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Studies on the Use of Unconventional Transport Vehicles and Fuels in the Island of Crete, Greece

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Abstract

Several alternative vehicles and zero-carbon fuels have been developed and used to mitigate climate change, reduce the air pollution in cities and the dependence on oil resources. Their use is necessary for achieving the net-zero emissions target in the next decades. Among these vehicles are electric vehicles and vehicles with ICEs using electricity, hydrogen and bio-fuels of organic origin. The possibility of using alternative vehicles and fuels in Crete, Greece for de-carbonization of vehicles transportation has been examined. The use of electric vehicles equipped with re-chargeable electric batteries, electric vehicles equipped with fuel cells using hydrogen and vehicles with internal combustion engines using bio-fuels has been studied. The required electricity for re-charging electric batteries and for electrolytic hydrogen production can be generated from the abundant local solar and wind energy resources. Taking into account the maturity and the cost-effectiveness of the solar-PV technology as well as the wind turbine's technology in Crete the use of electric vehicles powered by green electricity is prioritized for the green transition of the transportation sector. Bio-fuels which are used in conventional vehicles are not produced in the island. Each type of the abovementioned vehicles and fuels has several advantages and drawbacks which can accelerate or delay their use in Crete. It has been found that the green transition of vehicles transportation in the island has positive and negative economic impacts to all stakeholders. The results could be useful to policy makers, local authorities and to local stakeholders while they can assist in the development of a plan for de-carbonizing the island by 2050.

Keywords: Battery, Bio-fuels, Crete-Greece, Electricity, Fuel cell, Hydrogen, Vehicles

1. Introduction

The green energy transition in the island of Crete, Greece pre-supposes the replacement of oil-based fuels in vehicles' transportation with carbon-free fuels. Several unconventional vehicles using fuels with low- or zero-carbon emissions can be used for de-carbonization of the transportation sector. The use of electric vehicles with re-chargeable batteries has been studied (*Rangarajan et al, 2022, Liu et al, 2022, Bupesh et al, 2021, Verma et al, 2022*) as well as the use of electric vehicles equipped with fuel cells (*Sorlei et al, 2021, Weberforce et al, 2021, De Wolf & Smeers, 2023, Tanc et al, 2019*). The use of conventional vehicles with ICE using bio-ethanol and bio-diesel instead of gasoline or diesel oil has been also studied (*Elfasa Khang, 2019, Alizadeh et al, 2020, Alalwan et al, 2019, Vourdoubas, 2002*). Unconventional vehicles using sustainable fuels are necessary for de-carbonizing the transportation sector in Crete complying with the national and EU targets for achieving a net-zero emissions economy by 2050.

The aims of the current study are:

a) The mapping of the current situation in Crete regarding the transportation vehicles and the fuels currently used,
b) The examination of the different types of low- and zero-carbon fuels which can be used in vehicles' transportation and the possibility of producing green fuels in the island,
c) The preliminary analysis of the cost dimension of the green energy transition in vehicles' transportation in Crete and the presentation of the advantages and drawbacks of different types of unconventional vehicles and fuels.

The text is structured as follows: After the literature survey the mapping of the current situation in vehicles' transportation and the oil-based fuels used in Crete are stated. After that the different types of green fuels which can been used in unconventional vehicles and the possibilities of producing them in Crete are examined. Next, the cost of the green energy transition in vehicles' transportation in Crete is stated while the advantages and drawbacks of different types of unconventional vehicles are presented. The text ends with the discussion of the findings, the conclusion drawn and the citation of the literature used.

The current study is innovative since there are not similar studies regarding the de-carbonization of the transportation sector in Crete. It fills the existing gap related with the green energy transition of various sectors in the island. The current work could be useful to public and local authorities in the island, to companies selling conventional vehicles and electric vehicles (EVs), to enterprises related with conventional fuelling stations as well as to energy companies and to investors who are willing to invest in renewable electricity generation and in the production of green fuels in Crete.

2. Literature Survey

The literature survey is separated in three sections. The first section is focused on electric vehicles with re-chargeable batteries (BEVs), the second on electric vehicles with fuel cells (FCEVs) while the third section on vehicles equipped with internal combustion engines (ICEs) using bio-fuels.

