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Ultra-High Share of Renewable Energy Sources in Interconnected Island Systems †

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Abstract: The large-scale deployment of renewable energy sources (RESs) has sped up the transition to clean energy systems in response to depleting fossil fuel supplies and rising environmental concerns, resulting in a significant percentage of RES generation in power systems globally. A focused design that considers local limits is necessary for a more significant share of renewable energy in the power output. Setting clear rules for how to proceed, where to begin, and what expertise is required to accomplish such plans and efforts can help achieve this. A case study on the Greek interconnected electrical system in Crete considers two scenarios with high-RES penetration. The simulation's findings demonstrated that using RESs may considerably boost their penetration while also resulting in considerable fuel cost reductions.

Keywords: large-scale RES; interconnected island; ultra-high-share RESs

1. Introduction

Since the 1990s, the Greek parliament has adopted several energy policies and applied many legislation frameworks to gain independency on oil consumption for electricity generation. By exploiting more and more domestic energy sources, such as wind and solar energy, Greece and particularly Greek islands can achieve their energy transition to clean energy and eliminate the CO_2 emissions levels. Therefore, Greece, especially through the last two decades, has taken actions to motivate the private sector to invest in renewable energy sources (RES). Even though RES technology, such as solar and wind, has made leaps in recent years, its potential use is relatively limited [1].

Recently, due to the pandemic, the energy transition had been slowed down through the impact of the coronavirus lockdown in the last three years, putting renewable energy investments under pressure [2].

However, there are several studies investigating the potential of embedding solely RES power grids on a large scale, representing probably 95% of the net increase in electric power supply by the year 2025, while the most significant expected growth comes from wind and solar generation [3].

Greece's transition to more clean energy sources is presented in the national energy and climate plan (NECP), according to which, RESs should be integrated by up to 80% by 2030, from 40% today [4], especially as essential problems such as the location and licensing of RESs have been solved. Electricity is becoming a significant means of energy production and use, expanding its services by substituting conventional energy sources for fossil fuels, penetrating almost every industry, such as transport, heating/cooling, etc., while being a lever of growth.

The interconnection of current autonomous islands with the mainland is an essential development plan to strengthen the transmission system to be able to meet the specific

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goals of RES penetration. Two of the most significant interconnections in Greece are the ones on the island of Crete. The AC link of 200 MVA capacity is already operational, whereas the DC link of 1 GW capacity is expected to be active by the end of 2023 [5].

The exploitation of the island's renewable energy sources, in particular wind and solar energy, can help to balance supply and demand to reduce the cost of fuel consumption and greenhouse gas emissions [6,7]. Already, in the context of climate change and sustainable development, two main strategies have been studied by the European Union to maximize the share of renewable energy sources, based on of which the interconnected islands are seeking to improve their independence from the conventional plants they have had up to now [8,9].

Many methods have been introduced in the bibliography, such as the multi-objective optimization model solved by the mixed integer programming method [10] or modified mixed integer linear programming with a genetic algorithm considering technical restrictions [11]. Incorporating economic variables into the dynamic economic distribution analysis using a particle swarm optimization (PSO) algorithm combined with Monte Carlo simulation is proposed [12]. Ref. [13] approaches dynamic analysis considering load and generation variations to reduce the fuel costs of conventional generators.

In this paper, two alternative scenarios of high-RES penetration are analyzed, taking into account the economic dispatch and the optimal power flow in a specific interconnected island. The paper is organized as follows: Initially, the examined grid and power system is analyzed. In the Methodology section, the calculations' flowcharts are explained, and the OPF is formulated in Powerworld. In conclusion, the Results section presents the main outcomes of each scenario and compares the two cases.

2. Current State of Interconnected Islands: Case of Crete

Crete is the fifth largest island in the Mediterranean and the largest in Greece, recording approximately 620,000 inhabitants in an area of 8303 km^2. During the tourist season, which lasts from May to October, the population of Crete almost triples, and with it, the need for energy. Its power system was the most extensive autonomous electrical system in Greece until the first interconnection with the mainland grid occurred in the year 2021, while the second one is about to be operational by 2023 [4]. The island's electricity generation system is based mainly on three (3) oil-fired thermal power units.

The total capacity of the three power plants is 607 MW, with different technologies, fuels, and response characteristics. Specifically, there are Steam Turbines, Internal Combustion Engines (ICEs), Open Cycle Gas Turbines (OCGTs), and one combined cycle (CC) unit. The analysis per fuel for each thermal oil plant is shown in Table 1. The steam and diesel units mainly supply the base-load demand. The gas turbines normally supply the daily peak load or the load that the other units in outage conditions cannot supply [14].

