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Department of Mechanical and Aerospace Engineering

Energy Strategy of Crete: Potential Expansion of Renewable Systems with Interconnection

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Abstract

This study investigates the energy strategy of the non-connected island of Crete with target the 80% reduction of CO_2 emissions, compared to 2005, by 2050. The significance lies on the final agreement of the future interconnections of Crete with the Greek national electric network and the Euroasia intercontinental connection. The completion of those interconnections will enable Crete to further develop the renewable energy systems and initiate the exports of sustainable energy. The research analyses the topic with a scenario-based approach to investigate the outcomes of the maximisation of wind and solar development. Also, another target is to attempt to define the balance between solar and wind development. The conclusion was that Crete can support a very large capacity of wind technologies, only after the completion of the interconnections. An energy system that relies on wind energy is impossible to achieve security of the energy supply because of its unpredictable nature. On the other hand, solar energy increases the stability and security of the electric network during the day. For the solar technologies to contribute on the energy balance during the night is possible only with the integration of storage systems.

Keyword: Renewable energy systems, sustainability, solar energy, wind energy, storage, non-connected islands, interconnection, Crete

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Author

Nikolaos Marinos

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Glossary

BAU: Business As Usual

HVAC: High Voltage Alternating Current

HVDC: High Voltage Direct Current

GIETS: Greek Interconnected Electricity Transmission System

RES: Renewable Energy System

LCOE: Levelized Cost Of Electricity

HFO: Heavy Fuel Oil

CCS: Carbon Capture and Storage technologies

O&M: Operation and Maintenance costs

PPC: Public Production Corporation

IPTO: Independent Power Transmission Operator

CPV: Concentrated Photovoltaic

CCTG: Combined Cycle Gas Turbine

DNI: Direct Normal Irradiance

1. Introduction

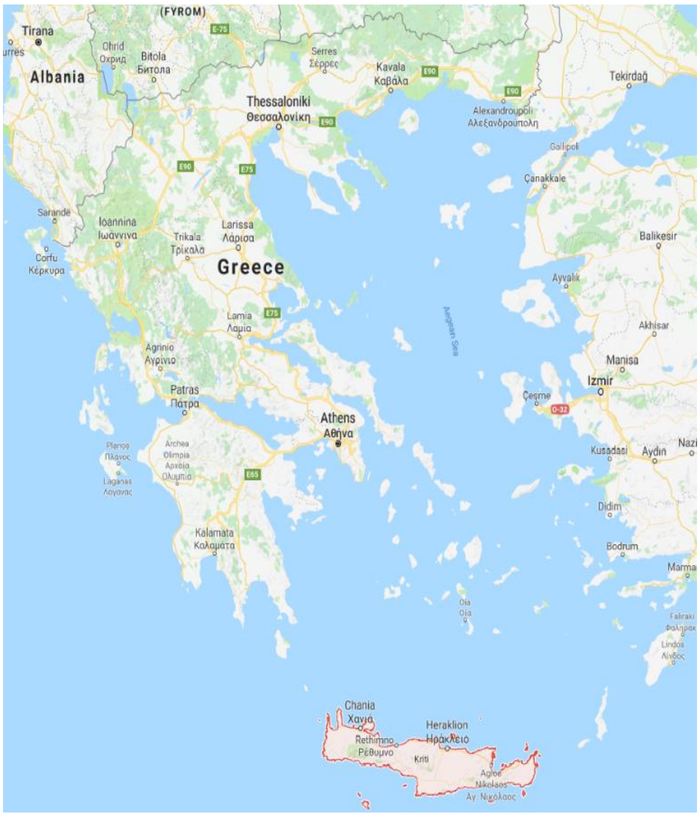


Figure 4: Island of Crete

Crete lies on the Eastern Mediterranean at the south end of Aegean Sea above the Libyan Sea, **Figure 1**. It's the largest island of Greece and the fifth largest in the Mediterranean Sea. Heraklion is the capital and the largest, among the six cities, of Crete, with nearly 180,000 population. The population of Crete is almost 700,000 citizens and there are over 4,000,000 visitors every year, most during the summer. Crete is energy autonomous, producing and distributing its own energy. The electricity is produced mostly from fossil fuel combustion with a share of wind and solar energy, (Anon., 2018).

Crete is a special energy case due to its geopolitical characteristics (location, size, development, large renewable potentials) but recently also because of the Euroasia intercontinental grid connection that is planned to be ready for commissioning in 2021 (1st Stage, more information in Section 2). There are also plans for a Euroafrica intercontinental connection, which still haven't reached on a final agreement. At the same time, Crete is going to be connected with HVAC sub-sea cable with the Greek Interconnected Electricity Transmission System (GIETS) by beginning of the next decade. Furthermore, according to the statement of Yannis Bassias, Chairman and CEO of Hellenic Hydrocarbon Resources Management, "At least 3 billion barrels of oil and estimated 4 trillion cubic feet of natural gas are hidden in the Ionian Sea and south of the island of Crete", (Anon., 2018), and the oil exploration tender was officially announced, (Anon., 2018). It appears that Crete is going to become an energy hub, between the three continents, with developing oil and gas power. As a non-interconnected island the security of energy supply is vital. At the same time, the protection of the enviroment is critical as it attracts a large number of tourists and the economy of Crete is mainly based on tourism. For those reasons the enviromental factor must be included in the future energy strategy. **Figure 2** in the next page, shows that the renewable potential of Crete is very high, both for wind and solar. With the new interconnection the conditions are set for the development of Renewable Energy Systems (RES) in order to transmit to a low carbon economy. The exploitation of sustinable energy is very importand for Crete, as well as for Greece since is a party of the Paris Agreement 2016. In order to achieve the targets of the 60% to 70%

reduction of greenhouse gases emissions, compared to 2005, by 2050 it is necessary to increase the energy efficiency of all the consumption sectors, (Anon., 2012) and minimise the emissions from energy production. Finally, the economic aspect of the energy strategy in all sectors is an essential strategic factor.

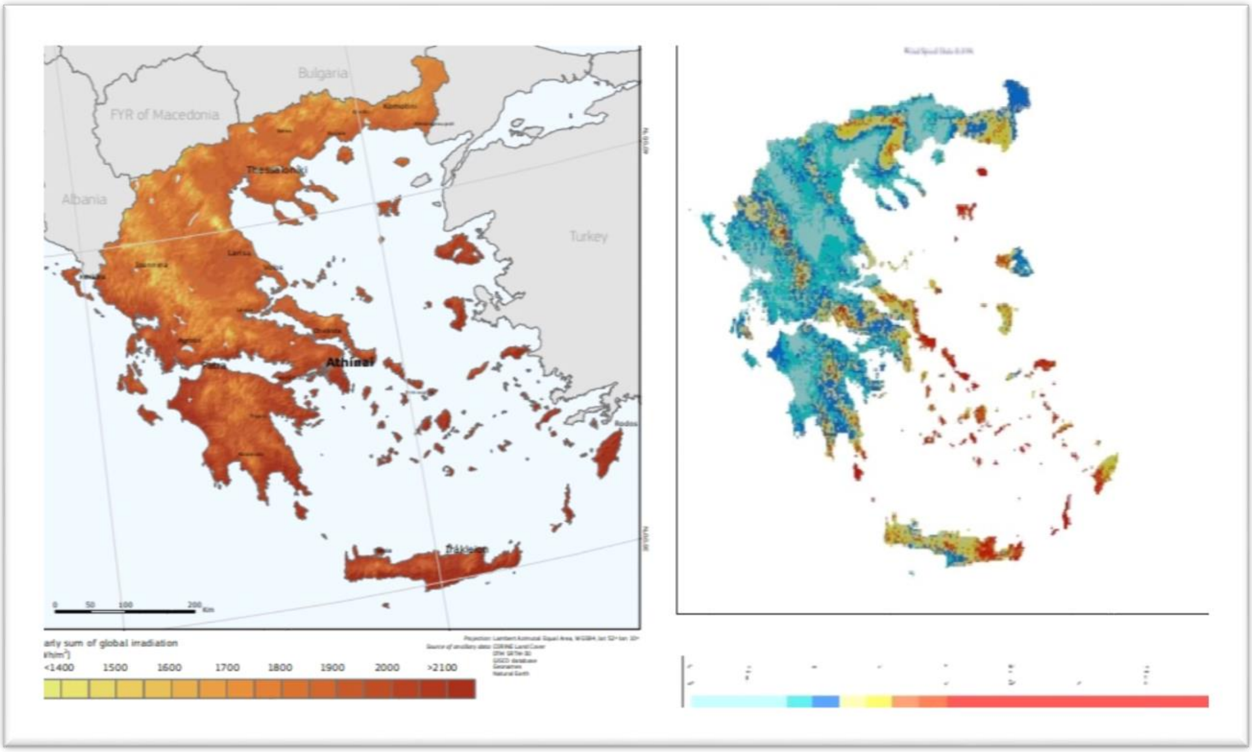


Figure 5: (Left) Solar irradiation and solar electricity potential, (Right) Wind energy potential

With primary motive the reasons stated above, this project will investigate the options for a sustainable future energy system of Crete by 2050, with target of at least 80% reduction of CO2 emissions. The study will focus on the design of a system that will secure energy supply and environmental objectives by analyzing the potential strategies of future energy mix and infrastructure. Planning should be realistic and feasible, so the analysis will include social, economic, technological and environmental challenges and opportunities that should be addressed in the short-term and long-term future. This study will use a scenario-based approach to examine the energy system of Crete. In order to simulate the scenarios the energy model of Crete will be developed and imported in an optimization energy system software HomerPro to conduct an energy and economic analysis.

The high-level requirements for the project have been listed below:

- To summarise the present energy system of the island through the latest studies and data collected from the official authorities.
- To estimate the condition (supply and demand) of the energy system of Crete in the horizon of 2050, creating possible scenarios of the system's future development.

- Develop energy model of Crete in optimisation software simulator, validate the model with real data, simulate the scenarios and evaluate the results in regards of energy, economic, social and environmental criteria to select the best option.
- Present and discuss upon the results.

More specifically, the deliverables of the project are:

1. Gathering, evaluation and investigation of studies and data
2. Develop a detailed and validated simulation model of the present system
3. Estimation of the configuration of energy system of Crete with 80% of CO2 emissions reduction (against 2005) by 2050 for the following scenarios:
    a. Business As Usual (BAU), with interconnection
    b. Wind energy growth, with interconnection
    c. Solar energy growth, with interconnection
    d. Wind and solar balance, with interconnection
4. Result
5. Discussion - Conclusions

This study targets to investigate the potentials future energy system of Crete including the grid connections that are verified to be finished within the next ten years. The significance of this study lies on the fact that the specifications of the upcoming grid connections have being continuously changing the past years and only recently have settled to a final design. This gives the opportunity to examine the potentials of the future system with the latest data and developments. The ultimate goal is to participate in an overall effort that is being made for the sustainable development of the Region of Crete.

2. Review of Literature

Section 2 contains the review of the literature that was used for the completion of this study. The review begins with a quick presentation of the national energy strategy of Greece and the national targets for 2050, then the present energy system of Crete is analysed with the energy demand specifications, levelized cost of electricity (LCOE) and the CO2 emissions of Crete. In continuous, the verified future developments of the grid, the power plans and the renewable systems are reviewed. Finally, there is a presentation of previous research material that are included in this study.

2.1 Future Energy Strategy of Greece

The energy sector is the foundation of economic growth and has a direct and indirect impact on all sectors of the economy. It is obvious that national energy planning is an important tool for implementing a country's development policies, with a huge impact on international level rather than just national. The present energy plan refers to the basic guidelines of the national energy strategy towards 2050, without adopting a strictly defined scenario for the evolution of the energy system. The main feature of the Greek energy mix is the high level of use of fossil fuels both for electricity production and energy consumption across all sectors. More specific the Greek electricity production is 30% natural gas, 30% lignite, 30% renewables and 10% heavy fuel oil (HFO) and diesel (10% is for the autonomous islands). The use of lignite has been a strategic choice, despite its environmental impact, since it is a domestic fuel, (Anon., 2012).

The short-term targets of Greece, until 2020, is to increase the renewable penetration to 40% in the energy sector, 20% for heating and cooling and 10% in the transport sector. It is estimated that the renewable systems capacity will expands to 13.3GW by 2020 and that Greece is on track to accomplish the national targets. The targets are listed below:

- Reduction of reliance on imported energy
- Increase the renewable penetration as much reasonably possible
- Significant reduction of CO2 emissions, by 2050
- Fortify the security of final consumers
- No use of nuclear energy
- Limited use of Carbon Capture and Storage technologies (CCS)

To further specify the targets and measures for the short-term (2020) and long-term (2050) period, the Greek government conducted and investigation that reflects the European Commission guidelines for 2020 and 2050, (Anon., 2012). The investigation consists of the following three scenarios:

1. **Existing Policies**: Moderate application of environmental and energy policies, expecting a modest level of CO2 emissions reduction of 40%, a moderate renewable penetration and energy saving.

2. **Measures Maximization RES**: Maximum levels of renewable penetration (100% in electricity generation), 60% -70% reduction of CO_2 emissions and parallel energy saving in buildings and transport. The scenario is studied under the assumption of imported electricity which will benefit in cost savings in electricity sector.
3. **Minimum Cost of Environmental Measures**: This scenario is the same as the second, but it evaluates the share of renewables in the energy mix to achieve the minimum cost. A variation of this scenario examines the addition of CCS.

The shape of the future energy system as indicated by the two basic energy policy scenarios 2 and 3 can be summarized in the following 10 points:

1. Reduction of greenhouse gas emissions by 60%-70% by 2050 in relation to 2005.

2. 85%-100% electricity generation from RES, via all commercially mature technologies.

3. Total penetration of renewables in gross final energy consumption by 2050.

4. Stabilization of energy consumption due to energy saving policies.

5. Relative increase in electricity consumption due to electrification of transport and larger use of heat pumps in the domestic and tertiary sectors.

6. Substantial reduction of oil consumption.

7. Improved use of biofuels in transportation sector at the level of 31% to 34% by 2050.

8. Main share of electricity in short-distance passenger transport and significant increase in the share of stable track public transport.

9. Significantly improved energy efficiency for the entire building stock and a large penetration of RES in buildings.

10. Development of decentralized production units and smart grids.

The primary crucial conclusion of this analysis was that the vision of existing policies does not achieve the 2050 national targets. On the other hand, the new energy policy scenarios, where the high penetration of renewables in gross final energy consumption leads, attain large CO_2 emission reduction (by 60% to 70% compared with 2005) while minimising energy imports and dependency from imported fossil fuels. In any case, the national energy system has the potential to differentiate significantly over the next years, fulfilling the commitments of the European energy policies while providing security and lower energy cost to the final consumer, (Anon., 2012).

2.2. Review of the Energy System of Crete

Crete has its own electricity grid network, see **Figure 3**, and it is not connected currently with the National Interconnected System (NIS). In total there are three power plants located in the west, central and east side of the island, **Figure 3**. All of them include a mix of generator units of steam turbines, internal combustion engines and combine cycle gas turbines, around 820 MW capacity, altogether. The development of the RES on Crete is limited in order to secure the balance of the network. There are 41 wind farms dispersed around the island, with total power of 200 MW, with 0.1716 MW being the smallest and 15 MW the largest. Also, there are 80 MW of Photovoltaic parks (PV) and 15 MW of PV on the roofs spread around the island. At last, there is a 0.6 MW of hydroelectric unit with a minor contribution and it’s used to balance the electric network. In **Table 1** the total implemented capacity of generators and the annual energy production by fuel can be seeing. The PV on roofs are not included in the table above, because their production is not added in the total energy consumption of Crete, rather is deducted from the energy consumption of the private owner. (Distribution, 2017)

Table 5: Energy Specifications by fuel (Distribution, 2017)

2017	Power (MW)	Energy Production per year (MWh)
crude oil	372	1,749,299
diesel	452.9	617,123.4
hydro	0.60	295.4
wind park	200	512,832.10
PV park	80	140,032.60
Total	1120	3,019,582.50

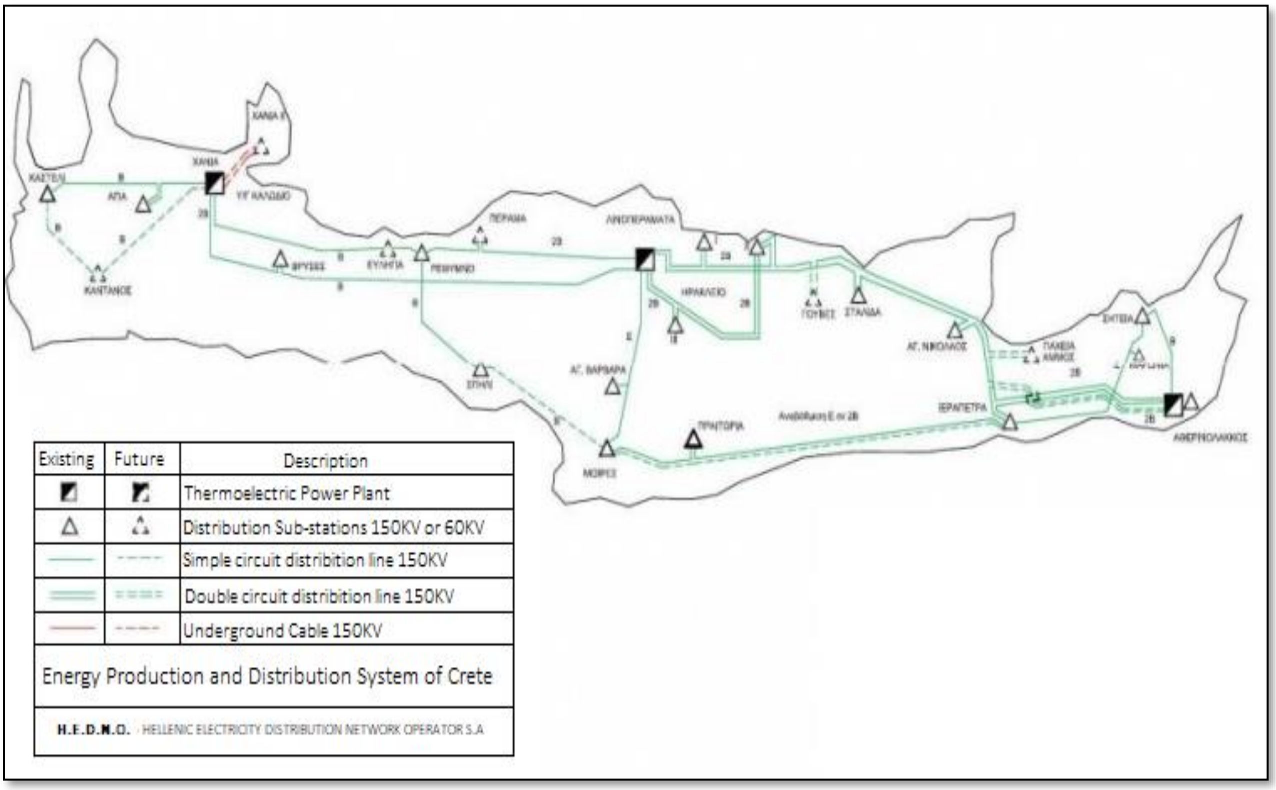


Figure 6: Electric Grid Network of Crete

2.3. Production

Most of the electricity produced in Crete is coming from combustion of fossil fuels. As it's shown in **Figure 4** below, the main fuels used are HFO 58% and Diesel 20,4% in 2017. The rest of the share comes from RES, where 17% is Wind energy, 4,6% is PV and 0,01% from Hydro. **Figure 5** shows that the use of Diesel was decreased after 2007 and replaced with HFO due to the lowest price of the second. At the same time, the penetration of wind energy has been strong after 2005, while the penetration of PV can be observed since 2010. In general, the RES gradually increased after 2002 from 7.5% to 21.6% in 2017. There is a lot of room for further development of PV, but not for wind. There are already a lot of requests for energy production licenses for projects that include wind technologies but have been rejected due to the saturation of wind production in Crete. The possible way to develop the wind power

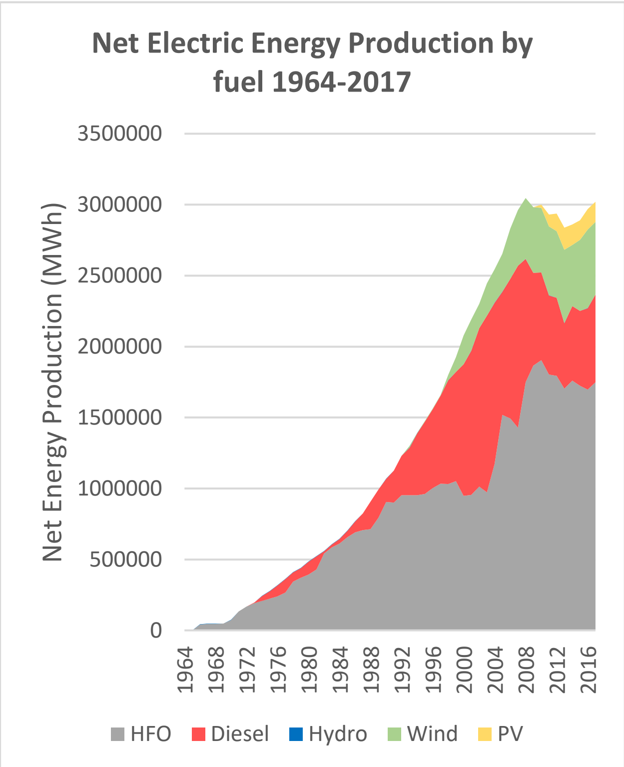


Figure 4: Net Electric Energy Production by fuel 1964-2017, (Distribution, 2017)

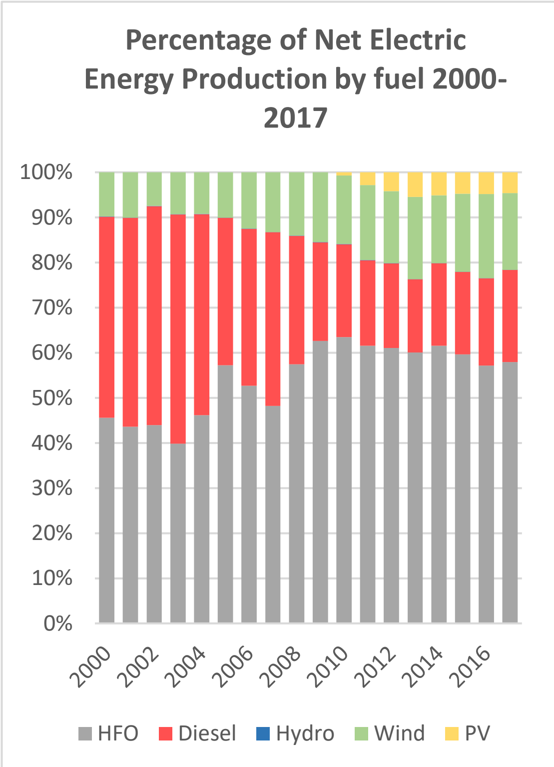
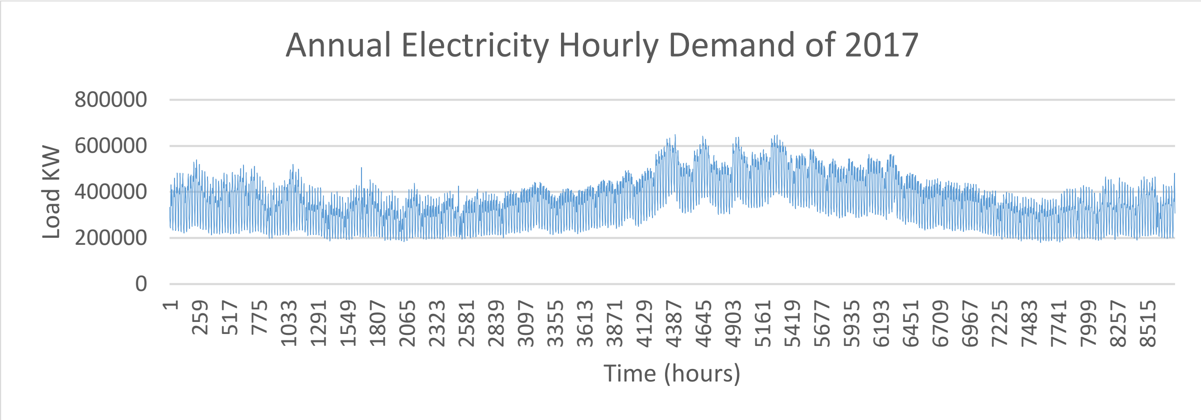


Figure 5: Percentage of Net Electric Energy Production by fuel 2000-2017, (Distribution, 2017)

it would be by connecting Crete with the main electric network grid of Greece, thus export the excess electric production, or by integrating energy storage technologies like pump hydro, solar thermal power generation (with storage) or chemical batteries, (E3M-Lab, 9.5.2016).