2.1 Electric Vehicles with Re-chargeable Batteries

Rangarajan et al, 2022 have studied the use of lithium-ion batteries in BEVs. The author stated that the best energy storage technology in BEVs is the Li-ion batteries. Their advantages include high efficiency, high energy density and long life-cycle. The authors stated that in the past two decades Li-ion batteries are increasingly used in several sectors including their use in BEVs. However, they mentioned, there is still a lot of room for improvement in terms of energy, cost, safety and fast charging capabilities. *Liu et al, 2022* have overviewed the batteries for BEVs. The authors stated that the increasing use of BEVs is an effective solution to improve carbon neutrality. They also mentioned that the main concerns for electric batteries are related with energy density, fast charging and safety issues. *Chian et al, 2019* have reviewed the recent progress in batteries for BEVs. The authors examined the oldest type of batteries, the lead-acid battery, to the latest technology, the lithium-ion battery. They stated that during their evolution several parameters have been significantly improved including specific energy, energy density, specific power, weight and size. *Alanazi, 2023* has studied the benefits and the challenges of BEVs. The author stated that BEVs are gaining popularity having many benefits including their independency from oil and the reduction of carbon emissions. However, he mentioned, there are various challenges hindering their adoption including the high cost of infrastructure, the scarcity of charging stations, their limited driving distance and the performance of batteries. *Bupesh et al, 2021* have studied the progress in battery technologies for BEVs. The authors stated that BEVs are growing fast and their demand is increasing worldwide. They also mentioned several challenges faced by BEVs such as lack of charging infrastructure, limited driving range and thermal management of batteries. *Li et al, 2015* have studied the benefits of BEVs in climate change mitigation. The authors stated that there is a debate whether the replacement of conventional vehicles by BEVs should be delayed or accelerated since BEVs have higher cost and cause more pollution in the manufacturing process. The authors pointed out two benefits of BEVs over conventional vehicles. First, BEVs emit much less heat than the conventional vehicles within the same mileage and they can mitigate urban heat island effect. Secondly, the energy consumption of air-conditioners will be decreased resulting in benefits in the local and global climate. *Van Mierlo et al, 2021* have studied the development of the next stage of BEVs' generation. The authors stated that the next generations of BEVs will comprise improvements in batteries, in energy management systems, in autonomous driving and in charging infrastructure. They also mentioned that the new innovations are related with vehicle components, charging infrastructure, interaction with the grid, battery materials and power electronics. *Hu et al, 2017* have studied the differences in energy consumption in BEVs with reference Beijing, China. The authors explored how the energy efficiency of BEVs is affected by driving behaviour, personal driving style, traffic conditions and infrastructure design using a Nissan LEAF in Beijing. They mentioned that both the physical environment and the personal driving style affect the energy efficiency in BEVs concluding that eco-driving substantially influence their energy efficiency. *Vourdoubas, 2018* has studied the electrification of the transport sector in Crete, Greece. The author stated that if all the existing conventional vehicles in Crete were to be replaced by BEVs with re-chargeable batteries the annual electricity requirements for re-charging the batteries would be between 1 092 568 MWh to 1 311 077 MWh depending on the type of batteries used. He also mentioned that the required size of the solar photovoltaic (solar-PV) plants and wind farms in Crete to generate the necessary electricity would be in the range of 728 MW_p to 874 MW_p and of 445