Table 1. Oil-fired conventional power units.

	Power Units	Installed Power (MW)	Fuel
1	Power Plant 1—STs	105	Mazut
2	Power Plant 1—ICEs	48	Mazut
3	Power Plant 1—OCGTs	100	Diesel
4	Power Plant 2—OCGTs	120	Diesel
5	Power Plant 2—CC	132	Diesel
6	Power Plant 3—STs	100	Mazut
7	Power Plant 3—ICEs	105	Mazut
	Total:	710	

The Cretan island's solar and wind speed potential is one of the highest in the EU, reaching up to 2100 kWh/m^2/year for solar radiation and over 8.5 m/s average wind speed in many locations. The total production from RESs was raised to 23.5% in 2021. Across the island, there are several wind parks installed with nominal power of 215.12 MW, as shown in Table 2. These WPs are connected to the grid through MV/HV substations of 20 kV/150 kV [15].

Table 2. Wind power plants' allocation.

S.L.	Prefecture of Wind Parks	Plants	%	Installed Power (MW)	%
1	Area 1	25	53%	107.12	50%
2	Area 2	8	17%	45.40	21%
3	Area 3	5	11%	24.30	11%
4	Area 4	9	19%	38.30	18%
	Total	47	100%	215.12	100%

Additionally, 1204 small PV plants of 80 kW nominal power each are already installed across the island, as shown in Table 3, most of which are interconnected to substations of 0.4 kV/20 kV [15].

Table 3. Photovoltaic power plants' allocation.

S.L.	Prefecture of Wind Parks	Plants	%	Installed Power (MW)	%
1	Area 1	25	53%	107.12	50%
2	Area 2	8	17%	45.40	21%
3	Area 3	5	11%	24.30	11%
4	Area 4	9	19%	38.30	18%
	Total	47	100%	215.12	100%

According to the data retrieved by local TSO and DSO, the annual demand for the island was 2.78 TWh in 2020 and 3.11 TWh in 2021, with the peak load reaching more than 600 MW and 650 MW, respectively. Figures 1 and 2 depict the production share of conventional units for diesel and mazut, the local RESs, and the AC link [14].

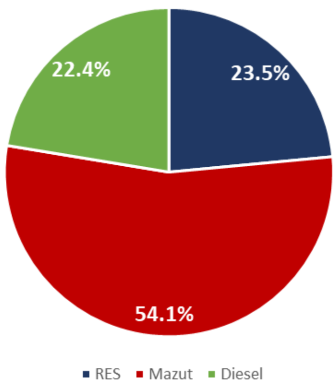


Figure 1. Annual energy share in 2020.

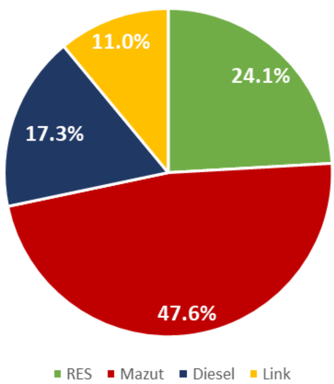


Figure 2. Annual energy share in 2021.

In general, the interconnection of the non-interconnected islands is a priority in reducing energy production costs. Therefore, regarding Greek islands' power systems, there are already approved transmission network development programs for Crete for 2023, the interconnection of the Cyclades for 2024, and the Dodecanese and the North Aegean for 2028 and 2029, respectively, as shown in Figure 3 [14], where red lines represents the ultra-high voltage (UHV-400kV) lines and green represents the high voltage (HV-150kV) lines.