2.4. Demand and Emissions

The annual energy demand of Crete is around 3.1 TWh with peak load of 637.9 MW. In **Figure 6 (top),** the electric demand profile of Crete can be seen, with summer having the increased demand due to the



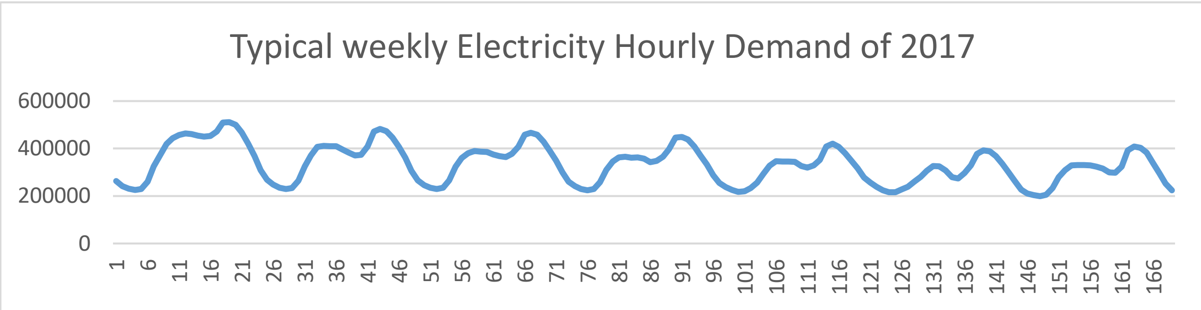


Figure 6: Annual and weekly demand of Crete 2017

tourism. In **Figure 6 (bottom),** a typical weekly hourly demand is plotted, showing the decreased demand during the weekend because of the public and commercial buildings (schools, councils etc) are closed. Also, during the day the first peak is around 10-11am and the second around 5-6pm. To have a deeper understanding in **Table 2** the energy demand of Crete is being divided by sector (Domestic, Agriculture, Industrial, Public & Commercial). From observation, the Public & Commercial is the most energy intense, half of the total energy consumption of electric energy, which it was expected since it includes tourism, all public buildings (e.g. Schools) and shops, (E3M-Lab, 9.5.2016). The transport sector emissions are 879,261 tCO2/yr, it is not included in the table because it is not using electric energy. The levels of CO2 emissions in 2005 was 2,599,509 tonCO2/yr (including the transport sector),

Table 6: Energy Demand and Carbon Emissions by Sector, (E3M-Lab, 9.5.2016)

By Sector	**Annual Demand (MWh)**	**Carbon Emissions tCO2**	**Percentage**
Domestic	1,016,419	684,832.6	33.6%
Public & Commercial	1,554,831	1,047,597	50.5%
Agriculture	207,805	140,015.4	6.9%
Industrial	240,528	162,069.6	7.9%
Total	3,019,583	2,034,514.5	100%

which is 300 ktonCO2 lower than the present value. The increase of CO2 emissions is a result of the increased electric demand in 2017 by 400 GWh.

2.5. Cost of Electricity

The Government's new plan for the development of RES in Greece includes large-scale investments in wind farms and photovoltaic parks as a result of competitions, but also with a fairly different model of compensation of the power plants from today. The feed-in tariff system currently in place in Greece, which is largely responsible for the excessive burden on consumers through the "RES fee", is ended for large investments and is replaced by a model that provides for compensation to producers the wholesale energy price plus a bonus based on the type of technology, return on capital, bank lending, etc. This premium bonus will be provided for at least 20 years. It is indicative that by 2015 RES had a total revenue of € 1.6 billion, but according to the Ministry of Environment and Energy, € 1.1 billion was state aid, the lion's share goes to photovoltaics, and another 430 million came from the sale of energy on the market. However, the first reactions of the market show that investments in photovoltaics will remain attractive at the incentive level, and investment in wind farms seems to be discouraged, as the plan seems to lead to a small decrease in energy sales fees, (Anon., 2018).

Table 3 shows how the price of electricity is increased depending on the consumers demand. The prices on the table refer to the prices on the main land of Greece. The starting price per kWh is 0.0946 €/kWh with the extra charges and VAT settles at 0.17836 €/kWh. In the non-connected islands, the prices are higher, (Anon., 2018). The extra charges, on the islands, are due to the use of imported fossil fuels and the higher Operation and Maintenance costs (O&M) of the power plans. The government uses the service of general interest which adds the extra cost of electricity from the islands and splits it to all the consumers to support the economies of the non-connected islands. In Crete the cost of electricity settles at 0.203 €/kWh, which is 0.02487 € extra per kWh, (Anon., 2014).

Table 7: Cost per kWh in correlation with 4 months demand (PPC)

Levels	**kWh**	**€/kWh**
First	≥ 1600	0,17836€
Sencond	1601-2000	0,18778€
Third	2001-3000	0,22420€
Forth	<3.000	0,22926€

2.6. Future Developments

This section, reviews the developments of the energy system of Crete, that are verified to be completed the next decade and are going to be included in this study.

2.6.1. Fossil fuels Power plans

As shown in Appendix 1, it is noted that substantial portion of the installed capacity already has more than 20 years of life, meaning that by 2020 these units should, in any case, be replaced because of age and the critical and imperative of the operational limitations imposed for environmental reasons by relevant Directives, (E3M-Lab, 9.5.2016).

According to Directives 2010/75 / EE and 2015/2193 / EE, a crucial issue arises as to the sufficiency of the installed capacity of thermal units in Crete, and in particular the capability of this power operating in accordance with the applicable environmental constraints, (E3M-Lab, 9.5.2016).

According to Directive 2010/75 / EU, more specific Article 34, it is stated that combustion plants which until 6 January 2011 are part of a small isolated system, may until 31 December 2019 be exempt from the obligation to comply to the SOx and NOx emission limit values. This means that from 1/1/2020, on the substance, none of Public Production Corporation 's (PPC) steam and gas turbine units in Crete fall within the limits of pollutants that are in effect from 1/1/2020, and therefore fall under a limited operating regime of 1500 and 500 hours for 2020 and 2030 respectively. Even with regard to internal combustion plants, similar restrictions are imposed, but these have not yet been defined by the EU, which allows for the use of such units in Crete for a short period of time, but obviously this is a conjectural and a short-term event, which in the long run is also expected to bring with it significant environmental constraints similar to those in force for 2019 for steam turbines and gas turbines, (Commision, 2010).

Also, according to Directive 2015/2193 / EU, strict limits are set for small combustion smoke pollutants, which practically cover all units on non-interconnected islands, and according to PPC estimates, all the units are restricted from 2025 for new plants and from 2030 for existing plants, (Commision, 2015).

The study about the energy strategy of Crete, that was contracted by the Region of Crete to the National Technical University of Athens, proved that the most cost-effective strategy is to replace the current units with Combined Cycle Gas Turbine units, fuelled by natural gas. Also, the Greek minister of Environment and Energy George Stathakis declared that "by 2030 it is within the plan to eliminate the use of HFO and Diesel power plans on the islands.", (Anon., 2018).

2.6.2. Development of the grid – Connections

The target to remove the HFO and the Diesel consumption on the islands, as mention above, will be achieved by connecting the autonomous islands with the main grid network of Greece. The plan for the connection of Crete is to install two HVAC sub-sea cables of 250MW, with real export capability of 235MW. Independent Power Transmission Operator S.A. took over the project and estimates to be finished by 2025, (ADMIE, 2018).

The other interconnection, that is expected to be finished within 2020 and 2030, is the Euroasia Intercontinental grid interconnection. The sub-sea cable will connect Israel – Cyprus, Cyprus – Crete, Crete – Attica and from there with Europe. The first stage of the project will be the installation of a 1000MW sub-sea HVDC cable with 1000MW exports and the second stage is to double the capacity. The scope of the project is to export the electricity produced from extracted natural gas, recently found in Cyprus, to Europe. In the table below the costs and the distance of the sub-sea cables are listed. The cost of the Cyprus-Crete cable in **Table 4** is one third of the actual price, because the values below are going to be used as capital costs of the energy system of Crete, (Anon., 2018).

Table 4: Cost and size of Grid connections, (Anon., 2018)

Inter-connection	**Capital cost (€)**	**Distance km**	**Capital cost €/km**
Cyprus - Crete	423333333.3	895	548677.8399
Crete - Attica	535000000	363	1709641.873
Crete - Peloponesse	324000000	173	2172485.549
total	1282333333	1431	4430805.262

The electrical interconnections of Crete result in, (E3M-Lab, 9.5.2016):

A. Completion of environmental duties from current combustion plants, which will be replaced.
B. Change of production from units located on the island from energy traded on the wholesale market, which are more economical than those that are or will be on the island, mainly due to size, technology and fuel they use.
C. They will allow further RES penetration, which will no longer be subject to production constraints and will "export" beyond their local consumption.
D. Further development of the RES to increase exports and maximise the use of the cable.

2.6.3. Renewable systems

The only RES future development that is going to be included on the study is the Concentrated Solar Power Tower (CPV). The developer of the project is NUR Energie, the land area of the project will be 2,200 hectares, the capacity 50MW (with 5 hours storage) and the will be €42 million, (NREL, 2017).

In this study the development of the wind technologies will focus on the development of the off-shore wind farms. The reason is that the citizens of Crete are against the large expansion of wind technologies on land. So, in **Appendix 2,** the potential locations of the off-shore wind farms and the wind data is presented.

2.7. Previous Research

There are numerous studies about the future energy system of Crete, but the most recent and reliable is the study of the National Technical University of Athens. This study was used for data resources such as estimations of the future demand and cost of technologies. The study was contracted by the authorities of Region of Crete in 2015 and the specifications of the new interconnection were finalised within the last year, so the specifications of the interconnector are outdated. In the next page, in **Figure**

7 the scenarios that were examined are reviewed and in **Appendix 3** are listed the financial details (2017-2050) of the all the components used.

Scenarios	Description	Energy System 2050 RES (MW)	Fossil Fuel (MW)	Interconnection
Benchmark (BAU)	In this scenario the trend of RES growth is formed without measures or intensification of policies while no electrical interconnection is foreseen. Therefore, RESs show the following growth (approximately 25% demand up to 2050). The increase in installed capacity concerns few additional projects or repowering existing ones. In PV, the increase is due to roof systems. Finally, there is an infiltration of hybrid projects (pumped storage) by 2050.	Wind - 250 PV farms - 100 PV roofs - 75 Hybrid Systems - 80	Modernised current system	No
Natural gas penetration interconnected	This scenario provides for the use of VAT. In power generation, moderate wind growth and increased penetration of other RES and limited power interconnection. The distribution and development of RES growth by 2050 is presented below.	Wind - 1281 PV farms - 400 PV roofs - 300 Solar Thermal PP - 100	Natural Gas	Yes
Non-interconnected natural gas penetration	This scenario is the same as the previous one with intensive energy saving interventions without interconnection. In this scenario, for RES, the allocation and development of the reference scenario was used (Table 7).	Wind - 250 PV farms - 100 PV roofs - 75 Hybrid Systems - 80	Natural Gas	No
Electrification of Crete	These scenarios are gradually being promoted by the electrification of Crete, through the substitution of fuels in the final consumption sectors including road transport, combined with different electrical interconnection scenarios.	Wind - 1281 PV farms - 400 PV roofs - 300 Solar Thermal PP - 100	NIS	Yes
Electrical interconnection of limited power	This scenario includes electrification, limited power interconnection, maintenance of conventional Electric energy production (after modernization), moderate wind potential development and increased penetration of other RES. The limit of the surface of wind installations includes NATURA 2000 areas in the excluded areas and then categorized, after multi-criteria assessment, the priority areas according to the potential.	Wind - 1281 PV farms - 400 PV roofs - 300 Solar Thermal PP - 100	Modernised current system	Yes
Increased RES Penetration Interconnection	In this scenario, electrification, increased RES penetration and high power interconnection scenarios are foreseen. This scenario distinguishes the following two cases:			
Case A	In this case, priority is given to wind energy with large wind projects. For the development of RES in the specific case, the following distribution and evolution was used.	Wind - 2300 PV farms - 200 PV roofs - 150 Hybrid Systems - 100	NIS	Yes
Case B	In this case, priority is given to solar energy mainly with PV on the roofs.	Wind - 500 PV farms - 700 PV roofs - 1200 Hybrid Systems - 291	NIS	Yes
Decreasing Fossil fules	This scenario foresees the complete detoxification of Crete by 2040-2050, with electrification, increased penetration of RES, increased demand reduction and no electrical interconnection.			
Conventional	The scenario examines the case of maximum penetration and the relative mix of RES technologies according to the applicable system operating rules (smaller RES cuts).	Wind - 300 PV farms - 200 PV roofs - 250 Hybrid Systems - 350 Solar Thermal PP - 150	Natural Gas	No
Advanced	In this scenario, it is assumed that smart grids will be developed by 2050 so that decentralized production can be managed. Decentralized production in 2050 is dominated by solar energy and storage	Wind - 500 Wind Offshore - 200 PV farms - 400 PV roofs - 800 Hybrid Systems - 350	No	No

Figure 7: Scenarios of investigation of the official report, (E3M-Lab, 9.5.2016)

In summary, the main conclusions are as follows, (E3M-Lab, 9.5.2016):

1) Continuing the current structure of the electric energy generation is impossible, but even if it was possible it is economically unprofitable and environmentally harmful. All alternatives are clearly cheaper.

2) Immediate action is needed to ensure the supply of electric energy Crete. New infrastructure should be in place in 2020 or at the latest 1-2 years after 2020. The type of new infrastructure selected will be to a large extent a long-term perspective.

3) The new infrastructure can be either the large-scale interconnection or the import of natural gas or the combination of these.

4) Following this decision, strategic dilemmas are put in place over the medium and long term, especially with regards to the RES mix. The dilemma is whether the development of RES will be based mainly on wind or, most importantly, on dispersed PV production. It is suggested the rational wind development and the maximum possible growth of photovoltaic roofs.

5) RES and energy savings are the only pillars of the long-term perspective in the context of fossil fuel dependency and drastic reductions in greenhouse gas emissions.

6) The interconnection (and only the large but also the combination of the two interconnections) is in fact the only way to develop RES in a conventional structure system such as the current one. In theory, renewable energy sources can be developed without interconnection but in the framework of a new smart technology system that will be mature in the long run.

7) Total cost is lower in the case of wind turbines, however, dispersed PV production and storage have significant advantages for demand management and economic growth.

8) The import of natural gas provides an immediate solution for low-cost and less polluting supplies, but the further development of RES requires interconnection (even medium-term), benefiting the system's viability.

9) The import of natural gas combined with LNG transshipment stations will allow uses in greenhouses, large trucks and ferries, with great environmental and economic benefits.

10) Extensive heat and transport electrification will allow the introduction of many innovations and the achievement of high energy efficiency at competitive costs. Long-term electrification is successfully combined only with the interconnections, and the benefits of developing RES and importing natural gas to ensure reserves and economy.

11) Smart grids and systems should be developed and combined with extensive use of roof photovoltaics and battery storage in the home and electric cars.

12) The combination of the above will lead Crete to complete detoxification from oil, a great environmental upgrading, innovation development and new activities (as well as employment) to support the development of scattered technologies.

13) Finally, the Region of Crete should investigate the possibility to undertake the competitive process under the new RES support system to be able to control the rational development of RES (especially wind in suitable locations) and to obtain economic benefits from the entire maturing process that can be undertaken.

3. Methodology

In section 3 the methods that were used to complete this study are presented in detail. The deliverables of this study are repeated underneath.

1. Gathering, evaluation and investigation of studies and data
2. Develop a detailed and validated simulation model of the present system
3. Estimation of the configuration of energy system of Crete with 80% of CO2 emissions reduction (against 2005) until 2050 for the following scenarios:
    a. Business As Usual (BAU), with interconnection
    b. Wind energy growth, with interconnection
    c. Solar energy growth, with interconnection
    d. Wind and solar balance, with interconnection
4. Result Analysis
5. Discussion - Conclusions

3.1. Study Design

A scenario-based approach was chosen to investigate this study. This method will be able to forecast the renewable energy capacities required too achieve the 2050 targets and evaluate the financial aspects (cost/benefits) of potential changes in combination with sustainable development. To simulate the scenarios a micro-grid simulation software 'HomerPro' was chosen, in which various energy generation and storage technologies can be integrated and simulated producing extractable data which will be analysed for most advantageous options.

Before simulating the scenarios, a prototype model will be developed from the data collected. The target of the prototype model (BAU 2017) is going to represent the current energy system of Crete. This task will uncover the software and data limitations.

In continues, the hourly data, imported in the software, will be manipulated to match the potential demand of 2050. The extra demand will be divided by the hours of the year and then added to each hour of the year of the present demand. This task will be done twice, once for BAU 2050 and once for the rest of the Scenarios since the demand includes electrification for the last three scenarios.

The common changes for all the scenarios are added into the model. The common changes are listed below:

- Replacement of the power plans with natural gas generators (back-up), (E3M-Lab, 9.5.2016)
- Grid interconnection, (Anon., 2018)
- CPV component (50MW), ((Alex Phocas-Cosmetatos, 2017)

The power plan is replaced, and the capital cost of the back-up generator is assumed zero, since the instalment is supposed to be completed until 2025 and working max 1500h/yr between 2020-2030 and less than 500h/yr from 2030-2050. Also, the power plant will be kept as a back-up after the interconnection, so the O&M costs should be kept at minimum.

The grid component will represent the three interconnections with Peloponnesus (235MW), Attica (2000MW) and Cyprus(2000MW). The cost per km was calculated by dividing the total cost of each interconnection, separately, with the distance of each cable. Then one third of the cost of the Cyprus-Crete cable was assumed to be carried by Greece and added with the rest of the costs. The cost was calculated in €/km. It needs to be noted that the cost of the grid is not going to be covered only by Greece, but Europe will also contribute, since the project is intercontinental interconnection and will supply energy to Europe as well. Because of this overestimation of the price, the cost of the converters (€1B) is not included, and a sensitivity test of the grid cost, will be conducted in order to capture economical changes as the cost reduction. For the sensitivity test the cost of grid is reduced by 90%, 75%, 50% and 25%, (Anon., 2018).

After the extra components have been added the financial details of all components are replaced with the estimation of 2050.

In continuous, the BAU 2050 was simulated and the results were extracted and presented in Section 4, compared with BAU 2017. For Scenario 2 the solar development was kept at the levels of BAU 2050 and a sensitivity test took place for the optimisation of the wind capacity, the opposite happened for Scenario 3. The storage technology was added in order to represent the storage units (e.g. hydro, battery, CPV with thermal storage) that could potentially support the balance of the system. When the simulation of Scenario 2 and 3 is completed, the results are extract and colour scaled table are developed for various desirable factors, in order to visualise the changes of the sensitivity analysis. The graphs of the energy system details were plotted for a week in January and Summer, as representative of the season's peak demand. Then, the grid exchanges and the financial results were presented. For Scenario 4, a large simulation took place that included both the alteration of PV and Wind. The range of the simulation is presented in **Table 24,** in Section 4 – Sc4. First the optimum capacity of the solar technologies was concluded. Then, another simulation will serve as a sensitivity test to specify the capacity of wind and storage. The results of Scenario 4 are presented the same way as the previous. Finally, the results of the optimum model of each scenario were gathered, in graphs and tables, and discussed in Section 5.

