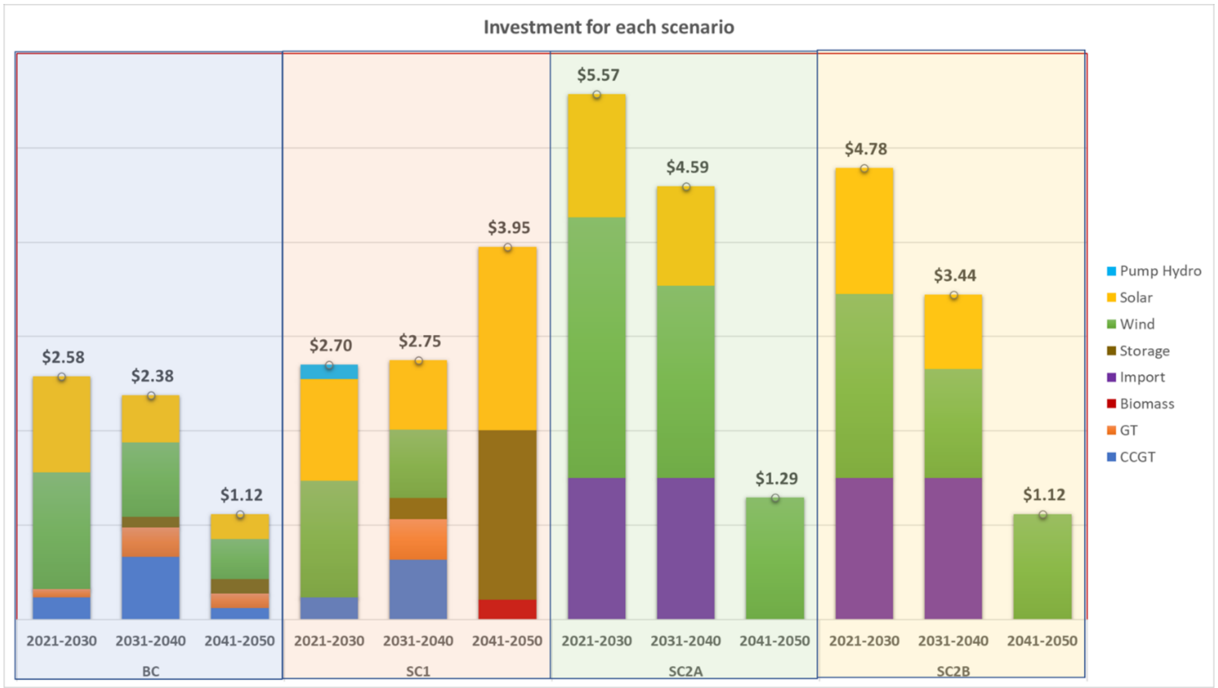

Figure 14. Investments cost for each scenario

In the figure above we can see investment in the base case remains steady at around 2-2.5 billion dollars every ten years from 2021-2040 and then dropping to 1.1 billion in the last decade. As it is expected Scenario 1 follows the same pattern until the year 2040, however in the last decade from 2041 to 2050, there is an almost doubling of investment in Solar plus storage technology and some biomass that will provide the last piece for completely decarbonizing the electricity system of Cyprus. This doubling in investment can be seen as increasing the levelized avoided cost of energy in Figure 13 and as we can see this is something that will be felt by ratepayers and utility rates will increase due this cost of decarbonization. In contrast to scenario 1 the two other scenarios, SC2A and SC2B we can see that even from the year 2021-2030 investment amounts will more than double reaching 4.7-5.5 billion dollars in investment split between Solar, Wind and the interconnection, however if we see in Figure 13 the cost of energy will continue its downward trend. This means that a lot more money will come to the economy of Cyprus through investments in renewable energy because of the opportunity that the country will have to become a net exporter. The 5.57 billion dollars that are shown from the year 2021-2030 for SC2A are the 22% of the country’s GDP in investment and this money will enter the Cyprus economy helping increase GDP growth to the country without increasing cost for ratepayer.

