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Aspects of Clean Energy Transition in the Island of Crete, Greece

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Abstract

Clean energy transition in islands is of paramount importance for climate change mitigation. Various aspects in de-carbonization of the island of Crete, Greece have been investigated in order to examine the difficulties in replacing fossil fuels with benign energy resources in energy generation and in transportation. De-carbonization in different socio-economic sectors in Crete has been studied in order to find out the feasibility of de-carbonizing them as well as the sustainable energy technologies that can be used for achieving that. The results indicated that the sectors of electricity generation and heat and cooling production can be de-carbonized rather easily in the short to medium term using the abundant renewable energies in Crete. Transportation inside the island can be de-carbonized in the medium to long-term replacing the old conventional vehicles with new electric vehicles. More difficult is the de-carbonization in the transportation to and from Crete, via aircrafts and ships, since the required technologies are not mature and reliable yet while the necessary fuels are not produced in large scale in a cost-efficient way. De-carbonization in this sector can be achieved only in long-term while various technological breakthroughs are required for that. It is concluded that the clean energy transition in Crete is technically and economically feasible in some sectors while in others could be achievable only in the long-term supported by new technological developments. The results could be useful to policy makers for the creation and realization of a clean energy transition plan in the island of Crete that is necessary for complying with the EU target for carbon neutrality in the continent by 2050.

Keywords: aviation; clean energy transition; Crete; electricity; heat and cooling; renewable energies; transportation; vehicles.

1. Introduction

Clean energy transition in European Union (EU) islands is urgent for climate change mitigation complying with the European target for zero carbon emissions by 2050. Many islands have abundant renewable energy resources that can be used in electricity, heat, and cooling generation. They can be also used in powering electric vehicles replacing conventional vehicles using fossil fuels.

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Their de-carbonization is rather complicated while it is relevant with the current EU policies and goals. Various mature, reliable and cost-efficient renewable energy technologies have been already used successfully in many islands proving that their clean energy transition is feasible. Island of Crete, Greece is located in the Eastern Mediterranean basin having more than 600,000 permanent residents and hosting more than five mil. tourists each year. Clean energy transition in the island of Crete, Greece presupposes that renewable energies (REs) can replace fossil fuels in all socio-economic sectors generating all the required energy in a cost-efficient way. Its successful achievement requires the active participation of all actors and stakeholders of the private, public and social sector of the economy. These actors should design, monitor and realize an ambitious and sustainable clean energy transformation in the island. A study of clean energy transition in Crete has been implemented focused in all socio-economic sectors including: a) electricity generation, b) heat and cooling production, c) transportation inside the island, and d) transportation to and from Crete. The energy consumption in the island, the benign energy technologies that can be used and the possibilities of financing them are examined and discussed indicating that the clean energy transition in the island of Crete can be realized in the coming decades.

2. Literature survey

2.1 De-carbonization in the island of Crete

Financing the low carbon energy transition in Europe has been examined [1]. The authors stated that under the current investment lending criteria the required funds for a successful energy transition are available. They also mentioned that institutional investors and lenders could provide the required financial resources for large scale energy investments while households could finance low-scale and low-risk energy projects. The energy transition of the Greek non-interconnected islands has been studied [2]. The author stated that in the next decade REs are going to replace gradually fossil fuels in energy generation. He also mentioned that the development of interconnections between the electric grids of continental Greece and various islands will play an important role in their clean energy transition. The interconnection of the electric grids between Crete and continental Greece has been examined [3]. The authors stated that interconnection of the two grids will increase the penetration of REs in the energy system of the island. They also mentioned that two grid interconnections will be realized. The first between Crete and Peloponnesos at 150 KV AC and the second between Crete and Attica at 2X350 MW DC. A report regarding the energy transition in EU islands has been published [4]. The report stated that EU islands vary greatly regarding electricity grids, geographic specificities, local population, tourism and various other aspects. It also provides various good examples regarding clean energy transition in EU islands with different features. A handbook related with the clean energy transition in EU islands has been published [5]. The handbook indicates the way to navigate the clean energy transition in islands completely de-carbonizing their energy and transportation systems. A political declaration regarding clean energy transition in EU islands has been agreed among EU countries [6]. The declaration indicated a political intent while it is not compulsory neither it established any new legal commitments. The current status of carbon dioxide capture and storage technologies has been overviewed [7]. The authors mentioned that carbon capture and storage technologies comprise various technologies that can be massively reduce CO_2 emissions while they are not widely deployed yet. Absorption is the most mature CO_2 separation process. They also mentioned that four main types of geological formations are considered for CO_2 storage including: a) depleted oil and gas reservoirs, b) un-mineable coal beds, c) saline aquifers, and d) basalts. The carbon sequestration potential in olive tree groves in

