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RESEARCH ARTICLE

The Interconnection of the Electric Grid in the Island of Crete, Greece, and its Contribution to the Clean Energy Transition

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ABSTRACT

The clean energy transition in islands is of paramount importance in the present era of climate change. The island of Crete, Greece has rich renewable energy resources which can be deployed for power generation. The clean energy transition of Crete, Greece, after the interconnection of its electric grid has been investigated. Solar and wind energy are already used with solar-PV systems and wind farms for electricity generation in Crete covering slightly more than 20% of its annual electricity demand. The elimination of fossil fuels' use in the electricity sector in Crete deploying endogenous renewable energies is going to assist the achievement of the national and European goal for moving to net-zero carbon emissions societies. The maximum power that can be transferred through the two undersea electric cables interconnecting the grids of Crete and continental Greece is higher than the maximum power demand in Crete which currently does not exceed 700 MW. The size of the solar-PV systems generating the same amount of electricity which is currently produced with fossil fuels in Crete is at 1,698 MW_p while their cost is around 2.04 bill. €. The corresponding size and cost of the wind farms are at 940.6 MW and 0.941 bill. €. Electricity storage in Crete either in PHES systems or in large-scale electric batteries will increase its energy security. The results, indicating that the de-carbonization of the electricity sector in Crete is technically and economically feasible, could be useful to policymakers, power companies, and local authorities on the island.

Keywords: Clean energy transition, Crete-Greece, electric grid, grid interconnection.

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1. Introduction

The clean energy transition is of paramount importance for the creation of net-zero emission societies in the near future. Crete is one of the largest islands in the Mediterranean region and a well-known and popular global tourism destination. Its electric grid was autonomous so far complicating its clean energy transition, although the island has rich solar and wind energy resources. Existing studies indicated that the development of solar photovoltaic (solar-PV) and wind power installations combined with the construction of pumped hydro-electricity storage (PHES) plants can minimize or totally eliminate its carbon footprint due to electricity generation [1], [2]. Several small-size islands have already achieved their clean energy transition [3]–[5]. Currently, the interconnection of the electric grids of Crete and continental Greece is under implementation [6]. The realization of the island's grid interconnection is expected to facilitate the clean energy transition in Crete, regarding its electricity sector, deploying its endogenous solar and wind energy resources and eliminating the use of fossil fuels.

The aims of the current research are:

a) To examine the possibility of the clean energy transition in the electricity sector after the interconnection of the electric grid,
b) To estimate the size and the cost of the necessary renewable energy systems in Crete which can be used in the clean energy transition and the possibility of promoting large-scale electricity storage on the island and

c) To assess the economic, environmental, and social consequences of the clean energy transition in the electricity sector in Crete.

The present study covers the knowledge gap regarding the clean energy transition in Crete. It has various innovative aspects regarding the clean energy transition of large islands which have different characteristics than several smaller islands that have already eliminated their carbon footprint [3]–[5], [7]. It can be useful to policymakers, power companies, environmentalists, and several stakeholders in Crete. The limitations of this study are related to the accuracy of the energy characteristics of Crete, the future projections regarding the electricity requirements, and the uncertainty regarding the construction of the planned PHES system.

The text is structured as follows: after the literature survey the characteristics of the electricity grid of Crete, the development of renewable energies in the island, and some details concerning the grids' interconnection are stated. Next, the possibility of electricity storage and the clean energy transition in several sectors in Crete are mentioned. After that, the zeroing of the net-carbon emissions in the electricity sector and the economic, environmental, and social consequences of the clean energy transition are analyzed. The text ends with a discussion of the findings, the conclusions drawn, and the citation of the references used.

2. Literature Survey

The literature survey is separated into four sections including: (a) the clean energy transition in islands, (b) the electric system in Crete, (c) electricity storage systems, and (d) de-carbonization in the transport sector.