## 4.4. Emissions

Part of my project objective was to identify pathways for the country to reduce its emissions and this part will show the emissions produce by each scenario and how emissions will evolve through the years based on the different environmental constrains of each scenario. Figure 15 below will show emissions for each scenario. Again the 2021 milestone was remarkably interesting to view, were emissions dropped by 35% from the year 2020 just from the introduction of natural gas to the mix and following a downward trend for both scenario 1 and Base case until the year 2030. After the year 2030 emissions remain almost constant for the Base case until the year 2050 with a minor decrease reaching 0.7 Million tons Co2 per year which is in fact the current European environmental goals reducing 60% of the country's emissions to the 1990s level. Scenario 1 precisely follows the emissions of the base case and after 2030 has a steeper downward slope with emissions reaching 0 at 2050. Surprisingly, Scenario 2A and 2B have an even steeper slope than the other 2 scenarios due to the interconnection replacing "dirtier" and with lower efficiency generators due to the marginal cost differences that were discussed in the previous part. Another surprise that can be seen in the figure below is that the interconnection can help the country reduce substantially its emissions and reach the zero-carbon mark between the year 2030-2040, which is the era that all current dispatchable generation will retire making the generation mix that we saw above solely supplied through Imports, Solar and Wind.

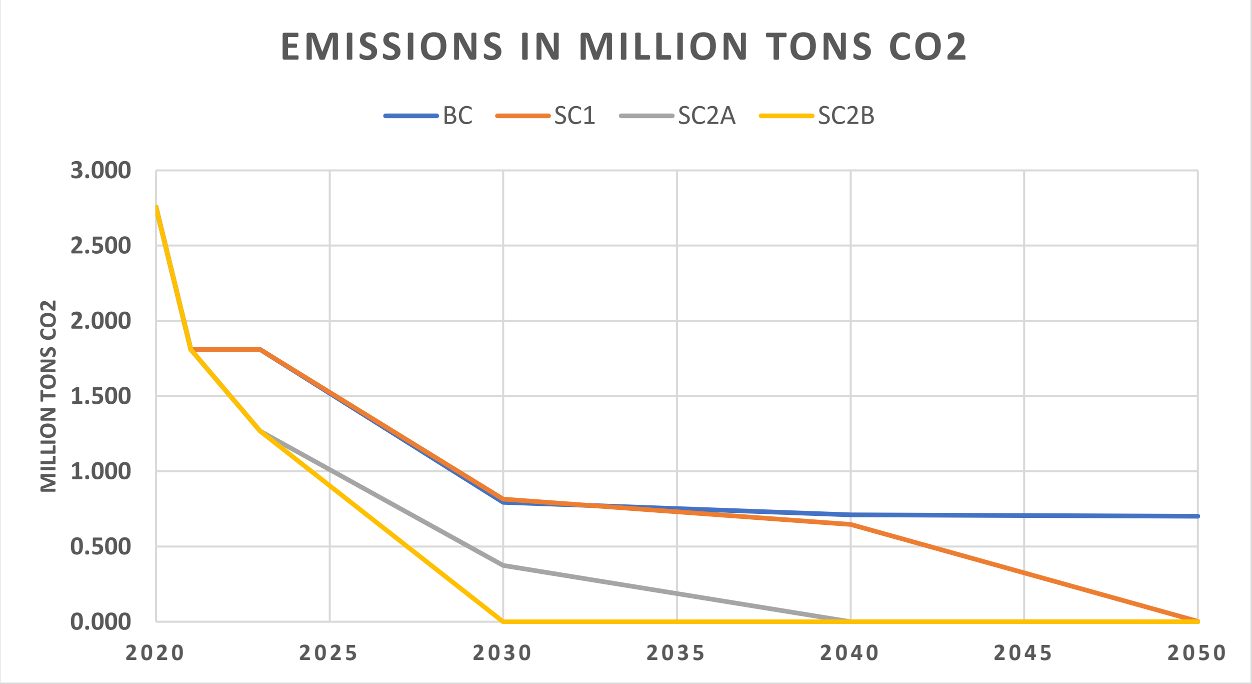

Figure 15. Emission of Co2 for each scenario

## 4.5. Land use

Something that came as a question during the development of this model was land use. Cyprus, as a small divided country, has limited available land to be used, especially for massively intense area uses such us building massive amounts of renewables. Figure 16 below will show some of the land requirements that each scenario