Spain has been investigated [8]. The authors stated that growth of various weeds among the olive trees results in higher atmospheric carbon sequestration and carbon fixation in the soil. The energy transition in Germany, the Netherlands and the United Kingdom has been compared [9]. The authors stated that energy transition towards a low-carbon society depends on specific transition governance that is different in various countries. They also mentioned that Germany, UK and Holland have achieved very good results focusing in different governance practices. A report on the electricity system of Crete has been released [10]. The Hellenic Electricity Distribution Network Operator stated that in 2018 the total installed power of RE systems in Crete corresponded at 30% of the total installed power in the island. It is also mentioned that the electricity generated by REs in Crete in the same year had a share at 21% in the overall electricity generation. A preliminary plan for the clean energy transition in the island of Crete, Greece has been prepared [11]. The plan stated that the share of energy consumption in various socio-economic sectors in Crete during 2018-2019 was: a) heat and cooling at 6%, b) electricity generation at 20%, c) transportation inside the island at 27%, and d) transportation to and from Crete at 47%.

2.2 Transportation to and from Crete

The production of aviation bio-fuels from REs has been studied [12]. The authors stated that production of bio-fuels is a highly promising technology which while they are expected to substitute kerosene. They also mentioned that H_2 and CH_4 are less suitable in aviation due to their high production cost. The technology myths regarding climate policy in aviation have been analyzed [13]. The authors stated that various technology myths hinder the development of the appropriate policy measures promoting sustainable aviation. A roadmap for de-carbonizing European aviation has been published [14]. The report stated that aviation is a major carbon emitter while emissions in Europe have doubled since 1990. It is also mentioned that the expected technology and operation improvements will not mitigate the foreseen GHG emissions growth. Carbon pricing, higher fuel efficiency standards, incentives for air-fleet renewal are required for mitigation of the carbon footprint in aviation. The use of sustainable aviation fuels has been investigated [15]. The author stated that the use of sustainable aviation fuels is the main way for de-carbonizing aviation. Large deployment of sustainable aviation fuels though requires large investments in new production facilities and high reduction in their production costs. The carbon emissions due to tourism industry in the island of Crete, Greece have been estimated [16]. The author stated that the total carbon emissions due to tourism in Crete, including international flights, corresponded at 59.19% in the total carbon emissions in the island. He also mentioned that international and domestic flights combined with tourist's arrival by ships in Crete have a share at 80.69% in the total carbon emissions attributed to the regional tourism industry. The carbon footprint of international air traffic in islands has been studied [17]. The authors stated that in Canary islands, Spain tourists arrive and depart by aircrafts. Carbon emissions due to air transportation to and from Canary islands are high having a share more than 50% in the total carbon emissions in the archipelago. The use of cleaner alternative fuels for maritime transportation has been investigated [18]. The authors stated that heavy fuel oils used in maritime transportation can be replaced with cleaner fuels including LNG, H_2, NH_3 and bio-fuels. They also mentioned that currently LNG presents a readily available transition fuel for maritime transportation resulting in lower GHG emissions. In the transition to H_2-based economy H_2 produced by LNG would serve as a bridge between the present fossil fuel economy and the future H_2-based economy. The potential and limitations of electric flights have been studied [19]. The author stated that electric aviation is today limited in small planes travelling in short distances. In order to power larger aircrafts significant developments in battery technology are required increasing the mass specific energy density (Wh/kg) by a factor of ten. He also mentioned that the required improvements in technology for electrifying aviation may take approximately 20-40 years. The use of electric aircrafts for civil transportation has been analyzed [20]. The authors stated that electric aviation is possible provided that the power density of electric batteries must be higher than their current levels at around 200-300 Wh/kg. They also mentioned that in electric aircrafts the appropriate power density in their batteries must be at around 1,000 Wh/kg. Power density in this level requires some new kind of battery technology that is not foreseen soon. The technological, economic and environmental prospects of electric aviation have been investigated [21]. The authors stated that promotion of electric aviation requires batteries with significant higher specific energy densities and lower costs coupled with lower electricity cost. They also mentioned that a global fleet of electric aircrafts serving all flights up to 1,111 km would demand an equivalent of 0.6-1.7% of the worldwide electricity consumption in 2015.