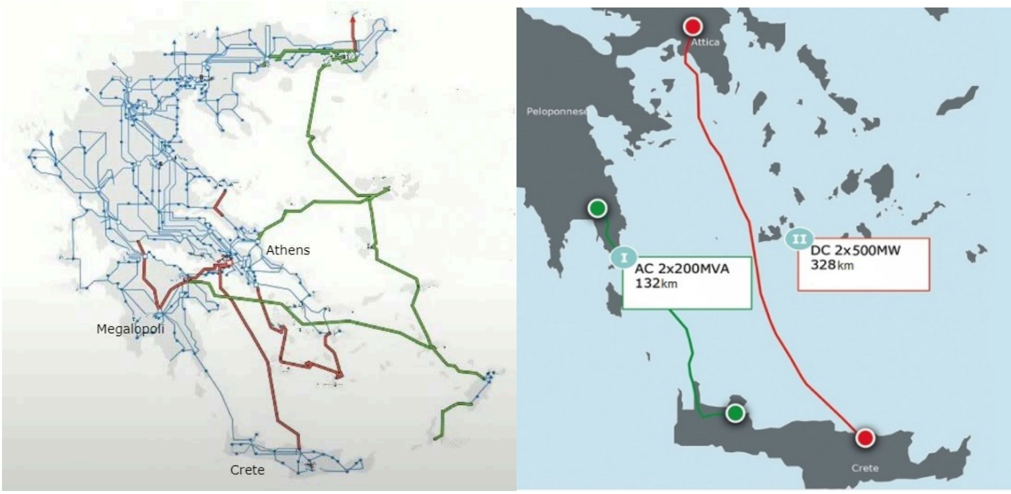


Figure 3. Greek TSO ten-year transmission network development plan [14].

The fact that electricity generation is based on heavy fuel oil (mazut) and diesel results in extremely high costs for power generation, particularly due to oil prices and taxes applied to them. The total cost of local production from oil-fired plants for the year 2021 amounted to EUR 383 million euro. Specifically:

- For Power Plant 1 (Linoperamata), the total operating cost amounted to EUR 206.1/MWh for 21% of the electricity production;
- For Power Plant 2 (Xilokamara), the corresponding prices were EUR 293.24/MWh and 10%;
- For the (Atherinolakkos) oil-fired power plant, they were 148.54 EUR /MWh and 34%.

Despite the high cost of electricity generation, consumers in Crete have electricity tariffs with the same prices as in the interconnected system. This is achieved through the mechanism scheme of the SGI, which provides for the distribution of the additional cost of power generation of the non-interconnected islands to all consumers in the country. The budget of the SGI exceeded EUR 340 million in recent years. It is therefore a particularly significant burden on electricity prices throughout the country. The reduction in the SGI for the islands through interconnection is a priority that has been set repeatedly by the Greek government. Additionally, CO_2 emissions for the region of Crete in 2021 amounted to 3129 ktCO_2.

Figure 4 shows the current energy cost allocation by applying the previously mentioned conventional generators' operating cost and the corresponding feed-in tariffs 250 EUR/ MWh for PVs and 98 EUR/MWh WTs, which were the tariffs for the currently installed RESs in Crete.

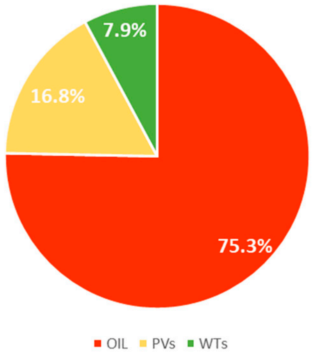


Figure 4. Annual market cost allocation.

The challenges that the region of Crete must face, both in the context of the objectives decided by the EU and in the context of the consolidation and efficient operation of the energy sector, are summarized as follows:

- The continuous reduction in CO_2 emissions from the energy sector toward a very low-emission economy in 2050;
- Gradual weaning from oil;
- The significant development of renewable energy sources as clean and local sources;
- Achieving the most competitive energy prices and costs possible.

3. Methodology

The operation of the power system focuses on the reliability and efficiency of the power grid to optimally meet energy demand to remain power balanced. The flow chart, as it is depicted in Figure 5, shows the power flow taking into account the load coverage from both conventional and renewable energy sources on the island while taking into account the energy flow to and from the island through the existing weak interconnection.

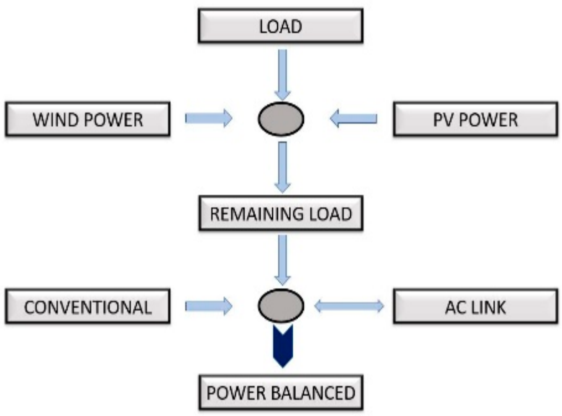


Figure 5. Power flow chart.

In order to proceed with the simulations of this study, integrated and reliable software for the methodology development was needed. Therefore, the presented simulations and the corresponding analyses of the results were made using Powerworld v23 software. It allowed for the input of both the technical characteristics of the generators and the load, as well as the parameters for calculating the losses on the transmission lines.