will have based on current renewable land use in Cyprus. Land use is a complicated matter, and integration of a GIS tool to the capacity expansion model that would set more constraints on land use can help in the future development of this model. Something that was incorporated in the figure below is due to the current occupation of the island by Turkey, a buffer zone controlled by the UN that exists in the country, and this buffer zone spans for 346 km2, which can help increase in the future land-use constraints on the model..

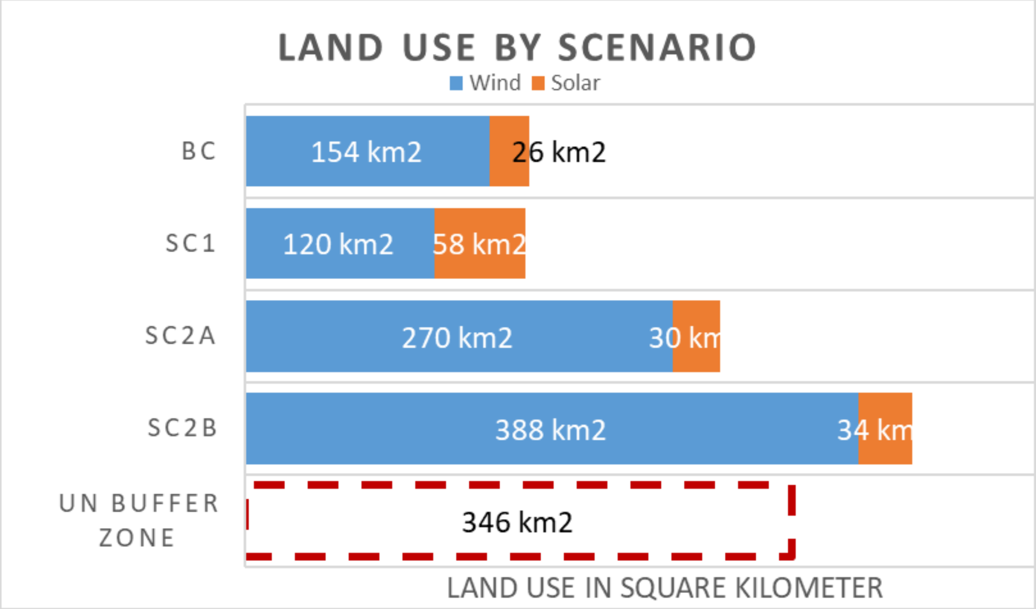

Figure 16. Land use per scenario for each renewable technology.

# 5. Conclusion

Concluding this report, the Cyprus grid will benefit economically and environmentally a lot through the importation of natural gas in 2021 with a reduction of 30% in the avoided cost of energy and a 35% reduction in emissions through just that one investment. The European environmental goals set in 2030 and 2040 will affect mildly the path that Cyprus is following right now considering the projected slight reductions in the cost of renewables through the years. An aggressive zero carbon goal without interconnection is not a wildly expensive scenario and does not increase the avoided cost of energy more than the 2020 level. Furthermore, interconnecting the country will allow Cyprus to become a net exporter in the region, pulling investments reaching ~20% of the nations GDP in the next ten years without increasing the cost of energy. Interconnection can also help accelerate the country's emission reduction and help the country reach zero emissions by 2040. The cost of electricity in the best-case scenario (SC2A) can be as low as 53.6$/MWh, 62% lower than today.

Through this report, more areas to research and model came into consideration that could be incorporated in a future report. These areas include:

1. Offshore wind
2. Renewable gas production and other biofuels
3. Incorporate land use constrains and hourly renewable generation data through GIS software.