2.1. The Clean Energy Transition in Islands

The energy transition of eight islands has been studied [3]. The authors stated that islands have different energy characteristics than mainland territories while they serve as a test bed for developing novel distributed energy generation technologies. They also mentioned that islands are favorable areas for energy renovation while the islands of Samsoe, Denmark and Hvaler, Norway are successful examples of renewable energy islands. The hybrid energy system based on renewable energy in El Hierro island, Spain has been studied [8]. The author stated that the hybrid energy system includes a wind farm and a pumped hydro storage power plant which was designed to cover all the power demand in the island. She also mentioned that the average share of renewable energy sources (RES) in the total energy mix during the first half of 2018 was only 59.67%. The potential of pumped-hydro power storage in Gran Canaria islands, Spain has been assessed [9]. The authors stated that the density of dams in Gran Canaria is the highest in the world while there are no applications of hydroelectricity generation on it. They also estimated that the size of the PHES system on the island is 5,996 MW. The energy transition in Sifnos Island, Greece has been investigated [1]. The authors stated that the energy transition in Sifnos has been undertaken by the Sifnos energy community, aiming to achieve 100% energy independence on the island. They also mentioned that the main sustainable energy system in Sifnos consists of a wind park and a PHES system. The low-carbon transition in Danish islands has been analyzed [4]. The authors stated that three Danish islands, Bornholm, Samso and Ero are particularly active in the promotion of renewable energies. These islands have developed several community-based renewable energy projects. They also mentioned that the abovementioned islands have combined their clean energy transition with the promotion of energy democracy. The opportunities for the low-carbon transition of the mobility systems in island states have been examined [10]. The authors focused on the insular mobility systems in the islands of Barbados, Fiji, and Mauritius. They mentioned that low-carbon mobility in these islands can be achieved by combining the use of electric vehicles with behavioral changes of the local residents and the tourists choosing low-carbon transport modes. The adaptation to climate change in Pacific islands has been studied [11]. The authors stated that these islands are being degraded by pollution and unsustainable development. They also face climate change impacts like sea-level rise, changing temperatures and rainfall patterns. Therefore, they are leading in climate adaptation strategies to help them cope with climate change impacts. The story of the green energy transition in Samso Island, Denmark has been reported [12]. The author stated that the island, with a joint community effort, has become self-sufficient in energy during 1997–2007 using locally available renewable energies. This was achieved with broad community participation and community ownership of various renewable energy projects leading to the clean energy transition in Samso island. The clean energy transition in two small islands in the Azores, Pico Island with 13,859 inhabitants, and Faial Island with 14,792 inhabitants have been studied [13]. The authors stated that both islands have a high potential for endogenous renewable energy resources which can be used for carbon-free energy generation. They also stated that the interconnection of the power systems of these two islands will facilitate their clean energy transition. The renewable energy transition of Caribbean islands focusing on Jamaica and the eastern Caribbean has been studied [14]. The authors developed the concept of "*island energy metabolism*" to conceptualize the relationships between the local energy sources and the territorial characteristics of the islands. They also mentioned that the analysis of their energy metabolism can facilitate their energy transition. The electrification of remote islands focused on the small Greek island Tilos has been investigated [15]. The author stated that Tilos Island has achieved its clean energy transition by developing a local microgrid using endogenous renewable energy resources. The microgrid consisted of a wind turbine at 800 kW, a solar-PV system at 160 kW_p, and a battery storage system at 2.88 MWh. The clean energy transition in several Greek islands has been studied [16]. The authors stated that the green energy transition in Greek islands results in their economic and social development. The authors highlighted the multiple benefits to insular societies due to the active involvement of the local residents in various innovative energy initiatives and projects. A report on the island Lido, Sweden as a zero-emission island has been published [5]. The report stated that the clean energy transition in Lido Island contributes to Sweden's goal to become carbon neutral from fossil fuels before 2045. A report on energy use in Samso Island, Denmark has been published [17]. The report stated that Samso island with 4,000 local residents has been energy-positive for the past decade producing more energy from wind and biomass resources than it consumes. A report regarding Europe's most sustainable islands has been published [7]. The report focused on Bornholm Island, Denmark located around 200 km east of Copenhagen in the Baltic Sea which is popular with tourists. It was also mentioned that the island is 100% carbon-free using solar photovoltaic panels, wind turbines, biomass burning systems, and district heating.