3.2. Data Sources & Collection

To ensure the integrity of the data, the authorities of the PPC of Crete, the energy office of the Region of Crete and the Independent Power Transmission Operator (IPTO) were contacted via e-mail and telephone. The IPTO supplied the annual report of the energy produced and distributed, the hourly demand and the hourly temperatures for the years of 2016 and 2017. The bureau of energy of the Region of Crete provided the report of the energy strategy for Crete. Last but not least, one of the directors of the PPC was contacted several times to verify that the assumptions included in this study are viable.

To adjust the data to be compatible with HomerPro, Microsoft Excel was used. Excel was used also to analyse the exported data and development of tables and graphs.

3.3. Assumptions, Delimitations, and Limitations

Below all the assumptions, delimitations, and limitations that were necessary for the completion of this study are present.

3.3.1. Demand

When the 2050 demand was calculated the electrification of the thermal demand and the transportations was included. The data included the total thermal demand in MWh of each sector per fuel (LPG, diesel and electricity) and usage (hot water, heating, cooling and other). The efficiency equations of different systems (gas boiler, diesel boiler) that are used in the present, were used to calculate roughly the thermal demand and then to calculate the electricity demand by replacing the technology with heat pumps, (Panagiotis, 2011). For the electrification of transport sector (electric vehicles), the estimation of the European Environment Agency about the penetration of electric vehicles in Europe (9.5% of total demand) was use, (EEA, 2016) . The details are not included because the final result was 15% off the demand used for the official study of the energy strategy of Crete, (E3M-Lab, 9.5.2016). More precise the final demand was calculated 4TWh/yr and the demand form the report is 4.6TWh. So, the assumption taken was that the forecasting of the previous study was much more precise, since it includes even the changes of electric appliances (and others) in great detail.

3.3.2. Energy production components and Grid

The maximum capacity of renewable installation is limited to 3717MW on land, (Theoharis, 2014). The same limitation was used for the energy strategy report, so the same levels of capacity were imported into the software in the first approach. The back-up generator was assumed to be natural gas (CCGT), since the outcome of strategy report proves the cost effectiveness of such replacement. The back-up generator replacement was also discussed with the director of PPC and confirmed that this choice was the most likely scenario, because Crete already possess CCGT (running with diesel) that could be easily converted to natural gas and also because of the new environmental regulations that will be forced after 2020. For the design of the power plans two component were added in the software (HFO and Diesel) and the hours of production were manipulated in order to match the data.

The interconnections were another subject that was discussed with the PPC’s director and he specified the details of the upcoming projects. For the Peloponnese HVAC interconnection, the export limit would be 235 MW including and for the Euroasia 2000 MW. The exchange rates (imports, exports) of electricity were provided from the energy strategy report, (0.1€/kWh imports, 0.07€/kWh export)

3.3.3. Storage

In reality the energy system of Crete includes 0.6 MW of pumped hydro and the 50 MW CPV (2020) includes 5 hours of storage capacity, (Distribution, 2017) and (Anon., 2017). During the design of the storage units in HomerPro, several complications occurred when tried to design a pumped hydro unit and a vanadium battery. The hydro had limited capacity, lower than needed, but the production could alter by changing the head start and the flow rate. The hydro component could be manipulated to the desirable output, but the correct functionality of the hydro was uncertain and there is no data for the costs of hydro in Crete. The complication of the vanadium battery was that it was working 100% the first month but for the rest of the year was inactive or depleted. Those options were excluded in order to minimise the flaws of the model. The only storage that the software could simulate correctly were the lithium-ion batteries and Tesla Powerpack was chosen because it can be fully discharged and there are numerous installations around the world. To be noted that the economical results are going to underestimated for the storage unit, because the price of a Tesla powerpack is obviously lower than the cost of a pumped hydro, (Anon., 2018). Even if the financial results are underestimated, it is important to investigate the configuration of the energy system with some support for the balance, otherwise the size of the capacity necessary to cover the demand is going to be massive as well as the energy excess of the model.

4. Results

In Section 4 the results from the simulations are presented and briefly commented on the findings. More detailed discussion follows in Section 5.

4.1. BAU

In this scenario the current system will be simulated in order to validate the model's results with the data collected. If the results are similar means that the model is simulates well the energy system of Crete. In continues the same model will be simulated with the forecasted conditions of 2050. The results from the 2050 model will be presented and serve as benchmark to compare with the rest of the models.

4.1.1. BAU 2017 model

The architecture of the energy system can be seen in **Table 5** in comparison with the actual data. In a first look the renewable systems were well simulated, even the production levels, **Table 6**, are accurate. Both the power plans needed less capacity in order to cover the demand, but the production was a little higher in the model. That must be because the three power plans consist from numerous different thermal units with different specifications (e.g. capacity, efficiency, location) and to design it, would exceed the limits of the data and the software. The total energy supplied is very close to the data only by 0.34% lower, but the CO2 emissions are 2.65% higher in the model. That is a result of the increase of HFO fuel which is 12.92% higher, **Table 6**. That concludes to a renewable fraction of 20.4% for the model, which is close to the 23.7% from the data, the difference was expected from the higher fuel consumption. To uncover more flaws of the model and try to understand the reason of the declination of the results, the hourly data of various functions were plotted.

Table 8: Scenario BAU 2017, Comparison of the capacity of the model and the data

	Capacity of Energy System (MW)				
	Pv	**Wind**	**HFO**	**Diesel**	**Back-up**
BAU 2017	78	200	320	440	60
Data	78	200	343.4	444.9	0
Differ. %	0.00	0.00	-6.81	-1.10	0.00

Table 6: Scenario BAU 2017, Comparison of the production, fuel consumption and emissions

	Annual Energy Production (MWh) and Fuel Consumption (Klt)								
	Ren Fra%	**HFO**	**HFO Fuel**	**Diesel**	**Diesel Fuel**	**Pv**	**Wind**	**Total**	**CO2 emissions (ton/year)**
BAU 2017	20.4	1,849	545,748	647	191,636	144	512	3,008	2,088,526
Data	23.7	1,749	483,300	617	191,658	140	5123	4,272	2,034,514
Differ. %	13.92	5.70	12.92	4.89	-0.01	2.99	0.00	38	2.65

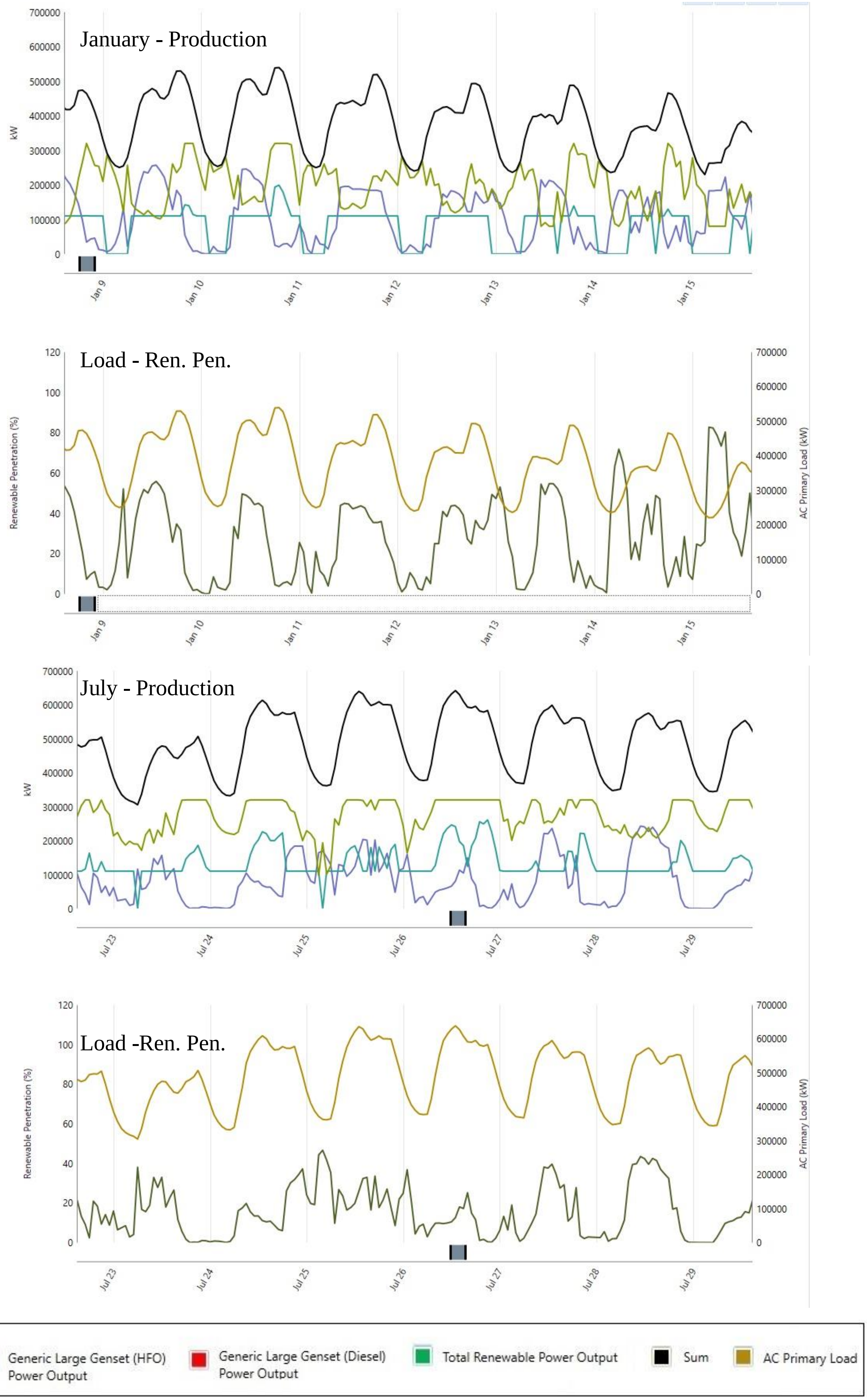


Figure 8: Scenario BAU 2017, Energy Balance Jan (Top) and July (Bottom)

In **Figure 8,** the black line represents the summation of all the electric energy produced and since the shape matches the corresponding loads, it means that the simulation succeeds. Focusing on the January, there are seven rises and drops that represent the days of the week, the two peaks during the day occur around 12 am and 6 pm, which is correct. Comparing the 6 pm peak during winter and summer, as expected the fluctuation of demand is lower since there is no electricity demand for heating during the summer and the peak demand is higher during the summer because it's the tourism peak season.

In **Figure 9**, at the top the PV production is following a normal day and night path, but compared to the summer season, **Figure 10** (next page), even with higher irradiation the hourly output at peak time is higher during winter rather than summer. The reason is that the simulation includes the effect of the ambient temperature to the efficiency of the PV, which are inversely proportional the higher the temperature the lower the efficiency. In conclusion for the PV the performance is satisfying.

The production from wind follows normally the wind speed, and by comparing the winter (**Figure 9**) and the summer (**Figure 10**), the winter is more productive. Those graphs are good indicators for the functionality of the model. If we compare the wind energy production of the model with the data, the difference is significant, **Figure 11**(next page). The software shows the turbines to produces close to max capacity almost every day, and that is obvious in Appendix 4 where the annual wind energy

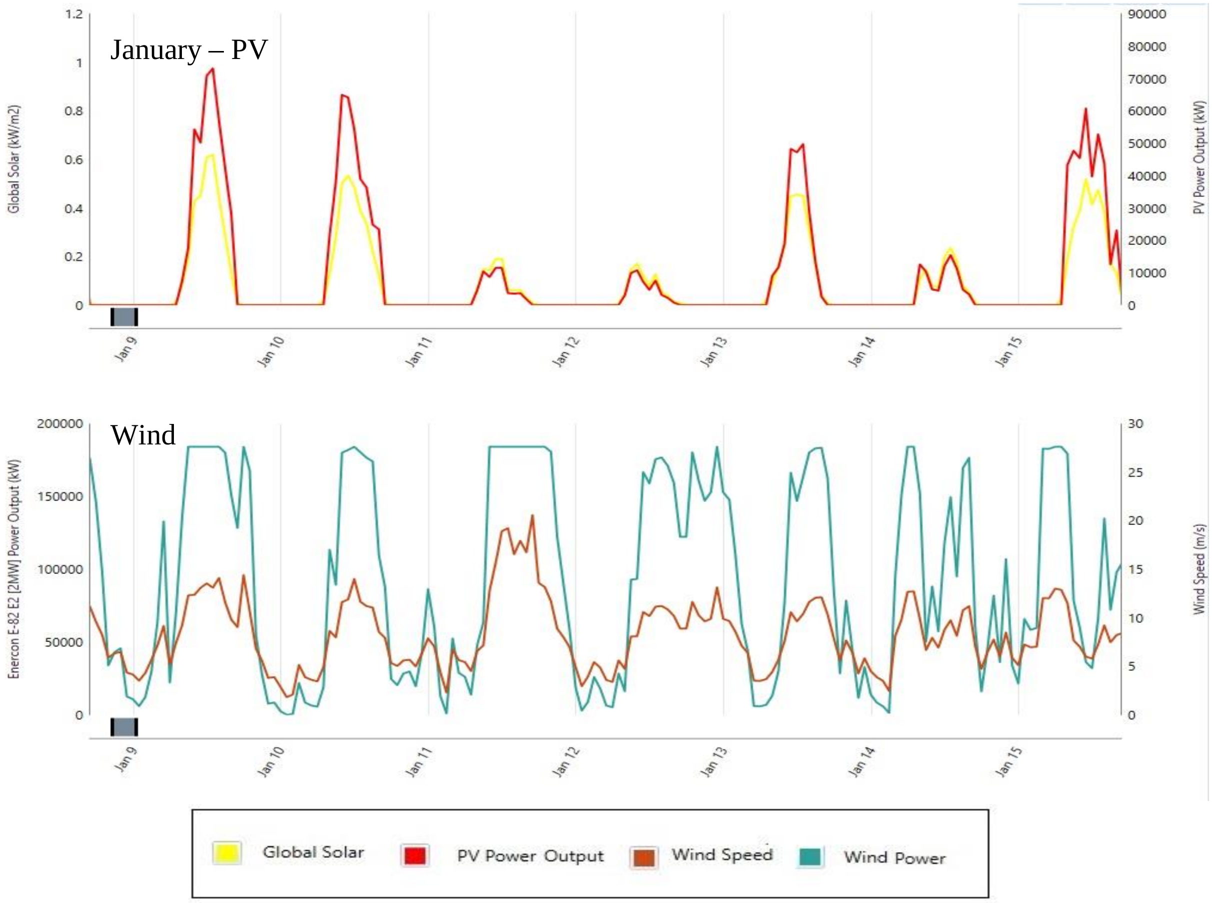


Figure 9: Scenario BAU 2017, PV production & Global irradiation and Wind production & Wind Speed for January

production of the model can be seen. In **Figure 11** the data indicates that the power output never actual reaches over 160 MW during 2017. That shows that the turbine of the model over-produces. That was noted during the simulations and in order to match the production 10.2% of Loss Factor was added. The reason of the over-production is the limitation of the data and the software, because in reality there are 41 wind farms of various sizes, across the island, operating under different conditions. Also, the wind speed used for this simulation was the one that HomerPro provided and even if the total energy produced is correct, if it cannot match the exact hourly production there is high chance that the system won't be able to absorb the energy. That means that if in a specific moment in reality the demand was covered form wind energy, but in the model the same moment there is no wind production, the software will supply the energy from the power plans, thus the increased HFO production.

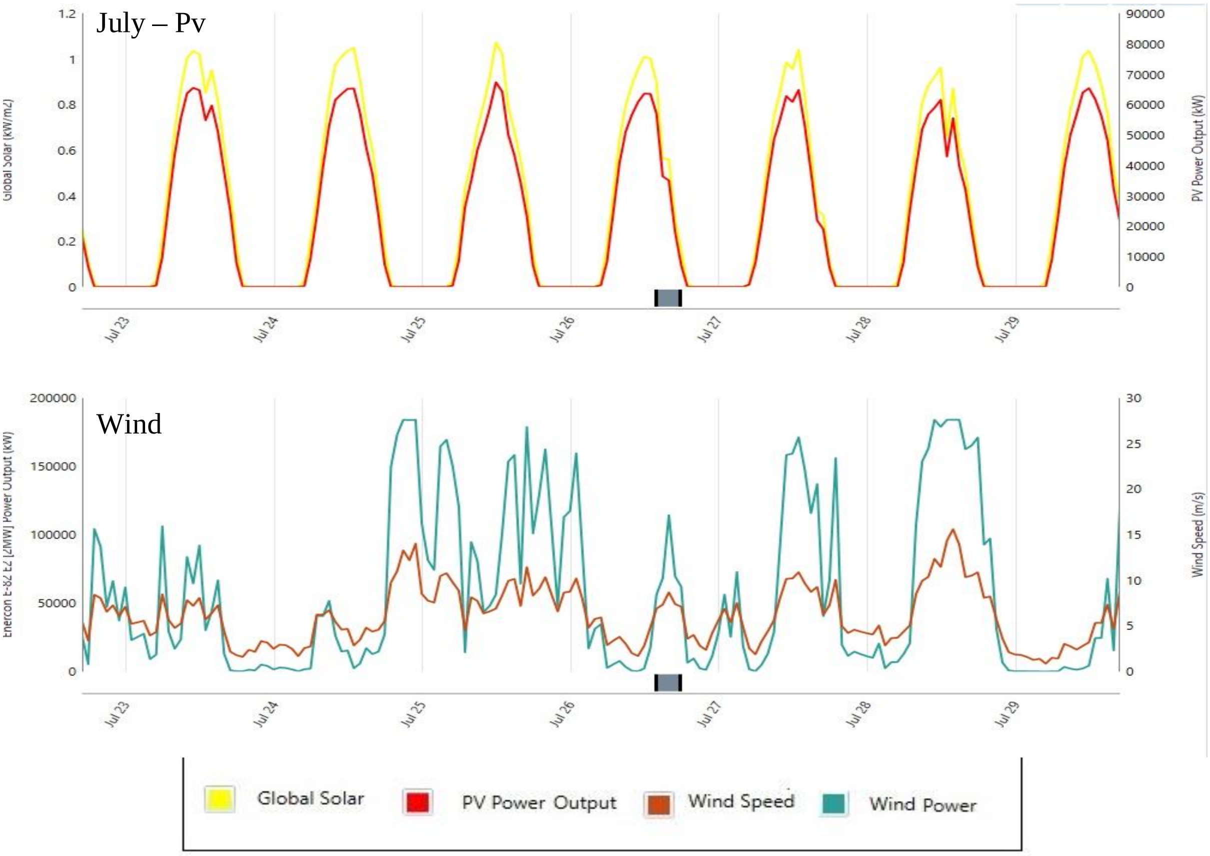


Figure 10: Scenario BAU 2017, PV production & Global irradiation and Wind production & Wind Speed for July

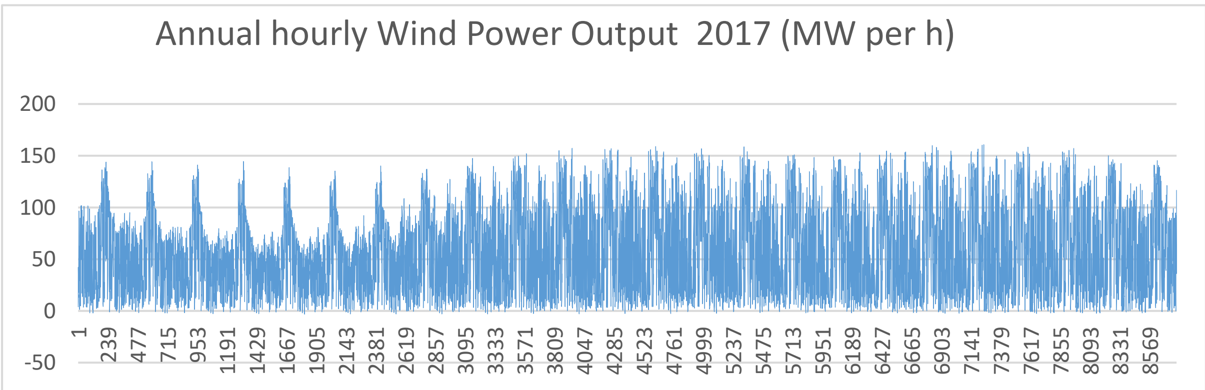


Figure 11: Data of annual hourly Wind Power Output 2017

The LCOE in the model is 0.166 €/KWh and by adding the extra charges 0.02487 €/KWh, it becomes 0.19087 €/KWh, 5.9% lower than the actual price. The NPC can be seen in **Table 7** and the detailed costs in **Table 8.** The values cannot be compared with the reality because of the data limitation. For that reason, these values will act as a benchmark that will indicate an approximate approach of the real cost.

Table 7: Scenario BAU 2017, Comparison of cost of the kWh

	Costs		
	LCOE (€/KWh)	**NPC (€)**	**Operating Cost(€)**
BAU 2017	0.19087	6.72B	495M
Data	0.203	N/A	N/A
Differ. %	-5.9%	-	-

The overall model is satisfying, it has some flaws simulating the balance of the system due to data limitation but is accurate enough on the CO2 emissions and the LCOE. Since on the rest of the Scenarios the power plans will be replaced, and the wind data also changes, the flaws are reduced for the rest of the Scenarios.