In addition to maintaining the technical stability of the electric network, one of the foremost parameters to be taken into account is the cost of operating the generators. The installation of new energy sources, such as renewables, must be based on reducing economic expenses while maintaining the optimal relationship between producers and consumers and determining minimum fuel cost [16].

To perform the simulation in the Powerworld software, the power grid was mapped as realistically as possible. First, the HV/MV central substations were mapped with buses, on which the load and the generators were connected, grouped according to the fuel they consume, and their technical characteristics such as nominal power, type of fuel, operating costs, etc., were recorded. Then, the high-voltage transmission lines were mapped, connecting the substations incorporating their technical aspects such as operating voltage, length, and ohmic and inductive resistance. Figure 6 depicts the Cretan electric grid as it was implemented and simulated in Powerworld software. Each bus of the system has the corresponding conventional generation, as steam turbines (STM), internal combustion units (DSL) and gas turbines (GAS) or dispersed generation, such as solar and wind parks. Additionally, most of the buses supply their local load demands (shown as arrows).

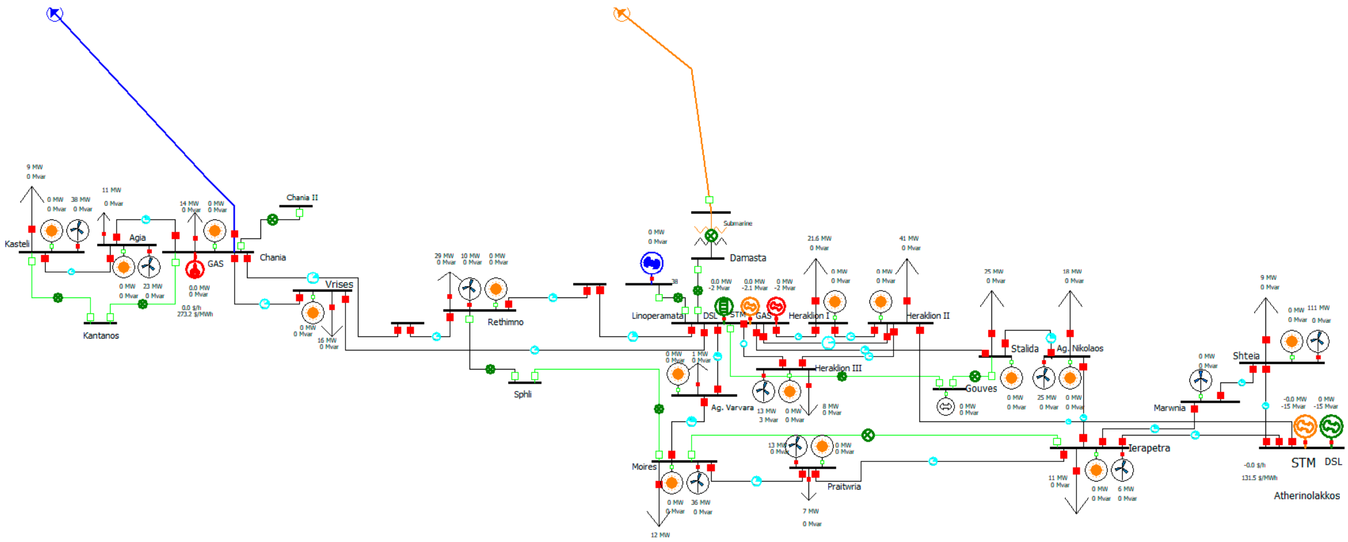


Figure 6. Electric grid of Cretan island simulated in Powerworld software.

The power system operation focuses on the reliability and efficiency of the power grid to optimally meet energy demand. The need to use an integrated tool to develop the methodology and analyze the results led us to use the software of Powerworld. This program was chosen over others because it allowed us to input a wide variety of variables, including information about generators, operating costs, transmission lines, and economic data obtained through cubic cost analysis, and it provided information about network stability, substation loading, and line loading, among other things.

In this study, optimal power flow was applied using the cubic total cost analysis. Cubic cost functions illustrate economies of scale, making quadratic average cost curves a straightforward means to demonstrate that concept. On the output side, this entails understanding unit costs. Unit costs can be analyzed using cost functions, which measure the cost of production as a function of the quantity of products produced.