2.2. *The Electric System in Crete*

The interconnection of the electric grids between Crete and continental Greece has been published [6]. The authors stated that the penetration of renewable energies in the electricity system of Crete is limited due to technical constraints related to the stability of the electric grid. They also stated that the interconnection of the island is realized with two undersea electric cables, (a) 150 kV AC interconnection 2 × 200 MVA (around 2 × 140 MW) capability between western Crete and Peloponnese, and (b) DC interconnection 2 × 350 MW capability between Heraklion and Attica. The characteristics of the electric system of Crete in 2018 have been analyzed by HEDNO [18]. The electricity generation, the power of the electricity generating stations, the carbon emissions, the fuel consumption, the maximum power demand, and many other parameters are stated. A hybrid energy system in Crete for the period of 2021–2023 has been developed [19]. It has been estimated that after the two interconnections of the electric grid all the power demand in the island, at 710 MW_{peak} and 3TWh annual consumption, will be fully covered for the next 25 years. An effective and rational energy transition in Crete, Greece has been proposed [20]. The authors stated that the energy transition of the island can be achieved with a set of 14 wind parks and 12 heat and power co-generation (CHP) plants dispersed along Crete. They also mentioned that Crete has abundant solar energy, wind energy, and biomass resources which can cover all the energy demand in the island in a cost-effective way. The use of RES for energy generation in rural areas in Crete has been studied [21]. The author stated that solar energy, wind energy, biomass, and low-enthalpy geothermal energy are currently used for heat and power generation on the island. He also mentioned that more than 20% of the electricity demand is currently generated by RES in Crete. The possibility of achieving carbon neutrality due to electricity consumption in Crete, Greece has been investigated [2]. The author stated that carbon neutrality can be achieved with the generation of "solar and wind electricity" on the island. He has also mentioned that the annual electricity demand in 2018 was at 3,043 GWh. He estimated that the electricity currently produced in Crete by fossil fuels at 2,398 GWh/year can be alternatively generated by solar-PV systems having nominal power at 1,698 MW_p or with wind farms having power at 950.6 MW. Several aspects of the clean energy transition in Crete, Greece have been analyzed [22]. The author has examined the possibility of de-carbonization in four socio-economic sectors including: (a) electricity generation, (b) heat and cooling production, (c) transportation inside the island, and (d) transportation to and from Crete. He also mentioned that de-carbonization in electricity generation and heat and cooling production can be achieved rather easily. De-carbonization in insular transportation can be achieved in the medium- to long-term while decarbonization in air and maritime transportation is more difficult to be achieved soon. A report regarding the interconnection of the grids of Crete with continental Greece has been published [23]. The report stated that the interconnection of the grids with two electric cables is going to unlock the unexploited renewable energy potential of Crete. It is also mentioned that renewable energy installations of more than 2,000 MW have been licensed in Crete which are going to be realized after the grids' interconnection. This could help Greece to achieve the target of carbon neutrality in the next decades. A hybrid energy system which is going to be constructed in Crete consisting of wind turbines and a PHES system has been analyzed [24]. The PHES system is going to store the excess wind electricity, which is rejected, when produced, from the grid. The authors stated that the annual electricity generation from the PHES system corresponds to around 2.2% of the annual electricity consumption on the island. An announcement regarding the largest hybrid energy system producing clean energy in Europe which is going to be developed on the island of Crete, Greece has been made [25]. It is stated that the project has achieved all the required licenses, but its construction has not started yet. The hybrid energy system consists of two wind farms at 89.1 MW and a PHES system at 93 MW which can generate annually 227 GWh of electricity corresponding to around 7.46% of the electricity consumption in Crete in 2018.