2.3 Electricity generation

A path to prosperity using REs in islands has been presented [22]. The report stated various case studies in small islands regarding real-life project viability and highlighting innovative solutions in order to promote the deployment of REs in them. The energy transition in Mediterranean region by 2040 has been investigated [23]. According to this scenario the followings are foreseen: a) 30% reduction in energy demand and 23% reduction in final energy consumption, b) increased share of REs at 27% of the energy mix in the region with renewable becoming the primary source in electricity generation, c) reduction of CO_2 emissions by 38%. The renewable energy utilization in islands has been examined [24]. The authors stated that utilization of REs in islands has received remarkable attention from both academia and industry. They also mentioned that various REs including solar energy, wind energy, biomass, ocean and geothermal energy can be utilized in islands as well as the advanced energy technologies including energy storage, micro-grids, distributed generation etc. Various renewable energy solutions in islands have been examined [25]. The authors investigated the use of intermittent REs in electricity generation that is stored as H_2 and used afterwards via fuel cells for co-generation of heat and power (CHP). An energy system with zero carbon emissions in South East Europe by 2050 has been studied [25]. The authors stated that achieving 100% renewable energy system by 2050 many technologies should be employed including solar-PV and wind energy systems, geothermal energy, solar thermal systems, CHP driven by biomass, hydroelectric power and synthetic fuel’s production technologies.

2.4 Heat and cooling production

The production of heat from REs has been reported [27]. The report stated that various REs can be used for heat generation comprising biomass use for space heating and hot water production, active solar systems for local space heating and hot water production as well as geothermal energy and heat pumps. It is also mentioned that heat generated by REs in terms of primary energy is six to seven times more than the electricity generated by REs excluding large hydro. A report regarding the best available solution to de-carbonize the heating sector has been published [28]. The report stated that there are various alternative solutions for minimizing fossil fuels use including: a) improvements in energy efficiency, b) use of REs, and c) electrification of the heating and cooling sector. The possibility of obtaining sustainable development exploring biomass resources in the island of Samothrace, Greece has been analyzed [29]. The authors proposed various policy measures for the promotion of biomass utilization in the island comprising: a) better exploitation of the olive groves, b) promotion of energy crops, c) recycling the solid wastes, and d) exploiting the available forest biomass resources. A report of solar heating, cooling and air-conditioning has been published [30]. The report mentioned that solar cooling technology consists of two different options including: a) solar-PV systems combined with vapor compression cooling machines, and b) solar thermal systems combined with absorption systems. It is also stated that more than 1,500 solar cooling systems, mainly based on solar thermal collectors, have been installed in recent years in Europe. The use of solar thermal systems in EU and in Greece has been studied [31]. The author stated that the installed solar thermal capacity in Greece is at around 220 KW_{th} per 1,000 inhabitants ranked third among EU countries compared with the EU average at 30.7 KW_{th} per 1,000 inhabitants.