Table 8: Scenario BAU 2017, Detailed cost of the system

	Capital (€)	**Replacement (€)**	**Operation & Maintenance (€)**	**Fuel (€)**	**Salvage (€)**	**Total (€)**
PV	85,800,000.00	0.00	196,879,613.27	0.00	0.00	282,679,613.27
Enercon (Wind]	220,000,000.00	9,564,220.50	550,712,204.96	0.00	5,390,051.63	774,886,373.83
(Back-up)	0.00	0.00	156,631,662.45	47,411.67	2,940,493.56	159,619,567.68
(Diesel)	0.00	0.00	356,602,725.79	2,019,061,577.88	0.00	2,375,664,303.67
(HFO)	0.00	0.00	784,561,671.51	2,328,206,163.84	0.00	3,112,767,835.34
System	324,067,487.50	17,314,637.38	2,045,387,877.98	4,347,315,153.38	3,908,264.75	6,730,176,891.49

4.1.2. BAU 2050 model

The architecture of the energy system can be seen in **Table 9** in comparison with the 2017 model. In this model, 50MW of wind capacity was added and all together the farms were relocated offshore, south east of Crete and the wind data was also changed. The wind energy production increased by 47%. The PV farms increased by 22% and 50 MW PV on roof and 50 MW of CPV were introduced, resulting in annual solar energy production of 371 MWh per year, 61% increase since 2017. For the system to be balanced at least 900 MW support of the grid is needed with 2.9 TWh purchases and 737 MWh sales. Also, in case of failure of the sub-sea cable a 900 MW CCGT (natural gas) was installed and didn't produce any energy but the maintenance cost was kept. To make sure that the system is balanced without grid, the model was simulated with zero purchases and the CCGT fully functioning. Finally, with total

Table 9: Scenario BAU 2050, Comparison of the capacity of the 2050 and 2017 models

	Capacity of Energy System (MW)					
	PV	**PV roof**	**Solar C. PV**	**Wind Offshore**	**Grid**	**NatGas Back-up**
BAU 2050	100	50	50	250	900	900
BAU 2017	78	-	-	200	-	-
Differ. %	22	-	-	20	-	-

consumption 4.2 TWh per year the renewable fraction rises to 31.1% and the CO_2 emissions drop almost by 13%. The CO_2 emissions reduction, compared to 2005 is only 29%, that show the inability of such system to obtain the long-term targets of 2050.

In **Figure 12,** the Sum of the renewable production and the grid purchases cover the load for 2050 and there is no energy shortage. For this simulation the days from 14th January until the 24th were plotted in order to show that the renewable penetration is reaching over 80%. Maximum penetration appeared in March at 102% which means that the load was covered all by renewable energy and there was excess energy sold to the grid. The period with the stronger penetration is the spring and the winter (except January) due to the lower demand and low fluctuation of wind speed. From **Figure 13** (next page) it is obvious that during January and summer the grid purchases are increased due to higher demand and the renewable penetration doesn't exceed 60%. That means that during the summer the addition of more PV in the system would increase the penetration and since the system haven't exported any significant amount of energy, the potentials for renewable development are large.

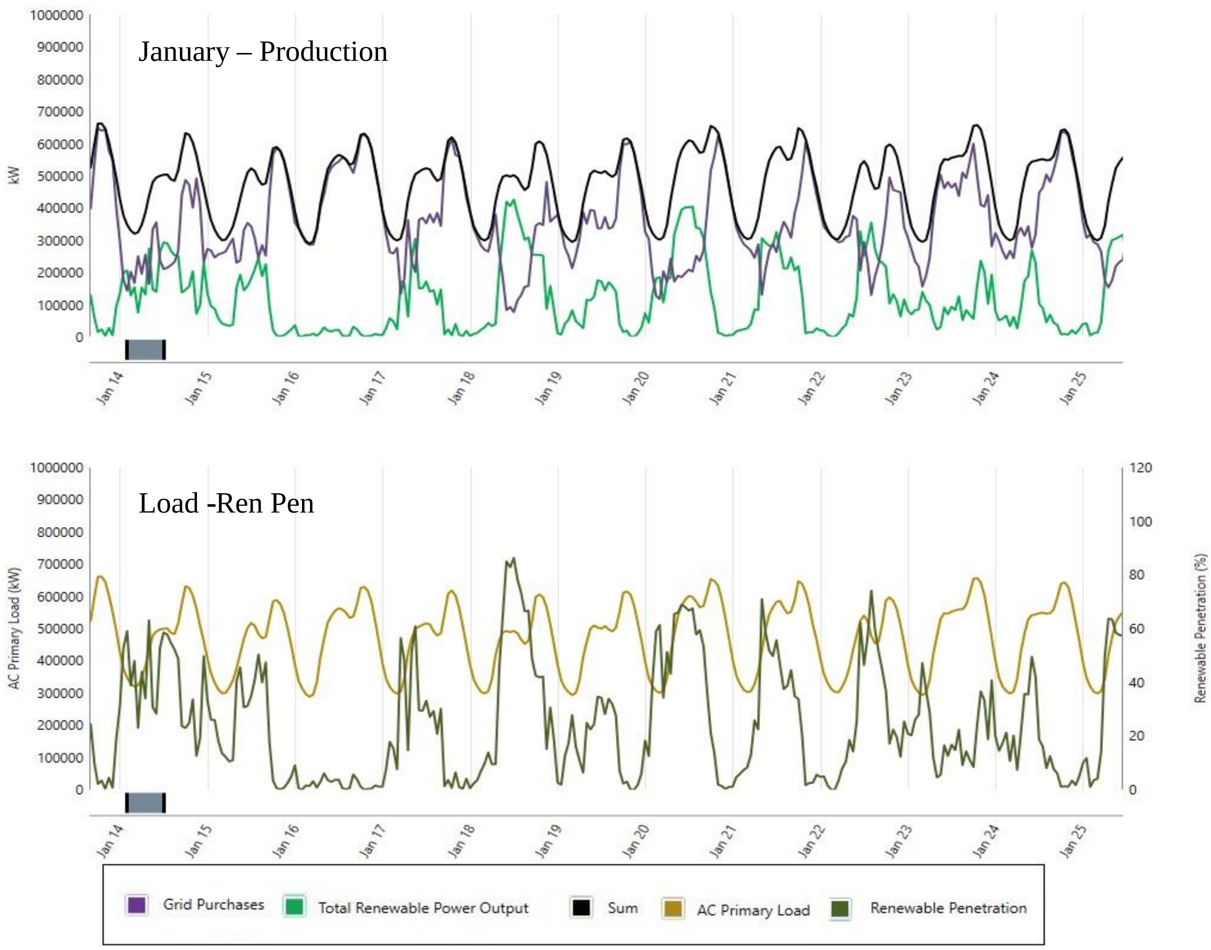


Figure 12: Scenario BAU 2050, Energy Balance Jan

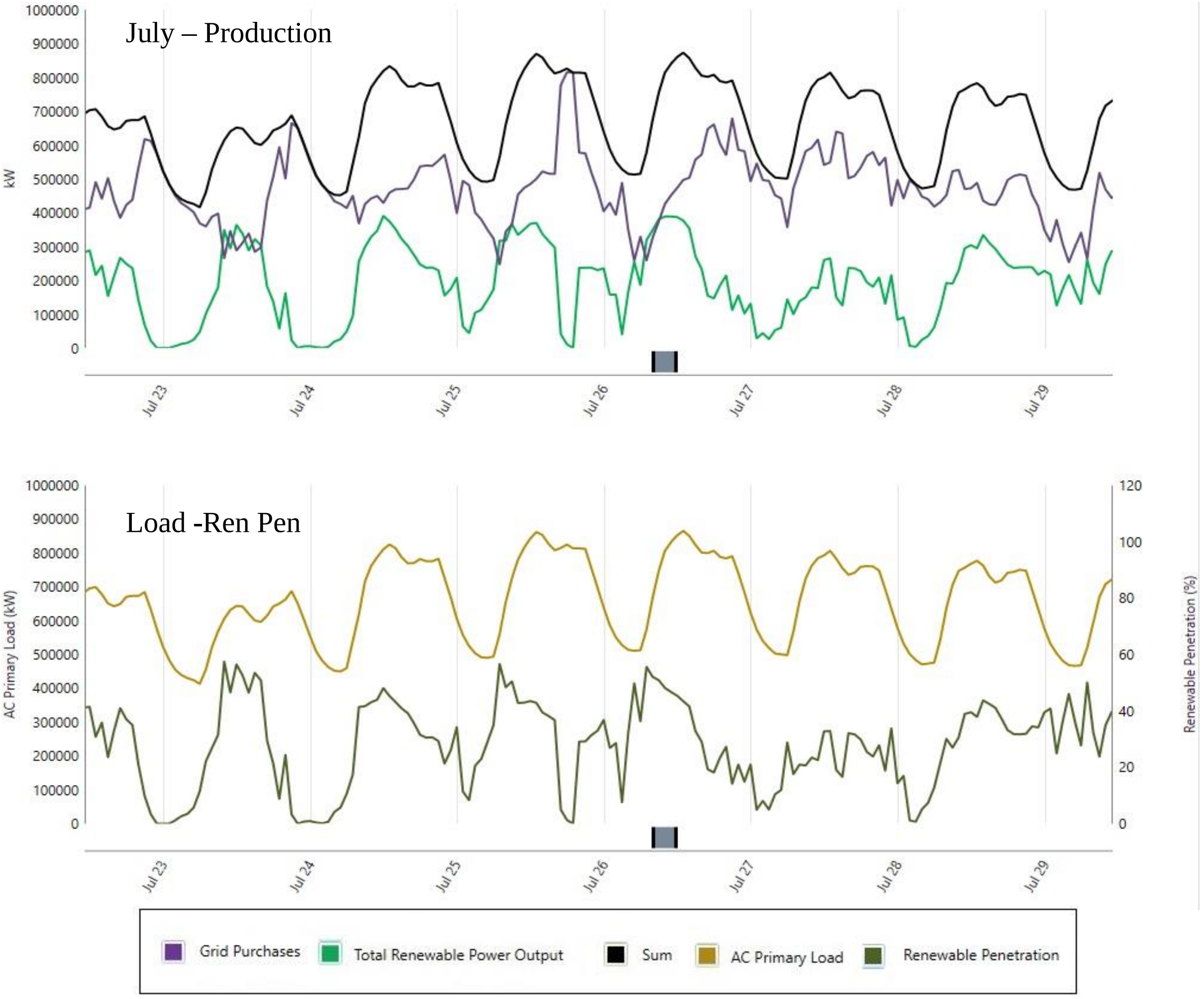


Figure 13: Scenario BAU 2050, Energy Balance Jul

In **Figure 14**, on the next page, the functionality of the renewable systems is shown. The solar energy production is clearly higher during the summer. The CPV follows the DNI and produces energy only during the day, with peak around 12am. The roof PV production follow the PV production at half the amount, which as shown in **Table 10.** The annual wind energy graph has a faint decrease during the summer, but that was anticipated knowing that the wind average speed reduces from 10m/s to 9m/s during the summer months. At the end of the 25th of July, in **Figure 14**, there is a sudden droppage of the wind production caused by the wind speed which reached the cut-out speed, at the same moment,

Table 10: Scenario BAU 2050, Comparison of the production, fuel consumption and emissions

	Annual Energy Production (GWh)							
	Ren Fra%	**PV**	**PV roof**	**Con. PV**	**Wind**	**Grid Purchases**	**Grid Sales**	**Total**	**CO2 emissions (ton/year)**
BAU 2050	31.1	185	82.5	103	970	2,930	0.737	4,272	1,852,195
BAU 2017	20.4	144	-	-	512	-	-	3,008	2,088,525
Differ. %	34.41	22.16	-	-	47.24	-	-	38	-12.76

in **Figure 13**, the grip purchase increases to support the balance of the system. This observation serves as an indicator that the system is working well.

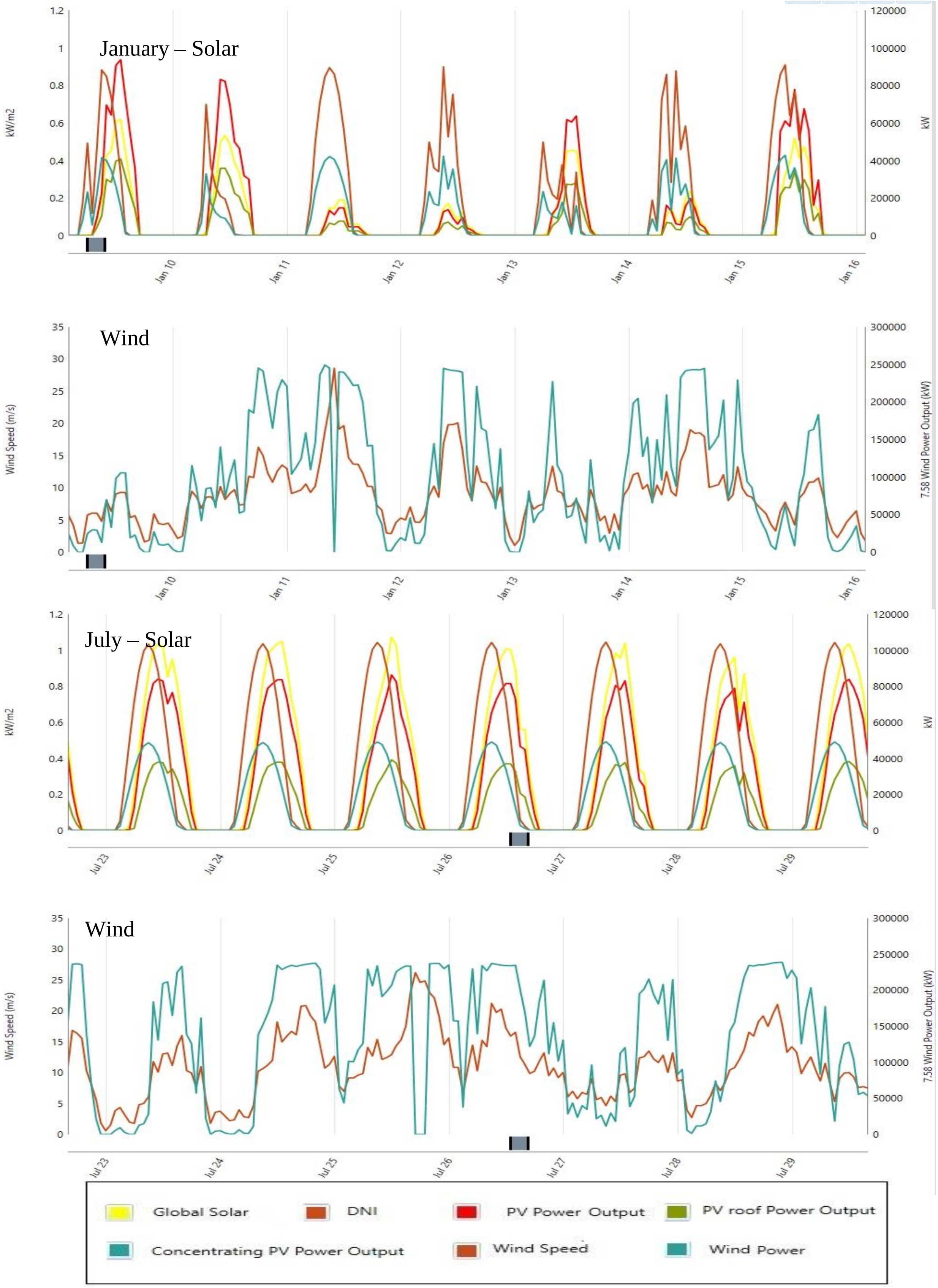


Figure 14: Scenario BAU 2050, Solar production & Global irradiation and Wind production & Wind Speed for January and July

The LCOE becomes 0.213 €/KWh and by adding the extra charges for the electricity 0.02487 €/KWh, it becomes 0.24 €/KWh, which results to 20% increase compared 2017 price. **Table 12** shows the potential cost of electricity depending on the O&M costs of the grid connections. The difference is significant, which it was expected since the grid is the most expensive investment of the system, **Table 13.** The NPC also changes and the case of 90% reduction it is lower than in 2017. The operating cost has dropped 35% due to the replacement of the HFO and Diesel power plans, **Table 11**. The values are only forecasting the order of magnitude of the project's cost and not the actual cost. Those results are going to be used to evaluate the other scenarios. The evaluation will show the difference of the costs of the different energy mix and the configuration of the LCOE.

Table 11: Scenario BAU 2050, Comparison of cost of the kWh

	Costs		
	LCOE (€/KWh)	**NPC (€)**	**Operating Cost(€)**
2050	0.213	11.7B	367M
2017	0.191	6.72B	495M
Differ. %	10.33	42.5	-34.8

Table 12: Scenario BAU 2050, Sensitivity analysis of LCOE and grid O&M costs

Grid cost reduction %	**LCOE (€/KWh)**	**LCOE with extra charges (€/KWh)**	**NPC (€)**
90	0.109	0.13387	5.99B
75	0.126	0.15087	6.95B
50	0.155	0.17987	8.53B
25	0.184	0.20887	10.1B
0	0.213	0.23787	11.7B

The overall model wouldn't be able to reach the targets for 2050 with only 29% of CO2 emissions reduction. This shows that the current business model is not drastic enough with so modest investment on the RES, will make Crete an extra burden for Greece on the race against the climate change. This model surely does not represent the extent of the sustainable development that Crete can support. On the rest of the scenarios the model is simulated on its limits, by trying to maximise the renewable fraction and the energy exports.

Table 13: Scenario BAU 2050, Detailed cost of the system

	Capital (€)	**Replacement (€)**	**Operation & Maintenance (€)**	**Fuel (€)**	**Salvage (€)**	**Total (€)**
PV	88,000,000	0	201,927,808	0	0	289,927,808
PV roof	44,000,000	0	100,963,904	0	0	144,963,904
Wind	450,252,000	0	1,033,163,632	0	0	1,483,415,632
Con. PV	28,846,154	0	3,729,091	0	0	32,575,245
Grid	6,340,482,330	0	3,408,481,600	0	0	9,748,963,930
NatGas	0	0	176,848	607,335	0	784,183
System	6,951,580,484	0	4,748,442,884	607,335	0	11,700,630,703

4.2. Scenario 2- Wind energy growth with interconnection

In Scenario 2 storage technology was included in order to increase the renewable fraction of the electric balance. In **Table 14** and **Table 15**, the results of the sensitivity test are presented. The factors that changed were the wind and the storage capacity (MW). The sensitivity test investigated the range of fluctuation of the renewable fraction (%), the CO2 emissions reduction (% against 2005 levels), the LCOE (€/kWh) and the NPC (Billions €). The scope was to find the design that would succeed the target of 80% CO2 reduction by 2050. The model managed to obtain the target in all the range of wind turbine capacity simulations, but with zero batteries the requirement was over 3,000 MW. In order to obtain the target with lower development of the wind technology the system needed dispatchable energy to serve the load in periods of low wind speed. The **bolded numbers** are the designs that obtained or surpassed the emission target.

Table 14: Scenario 2, Renewable Fraction % and CO2 Reduction % (2005) results

		Wind Capacity (MW)					
Battery Capacity (MW)	**Ren. Fraction %**	**1,137**	**1,516**	**1,895**	**2,274**	**2,501**	**3,009**
	100	79.8	85.6	89.1	91.4	92.5	<u>**93.9**</u>
	250	81.4	87	90.4	**92.5**	**93.4**	94.8
	375	83.5	88.9	**91.9**	93.9	94.7	95.9
	500	86.1	91.2	93.9	95.5	96.2	97.2
	1000	88.8	93.9	96.1	97.3	97.8	98.5
	2500	92.2	97.1	98.5	99.1	99.3	99.6
	%CO2 Emission Reduction (2005)	**1,137**	**1,516**	**1,895**	**2,274**	**2,501**	**3,009**
	100	67	71.5	74.6	76.8	77.9	<u>**79.9**</u>
	250	70.5	74.8	77.8	**80**	**81**	82.9
	375	74.7	79	**81.8**	83.9	84.9	86.7
	500	79.4	84	86.7	88.5	89.4	91
	1000	84.1	89.3	91.8	93.3	94	95.2
	2500	89.5	95.1	97	97.9	98.2	98.6

Table 15: Scenario 2, LCOE(€/kWh) and NPC (billion €) results

		Wind Capacity (MW)					
Battery Capacity (MW)	**LCOE(€/kWh)**	**1,137**	**1,516**	**1,895**	**2,274**	**2,501**	**3,009**
	100	0.153	0.132	0.116	0.104	0.099	<u>**0.094**</u>
	250	0.158	0.135	0.119	**0.106**	**0.1**	0.095
	375	0.165	0.14	**0.122**	0.109	0.103	0.097
	500	0.175	0.147	0.128	0.113	0.107	0.1
	1000	0.187	0.157	0.135	0.119	0.111	0.104
	2500	0.212	0.177	0.15	0.131	0.122	0.113
	NPC (Billions €)	**1,137**	**1,516**	**1,895**	**2,274**	**2,501**	**3,009**
	100	13.3	13.9	14.5	15	15.4	<u>**16.6**</u>
	250	13.4	14	14.5	**15.1**	**15.5**	16.7
	375	13.5	14.1	**14.7**	15.3	15.6	16.8
	500	13.7	14.3	14.9	15.5	15.8	17
	1000	14.1	14.7	15.3	15.9	16.2	17.4
	2500	15.3	15.9	16.4	17	17.4	18.6

The design with the lowest LCOE and higher renewable fraction is the <u>**underlined**</u> with zero storage and 3,009 MW wind capacity. Even though such a large off-shore wind farm does not exist now, it is assumed that with the development of the technology and the decrease of the prices by 2050, such an investment is feasible. For the study the feasibility of such investment is not necessary, since the purpose is to find the smaller investment per technology needed to obtain the CO_2 emission target for 2050.

The architecture of the energy system can be seen in **Table 16** in comparison with the BAU 2050 model. The wind capacity has been increased by 1103.6% from 250 MW to 3,009 MW and produces 12.8 TWh per year, **Table 17**. For the solar development the only change was the installment of extra 100 MW PV on roof in order to avoid the reduction of the renewable penetration during the summer. The total energy of the system is the sum of all the production and purchases in one year. The excess energy produced was 500 GWh that could not be absorbed from the system. This energy could also be stored and supplied as shown in **Table 14** and **Table 15.** The sensitivity analysis showed that this design can reach 99.6% renewable fraction and 98.6% CO_2 emissions reduction with the 2.5 GW storage, keeping a lower than the present LCOE of 0.113€/kWh but with and NPC of 18.6 billion euros.