2.3. *Electricity Storage Systems*

The energy storage in electric batteries has been studied [26]. The authors stated that electricity storage is necessary for increasing the development of renewable energies in daily applications while batteries in several types and sizes are considered as a very good method to store electricity. They also mentioned that large-size batteries (>50 MW) should be compared with other alternative energy storage technologies in terms of sustainability. Several novel large-scale energy storage technologies have been studied [27]. The authors stated that energy storage systems can store surplus electricity generated by intermittent renewable energies increasing the stability of the grid. They have also compared wind electricity storage in the U.K. with PHES systems and lithium-ion batteries. The energy storage in hydrogen has been studied [28]. The author stated that the recent advances in hydrogen technologies have increased the interest in using hydrogen for storing electricity generated by intermittent renewable energy sources. The use of hydrogen as an energy-storage-medium and fuel has been studied [29]. The author stated that hydrogen can be used for energy storage to compensate for the fluctuations in the power output of several primary energy sources. He also mentioned that hydrogen can be also used as low-carbon fuel in electric vehicles. The impacts of electricity storage in batteries in residential buildings on energy transition have been investigated [30]. The authors stated that households can become "prosumers", producing and consuming electricity, while the installed home batteries can facilitate the green energy transition. At the same time, households achieve their energy autonomy and security. The regional innovation systems during the energy transition in small-scale regions have been studied [31]. The authors examined the energy transition in two German cities Emden and Bottrop focusing on their regional innovation systems. They stated that the interaction of several subsystems including science, politics, public administration, industry, finance, intermediaries and civil society were important for their clean energy transition. The hydrogen energy storage systems integrated with renewable energy sources have been reviewed [32]. The authors stated that hydrogen energy storage systems are gaining popularity due to their benefits including (a) energy security, (b) resilience through the use of renewable energies, (c) reduced pollution, and (d) cost-effectiveness. Several characteristics of electricity storage systems in batteries have been reviewed [33]. The authors stated that the power industry is moving to alternative energy resources such as solar photovoltaics, wind parks, and electric batteries. They also mentioned that the use of battery storage systems requires efficient optimization in order to achieve optimum performance.

2.4. *De-Carbonization in the Transport Sector*

The de-carbonization in ships, planes, and trucks has been examined [34]. The authors stated that low-carbon energy carriers including electricity, biofuels, hydrogen, and electro-fuels can be used to de-carbonize them. They assessed the energy carriers according to their energy density, specific energy, cost, lifecycle greenhouse gas emissions, and land use. The low-carbon aviation fuels have been studied [35]. The authors stated that lower-carbon aviation fuels are fuels based on fossil fuels which result in at least 10% lower life-cycle greenhouse gas (GHG) emissions compared to benchmark values. They also mentioned that there is no single low-carbon aviation fuel that can reach the required 10% carbon reduction. The sustainable aviation fuels have been reviewed [36]. The authors stated that aviation fuels are currently based on kerosene while their demand is expected to grow in the next decades. They also mentioned that the de-carbonization of aviation fuels should be based on alternative fuels including hydrogen and electricity. A report regarding the de-carbonization of maritime transport in Sweden has been published [37]. The report stated that the de-carbonization of maritime transport in Sweden is at an early stage while some shipping companies are using vessels fueled by methanol, liquified natural gas (LNG), and electricity. The transition to net-zero carbon cities has been investigated [38]. The authors stated that cities can become carbon neutral with systemic transformation. This cannot be achieved with the elimination of GHG emissions in their territory only. The de-carbonization in the supply chains is also required combined with the use of urban and regional landscapes for atmospheric carbon sequestration. The economic and social benefits of low-carbon cities have been analyzed [39]. The authors focused on three sectors including (a) energy-efficient buildings, (b) low-carbon transport, and (c) solid-state waste management. The authors identified and assessed in each sector four co-benefits including: (a) public health, (b) employment, (c) congestion, and (d) inclusion. They concluded that there are many synergies and co-benefits between urban development and climate change actions. The net-zero energy transition in Asia and the Pacific focused on blue and green hydrogen use in the industrial sector has been investigated [40]. The authors stated that the development of clean hydrogen energy is faced with major challenges before maturing including high cost, technical barriers, lack of a market, and lack of sufficient ambitious policies.