The selected software allowed all the parameters to be imported for calculating the economic analysis using the cubic cost model. Relative data were gathered from the local DSO (HEDNO) [5], such as unit fuel cost and cubic inputs in MBtu/h. The cubic cost formula is shown in the following Equation (1):

$$\mathrm{Ci(Pgi)} = \mathrm{Fi} + \left(\mathrm{Ai} + \mathrm{Bi} \times \mathrm{Pgi} + \mathrm{Ci} \times \mathrm{Pgi}^2 + \mathrm{Di} \times \mathrm{Pgi}^3\right) \times \mathrm{Fc} + \mathrm{Vom} \times \mathrm{Pgi} \quad (1)$$

where:

C_i is the total cost of power flow in EUR/h;
F_i is fuel cost independent value (EUR/h);
A_i is fuel cost dependent value (MBtu/h);
B_i is the linear coefficient of fuel cost (MBtu/h);

C_i is the quadric coefficient of fuel cost (MBtu/h);
D_i is the cubic coefficient of fuel cost (MBtu/h);
Pg_i is power of each generator (MW);
F_c is the fuel cost (EUR);
V_{om} is the variable operation and maintenance cost (EUR/h).

In addition, a standard cost of renewable energy plants was applied as 98 EUR/MWh for wind energy plants and 250 EUR/MWh for PV plants.

Despite the temporary stabilization of electricity demand in recent years, due to the economic crisis and the pandemic, it is estimated that in the long term, there will be an increase in energy demand, mainly due to electrification in transport and the high penetration of heat pumps in the building sector.

In this paper, mathematical models were designed in order to determine the functions that relate the nominal power of the photovoltaics and wind turbines that are planned to be installed with:

- The annual energy produced by RESs;
- The annual amount of energy imported;
- The annual amount of energy rejected by the local power system.

Numerical solution algorithms were used to determine the optimal nominal powers for each case, whereas three cases were considered regarding the power system of Crete:

1. Case 1: Increasing RESs by installing additional photovoltaics;
2. Case 2: Increasing RESs by installing additional wind turbines;
3. Case 3: Increasing RESs by installing additional solar panels and wind turbines.

Finally, two basic scenarios of high-RES shares were analyzed, which are the needed shares in order for the targets of Crete's island energy transition for 2030 and 2050 to be met. In the first scenario, an increase of 200% of RESs on the island was taken, analyzing the results from a technical and economic point of view. In the second scenario, a total increase of 300% RESs was applied to receive the corresponding results.

The stability of the electricity network was checked in both scenarios, where charging did not exceed 75% at any substation or transmission line, given that an increase in RESs caused a reduction in production from conventional fuel plants, while the island's electricity network's weak interconnection with the mainland also served as an auxiliary.

As was previously mentioned, for the purpose of this study, hourly data of Crete's power system operation were taken from 2021, including:

- Electric load demand;
- RES production;
- Import/export power from the interconnection with mainland power grid;
- Production from the conventional generators;
- Normalized power output of solar panels and wind turbine parks.

4. Results

In this section, the results of all the simulations are shown. The load was entered on an hourly basis, whereas a 24 h profile was depicted in all cases. The power system simulation took into account the capacity of each transmission line and corresponding substation of the system, in order to address any conjunctions. These specific data were retrieved by local DSO. Furthermore, after applying the cost data to the generators and RESs, the Powerworld simulation executed Optimal Power Flow. Furthermore, the excess or shortage of energy on the island was covered by the AC interconnection with the Greek mainland system, calculating the corresponding revenue or cost. Figure 7 shows the energy balance and the cost allocation of the first scenario, implementing a 200% rise in RESs in the system.