MW_{el} to 534_{el} MW respectively. *De Cauwer et al, 2015* have studied the prediction of energy consumption in BEVs. The authors used real-world data from energy consumption of BEVs to construct three energy consumption models. They stated that these models had a prediction error within 25%. *Li et al, 2016* have examined the main factors influencing the energy consumption in BEVs. The authors stated that the energy consumption of BEVs depends on a number of factors such as road conditions, transport conditions et cetera. They have constructed a model with four parameters including: a) infrastructure, b) traffic, c) topography, and d) climate. They mentioned that this model can be used only for rough estimations while its validity must be validated in other regions. *Wu et al, 2015* have measured the energy consumption in BEVs. The authors stated that BEVs are more efficient when driving on in-city routes than driving on freeway routes. They also mentioned that their proposed model can successfully estimate the instantaneous power and the trip energy consumption of BEVs. *Chen et al, 2021* have reviewed the energy consumption estimation models for BEVs. The authors stated that the successful adoption of BEVs depends on energy consumption models that accurately estimate the electricity consumption. They mentioned that there are four categories affecting the energy consumption of BEVs including vehicle components, vehicle dynamics, traffic and environmental-related factors. *Holland et al, 2016* have studied the environmental benefits from driving BEVs. The authors stated that ignoring local pollution leads to an overestimation of the benefits of BEVs and an underestimation of geographic heterogeneity. They mentioned that accounting for both local and global pollution BEVs generate negative environmental benefits at 0.73 cents per mile on average relatively to comparable gasoline-fuelled vehicles. BEVs have positive environmental benefits in polluted urban areas and negative in less polluted rural areas. *Panday & Bansal, 2014* have reviewed the optimal energy management strategies for hybrid electric vehicles (HEVs). The authors stated that reduced liquid fuel consumption and larger electric operating range without compromising with the speed and the performance of the vehicle can be achieved with the use of plug-in hybrid electric vehicles (PHEVs). *Verma et al, 2022* have reviewed the existing life cycle assessment of BEVs compared to combustion engine vehicles. The authors stated that the adoption of BEVs results in the reduction of greenhouse gas (GHG) emissions while it increases the human toxicity level due to larger use of metals, chemicals and energy. Regarding the life cycle cost analysis BEVs have a higher initial cost due to the high cost of batteries while it is difficult to predict the cost of gasoline and the electricity mix in the future. *Mamala et al, 2021* have studied the energy consumption of a PHEV in real-world conditions with total travelling at 5 000 Km. The authors estimated that the average instantaneous energy consumption was at 208 Wh/Km for the electric motor while the corresponding value for a combustion engine was at 894 Wh/Km. *Vourdoubas, 2023* has studied the interconnection of the electric grid in the island of Crete, Greece and its contribution to the clean energy transition. The author stated that currently the generation of solar-PV and wind electricity covers more than 20% of the annual power demand in the island. He also mentioned that the implementation of the interconnection of the electric grid of Crete in the next 1-2 years will allow the full development of the rich solar and wind energy resources for power generation in the island.

2.2 Electric Vehicles with Fuel Cells

Sorlei et al, 2021 have reviewed the energy management strategies in FCEVs. The authors stated that the main challenges for the adoption of FCEVs are: a) the development of infrastructure of hydrogen (H_2) stations, b) The high cost of H_2 production, c) the lower power density of batteries, and d) the low flexibility in controlling the power flow. *Weberforce et al, 2021* have studied the developments of BEVs and FCEVs. The authors stated that fuel cell hybrid electric vehicles (FCHEVs) have integrated a battery or an ultra-super capacitor which are used as an additional energy system which can be charged or discharged. They also mentioned that there are five main types of batteries used in BEVs including: a) lead-acid batteries, b) nickel batteries, c) zinc batteries, d) lithium-ion batteries, and e) metal air batteries. *Shekhar Das et al, 2017* have studied the FCHEVs. The authors stated that a FCHEV consists of a fuel cell, a battery and/or an ultracapacitor. They also mentioned that if the price of fuel cells and H_2 will drop in the future the FCHEVs would be competitive to conventional BEVs. *Thomas, 2008* has compared FCEVs with BEVs. The author stated that FCEVs have six advantages compared to Li-ion battery BEVs. These are: a) less weight, b) fuel cell takes less space on the vehicle, c) generate less GHGs, d) cost less, e) require less well-to-wheels energy, and f) take less time to refuel. *Kurtz et al, 2019* have studied the durability and the performance of FCEVs. The authors stated that their durability has increased over the years. They also mentioned that their performance approaches their target values regarding their efficiency while the manufacturers with new improvements could achieve them. *De Wolf & Smeers, 2023* have compared BEVs with FCEVs. The authors stated that the main advantages of H_2 vehicles are autonomy and fast re-charging while of the BEVs are the lower price and the wide availability of the electricity grid. They also mentioned that both types of EVs need new infrastructure either battery re-charging networks or H_2 refuelling stations. *Offer et al, 2009* have implemented a comparative analysis of BEVs, FCEVs and FCHEVs. The authors stated that in 2030 FCEVs could achieve life cost parity with conventional gasoline vehicles. However, they mentioned, BEVs and FCHEVs have significantly lower lifecycle cost. *Sacid Endiz, 2023* has compared the BEVs and FCEVs. The author stated that although the majority of automakers favours the BEVs both of them have advantages and drawbacks while the conventional vehicles are going to be replaced in the future by them. *Parikh et al, 2023* have made a comparative analysis between BEVs and FCEVs. The authors stated that the lifecycle costs of BEVs and FCHEVs are comparable while depending on the driving pattern one may be more advantageous than the other. They also mentioned that FCEVs probably will be used in heavy-duty vehicles while lithium-based BEVs seem to be the best short-term solution. *Contestabile et al, 2011* have compared BEVs, FCEVs and vehicles using biofuels. The authors reviewed seven detail studies comparing various types of vehicles and fuels. They stated that in the long run the EVs are expected to prevail while BEVs and FCEVs are going to serve different segments of the market. *Eberle et al, 2012* have assessed the FCEVs and the H_2 infrastructure in 2012. The authors stated the existing limitations in battery's capacity of BEVs to allow traveling in long distances. They mentioned that FCEVs and H_2 consist of an advanced zero-emission transport system with refuelling times of 3 to 5 minutes which though require the development of the necessary infrastructure. *Tanc et al, 2019* have assessed several studies and overviewed the future of