3. The Electric System of Crete

The electric system of Crete was until recently autonomous while currently, its interconnection with the grid of continental Greece is under implementation. Electricity is mainly generated by fossil fuels including heavy oil and diesel oil, at around 80%, and from renewable energies at around 20%. There are three thermos-electric plants in Crete located in the prefectures of Chania, Heraklion, and Lasithi which use heavy oil and diesel oil to generate electricity. Additionally, green electricity is mainly generated by solar photovoltaic plants and wind farms while small quantities are also generated from biogas and hydro-electric plants. The total energy consumption in 2018 was at 3,043 GWh while the maximum power of the grid was slightly less than 700 MW [18]. Renewable energy installations are dispersed along the island. Several characteristics of the electric system of Crete are presented in Table I.

TABLE I: Several Characteristics of the Electric System of Crete (2018)

Parameter	Value	%, of total
Annual electricity generation	3,043 GWh	100
Maximum power demand (at 23/7/2018)	684.6 MW	
Average annual power demand	347.4 MW	
Total installed power of thermoelectric plants	824.6 MW	73.56
Annual electricity generation from thermoelectric plants	2,398 GWh	78.80
Total installed power of wind parks	200.3 MW	
Total installed power of solar-PV plants	95.5 MW	
Total installed power of hydroelectric plants	0.6 MW	
Total installed power of renewable energy plants	296.4 MW	26.44
Annual electricity generation from renewable energy plants	645 GWh	21.20
Total installed power in Crete	1,121 MW	100

Source: [18].

TABLE II: Installed Power of Various Renewable Energy Systems and Green Energy Generation in Crete (2018)

Renewable energy source	Generated energy	Installed power	Amount of generated electricity (MWh/year)	%, of total electricity generation
Solar energy	Electricity	95.5 MW_p	134,808	4.43
Solar energy	Heat	186.4 MW_{th}		
Wind energy	Electricity	200.3 MW_{el}	510,059	16.76
Hydropower	Electricity	0.6 MW_{el}	257	0.01
Solid biomass	Heat			
Biogas	Heat and electricity			
Total		296.4 MW_{el} and 186.4 MW_{th}	645,124	21.20

Source: [18], Own estimations.

TABLE III: Current and Future Applications of Renewable Energies and Energy-Storage Technologies in Crete

Renewable energy source	Technology used	Energy produced	Applications	Current uses
Solar energy	Solar thermal systems	Hot water	Domestic hot water in buildings	Yes
Solar energy	Solar photovoltaic systems	Electricity	Electric grid	Yes
Solar energy	Solar thermal power systems	Electricity	Electric grid, self-consumption	No
Solar energy	Solar thermal systems-absorption cooling	Cooling energy	Space cooling in buildings	No
Wind energy	On-shore wind turbines	Electricity	Electric grid, self-consumption	Yes
Wind energy	Off-shore wind turbines	Electricity	Electric grid	No
Hydro energy	Hydroelectric turbines	Electricity	Electric grid	Yes
Solid biomass	Burning	Heat	Buildings, industry, greenhouses	Yes
Various organic-based wastes and by-products	Chemical and microbial processes	Biogas used for heat and electricity generation	Use in several sectors	Yes
Biogas	Burning	Heat and electricity	Various heat energy uses, electric grid	Yes
Ambient heat	High efficiency heat pumps	Heat and cooling	Buildings, industry	Yes
Solar and wind energy	Water electrolysis	Green hydrogen used for heat and electricity generation	Use in several sectors	No
Storage of surplus solar and wind electricity	Pumped-hydro storage systems	Electricity	Electric grid	No
Storage of surplus solar and wind electricity	Large-scale lithium-ion batteries	Electricity	Electric grid	No

Source: Own estimations.

4. Use of Renewable Energies for Heat and Power Generation in Crete

The island of Crete has abundant renewable energy resources particularly solar energy, wind energy, and biomass. The annual solar irradiance is very high while the average annual wind speed in many locations is also high. Additionally, the island has many biomass resources based on olive tree cultivation. All of them are used for heat and electricity generation. Since the electric grid of Crete has been autonomous so far there are technical constraints, related to the stability of the grid, for the installation of more wind farms and solar-PV plants although the interest of the investors was very high. The installed power of various renewable energy systems and the energy generation in Crete are presented in Table II.