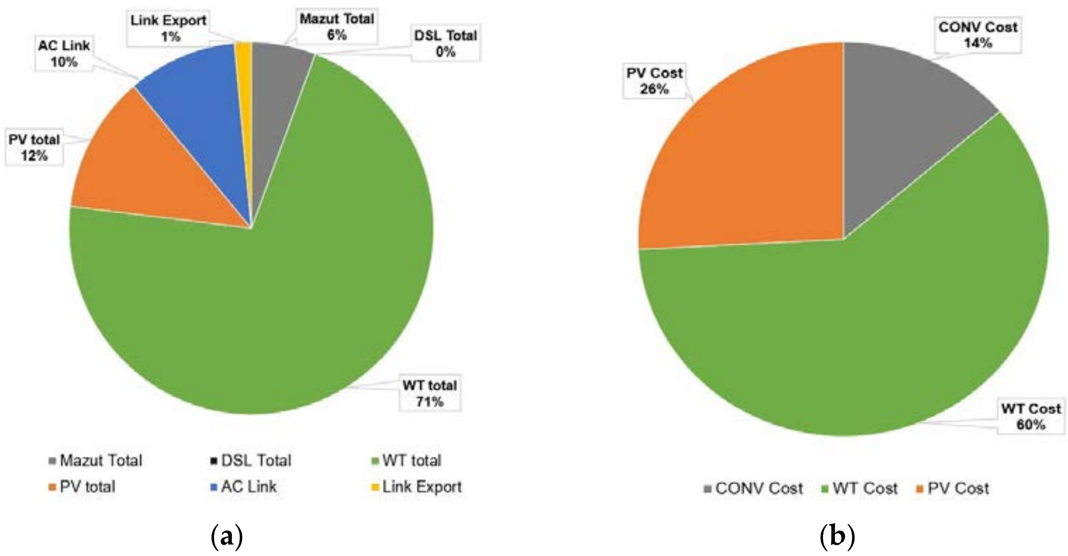


Figure 7. Annual energy balance (**a**) and cost allocation with 200% rise in RESs (**b**).

Figure 8 shows the total energy produced in the first scenario and also calculates the losses in a 24 h projection. Furthermore, in this graph, the total cost in the 24 h projection is shown, while the energy imported by the link is depicted as negative energy of the system. The following figure clearly depicts a marked decrease in the participation of conventional units in the system. It also shows the possibility of exporting energy through interconnection when we have the maximum PV production at midday. At the same time, the optimal operation of the system is captured as the losses are at the minimum level.

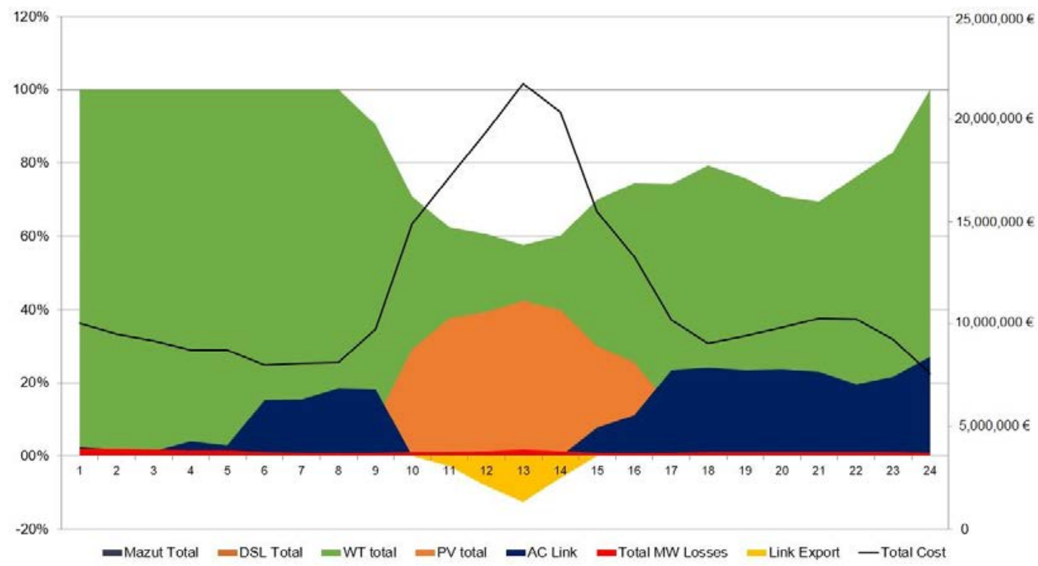
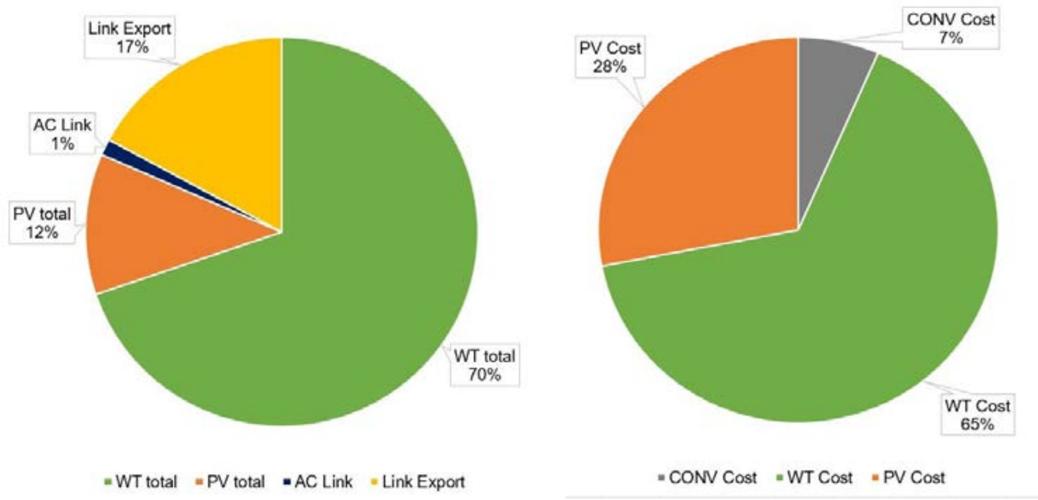