2.5 Transportation inside the island

The electric vehicles equipped either with batteries or with fuel cells have been compared [32]. The author stated that a combination of pure electric vehicles, hybrid vehicles as well as vehicles using bio-fuels is required for achieving 80% reduction of GHG emissions below 1990 levels. The use of bio-fuels promoting low carbon economy in Europe has been examined [33]. The authors have highlighted the advantages, drawbacks, negative externalities and constraints of the fourth generation bio-fuels. They mentioned that there is not clear answer on which generation bio-fuels meet better the global sustainability criteria. The electrification of the transportation sector inside the island of Crete, Greece has been studied [34]. The author mentioned that if all the existing conventional vehicles in Crete will be replaced by electric vehicles equipped with re-chargeable batteries the annual electricity requirements for powering their batteries would vary between 1,092,568 MWh and 1,311,077 MWh depending on batteries' type. He also stated that the required size of solar-PV plants generating the electricity needed would be between 728 MW_p to 874 MW_p while the size of wind parks between 445 MW to 534 MW. A solar-electric boat with zero environmental impacts has been analyzed [35]. The authors stated that a solar boat can be powered by lithium-ion batteries and it can be charged anytime by solar-PV panels placed on a flat top structure. They also mentioned that solar-electric boats can be used for brief trips along coasts avoiding other polluting modes of transportation. The electric and solar boat market in France has been overviewed [36]. The authors mentioned that electric boats in France include pure electric and hybrid boats using lead acid, NiCad and Lithium batteries. They also stated that zero emission electric ships have been developed in France since the end of nineties. The estimated total carbon emissions in the island of Crete have significant differences in two studies (11) and (16). A more accurate calculation is required for achieving more reliable results. *Aim of the current work is the investigation of various aspects of clean energy transition in the island of Crete, Greece* After the literature review the de-carbonization in various socio-economic sectors in Crete is analyzed. Separation in four different sectors has been made including electricity generation, heat and cooling production, transportation inside the island and transportation to and from Crete. After that the possibilities of financing the clean energy transition of the island are mentioned followed by the discussion of the findings and the conclusions drawn.

3. Energy consumption and carbon emissions in Crete

Energy is used in Crete in buildings, in industry, in agriculture and in transportation. The main energy sources used include fossil fuels and REs. Among fossil fuels, that are not produced in the island, are: fuel and heating oil used in electricity generation, heating oil used in heat production and diesel oil and gasoline used as vehicle fuels. Renewable energies comprise: solar energy, wind energy, hydro energy, biomass and low enthalpy geothermal energy used for electricity and heat generation. Kerosene and bunker fuels are used in transportation to and from Crete via airplanes and ships although the consumption of these fuels can not be attributed only to Crete. The energy sources that are used in Crete are presented in table 1 while the final energy consumption in the island is presented in table 2.

Table 1: Energy sources that are currently used in Crete

Energy source [1]	Energy generated	Is the energy source locally available?
Fuel oil	Electricity, heat	No
Diesel oil	Heat, vehicle's transportation	No
Heating oil	Electricity, heat	No
Gasoline	vehicle's transportation	No
Solar Energy	Heat, cooling, electricity	Yes
Wind energy	Electricity	Yes
Hydro energy	Electricity	Yes
Biomass	Electricity, heat	Yes
Low enthalpy geothermal energy	Heat and cooling	Yes

[1] Fuels used in ships and aircrafts are not included, Source: own estimations

Table 2: Final annual energy consumption in Crete (2018 and 2019)

Energy sector	Annual energy consumption (MWh)
Electricity generation (2019)	3,071,926
Transportation in the island (2018)	3,987,906
Heat and cooling excluding electric systems (2018)	843,648
Total without transportation to and from Crete	7,903,480
Transportation to and from Crete (estimations)	7,099,450
Total	15,002,930

Source: Draft plan for clean energy transition in the island of Crete, Greece, 2020

Table 2 indicates that the energy consumption during transportation to and from Crete is almost equal with the energy consumption in all socio-economic sectors in the island. Taking into account that the permanent population in Crete is at 623,065 inhabitants [37] the annual energy consumption, without including energy consumption during transportation to and from Crete, is 12.68 MWh/capita. The annual carbon emissions in Greece in 2018 have been estimated at 6.08 tnCO_2 per capita [38].

4. De-carbonization of electricity generation

Electricity is currently generated in Crete from fossil fuels and REs. Three thermal power stations using fuel and heating oil generate approximately 80% of the island's annual electricity generation. Various REs including solar-PV energy, wind energy, hydro energy and biogas generate approximately 20% of the island's annual electricity generation. The electric grid of Crete was autonomous so far. Its interconnection with the grid of continental Greece is currently under implementation with two undersea electric cables. It is foreseen that soon electricity will be transferred from continental Greece to Crete and vice-versa. De-carbonization of electricity generation in Crete is technically and economically feasible. In order to achieve that the following conditions should be fulfilled:

a) The annual electricity generation by REs in Crete should be equal to the annual electricity consumption. Various renewable energy technologies can be used including solar-PV systems, solar thermal power plants, wind parks, biogas plants and small hydroelectric systems. The most of them are already used in the island. Their technologies are mature, reliable and cost-efficient. Electricity generated by intermittent energy sources, like solar and wind energy, can be stored in pump hydro storage systems facilitating their further development, and
b) Electricity transferred from continental Greece to Crete via the two undersea electric cables should be offset annually with green electricity generated by REs in Crete and transferred to continental Greece. It should be mentioned that the solar and wind energy resources are abundant in Crete while their utilization was limited so far due to grid stability reasons. REs that can be used for de-carbonization of electricity generation in Crete are presented in table 3.