Several renewable energy technologies are currently used in Crete [21] while more are expected to be used in the near future after the interconnection of its electric grid. The interconnection will allow the installation of more wind farms and solar-PV plants in Crete. The integration of renewable energies in the electricity system requires the development of energy storage systems including PHES systems and large-scale electric batteries. The advances in various renewable energy technologies like off-shore wind farms, solar thermal power systems, green hydrogen production will also allow the development of more benign carbon-free energy systems on the island. The current and future applications of renewable energies and energy-storage technologies in Crete are presented in Table III.

5. The Interconnection of the Electric Grid of Crete

The interconnection of the electric grids of Crete and continental Greece is currently under implementation and it is expected to be ready in the next 1–2 years. This is achieved with two undersea electric cables [6] as follows:

a) Small-scale interconnection between the prefecture of Chania and Peloponnese, 150 kV AC, 2 × 200 MVA (capability at around 2 × 140 MW). It is foreseen that the power that could be transferred will fluctuate between 150 MW to 180 MW. This project is already finalized.

b) Large-scale interconnection between the prefecture of Heraklion and Attica, DC interconnection, capability 2 × 350 MW. This project is currently under implementation, and it will be finalized in the next 1–2 years.

The small-scale interconnection can cover only part of the island's peak power and electricity demand which are estimated at around 710 MW_{peak} and around 3,000 GWh annual consumption [18], [19]. Both cables though are expected to cover the requirements of Crete for the next 25 years. The total length of both undersea cables is around 350 km while the maximum depth at 1,000 m. The electricity that could be transferred through both cables is estimated at

$$150\ \text{MW} \times 8,760\ (\text{hours/year}) + 300\ \text{MW} \times 8,760\ (\text{hours/year}) = 3,942\ \text{GWh/year}$$

exceeds the projected electricity demand in Crete estimated at around 3,305–3,439 GWh/year [19].

Additionally, the interconnections of the electric grid of Crete with Cyprus and Egypt are planned and hopefully they will be realized in the coming years.

6. Possibilities for Electricity Storage in Crete

Energy transition to carbon neutrality requires the increasing use of renewable energies replacing the use of fossil fuels. Some renewable energies such as solar energy, wind energy, and small-size hydroelectric energy cannot deliver constant power to the grid. Energy-storage systems can store the surplus electricity generated by intermittent renewable energies, such as solar and wind energy, which otherwise could be lost [27]. Crete has abundant solar and wind energy resources. Their deployment can be facilitated with the development of energy storage systems that can store the generated electricity when the grid power demand is low. The most popular and broadly used electricity storage system so far is the pumped hydro storage transforming electric energy into dynamic energy. It has many advantages compared with other electricity storage technologies [1], [8], [9]. Electricity storage as chemical energy based on large-scale lithium-ion electric batteries is also reliable and cost-efficient due to recent advances in battery's technologies [15], [26], [33]. A new emerging technology is related to electricity storage as chemical energy producing hydrogen. Hydrogen technology is expected to be commercialized in the next decade [28], [32]. Surplus electricity can be used to electrolyze water producing hydrogen which can be stored and used when it is needed later. Each storage technology has advantages and drawbacks which should be carefully assessed before their application. It should be mentioned that large-scale electricity storage systems have not been developed so far on the island. All the above-mentioned storage technologies can be used in Crete storing electricity generated locally by intermittent benign energy resources like solar and wind energy. The geomorphology of the island facilitates the use of PHES systems while locally generated solar and wind electricity can be used to produce green hydrogen. Additionally, large-scale electric batteries with a capacity higher than 30 MW to 50 MW can be easily installed in Crete.

TABLE IV: Time Frame for the Clean Energy Transition of Crete

Socio-economic sector	Time-frame for de-carbonization
Electricity generation	Short to medium term
Heat and cooling production	Short to medium term
Insular transportation	Medium to long term
Transportation to and from Crete	Long term

Source: [22].