Figure 8. Energy produced on a 24 h basis, including losses and relevant costs in the case of scenario A.

Simulation changes were then applied to the software, increasing RES penetration to 300%. The results show an even more significant reduction in the dependence on conventional energy sources in the energy mix, as illustrated in Figure 9.



(**a**) (**b**)

Figure 9. Energy produced in 24 h bases, including losses (**a**) and cost with 300% rise in RES (**b**).

The increase in export energy by the AC link interconnection is evident in Figure 10, assuming that energy consumption is kept at the same level as in the initial simulation. Furthermore, in this scenario, conventional plants have a negligible contribution to the island's energy mix.

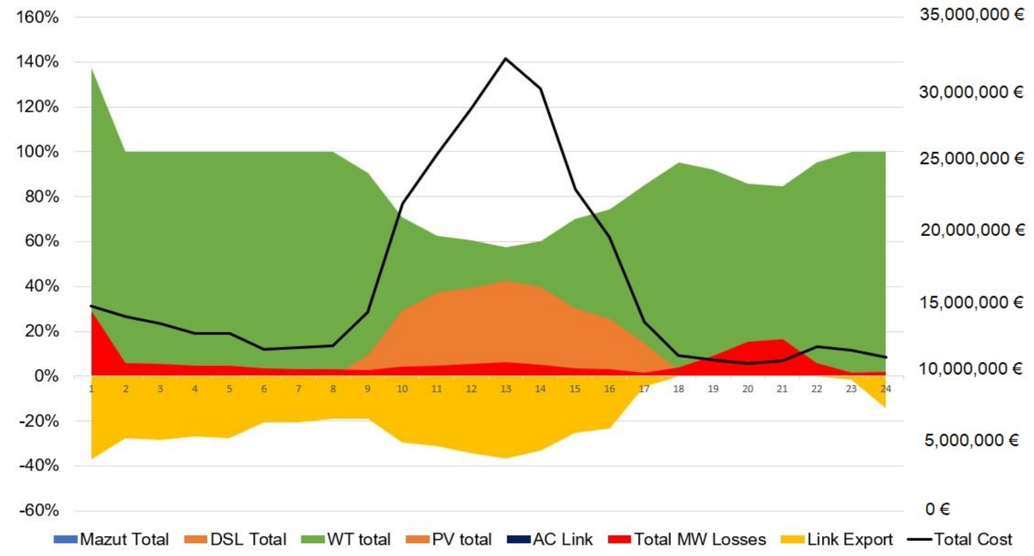


Figure 10. Energy produced on a 24 h basis, including losses and relevant costs in the case of scenario B.

Apart from the above-mentioned significant results, what seems to be of critical importance is the change in the cost of energy in the case of the two scenarios. As it can be seen from the corresponding graphs in Figures 11 and 12, when the 200% increase in power from RESs was simulated, the total cost of energy production increased by 50% at its maximum value. At the same time, there was an hourly time interval when it had a negative value. The simulation results in both scenarios show that the change in costs is directly influenced by the participation of RESs in the grid and the corresponding reduction in conventional units, which have higher operating costs.