Table 16: Scenario 2, Comparison of the capacity

	Capacity of Energy System (MW)						
	PV	**PV roof**	**Solar CPV**	**Wind Offshore**	**Battery**	**Grid**	**NatGas Back-up**
Sc2	100	150	50	3,009	0	900	900
BAU 2050	100	50	50	250	-	900	900
Differ. %	0.00	200	0.00	1103.6	-	0.00	0.00

Table 17: Scenario 2, Comparison of the production, grid exchanges and emissions

GWh	**Sc2**	**BAU 2050**	**Differ. %**
PV	185	185	0.00
PV roof	247	82.5	199.39
Con. PV	103	103	0.00
Battery	-	970	-
Wind	12,824	2,930	337.68
Grid Purchases	827	0.737	-
Grid Sales	9,051	4,272	111.87
Total	23,237	7,573	206.83
Ren Fra%	93.9	31.1	201.93
CO2 emissions (ton/year)	523,217	1,852,195	-71.75

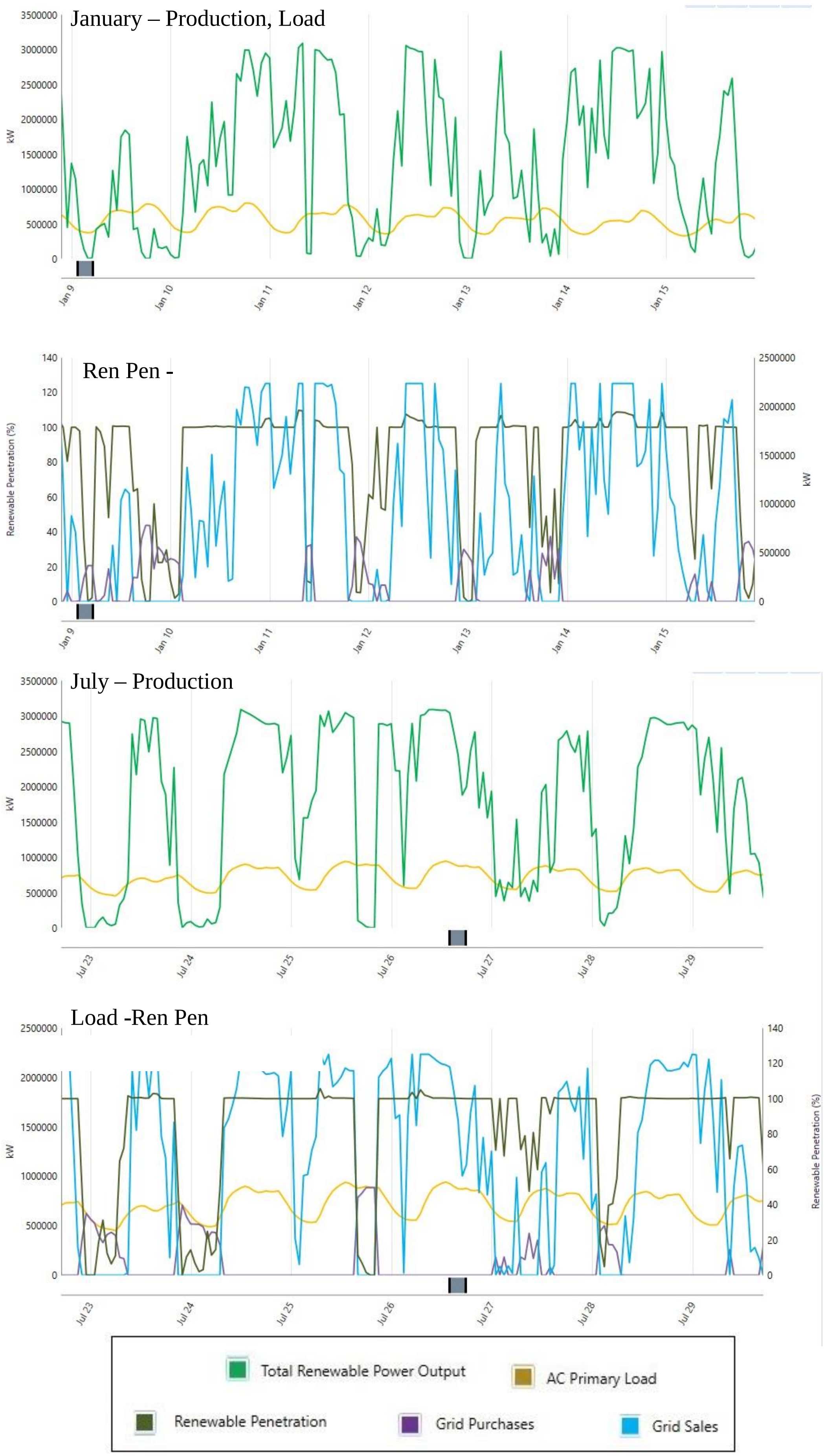


Figure 15: Scenario 2, Energy Balance January and July

In **Figure 15,** the the top graph shows the renewable production to have excess on the 11th of January, and below the grid sales are maximised. The renewable penetration is strong during the winter and the system reaches the export limit (2,235 MW) with the annual excess electricity of 3.4% (500 GWh), considered a fine value for such a large system. The grid sales are mainly driven by the wind energy production, with a small boost at the peak hours of solar production. Summer is the most vulnerable season for the system with limited solar capacity, higher demand load and high probability of days of wind lull, which is a common phenomenon. For those reasons, the connection with the grid is most needed for support during the summer and that can be seen more clearly on the **Figure 16,** where the grid purchases hit the peak demand of 887 MW in July and reaches 53 GWh purchases in August compared to 108.8 GWh in January and 42 GWh in November. In **Figure 17** the grid sales are disperced during the day and focus more during in the night. The grid is used to balance the energy system since the energy production is unpredictable.

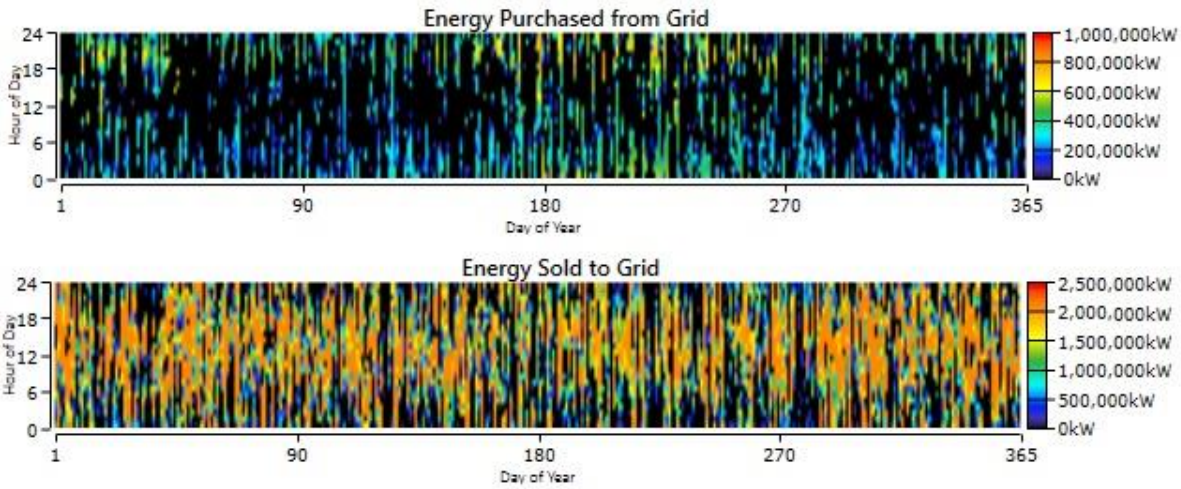


Figure 16: Scenario 2, Grid connection annual energy exchanges

In the next page, **Figure 17** shows the production of the different renewable technologies. The solar energy production reaches its peaks during the summer and the wind during the winter. The renewable technologies follow their relevant weather indicator’s path and produce energy within the anticipated range. This serves as a quality check of the simulation model to verify its correct fuctionality.

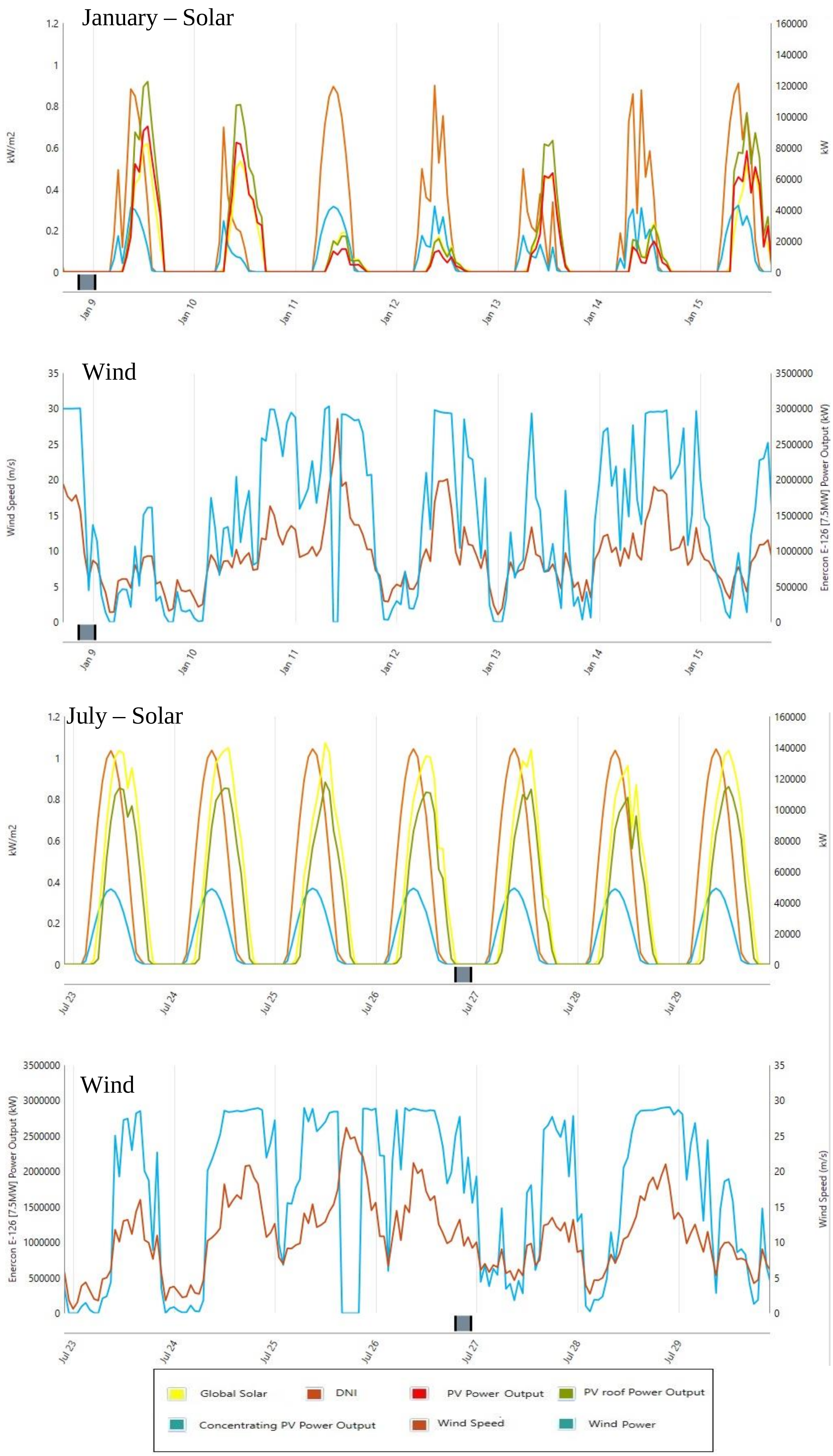


Figure 17: Scenario 2, Solar production & Global irradiation and Wind production & Wind Speed for January and July

An investigation took place in order to find what does the system need to reach 100% renewable fraction. The energy system required 3,932 MW of total renewable capacity (Wind 3032 MW, total PV 600 MW and CPV 300 MW) and 3,500MW of storage compared to the current model of 3259MW and zero storage. Yet, when the software was showing 100% renewable fraction the grid purchases were not zeroed, thus the CO2 emissions weren't zero as well. The value is ideal and the same occurred in multiple simulations with 100% result. That shows that it hits a bottleneck, the higher the CO2 reduction the more difficult to reduce. Although the model showed 100% renewable fraction the results were rounded because the system was still purchasing energy from the grid. For example, At the 14th of August the renewable generation is dropping for three days, at the 14th and from 8pm energy was purchased from the grid, **Figure 18**. This shows the stochastic nature of the renewable systems and the challenge to build a sustainable energy system that can secure the energy supply under extreme conditions. However, there is still the potential of smart systems with demand site management. For example, in the last simulation if the system could include boilers with thermal storage that could saved energy from solar thermal panels until 7 pm, **Figure 18**, and cover the demand later that day, theoretically the system would be 100% renewable and independent from the grid.

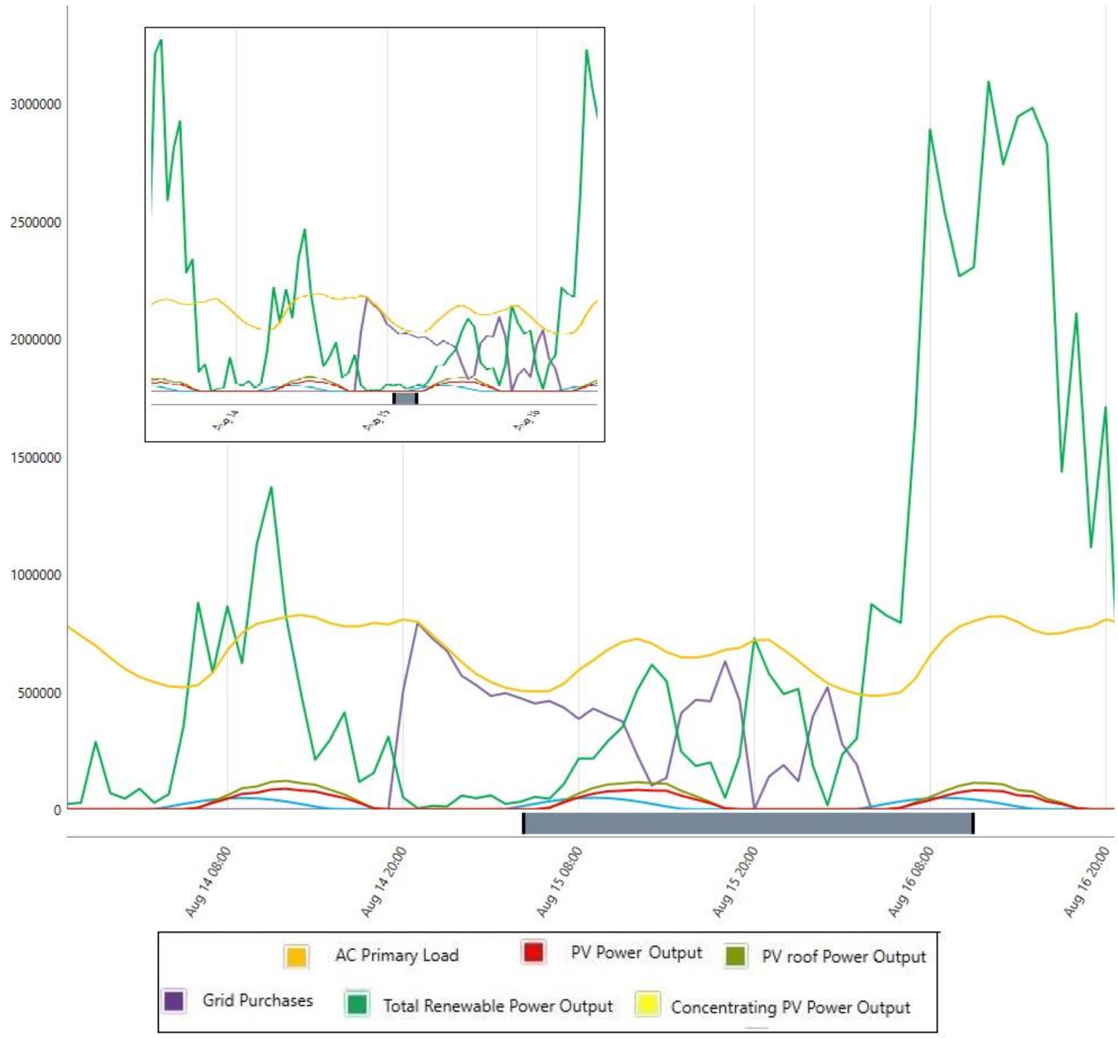


Figure 18: Scenario 2-100%RenFra, Energy System State August

The LCOE becomes 0. 0943 €/KWh and with the extra charges it becomes 0.119€/KWh, which is 38% reduced compared with the BAU 2050. **Table 19** shows the potential cost of electricity depending on the O&M costs of the grid connections. The LCOE is decreasing dramatically. If the O&M is 10% of the capital cost the LCOE becomes 0.09€/KWh, with the extra charges. This shows the large effect of the grid running costs to the system. The NPC also changes drastically, and the most economic result was 10.9 billion euros.

Table 18: Scenario 2, Comparison of cost of the kWh

	Costs		
	LCOE (€/KWh)	**NPC (€)**	**Operating Cost(€)**
Sc2	0.0943	16.6B	360M
BAU 2050	0.191	11.7B	367M
Differ. %	-50	42.7	-1.91

Table 19: Scenario 2, Sensitivity analysis of LCOE and grid O&M costs

Grid cost reduction %	**LCOE (€/KWh)**	**LCOE with extra charges (€/KWh)**	**NPC (€)**
90	0.06	0.09	10.97
75	0.07	0.09	11.92
50	0.08	0.10	13.51
25	0.09	0.11	15.09
0	0.09	0.12	16.68

The model achieves the satisfying reduction targets for 2050 with 9.051 TWh of exports. The system was tested for 100% renewable fraction and it succeeded, the details are presented together with the Scenario 3. Under 100% CO2 reduction conditions the system couldn't secure the supply of energy due to lack of dispatchable energy, so it purchased electricity from the grid. **Table 20** shows the economical details of the system and how the NPC is calculated. The Natural Gas power station is used as a backup, but in order to keep the O&M cost the component was put under maintenance for all the year except for one hour (software limitation). That is the reason the fuels are not zero. The effect on the energy balance is negligible.

Table 20: Scenario 2, Detailed cost of the system

	Capital (€)	**Replacement (€)**	**Operation & Maintenance (€)**	**Fuel (€)**	**Salvage (€)**	**Total (€)**
PV	88,000,000	0	201,927,808	0	0	289,927,808
PV roof	132,000,000	0	302,891,713	0	0	434,891,713
Con. PV	40,384,615	0	5,220,728	0	0	45,605,343
Wind	5,416,668,000	0	12,429,271,574	0	0	17,845,939,574
Grid	6,340,482,330	0	8,281,607,567	0	0	1,941,125,237
NatGas	0	0	49,797	607,334	0	657,132
Battery	0	0	0	0	0	0
System	12,017,534,945	0	4,657,754,053	607,334	0	16,675,896,333

4.3. Scenario 3- Solar energy growth with interconnection

In Scenario 3 the same sensitivity test took place in order to develop a design with at least 80% of CO2 emission reduction. In **Table 21** and **Table 22**, the results of the sensitivity test are presented. The factor that changed were the PV on roof, PV and the storage capacity in MW. The model managed to obtain the target in all the range of solar capacity simulations, but with at least 375 MW of storage. The system depends from the storage and the grid to cover the demand during the night hours. The design with the lowest LCOE and higher renewable fraction is the underlined with 375 MW storage, 1,350 MW of PV on roofs and 900 MW PV capacity.

Table 21: Sc3, Renewable Fraction % and CO2 Reduction %(2005) results

		PV on roof/PV Capacity (GW)			
Battery Capacity (MW)	***%CO2 Emission Reduction (2005)***	**1.35/0.9**	**1.3/0.9**	**13.5/0.8**	**1.3/0.8**
	100	72.7	72.7	72.6	72.5
	250	77.3	77.2	77.1	77.1
	375	**80.7**	**80.7**	**80.6**	**80.5**
	500	83.8	83.8	83.6	83.6
	1000	93	92.9	92.8	92.7
	2500	99	98.9	98.9	98.8
	Ren. Fraction %	**1.35/0.9**	**1.3/0.9**	**13.5/0.8**	**1.3/0.8**
	100	85.66	85.49	85.24	85.07
	250	87.72	87.57	87.34	87.18
	375	**89.4**	**89.2**	**89**	**88.9**
	500	90.89	90.76	90.56	90.43
	1000	95.78	95.7	95.56	95.46
	2500	89.5	95.1	97	97.9

Table 22: Sc3, LCOE(€/kWh) and NPC(billion €)) results

		PV on roof/PV Capacity (MW)			
Battery Capacity (MW)	**LCOE(€/kWh)**	**1.35/0.9**	**1.3/0.9**	**13.5/0.8**	**1.3/0.8**
	100	0.146	0.147	0.148	0.149
	250	0.151	0.152	0.154	0.155
	375	**0.155**	**0.156**	**0.158**	**0.159**
	500	0.16	0.161	0.162	0.163
	1000	0.174	0.175	0.177	0.178
	2500	0.194	0.196	0.198	0.2
	NPC (Billions €)	**1.35/0.9**	**1.3/0.9**	**13.5/0.8**	**1.3/0.8**
	100	14.76	14.7	14.66	14.59
	250	14.88	14.81	14.77	14.71
	375	**15**	**14.9**	**14.9**	**14.8**
	500	15.06	15	14.96	14.9
	1000	15.44	15.37	15.33	15.27
	2500	16.56	16.5	16.46	16.39

The architecture of the energy system can be seen in **Table 23** in comparison with the Sc2 model. The wind capacity has been decreased by nine folds from 3,009 MW to 606 MW and production is 2.58 TWh per year, **Table 24**. The solar technology configuration was 200MW CPV, 900MW PV farms and 1,350MW PV on the roof.