7. The Green Energy Transition on the Island of Crete

Crete should promote its clean energy transition complying with the national, European, and global target for achieving net-zero carbon emissions societies by 2050. All the socio-economic sectors in Crete should be decarbonized [22] including:

(a) Electricity generation,
(b) Heat and cooling production,
(c) Insular transportation, and
(d) Transportation to and from Crete via aircrafts and ships.

It has been indicated that the sectors of electricity generation and heat and cooling production can be decarbonized rather easily using the rich renewable energy resources of Crete [22]. Insular transportation is more difficult and can be achieved with the use of electric vehicles with re-chargeable batteries which can be powered with locally generated green electricity. Finally, de-carbonization of the transportation sector to and from Crete is more difficult to achieve due to the fact that the required technologies and the carbon-free fuels for long-haul aircrafts are not currently mature and cost-efficient [34]–[36]. Additionally, the technologies and the fuels required for de-carbonization of large-scale cruise ships and ferryboats carrying passengers to and from Crete are not commercialized yet [37]. The time frame for the clean energy transition of Crete is presented in Table IV.

8. Zeroing the Net-carbon Emissions of the Electricity Sector on the Island

It has been mentioned previously that the decarbonization of the electricity sector in Crete does not present major difficulties. It can be achieved, after the grids' interconnection when the following conditions are fulfilled [22].

(a) Electricity should be generated in Crete only with the locally available renewable energy resources,
(b) Since electricity generated by fossil fuels will be transferred from continental Greece to Crete equal amount of "*green electricity*" should be transferred back annually. It should be mentioned thought that

TABLE V: Size and Cost of the Required Solar-PV Systems and Wind Parks Generating Annually the Electricity Currently Produced by Fossil Fuels in Crete (2018)

	Solar-PV systems	Wind energy systems
Total electricity generation in Crete	3,043,000 MWh	3,043,000 MWh
Current electricity generation by fossil fuels	2,393,682 MWh	2,393,682 MWh
Current electricity generation by renewable energies	645,124 MWh	645,124 MWh
Size of the required renewable energy systems	1,698 MW_p	940.6 MW_{el}
Size of the existing solar and wind power installations	95.5 MW_p	200.3 MW_{el}
Cost of the required renewable energy systems	2.04 bil. €	0.941 bil. €
Cost of the required renewable energy systems per inhabitant	3,213 €/capita	1,482 €/capita

Source: [2], [18].

only a part of the electricity transferred through the undersea cables to Crete is generated by fossil fuels and the rest by renewable energies, and

(c) If necessary, any remaining carbon emissions should be offset with the existing carbon offsetting mechanisms.

Carbon-free electricity can be generated in Crete from the endogenous renewable energy resources developing new solar-PV plants and wind farms on the island in additional to the existing installations. The size and the cost of the required solar-PV systems and wind parks generating the electricity currently produced by fossil fuels in Crete are presented in Table V.

In order to cope with unexpected and undesired events and emergency cases which could result in the interruption of the electricity transfer to Crete the development of electricity storage systems in the island is necessary combined with one or more thermo-electric plants in stand-by mode. Several events can interrupt the electricity transfer in the island including operating failures in the undersea cables caused by earthquakes, terrorist attacks, war attacks, blackmail from hackers, failure in delivering electricity from continental Greece to the cables, et cetera. Electricity storage in Crete can be achieved either with PHES systems or with large-scale electric batteries. The stored electricity must cover the electricity needs of Crete in the period until the operation of the thermo-electric stations and for a certain period until the emergency case is over. A large-scale hybrid energy project, consisting of wind turbines and a PHES system, is under development in Crete [24]. The power of the planned PHES system is 93 MW while the power of the existing wind farms in Crete is at 200.3 MW and of the solar-PV systems at 95.5 MW_p, a total of 295.8 MW [18]. The delivery of constant solar and wind power, at 295.8 MW, into the grid is not guaranteed. The average annual power demand in the electric grid is 347.4 MW [18]. Additional electricity storage systems, including one or more PHES systems and/or large-scale electric batteries, combined with stand-by thermo-electric plants are required in Crete to cope with emergency cases disrupting the electricity flow through the undersea electric cables into the island.