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# Appendices

## Appendix I

Nameplate capacity in MW for each scenario.

This will show how much capacity must be installed per decade

### BASE CASE SCENARIO

| **YEAR** | | 2020 | 2020-2030 | 2030-2040 | 2040-2050 |
|---|---|---|---|---|---|
| **CCGT** | MW | 440 | 260 | 727 | 135 |
| **GT** | MW | 188 | 131 | 469 | 225 |
| **ST** | MW | 750 | - | - | - |
| **ICE** | MW | 102 | | - | - |
| **SOLAR** | MW | 113 | 924 | 499 | 297 |
| **WIND** | MW | 155 | 970 | 685 | 404 |
| **STORAGE** | MW | - | - | 118 | 185 |
| **BIOMASS** | MW | 10 | - | - | - |
| **PUMP HYDRO** | MW | - | - | - | - |
| **CURTAILMENT** | % | - | 19.1 | 24.1 | 25 |
| **ANNUAL COST** | Million $ | 748 | 484 | 547 | 623 |

### SCENARIO 1 ZERO CARBON

| **YEAR** | | 2020 | 2020-2030 | 2030-2040 | 2040-2050 |
|---|---|---|---|---|---|
| **CCGT** | MW | 440 | 260 | 701 | - |
| **GT** | MW | 188 | - | 630 | - |
| **ST** | MW | 750 | - | - | - |
| **ICE** | MW | 102 | - | - | - |
| **SOLAR** | MW | 113 | 977 | 738 | 2159 |
| **WIND** | MW | 155 | 970 | 625 | - |
| **STORAGE** | MW | - | - | 240 | 2141 |
| **BIOMASS** | MW | 10 | - | - | 97 |
| **PUMP HYDRO** | MW | - | 130 | - | - |
| **CURTAILMENT** | % | - | 18.2 | 24.4 | 25 |
| **ANNUAL COST** | Million $ | 748 | 485 | 549 | 815 |

### SCENARIO 2A INTERCONNECTION 65$/MWH

| YEAR | | 2020 | 2020-2030 | 2030-2040 | 2040-2050 |
|---|---|---|---|---|---|
| **CCGT** | MW | 440 | - | - | - |
| **GT** | MW | 188 | - | - | - |
| **ST** | MW | 750 | - | - | - |
| **ICE** | MW | 102 | - | - | - |
| **SOLAR** | MW | 113 | 1188 | 1052 | - |
| **WIND** | MW | 155 | 2166 | 1769 | 1239 |
| **STORAGE** | MW | - | - | - | - |
| **BIOMASS** | MW | 10 | - | - | - |
| **PUMP HYDRO** | MW | - | - | - | - |
| **IMPORT** | % | - | 2.6 | 11.6 | 10.2 |
| **EXPORT** | % | - | 43.4 | 94.6 | 94.5 |
| **CURTAILMENT** | % | - | 6.1 | 6.5 | 11.9 |
| **COST** | Million $ | 748 | 472 | 441 | 431 |

### SCENARIO 2B INTERCONNECTION 45$/MWH

| YEAR | | 2020 | 2020-2030 | 2030-2040 | 2040-2050 |
|---|---|---|---|---|---|
| **CCGT** | MW | 440 | - | - | - |
| **GT** | MW | 188 | - | - | - |
| **ST** | MW | 750 | - | - | - |
| **ICE** | MW | 102 | - | - | - |
| **SOLAR** | MW | 113 | 1211 | 791 | - |
| **WIND** | MW | 155 | 1531 | 1000 | 1075 |
| **STORAGE** | MW | - | - | - | - |
| **BIOMASS** | MW | 10 | - | - | - |
| **PUMP HYDRO** | MW | - | - | - | - |
| **IMPORT** | % | - | 26.4 | 19.1 | 15.8 |
| **EXPORT** | % | - | 30.5 | 57.5 | 65.3 |
| **CURTAILMENT** | % | - | 2.2 | 1.1 | 3.8 |
| **COST** | Million $ | 748 | 503 | 511 | 522 |