Table 23: Scenario 3 Comparison of the capacity

	Capacity of Energy System (MW)						
	PV	**PV roof**	**Solar CPV**	**Wind Offshore**	**Battery**	**Grid**	**NatGas Back-up**
Sc3	900	1,350	200	606	375	900	900
Sc2	100	150	50	3,009	-	900	900
Differ. %	0.00	200	0.00	900.56	-	0.00	0.00

The PV on the roof is equivalent of 6 kW installment to 225,000 roofs (domestic, public and commercial sectors).

Table 24: Scenario 3, Comparison of the production, grid exchanges and emissions

GWh	Sc3	Sc2	Differ. %
PV	1,720	185	830
PV roof	2,229	247	802
Con. PV	412	103	300
Battery	495	-	-
Wind	2,584	12,824	-79.8
Grid Purchases	789	827	-4.6
Grid Sales	2,815	9,051	-68.9
Total	10,054	23,237	-56.7
Ren Fra%	89.4	93.9	-4.8
CO2 emissions (ton/year)	500,928	523,217	-4.3

The storage system was introduced since the renewable production system required dispatchable energy during the night times, and the optimum for this model was 375 MW of storage capacity. **Table 21** contains the results from a sensitivity analysis CO2 reduction (compared to 2005 levels) against the storage and solar capacity. The highest reduction was 98.8%, but with the highest NPC of 16.39 billion euros. The total energy purchases have been reduced by 4.6% which means the model is closer to decarbonize of electric energy than in Scenario 2.

The renewable penetration is still at the same levels during the January and the summer, because of the higher demand. The penetration is stronger during the spring and reaches its peak of 238% on 6th April. The reason of high penetration was that at 5 am on the 6th of April the load was still low at 300 MW but the total renewable output was at 710 MW, that was the only day with electricity excess. The system never reaches the export limit with the annual excess electricity of 0.0008% (59MWh), considered avery good. In **Figure 19**, the thermal image of the grid sales and purchases makes clear that the energy system is using the grid to supply the demand mostly during the night. During the spring, with higher

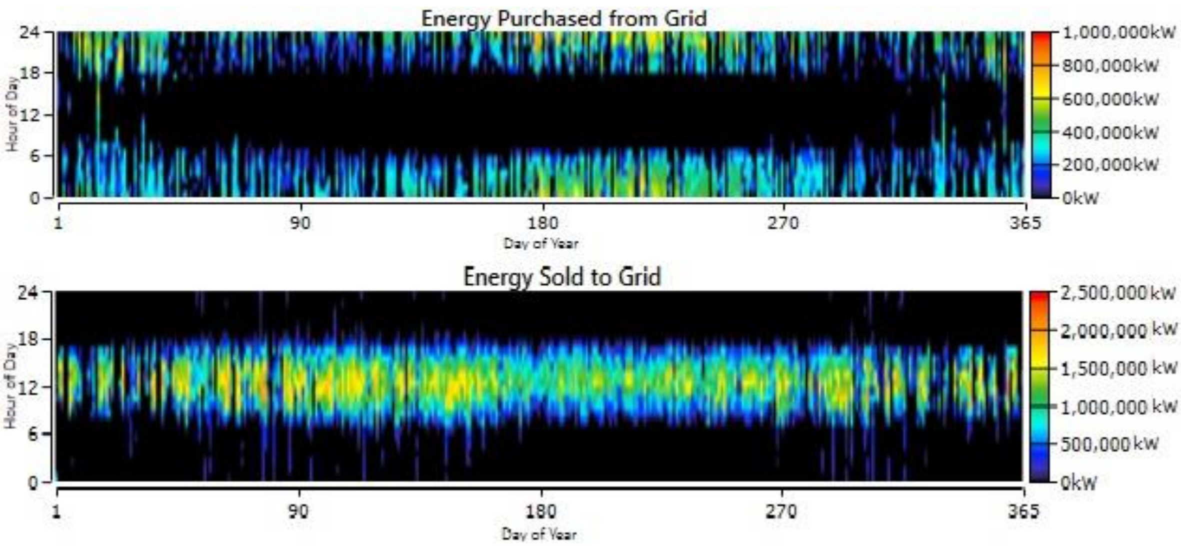


Figure 19: Scenario 3, Grid connection annual energy exchanges

renewable penetration, the sales are thinker and yellow and the purchases during the night became shades of blue and black. The peak demand from the grid is still 854 MW occuring in July. By recalling the thermal image of the Scenario 2, where the sales and the demand where dispersed, and comparing it with Scenario 3, its noticed that the shape of latest is much more focused and neat. This model has lower sales than Scenario 2 but is more predictable with lower emissions, **Table 24.**

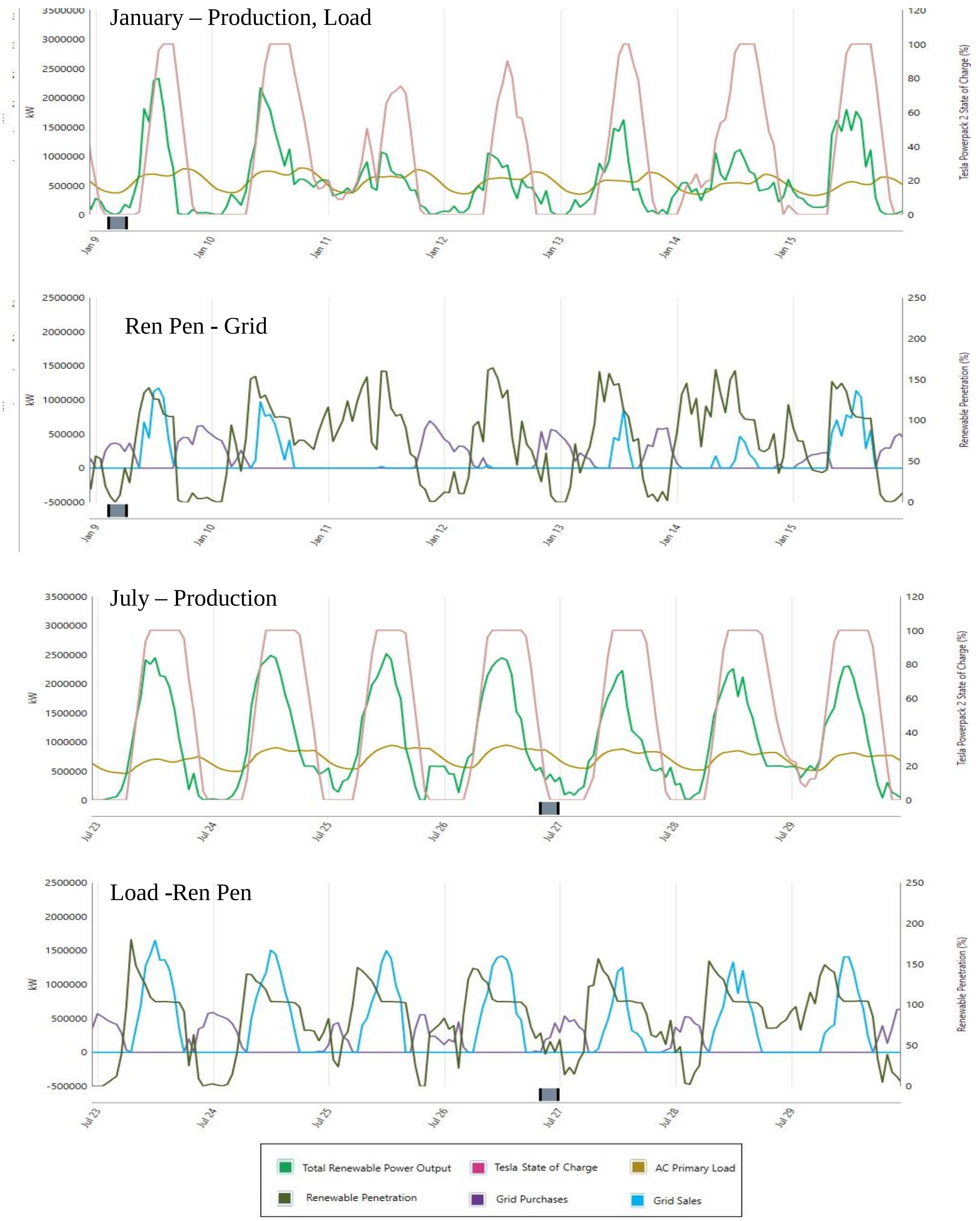


Figure 20: Scenario 3, Energy Balance January and July

In **Figure 20,** the top graph shows how the battery discharges as soon as the production of renewable energy drops. The battery follows the path of the renewable production but with a declination to the right, because the system first covers the load and when there is excess energy it charges the battery and sells to the grid. The battery will always deplete and only then the imports from the grid will begin. **Figure 21** shows the renewable production follows the same pattern as the rest of the scenarios since the weather datra is the same. The fuctionality of the system is correct, so the quality test is positive to verify its correct fuctionality.

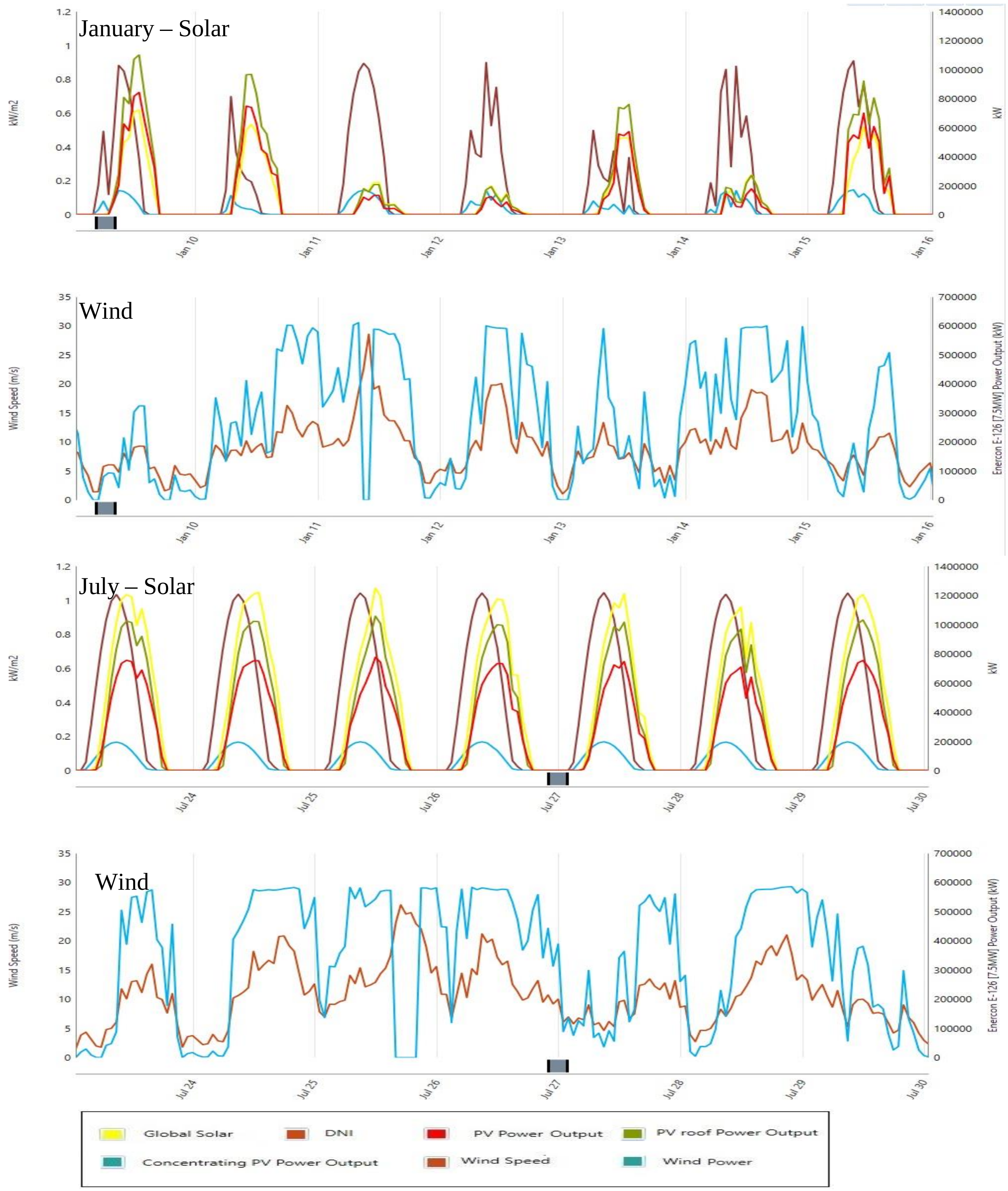


Figure 21: Scenario 3, Solar production & Global irradiation and Wind production & Wind Speed for January and July

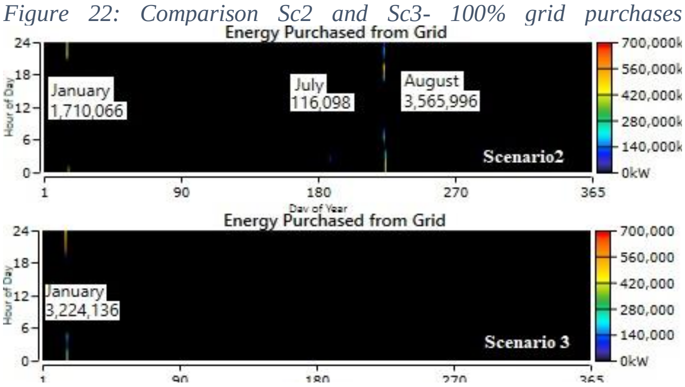
For the 100% renewable fraction investigation the requirements of the model are listed in **Table 25** with a comparison against Scenario 2. The rounding of the renewable fraction occurred in Scenario 3 as well. Scenario 3 is more economic with NPC 7,7% lower than Scenario 2. The LCOE for both the scenarios is lower than the current prices, with the solar being 36.6% higher. The total renewable systems installed is very close and the storage capacity 16.7% higher in the solar model.

Table 25: Comparison of Sc 2 and Sc 3 – 100% Renewable Fraction

(GW)	CPV	PV roof	PV	Wind	Battery	Total	CO2 emissions (ton/yr)	LCOE (€/kWh)	NPC (€)
Sc 2	0.3	0.3	0.3	3.0	3.0	3.9	3,708	0.112	19.4
Sc 3	0.3	1.4	1	1.1	3.5	3.8	2,338	0.153	17.9
Differ.%	0.0	366.7	0.0	-63.5	16.7	-2.6	-37.0	36.6	-7.7

Figure 22 shows the purchases from the grid for both Scenarios. The wind model needed the grid for energy balance three times and the solar once, **Figure 23**. The solar model is more reliable and economic than the wind model. The wind model has higher grid sales, considered a good factor. The total energy consumption in Greece for 2016 was 51.8 TWh, (IEA, 2016), and the total of 9 TWh were exported from Scenario 2 – 100%, which means that the 17% of the Greek total consumption ideally it could be covered from the exports of Crete.

Figure 22: Comparison Sc2 and Sc3- 100% grid purchases



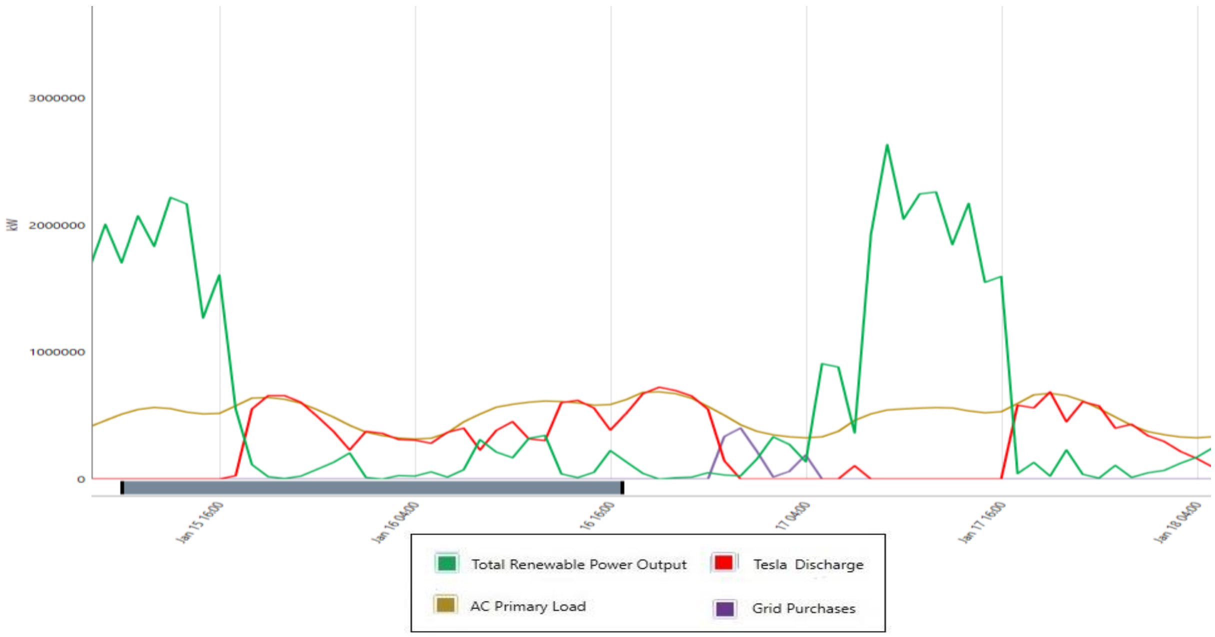


Figure 23: Scenario 3-100%, Grid purchase

The LCOE becomes 0.155 €/KWh and with the extra charges it becomes 0.182 €/KWh, which is 40% higher than in Scenario 2. **Table 27** shows the potential cost of electricity depending on the O&M costs of the grid connections.

Table 26: Scenario 3, Comparison of cost of the kWh

Costs			
	LCOE (€/KWh)	**NPC (€)**	**Operating Cost(€)**
Sc3	0.155	15B	409M
Sc2	0.0943	16.7B	360M
Differ. %	39.64	-9.64	13.61

Table 27: Scenario 3, Sensitivity analysis of LCOE and grid O&M costs

Grid cost reduction %	**LCOE (€/KWh)**	**LCOE with extra charges (€/KWh)**	**NPC (€)**
90	0.097	0.122	9.32B
75	0.107	0.132	10.27B
50	0.124	0.149	11.86B
25	0.140	0.165	13.44B
0	0.152	0.182	15.03B

The solar model also achieves satisfying targets for 2050, but with exports of 2.5 TWh, much lower than in Sc2. In the test for 100% renewable fraction the model was more economic than the wind model, almost by 10%, but with 36% higher LCOE. In the simulation for 100% CO2 reduction since the system couldn't supply energy during the night the only way to balance the energy was with the development of storage systems. **Table 28** includes the economic details of the system.

Table 28: Scenario 3, Detailed cost of the system

	Capital (€)	**Replacement (€)**	**Operation & Maintenance (€)**	**Fuel (€)**	**Salvage (€)**	**Total (€)**
PV	792,000,000	0	1,817,350,276	0	0	2,609,350,276
PV roof	1,188,000,000	0	2,726,025,415	0	0	3,914,025,415
Con. PV	161,538,462	0	20,882,911	0	0	182,421,373
Wind	1,091,520,000	0	2,504,639,108	0	0	3,596,159,108
Grid	6,340,482,330	0	1,896,368,498	0	0	4,444,113,832
NatGas	0	0	49,797	607,335	0	657,132
Battery	165,000,000	132,515,644	1,939,127	0	17,966,839	281,487,933
System	9,738,540,791	132,515,644	5,174,518,137	607,335	17,966,839	15,028,215,069

4.4. Scenario 4 – Wind and Solar Balance

In this scenario a large simulation took place that included a wide range of renewable technology capacities for all the different components in order to find the optimum energy balance that can achieve 80% reduction of CO2 emissions. In **Table 29** the range of the capacities simulated per technology are listed. From this simulation the configuration of solar energy was optimized at 100/100 MW for PV/PV on roof and 150 MW for CPV. A sensitivity simulation followed and from the data attained color scaling tables were developed to visualize the flow on the NPC in billion €, the LCOE in €/kWh, the CO2 reduction (% against 2005), the Renewable Fraction in %, the Initial Cost in billion € and the Operation Cost in million €. The sensitivity simulation investigates the wind capacity from 947MW to 3,009MW and storage capacity from 0MW to 2,500MW. In **Table 30**, the **bolded numbers** are the models that came close or achieved the 2050 emission target and the optimum solution was **underlined**. By comparing with tables **30** till **32,** the flow of each value can be seen. The NPC results are 0.5 billion € higher than Sc3 and 1.2 billion € lower than Sc2, the closer the system is to decarbonization the more expensive it becomes, **Table 30 & 31**. The LCOE has the opposite flow,

Table 29: Scenario 4 Range of capacities simulated per component

	Capacity range (MW)	
	min	***max***
PV	50	1000
PV roof	50	1500
CPV	50	300
Wind	947.5 (125)	3009 (397)
Battery	0	2500

Table 30: Scenario 4, sensitivity analysis - CO2 Reduction against 2005 emissions in %

CO2 %	**947.5**	**1137**	**1326.5**	**1516**	**1895**	**2274**	**2653**	**3009**
0	-65.18	-68.24	-70.61	-72.55	-75.51	-77.67	**-80**	**-80.63**
100	-68.55	-71.65	-74.01	-75.88	-78.73	**-80.82**	-82.40	-83.60
250	-72.54	-75.85	-78.18	**-79.99**	-82.71	-84.71	-86.21	-87.33
375	-75.06	-78.54	**-80.92**	-82.70	-85.33	-87.24	-88.68	-89.73
500	-76.93	**-80.59**	-83.11	-84.88	-87.44	-89.24	-90.56	-91.56
1000	-81.03	-85.26	-88.27	-90.11	-92.40	-93.84	-94.84	-95.58
2500	-85.14	-90.63	-93.86	-95.72	-97.31	-98.10	-98.49	-98.82

Table 31: Scenario 4, sensitivity analysis – NPC configuration in € for 25 years

NPC(B€)	**947.5**	**1137**	**1326.5**	**1516**	**1895**	**2274**	**2653**	**3009**
0	12.85	13.13	13.41	13.70	14.28	14.87	**15.51**	**16.53**
100	12.93	13.21	13.50	13.78	14.36	**14.95**	15.59	16.59
250	13.06	13.34	13.62	**13.91**	14.49	15.08	15.71	16.69
375	13.16	13.45	**13.73**	14.02	14.60	15.18	15.82	16.79
500	13.26	**13.55**	13.84	14.12	14.70	15.29	15.92	16.89
1000	13.65	13.94	14.23	14.52	15.10	15.69	16.32	17.29
2500	14.79	15.09	15.39	15.67	16.25	16.83	17.47	18.45

Table 32: Scenario 4, sensitivity analysis – LCOE configuration in €/kWh

LCOE (€/kWh)	**947.5**	**1137**	**1326.5**	**1516**	**1895**	**2274**	**2653**	**3009**
0	0.163	0.150	0.139	0.129	0.114	0.102	**0.094**	**0.093**
100	0.169	0.155	0.143	0.132	0.116	**0.104**	0.096	0.094
250	0.176	0.161	0.148	**0.137**	0.120	0.107	0.098	0.096
375	0.182	0.166	**0.152**	0.141	0.123	0.109	0.100	0.097
500	0.186	**0.170**	0.156	0.144	0.125	0.111	0.101	0.099
1000	0.199	0.182	0.167	0.153	0.132	0.117	0.106	0.103
2500	0.224	0.207	0.189	0.172	0.146	0.128	0.115	0.111

the higher the decarbonization the lower the LCOE. Compared to the previous scenarios the LCOE is just under Sc2's and 0.061 €/kWh lower than in Sc3. The price of electricity by adding the charging cost becomes 0.11487 €/kWh, significantly decreased compared to the BAU scenarios. To decrease the LCOE more, wind capacity is necessary. The minimum LCOE obtained from simulations was 0.093 €/kWh, **Table 32**, with maximum wind capacity installed and zero storage. The renewable fraction in **Table 33** is very high, achieving 93.3% for the optimum scenario and becomes higher as we move to the bottom right of the table. It must be noted that the system works in ideal conditions and the real renewable fraction could be better or worst depending on the consumption efficiency, the demand side management, the weather and other unpredictable factors.