9. Economic, Environmental, and Social Consequences of the Clean Energy Transition in the Electricity Sector in Crete

The clean energy transition in the electricity sector in Crete is expected to result in many economic, environmental, and social benefits. The positive economic impacts include:

(a) The increase in cost-effective green energy investments in Crete,
(b) The use of endogenous renewable energy resources instead of imported fossil fuels for energy generation and the reduction of the financial resources used for importing fossil fuels, and
(c) The decrease of the present fossil fuels-related electricity generation cost in Crete taking into account that electricity generation from solar and wind energy in the island is much cheaper.

The positive environmental impacts include:

(a) The reduction of GHG emissions from the conventional thermal power plants operating in Crete, and
(b) The reduction of the atmospheric pollution caused in nearby areas by the operation of the three conventional thermal power plants on the island.

The positive social impacts include:

(a) The decrease in social protests, due to environmental pollution, from the residents of communities located near the existing thermal power plants.
(b) The involvement of local engineers and technicians in the installation, operation, and maintenance of new green electricity generation plants.
(c) The familiarization of the residents and the young people in Crete with renewable energy technologies and their advantages. This fact will promote the diffusion of solar and wind energy technologies in residential buildings and local enterprises, and
(d) The contribution to the achievement of the national and European target of net-zero carbon emission societies in the coming decades.

10. Discussion

It has been indicated that the interconnection of the electric grid in the island of Crete, which is currently under construction, facilitates its clean energy transition in the electricity sector. The de-carbonization of the power sector on the island can be achieved with the replacement of the existing thermal-power stations, using fossil fuels, with wind farms and solar-PV plants using the abundant endogenous solar and wind energy resources. The development of large-scale electricity storage plants in Crete will increase its energy security helping to cope with unexpected and undesired events which could disrupt the continuous electricity transfer through the undersea electric cables. The de-carbonization of the electricity sector on the island is going to result in many economic, environmental, and social benefits. Our results indicate that the de-carbonization of the electricity sector in Crete is desired, beneficial, and achievable, and it should be accelerated. It complies with the current national, European, and global policies for transition to net-zero carbon societies in the next decades to mitigate climate change. It also increases Crete's energy self-sufficiency and security. Our results do not indicate the size of the electricity storage plants in Crete which are necessary to avoid outages in the grid in the case of catastrophic events. They do not also analyze the effect that the future interconnection of the Cretan grid with Cyprus and Egypt is going to have in the de-carbonization of the island's electricity sector. Further studies should be focused on the spatial planning of the solar-PV plants and wind farms which are necessary for de-carbonization. They should also estimate the electricity demand due to electrification of heat and cooling production and insular transportation, which is necessary for the de-carbonization of other sectors on the island.

11. Conclusions

The possibility of a clean energy transition in the electricity sector, after the interconnection of the electric grid, on the island of Crete, Greece has been investigated. The main findings of the present study are:

(a) The interconnection of the electric grid with two undersea electric cables, which is expected to be completed soon will facilitate the clean energy transition of the island's electricity sector.
(b) The de-carbonization can be achieved with the use of rich endogenous renewable energy resources like solar and wind energy replacing the current use of fossil fuels.
(c) The maximum power that can be transferred through the two undersea electric cables is higher than the maximum annual power demand in Crete which currently does not exceed 700 MW.
(d) Electricity storage in Crete either in PHES systems or in large-scale electric batteries will increase its energy security ensuring the delivery of electricity into the grid in cases of emergency and failures in the operation of the undersea electric cables.
(e) The size of the solar-PV systems generating the same amount of electricity which is currently produced with fossil fuels in Crete is 1,698 MW_p while their cost at around 2.04 bil. €.
(f) The size of the wind farms generating the same amount of electricity which is currently produced with fossil fuels in Crete is 940.6 MW while their cost at around 0.941 bil. €.
(g) The de-carbonization of the electricity sector in Crete can be achieved in short- to medium-term while it will result in many economic, environmental, and social benefits.

Concluding, after the finalization of the grid's interconnection, the electricity sector in Greece can be easily de-carbonized, using the rich local benign energy resources, contributing to the national and European target for the transition to a net-zero carbon economy in the near future.

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