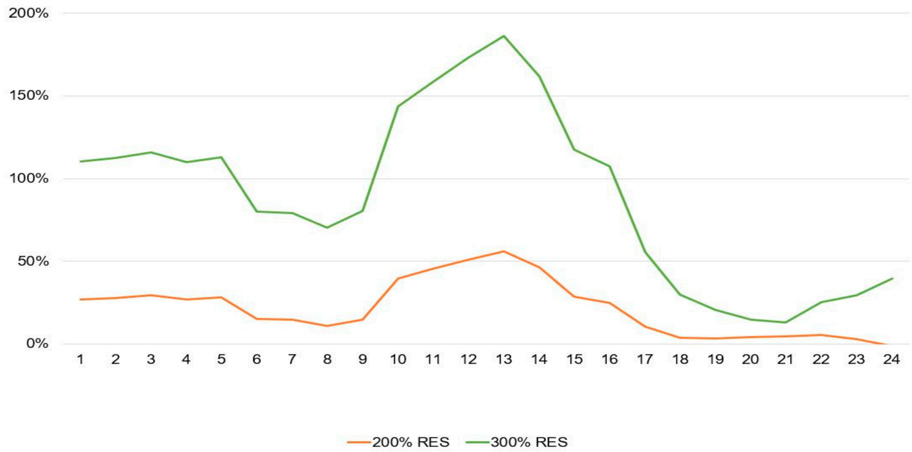


Figure 11. Percentage variation in the costs of the two scenarios.

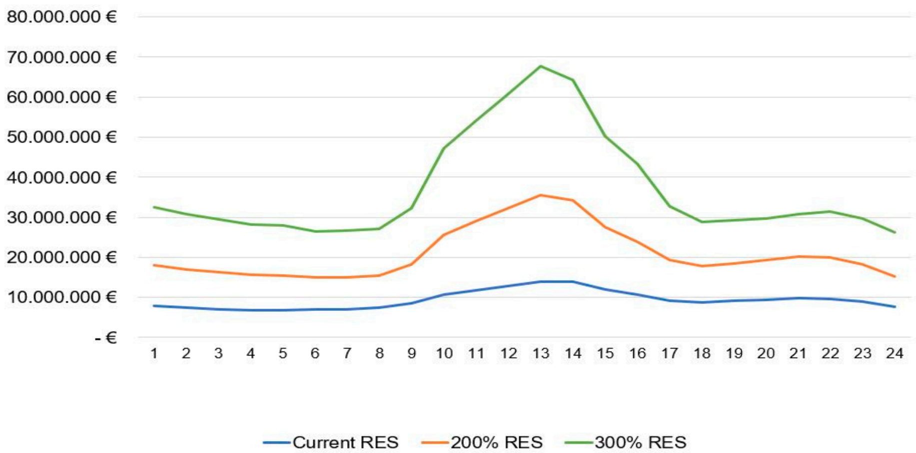


Figure 12. Total 24 h basis costs of the two scenarios.

5. Conclusions

It is well known that only the addition of new power-generating units and modifications of existing power-generating systems can meet the rising energy demand. Furthermore, it is also necessary to search for the further utilization of environmentally friendly energy technologies [17] to supply this expected need for energy. The research conducted in this paper suggests a reliable software tool to assess the highest share of PV and wind turbines' penetration that can be incorporated into an interconnected island power system in order for the required energy transition targets for 2030 and 2050 to be met, as they are described in the national energy and climate plan [4].

Additionally, this paper analyzes the required levels of the increased integration of RESs into an island system, where a weak interconnection exists. The case of the Cretan Island was used as a representative island power system, which has been recently interconnected and which has significant solar and wind energy potential. The optimal power flow methodology of the Powerworld software is used, considering all the technical details of the current transmission line and relevant substations, with the addition of economic variables of a cubic fuel cost equation. Regarding RES feed-in tariffs, the current real values, based on which, the relevant calculations were made were 98 EUR/MWh for WTs and 250 EUR/MWh for PV's. Furthermore, the estimates of the operating costs of the conventional plants were made using cubic cost analysis by introducing the known operational costs of the power plants on the island. In addition to the above, technical constraints were introduced in the simulation, such as the minimum technical power of the units and the maximum power ratings, but also the technical parameters of the network, such as transmission lines and transformers' capacities.

Two different scenarios were analyzed to increase the RES penetration, assuming that demand-side energy demand remained constant. Initially, by increasing the installation of RESs by 200% and extracting the results, it was found that on one hand, the balance of the system was maintained, and on the other hand, the total normalized cost of electricity production ranged from −1% to 50% at its peak. In the simulation of the second scenario with the application of a 300% increase in the penetration of RESs on the island, similar results were obtained regarding both the operation of the grid and the total cost, which in this case ranged from an 8% to 130% increase from the initial cost. However, larger percentages of rejections were recorded, as was expected.

A full economic analysis which will take into consideration all the financial data (CAPEX and OPEX) will obviously lead to more accurate calculations. Therefore, future work could follow the described simulation method and re-run the calculations when more data become accessible. Furthermore, using the suggested optimization technique and simulation platform, the EVs and BESSs placements, numbers, and rated powers in the distribution system, in parallel with their costs, could be assessed, whereas a complex collaboration between them and ultra shares of RESs can be analytically investigated and explored.

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