Table 33: Scenario 4, sensitivity analysis – Renewable Fraction configuration in %

RenFra %	**947.5**	**1137**	**1326.5**	**1516**	**1895**	**2274**	**2653**	**3009**
0	76.5	80.7	83.9	86.3	89.6	91.8	**93.3**	**94.2**
100	78.2	82.4	85.4	87.7	90.8	**92.9**	94.2	95.0
250	80.3	84.5	87.4	**89.5**	92.4	94.2	95.4	96.1
375	81.7	85.9	**88.7**	90.8	93.5	95.1	96.2	96.8
500	82.8	**87.0**	89.9	91.8	94.3	95.8	96.8	97.4
1000	85.3	89.8	92.7	94.4	96.5	97.6	98.2	98.6
2500	88.0	93.2	96.0	97.5	98.7	99.2	99.5	99.6

Table 34: Scenario 4, sensitivity analysis – O&M configuration in Million € per year

O&M (M€)	**947.5**	**1137**	**1326.5**	**1516**	**1895**	**2274**	**2653**	**3009**
0	348.48	343.85	339.53	335.40	327.55	320.07	**317.17**	**346.04**
100	351.42	346.80	342.48	338.34	330.48	**323.00**	319.58	347.32
250	356.10	351.56	347.24	**343.08**	335.18	327.68	324.02	350.14
375	359.95	355.54	**351.25**	347.09	339.16	331.64	327.99	353.26
500	363.58	**359.29**	355.08	350.93	342.98	335.41	331.79	356.87
1000	376.64	372.84	368.94	364.90	356.93	349.24	345.63	371.08
2500	413.67	410.40	406.87	402.85	394.71	386.88	383.16	409.29

Table 35: Scenario 4, sensitivity analysis –Initial Cost configuration in Billion €

Initial (B€)	**947.5**	**1137**	**1326.5**	**1516**	**1895**	**2274**	**2653**	**3009**
0	8.34	8.68	9.03	9.37	10.05	10.73	**11.41**	**12.05**
100	8.39	8.73	9.07	9.41	10.09	**10.77**	11.46	12.10
250	8.45	8.79	9.14	**9.48**	10.16	10.84	11.52	12.16
375	8.51	8.85	**9.19**	9.53	10.21	10.90	11.58	12.22
500	8.56	**8.90**	9.25	9.59	10.27	10.95	11.63	12.27
1000	8.78	9.12	9.47	9.81	10.49	11.17	11.85	12.49
2500	9.44	9.78	10.13	10.47	11.15	11.83	12.51	13.15

Comparing the O&M Cost per year, scenario 4 obtains lower values than all the previous scenarios. In **Table 34**, shows that the chosen combination has the lowest possible O&M Cost of 317.17 million €, following the path of Sc2, but anymore wind capacity would increase the O&M Cost. The reason is that the system reaches the grid export limits and there is high electricity excess. The Initial Cost is presented in **Table 35**, with Sc4 being in the red/orange zone of the table. That was expected since the storage is cheaper than the wind technology in the simulation. It needs to be noted that if the cost of storage was risen the color scale would change significantly on most of the tables. The underestimation of the cost of the storage technologies effects the tables related with the economical values. Under these conditions the chosen model, has more realistic values compared for example with the bottom left (**bold) model** with the lowest NPC, due to less accurate details. That was an important point for the selection of the optimum scenario.

Table 36: Scenario 4 Comparison of the capacity

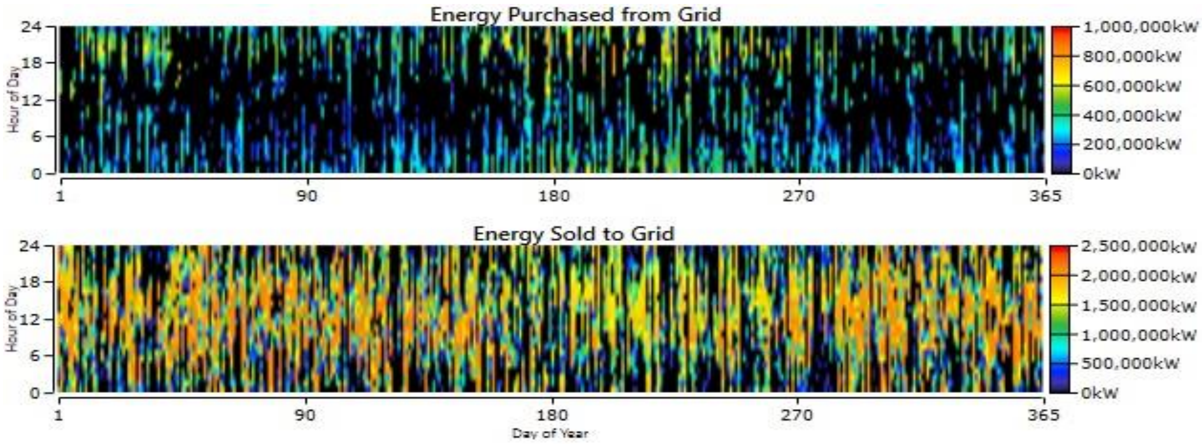
	BAU 2050	***Sc3***	***Sc2***	***Sc4***
PV	100	900	100	100
PV roof	50	1,350	150	100
CPV	50	200	50	150
Wind	250	606	3,009	2,653
Battery	-	375	-	-
Grid	900	900	900	900
Back-up	900	900	900	900

In **Table 36** the optimum configuration of the energy system is presented. There is low investment in the solar technology 350MW all together and 2,653MW of wind capacity. The model is very similar to Scenario 2 with only difference is 50 MW wind capacity less and 100MW of CPV. The solar is just the 5.15% of the total electricity that passes through the system. The grid sales have quadrupled compared to Sc3. In **Figure 24**, the grid exchanges take the same dispersed shape with the Sc2 with a small difference. The total energy excess is 57GW, almost 10% of the excess of Sc2 (500GW). **Figure 24** shows that this model needs the support of the grid mostly during the night. After the sun is down the grid purchases emerge in order to cover the gaps of the wind production. In **Figure 24**, the purchases are more concentrated in the late hours and during the summer the grid is most needed. The peak demand is 827MW in July and the month highest purchases in August with 112MW. The maximum renewable penetration is 112% in April, with spring and early winter having the highest absorption, similar results with the second scenario in different levels.

Table 37: Scenario 4, Comparison of the production, grid exchanges and emissions

GWh	**PV**	**PV roof**	**CPV**	**Battery**	**Wind**	**Grid Purchases**	**Grid Sales**	**Total**	**Ren Fra%**	**CO2 emissions (ton/year)**
Sc4	185	165	310	-	11,306	849	8,093	20,908	93.3	536,932
Sc3	1,720	2,229	412	495	2,584	789	2,815	10,054	89.4	500,928
Sc2	185	247	103	-	12,824	827	9,051	23,237	93.9	523,217

Figure 24: Scenario 4, Grid connection annual energy exchanges



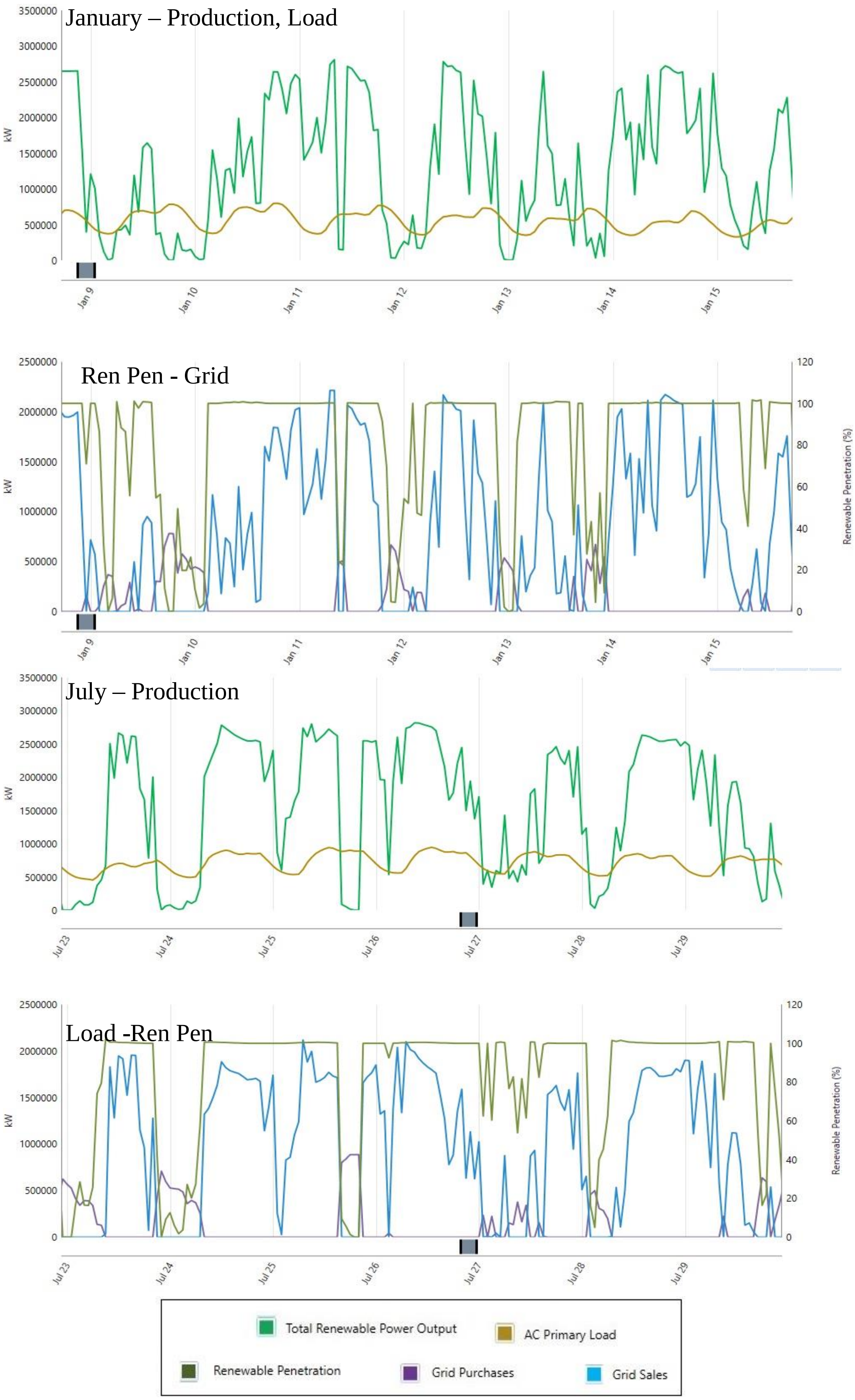


Figure 25: Scenario 4, Energy Balance January and July

Figure 26 is similar to **Figure 14** from Scenario2. The differences are the higher production levels of the CPV and the lower production level of wind energy.

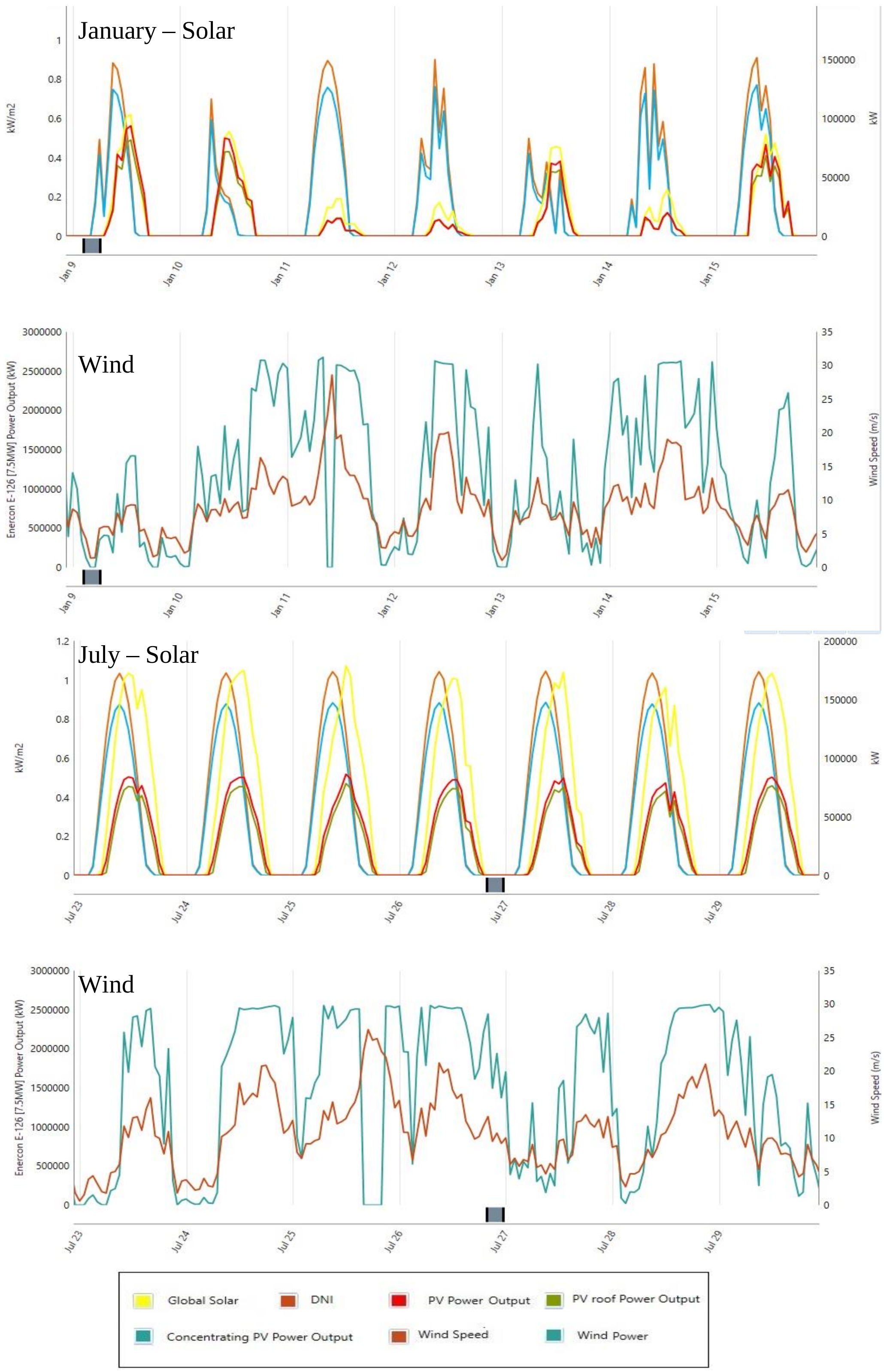


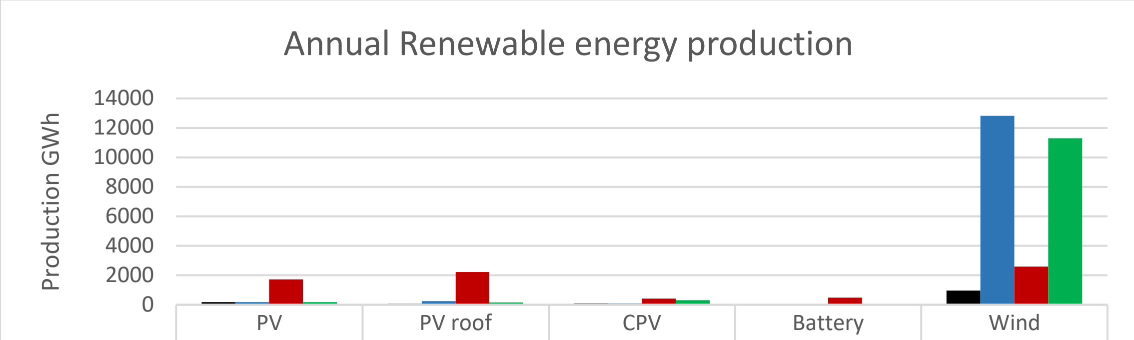
Figure 26: Scenario 4, Solar production & Global irradiation and Wind production & Wind Speed for January and July

The forth model achieved the targets for 2050, with high exports and no storage capacity. This model was not tested for 100% renewable fraction, since the purpose of this test was to uncover the weaknesses of the different technologies and the similarity of Sc4 and Sc2 would lead to similar results. In **Table 38** shows the detailed costs of the system.

Table 38: Scenario 4, Detailed cost of the system

	Capital (€)	Replacement (€)	Operation & Maintenance (€)	Fuel (€)	Salvage (€)	Total (€)
PV	88,000,000	0	201,927,808	0	0	289,927,808
PV roof	88,000,000	0	201,927,808	0	0	289,927,808
Con. PV	121,153,846	0	15,662,184	0	0	136,816,030
Wind	4,775,400,000	0	10,957,796,098	0	0	15,733,196,098
Grid	1,585,120,583	0	7,277,595,914	0	0	5,692,475,331
NatGas	0	0	49,797	607,335	0	657,132
System	6,657,674,429	0	4,099,767,782	607,335	0	10,758,049,546

5. Discussion & Conclusion



	PV	PV roof	CPV	Battery	Wind
BAU 2050	185	82.5	103	0	970
Sc2	185	247	103	0	12.824
Sc3	1.720	2.229	412	495	2.584
Sc4	185	165	310	0	11.306

Figure 27: Annual Renewable energy production summary

In **Figure 27,** the annual production levels of all the scenarios per renewable component are summarised. The wind capacity that the system can support is massive due the grid interconnection of 2,350MW and the exports can reach up to 9TWh per year in Scenario 2. In Scenario 3 the total solar energy production is 4,4TWh, which is lower than the 4,6TWh load, so the development of wind technology is essential in order to cover the demand. On the other hand, for Scenario 2 the instalment of the solar technology was also important for the balance of the system, even if it was kept at the minimum. Scenario 4 shows the least amount of installed technology necessary to succeed the reduction levels for 2050. The PV are kept to the minimum and the CPV was raised by 100MW. The Sc4-model also has large wind capacity, that the system can support only because of the grid. A lower export limit would change the results of the study and the emission levels could not be achieved without the instalment of storage units.