Table 3: Renewable energies that can be used for de-carbonization in electricity generation in Crete

Energy source	Technology	Availability in Crete	Current use of technology in Crete
Solar energy	Solar-PV	High	Yes
Solar energy	Solar thermal power	High	No
Wind energy	Wind turbines	High	Yes
Hydro energy	Hydro turbines	Low	Yes
Biogas	Burning	Low	Yes
Solid biomass	Burning	Medium	No

Source: Own estimations

5. De-carbonization in heat and cooling production

Heat and cooling are required in private and public buildings, in industry as well as in agriculture. The main energy sources and fuels currently used for that in Crete comprise:

a) Electricity,
b) Solar energy,
c) Solid biomass resources that are locally available,

d) LPG,
e) Heating oil, and
f) Ambient heat via heat pumps.

Due to the severe economic crisis in Greece during the last ten years many households have reduced the use of fossil fuels in their residential buildings replacing them either with local and cheap solid biomass resources or with energy efficient heat pumps. De-carbonization of the heating and cooling sector in Crete can be achieved with:

a) Electrification in heat and cooling production,
b) Replacement of fossil fuels used in heat and cooling generation with renewable energies that are abundant in the island like solid biomass and solar energy, and
c) Generation of green electricity from the abundant solar and wind energy resources of Crete and its use in heat and cooling production. Already green electricity is generated in the island from solar-PV systems and wind parks.

The following zero-carbon emission energy sources can be used for de-carbonization in the heat and cooling sector in the island.

a) Green electricity for space heating, hot water, steam and cooling production with electric devices,
b) Solar thermal energy for hot water production, space heating and space cooling, and
c) Solid biomass for space heating and hot water production. It is based on olive tree residues, by-products and pruning. Forest residues as well as other agricultural residues in Crete can be also used.

Table 4: Renewable energies that can be used for de-carbonization of heat and cooling production in Crete

Energy source	Technology	Availability in Crete	Current use of technology
Solar energy	Solar thermal	High	Yes, mainly for hot water production
Solid biomass	Burning	High	Yes, for space heating and hot water production
Biogas	Burning	Low	Yes, for CHP. Use of heat for space heating and hot water production
Ambient heat combined with green electricity	Heat pumps	High	Yes, for space heating and cooling, hot water production
Green electricity	Various electric devices	High	Yes, for space heating and cooling, hot water production

Source: Own estimations

The required benign energy technologies for heat and cooling production with zero carbon impacts are currently mature, reliable, well-proven and cost efficient. The government is already promoting them offering financial incentives in households as well as in enterprises regarding their installation in buildings, industry and in agriculture. REs that can be used for de-carbonization of heat and cooling production in Crete are presented in table 4.

6. De-carbonization in transportation inside the island

Vehicles in Crete are fueled with gasoline and diesel oil while the use of electric vehicles is currently rare although the government has started to offer incentives to citizens for buying them. Zeroing carbon emissions due to transportation in Crete can be achieved with the use of:

a) Electric vehicles with re-chargeable batteries,
b) Electric vehicles with fuel cells,
c) Conventional vehicles using either bio-ethanol or bio-diesel, and
d) Solar boats or boats fueled by bio-fuels travelling in small distances among various ports serving tourists and the local population.

The batteries of the electric vehicles should be re-charged with green electricity generated preferably with solar or wind energy. Solar-PV systems and wind parks should be installed to generate the required electricity in transportation. The number of batteries' re-charging stations in Crete is limited to day. Vehicles equipped with fuel cells should be fueled with green electrolytic H_2. The production cost of electrolytic H_2 is higher than the cost of other fuels while the necessary infrastructure regarding H_2 storage and transportation is negligible in the island to day. The initial cost of electric vehicles equipped either with re-chargeable batteries or with fuel cells is still high compared with the cost of conventional vehicles equipped with internal combustion engines. Use of conventional vehicles in Crete fueled by bio-fuels has the drawback that bio-fuels are not currently produced in the island. The possibilities of de-carbonizing transportation inside Crete are presented in table 5.