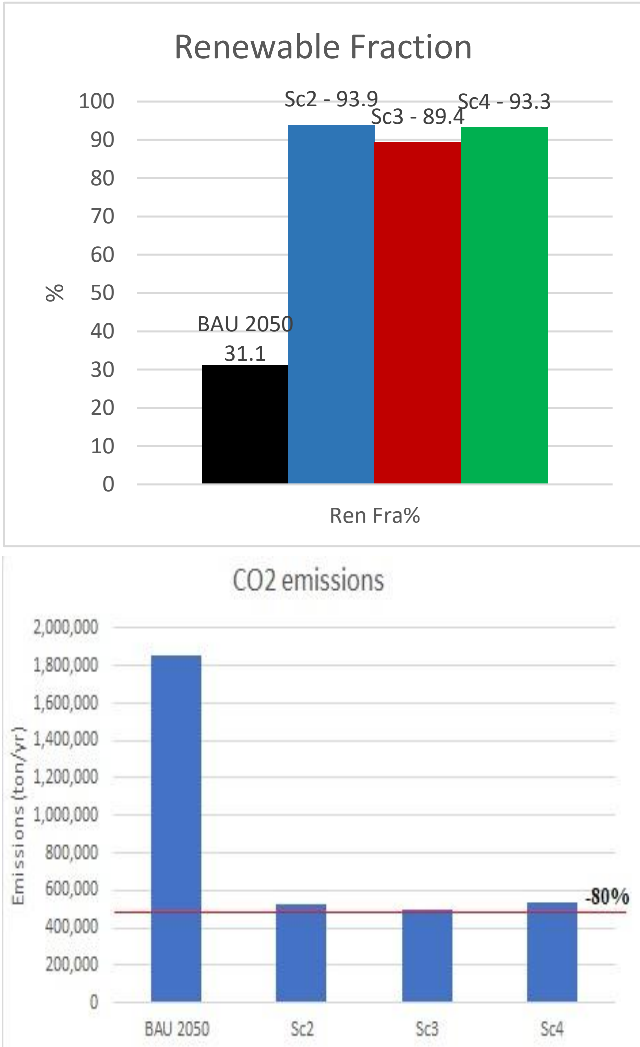
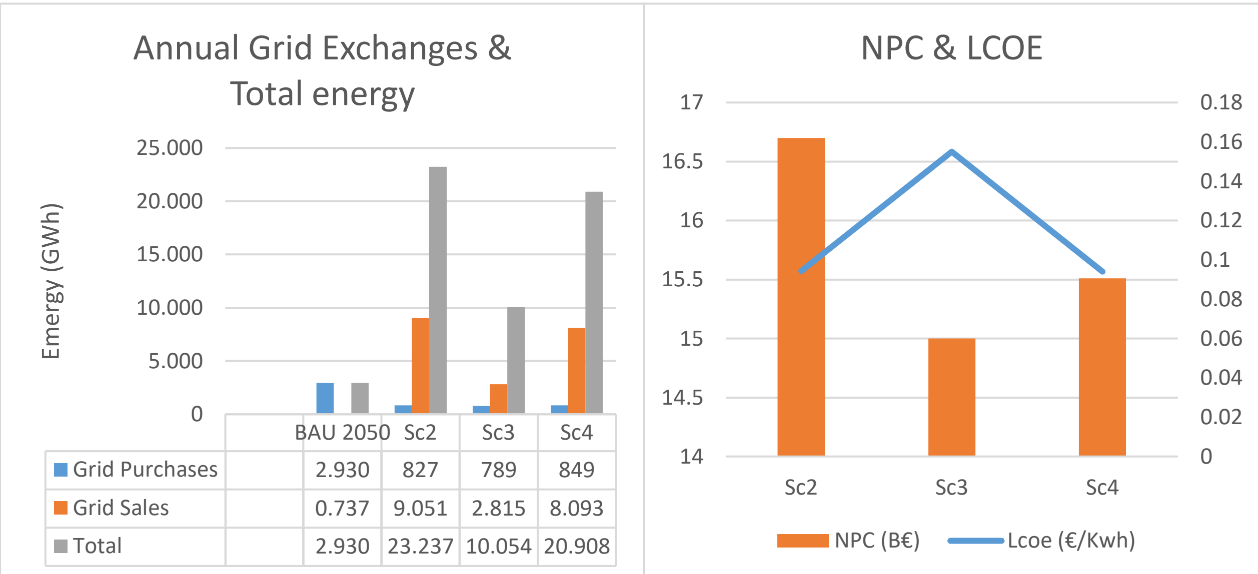


Figure 28: Summary of Renewable Fraction and CO2 emissions

Figure 28 shows the summary of the renewable fraction and CO2 emissions reduction for all the scenarios. The results of Scenario 2 and 4 are very close, only 0.6 higher renewable fraction for the Sc2, but Sc4 obtains 0.1 higher reduction of CO2 emissions. Also, from the 100% renewable fraction simulations, the models showed the need of 3-3.5GW storage capacity. The largest pumped hydro in the world is 3GW, (Anon., 2018), so technically it is feasible, but the existence of the space for such a large installation is uncertain. Such task it would be more feasible with the combination of smaller storage units and demand side management or with the development of hydrogen technology, by 2050. The reason for such a large storage is the big fluctuation of the energy demand during the summer and the periods of wind dull. Even with such storage capacity the energy system would still require more dispatchable energy to balance, just like in the 100% RenFra-models. **Figure 29** shows that with the expansion of the solar capacity the grid exports can reach 2,5TWh, one forth compared with the development of wind technology. The grid purchases are similar and very low compared with the size of the energy mix. The reason is the lack of dispatchable energy from the system, which means that with the integration of smart systems, storage units and/or biomass the scenarios two to four could reach the 2050 target with lower investment. Another indicator of this is the excess energy of Scenario 2, which is 500GWh compared to the grid purchases of 827Gwh. Even though it is not a positive factor, excess energy shows that the energy system can support more load. Thus, the development such as desalination plans and Carbon Capture and Storage (CCP) technologies that are very energy intensive could be supported from such system.



	BAU 2050	Sc2	Sc3	Sc4
Grid Purchases	2.930	827	789	849
Grid Sales	0.737	9.051	2.815	8.093
Total	2.930	23.237	10.054	20.908

Figure 29: Summary of Grid exchanges, Total energy, NPC and LCOE

The results indicate that the wind technology has huge potential for development, but only after the grid connection is installed. Thus, the development of wind technology with grid exports, is a very powerful combination with many advantages like low LCOE, high exports and with the integration of storage system, significant increase of the renewable fraction. On the other hand, the unpredictable nature of the wind speed makes difficult for a system to secure the energy supply throughout the year, even if the total renewable production is 160% higher that the annual demand. Thus, the wind technology can be a good supporting unit of a system, but it is not possible to achieve energy balance and sustainability without other support. The development of solar technology empowers the stability of the energy system during the day and only in combination with storage, it can contribute during the night. Solar energy is a key for the stability of the system, during the day, by covering the voids of the wind technologies. In conclusion, wind and solar energy can cover most of the demand load, but the energy balance cannot be secured through these technologies. In the simulations, the stability of the system is achieved with the support of the grid interconnection and a back-up generator. To decarbonise the energy system of Crete, the present of dispatchable energy units (biomass, hydrogen fuel cells or storage) is necessary, mostly during the night.

Taking in consideration the short-term and long-term challenges of the energy system of Crete the following steps are suggested for the development of the energy sector:

1. Replacement of the HFO and Diesel generators, to decrease the CO_2 emissions short-term and achieve the 2020 targets.
2. Parallel development of the PV to the suggested levels, to increase the renewable penetration during the daytime.
3. Begin of the environmental impact assessment for the development of off-shore wind farms, so that the location of the farms will be defined by the time of the interconnection.
4. After the completion of the 1st stage of the Euroasia interconnector (1,000MW) and the Peloponnese interconnection (235MW exports), anticipated no later than 2025, the development of the wind capacity can begin, limited to the export levels.
5. Investigation of new technologies of renewable dispatchable units and demand side management to increase the renewable penetration during the big fluctuations of the renewable production.
6. After the completion of the 2nd stage of Euroasia (not yet announced), further development of wind capacity to maximise exports.
7. In case of more interconnections (Euroafrica) or change of the export levels, the limits of the renewable development should be re-investigated.

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Appendix

1

Table 39: Fossil fueled generation units of Crete, expiring dates

	ΑΡΧΙΚΑ ΣΤΟΙΧΕΙΑ ΑΔΕΙΑΣ ΠΑΡΑΓΩΓΗΣ				ΣΤΟΙΧΕΙΑ ΑΙΤΗΣΕΩΝ ΤΡΟΠΟΠΟΙΗΣΗΣ					ΠΑΡΑΤΗΡΗΣΗ/ΣΧΟΛΙΑ
	ΜΟΝΑΔΑ	ΚΑΥΣΙΜΟ	ΙΣΧΥΣ (kW)	ΕΤΟΣ ΛΗΞΗΣ ΑΠ	ΜΟΝΑΔΑ	ΚΑΥΣΙΜΟ	ΟΝΟΜ. ΙΣΧΥΣ (kW)	ΑΠΟΔ. ΙΣΧΥΣ (kW)	ΕΤΟΣ ΛΗΞΗΣ ΑΠ	
ΘΕΡΜΙΚΕΣ ΜΟΝΑΔΕΣ ΣΤΑ ΣΥΣΤΗΜΑΤΑ ΚΡΗΤΗΣ ΚΑΙ ΡΟΔΟΥ										
ΑΗΣ ΛΙΝΟΠΕΡΑΜΑΤΩΝ	ΑΗΜ 1	ΜΑΖΟΥΤ	6.25		ΑΗΜ 1	ΜΑΖΟΥΤ				Αίτημα κατάργησης και διαγραφής
	ΑΗΜ 2	ΜΑΖΟΥΤ	15	2011	ΑΗΜ 2	ΜΑΖΟΥΤ	15	14.3	Μέχρι διασύνδεση	Αίτημα επέκτασης της διάρκειας της ΑΠ
	ΑΗΜ 3	ΜΑΖΟΥΤ	15	2011	ΑΗΜ 3	ΜΑΖΟΥΤ	15	14.3	Μέχρι διασύνδεση	Αίτημα επέκτασης της διάρκειας της ΑΠ
	ΑΗΜ 4	ΜΑΖΟΥΤ	25	2017	ΑΗΜ 4	ΜΑΖΟΥΤ	25	23.5	Μέχρι διασύνδεση	Αίτημα επέκτασης της διάρκειας της ΑΠ
	ΑΗΜ 5	ΜΑΖΟΥΤ	25	2021	ΑΗΜ 5	ΜΑΖΟΥΤ	25	23.5	Μέχρι διασύνδεση	Αίτημα επέκτασης της διάρκειας της ΑΠ
	ΑΗΜ 6	ΜΑΖΟΥΤ	25	2021	ΑΗΜ 6	ΜΑΖΟΥΤ	25	23.5	Μέχρι διασύνδεση	Αίτημα επέκτασης της διάρκειας της ΑΠ
	Α/Σ 1	DIESEL	16.25	2012	Α/Σ 1	DIESEL	16.25	15	Μέχρι διασύνδεση	Αίτημα επέκτασης της διάρκειας της ΑΠ
	Α/Σ 2	DIESEL	16.25	2013	Α/Σ 2	DIESEL	16.25	15	Μέχρι διασύνδεση	Αίτημα επέκτασης της διάρκειας της ΑΠ
	Α/Σ 3	DIESEL	43.337	2027	Α/Σ 3	DIESEL	43.3	42.7	2027	
	Α/Σ 4	DIESEL	14.72	2026	Α/Σ 4	DIESEL	14.72	13.5	2026	Καμία αλλαγή
	DIESEL 1	ΜΑΖΟΥΤ	12.28	2019	DIESEL 1	ΜΑΖΟΥΤ	12.28	11	Μέχρι διασύνδεση	Αίτημα επέκτασης της διάρκειας της ΑΠ
	DIESEL 2	ΜΑΖΟΥΤ	12.28	2019	DIESEL 2	ΜΑΖΟΥΤ	12.28	11	Μέχρι διασύνδεση	Αίτημα επέκτασης της διάρκειας της ΑΠ
	DIESEL 3	ΜΑΖΟΥΤ	12.28	2019	DIESEL 3	ΜΑΖΟΥΤ	12.28	11	Μέχρι διασύνδεση	Αίτημα επέκτασης της διάρκειας της ΑΠ
	DIESEL 4	ΜΑΖΟΥΤ	12.28	2019	DIESEL 4	ΜΑΖΟΥΤ	12.28	11	Μέχρι διασύνδεση	Αίτημα επέκτασης της διάρκειας της ΑΠ
ΑΗΣ ΧΑΝΙΩΝ	Α/Σ 1	DIESEL	16.2	2010	Α/Σ 1	DIESEL	16.2	14	Μέχρι διασύνδεση	Αίτημα επέκτασης της διάρκειας της ΑΠ
	Α/Σ 4	DIESEL	24	2010	Α/Σ 4	DIESEL	20	19.75	Μέχρι διασύνδεση	Αίτημα επέκτασης της διάρκειας της ΑΠ
	Α/Σ 5	DIESEL	30	2011	Α/Σ 5	DIESEL	30	29.2	Μέχρι διασύνδεση	Αίτημα επέκτασης της διάρκειας της ΑΠ
	Α/Σ 11	DIESEL	59.4	2023	Α/Σ 11	DIESEL	59.37	58	2023	
	Α/Σ 12	DIESEL	59.4	2023	Α/Σ 12	DIESEL	59.37	58	2023	
	ΣΥΝΔ/ΝΟΥ	DIESEL	132.3	2030	ΣΥΝΔ/ΝΟΥ	DIESEL	132.3	126	2030	Καμία αλλαγή
ΑΗΣ ΑΘΕΡΙΝΟΛΑΚΟΥ	DIESEL 1	ΜΑΖΟΥΤ	75-85	2034	DIESEL 1	ΜΑΖΟΥΤ	51.12	49.67	2034	Αίτημα αύξησης ισχύος
	DIESEL 2	ΜΑΖΟΥΤ		2034	DIESEL 2	ΜΑΖΟΥΤ	51.12	49.67	2034	Αίτημα αύξησης ισχύος
	ΑΗΜ 1	ΜΑΖΟΥΤ	100-110	2047	ΑΗΜ 1	ΜΑΖΟΥΤ	46.5	43.2	2047	Αίτημα αύξησης ισχύος
	ΑΗΜ 2	ΜΑΖΟΥΤ		2048	ΑΗΜ 2	ΜΑΖΟΥΤ	46.5	43.2	2048	Αίτημα αύξησης ισχύος

2

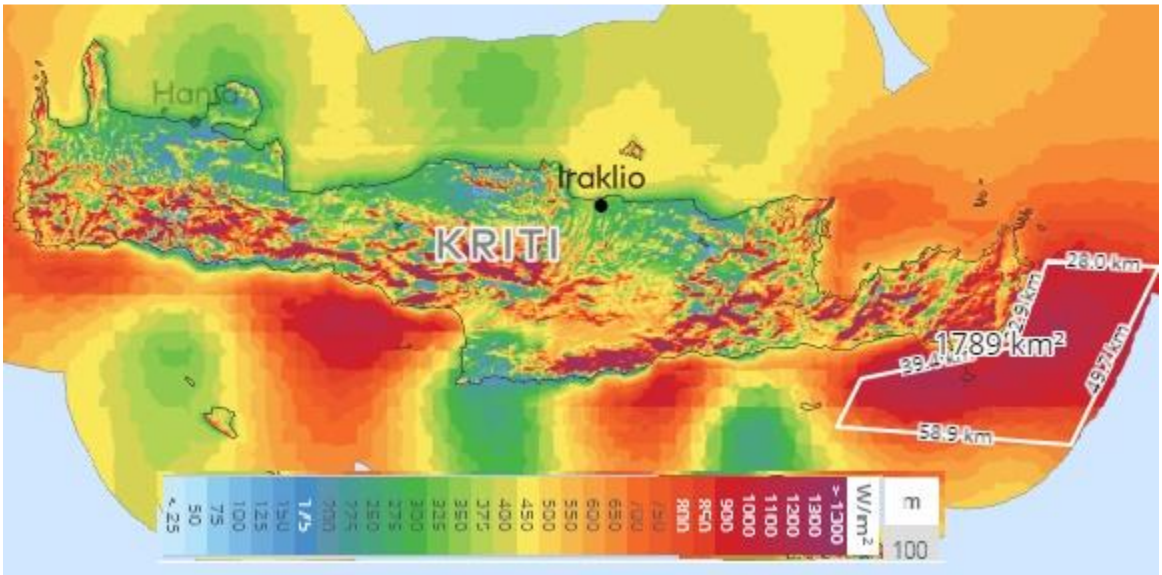

Figure 29: Potential location for off-shore wind farms

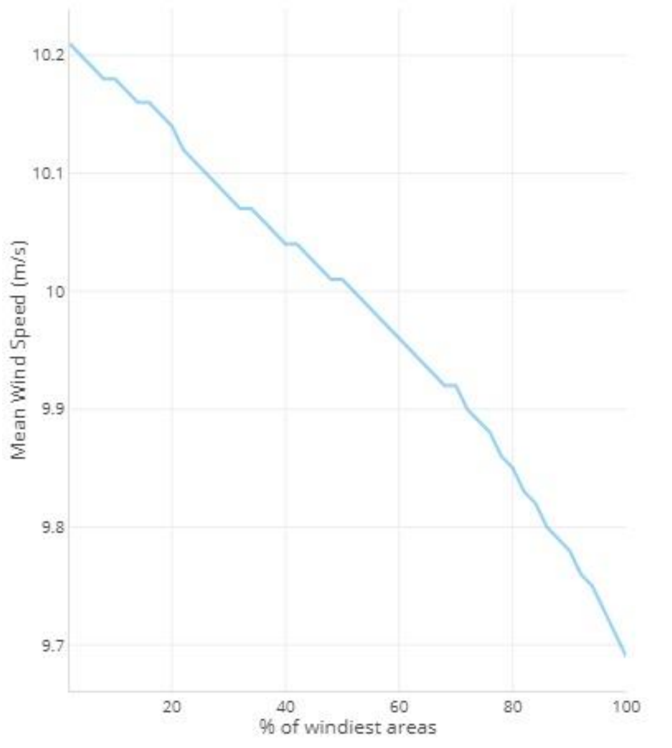

Figure 30: Wind speed of the location over the year

3

Table 40: Capital and O&M costs of renewable technologies for 2015 to 2050

	Cost per MW ('000€)	
	2015	2050
Wind farm	1200	1100
Off-shore wind farm	2100	1800
PV farm	1100	880
PV roof	1100	880
PV roof (storage)	2000	1048
Hybrid	2700	2400
Solar Thermal Units	3400	2800
	Annual Cost per MW (€)	
	2015	2050
Wind farm	213.000	195.250
Off-shore wind farm	372.750	319.500
PV farm	195.250	156.200
PV roof	195.250	156.200
PV roof (storage)	355.000	186.020
Hybrid	479.250	426.000
Solar Thermal Units	603.500	497.000

Table 41: Capital and O&M costs of Fossil fuelled technologies for 2015 to 2050

Type of Unit	Capital Cost ('000 €/MW)	Total Annual Cost (€/MW-
CCGT	750	133.125
Gas Turbine	550	97.625
Steam turbine	1200	213.000
Internal combustion engine	700	103.000

4

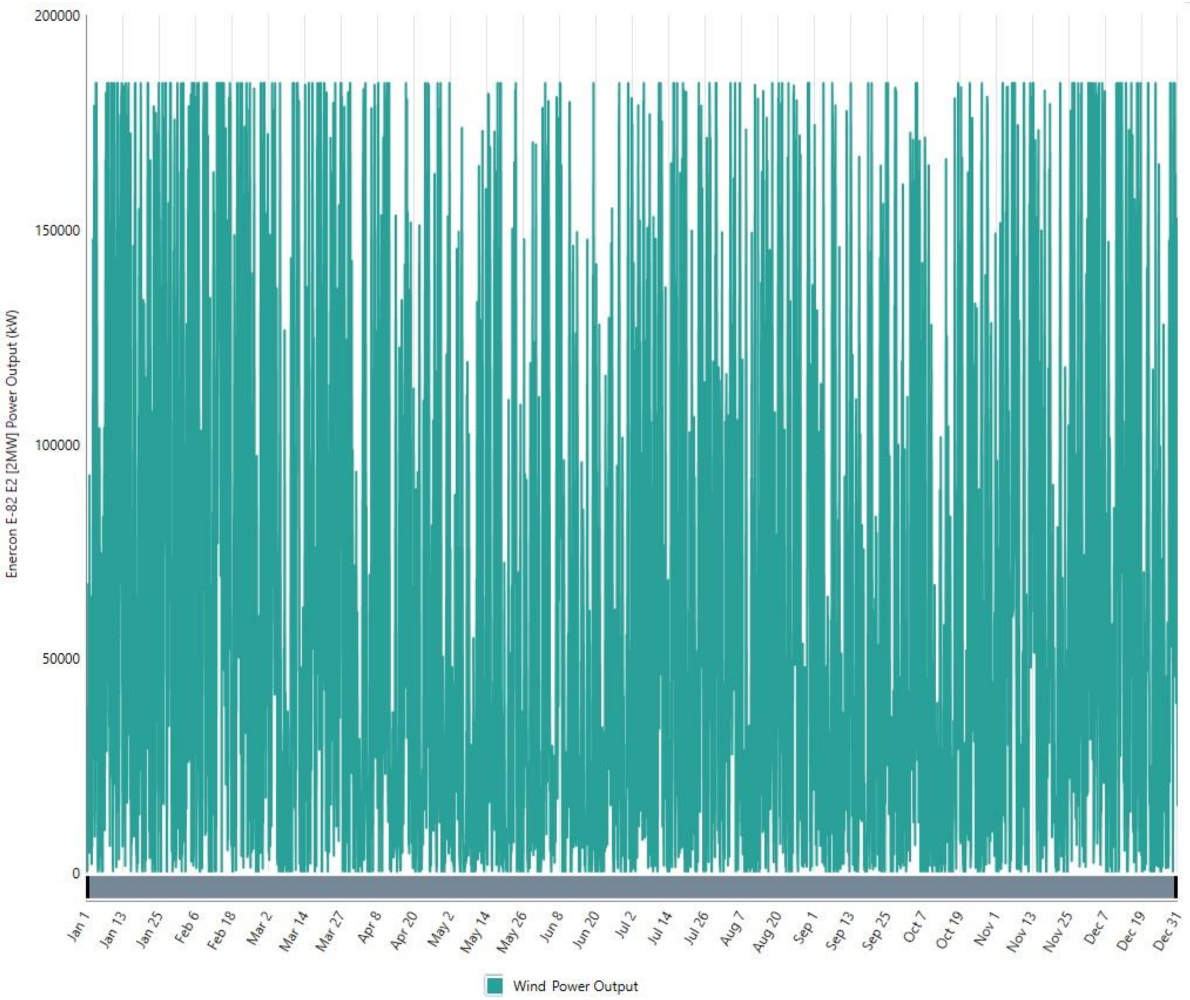

Figure 31: Hourly wind power output of 2017