Table 5: Possibilities of de-carbonizing transportation inside Crete

Technology	Fuel/energy	Is the fuel/energy produced in Crete?	Is the technology currently used in Crete?
Electric vehicles with re-chargeable batteries	Green electricity	Yes, mainly with solar and wind energy	The government has started to subsidy financially the buying cost of electric vehicles
Electric vehicles with fuel cells	H_2	Electric vehicles with fuel cells	No
Conventional vehicles using bio-fuels	Bio-ethanol, bio-diesel	No	No
Boats used in small distances	Bio-fuels or solar-PV energy	Bio-fuels are not produced, Solar electricity is generated in Crete	No

Source: Own estimations

7. De-carbonization in transportation to and from Crete

The majority of people arriving and departing from Crete, including tourists, use either airplanes or ships. The most of tourists travelling long distances prefer aircrafts. Both airplanes and ships utilize fossil fuels while the use of REs in air and maritime transportation is currently negligible. The energy of the transportation fuels has a high share in the overall energy consumption in Crete while their carbon emissions are also high (**Vourdoubas,**

2019). Various efforts have been made worldwide to reduce carbon emissions in aviation and in maritime transportation. The results however were not satisfactory so far. The proposed technological and non-technological measures comprise:

a) Use of new and more energy efficient aircrafts and ships,
b) Use of low or zero carbon emissions fuels in aviation and in maritime transportation. Kerosene and fuel oil should be replaced with natural gas, bio-fuels, H_2 and electro-fuels. Bio-fuels replacing conventional fuels can sharply reduce carbon emissions. Their production however in large scale is not easy while it requires large investments in production plants and large land areas for the cultivation of various energy crops. It should be noted that in Crete there is not availability of large land areas for bio-fuels production. This could create conflicts regarding the land use for food and animal feed production. Electrification in short haul aviation is foreseen soon but in medium and long-haul aviation is not expected in the next ten or fifteen years,
c) Higher taxation of fuels used in aviation and in maritime transportation,
d) Volunteer offsetting of carbon emissions during travelling by the passengers,
e) Limitations in air travelling per year per passenger,
f) Offsetting the carbon emissions in air and maritime transportation using the clean development mechanism. Air transportation companies could finance or co-finance the carbon offsetting in aviation.

The abovementioned technological and non-technological measures could increase the travelling cost to Crete having negative impacts in the island's flourishing tourism industry. De-carbonization of air transportation to and from Crete is more difficult compared with de-carbonization in the other socio-economic sectors in the island. It requires technological innovations and breakthroughs as well as well designed policy measures that should be acceptable by all stakeholders including governmental authorities, private enterprises and citizens. Currently, worldwide and in Crete, the extensive use of bio-fuels in aviation is not feasible.

8. Financing the clean energy transition in Crete

Financing the clean energy transition in the island of Crete requires large amounts of capital. Investments are necessary in new infrastructure as well as in the implementation of large, medium and small-scale sustainable energy systems generating electricity, heat and cooling. Additional investments are also required in the transportation sector including replacement of the old conventional vehicles with new electric vehicles, replacement of the old airplanes and ships with new energy efficient aircrafts and ships. Investments are also needed in batteries' re-charging stations, in H_2 production systems as well as in H_2 storage and transportation. Many financial actors should be mobilized in order to participate in the effort of clean energy transition including:

a) Institutional investors including pension funds who will contribute in financing large scale investments expecting a reasonable and stable return in their investments,
b) Private investors participating in the implementation of large-scale energy projects including electricity generation by solar and wind energy systems,

c) Households that will contribute in the realization of small-scale and low-risk energy projects in their residential buildings. These include the use of solid biomass for heat generation and the use of solar energy for heat and electricity generation,

d) The government that should co-finance the energy renovation in public buildings and should also support low-income households in improving the energy performance in their residential buildings,

e) Energy service companies that will participate in the financing and implementation of various benign energy projects in the private and public sector, and

f) Private enterprises in the primary, secondary and tertiary sector who will realize various clean energy investments in their facilities expecting attractive returns in their investments.

The role of banks in financing various sustainable energy investments is important as well as the role of European structural funds that should also support the implementation of various low carbon energy projects complying with the EU goal for carbon neutrality by 2050. The time frame for the clean energy transition in Crete is presented in table 6.

Table 6: Time frame for the clean energy transition in the island of Crete

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

Source: own estimations

9. Discussion

The de-carbonization in four socio-economic sectors in the island of Crete, Greece has been analyzed focusing in technical aspects. Many different benign energy technologies are currently mature, reliable and cost-efficient and they can be used for heat, cooling and electricity generation as well as in carbon-free transportation. It has been indicated that de-carbonization in electricity generation is technically feasible taking into account the abundant solar and wind energy resources in the island and the interconnection of the electric grids of Crete and continental Greece which allows the offsetting of green electricity with fossil fuels-based electricity. It should be noted that estimation of carbon emissions due to electricity generation in Crete, reported in (11), are high and probably a more accurate estimation should be made. De-carbonization of heat and cooling production in Crete is also feasible using the locally available REs and electrifying the heat and cooling generation using green electricity. De-carbonization both in electricity generation and in heat and cooling production is achievable in the short and medium term. De-carbonization in transportation inside the island is feasible, in the medium to long-term. It requires replacement of the existing conventional vehicles equipped with internal combustion engines with electric vehicles preferably equipped with re-chargeable batteries. Although the use of electric vehicles in Crete is in the infant stage and the necessary infrastructure regarding batteries' recharging is lacking the government is currently supporting financially the citizens to buy electric vehicles. De-carbonization to and from Crete via airplanes and ships is more difficult compared with the other abovementioned socio-economic sectors. Use of bio-fuels replacing kerosene and heavy fuel oil as well as electrifying aviation and maritime transportation could assist in the medium and long-term de-carbonization of transportation to and from Crete via aircrafts and ships. Carbon sequestration due to tree plantations in Crete should be taken into account in the clean energy transition. New emerging technologies, like carbon capture and storage that could be commercialized in the near future could also help in de-carbonization of the island. It has been also indicated that various actors should participate in financing the clean energy transition investing in small or large-scale energy projects and in the necessary infrastructure in Crete. Our findings could be useful to public authorities, policy makers and to various stakeholders who are willing, through a participatory procedure, to create a plan for the clean energy transition in the island and to realize it afterwards. The present work does not estimate the size of the required benign energy systems generating heat and electricity as well as the cost for de-carbonizing Crete due to the necessary energy investments and its distribution among stakeholders. Further work should be focused a) In sizing the benign energy systems generating the necessary carbo-free energy in Crete, b) In estimating the capital cost of the necessary sustainable energy systems, and c) In the preparation of an overall clean energy transition plan for the island.

10. Conclusions

Investigation of various aspects in energy transition in Crete has been implemented. De-carbonization in different socio-economic sectors has indicated that:

a) De-carbonization in electricity generation is achievable using the abundant local REs generating electricity equal to island's annual consumption. Equal amounts of electricity could be transferred annually, via the two undersea electric cables, between Crete and continental Greece offsetting fossil fuels-based electricity with green electricity generated in Crete,
b) De-carbonization of heat and cooling production is achievable using the local REs and electrifying the heat and cooling generation. Electric devices should be powered by green electricity,
c) De-carbonization of transportation inside the island is achievable using electric vehicles equipped with re-chargeable batteries and powered by green electricity,
d) De-carbonization of transportation to and from Crete via airplanes and ships is achievable using either bio-fuels or electrifying aviation and maritime transportation.

There are various possibilities for financing the necessary investments in sustainable energy generation systems and in the required infrastructure for clean energy transition in the island. Today there is a lack of studies regarding de-carbonization in various socio-economic sectors in Crete as well as in clean energy transition taking into account the island's specific features and conditions. Current work contributes in the existing knowledge regarding the possibilities for lowering or zeroing the carbon foot print due to energy use in Crete. Examining and analyzing the opportunities and difficulties in de-carbonizing various socio-economic sectors in Crete facilitates the creation of a regional clean energy transition plan in accordance with the EU policies and goals for carbon neutrality in the coming decades.

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