FCEVs. The authors stated that BEVs and FCEVs are the main focus of cars manufacturers. They mentioned that between 2030s - 2050s the demand for FCEVs will increase due to their cost reduction and the increase in H_2 refuelling stations. *Wassen et al, 2023* have studied the fuel cell-based hybrid BEVs. The authors stated that FCHEVs will help battery-powered vehicles in several circumstances. They mentioned that there are several challenges for FCHEVs such as low fuel cell performance, cold starts, hydrogen storage, cost reduction and safety concerns. *Selmi et al, 2022* have studied the technologies and challenges of fuel cell-based EVs. The authors stated that the standard EV technologies include the fuel cell BEVs, the battery BEVs, the PHEVs, the hybrid BEVs and the flexible fuel vehicles. They also mentioned that yet the FCEVs have not many advantages over the other vehicles' technologies. *Armenta-Deu & Arenas, 2023* have analysed the EVs with a fuel cell hybrid system. The authors stated that the use of super capacitors for acceleration process improves the performance of hybrid BEVs. They also mentioned that the combination of supercapacitors and fuel cells in hybrid systems to power BEVs results in a reduction to power supply capacity and in an average reduction in energy consumption at 37%. *Vourdoubas, 2021* has studied the use of renewable energies for H_2 production and its use for powering fuel cell vehicles in the island of Crete, Greece. The author stated that Crete has abundant solar and wind energy resources which are currently used for power generation. He estimated that, if all the existing vehicles in Crete were equipped with fuel cells, the required H_2 to power them would be at 53 037 tnH_2/year. He also calculated the nominal size of the solar-PV systems to generate all the carbon-free electricity necessary in water electrolysis and H_2 production at 2 710 MW_p while the corresponding power of the wind farms was at 1 501 MW_{el}.

2.3 Vehicles with Internal Combustion Engines Using Biofuels

Vourdoubas, 2002 has studied the possibilities of producing bio-ethanol and bio-diesel in Crete. The author stated that biofuels are not produced currently in the island. He also mentioned that carob pods rich in sugars have been used experimentally for bio-ethanol production while fried vegetable oils from restaurants and households can be used for bio-diesel production. *Elfasa Khang, 2019* has studied the use of bio-fuels in automobiles. The author stated that the use of bio-fuels in vehicles has several advantages such as favourable well-to-wheel carbon dioxide (CO_2) balance for environment, higher engine power and efficiency and improved fuel combustion. He also mentioned that they have drawbacks such as high corrosiveness to engine systems and low heating values. *Alizadeh et al, 2020* have studied the future of bio-fuels. The authors have reviewed the literature regarding the future of bio-fuels. They stated that bio-fuels economy would develop gradually while the shift to bio-fuels would require high governmental support as well as technology breakthroughs, higher oil prices and significant changes in environmental policies. *Alalwan et al, 2019* have studied the evolution of different generations bio-fuels. The authors stated that in contrast to other green energy resources bio-fuels can provide liquid fuels which are essential for transportation. They classified bio-fuels in four generations including: a) first generation utilizing edible biomass, b) second generation using non-edible biomass, c) third generation using microorganisms as feedstock, and d) fourth generation focused on genetically modified microorganisms. *Meyer et al, 2011* have studied the use of bio-fuels and natural gas on heavy-duty vehicles. The authors stated that the use of bio-fuels and natural gas as alternative fuels are promoted in heavy-duty vehicles. They evaluated the total life-cycle emissions of CO_2, nitrous oxide (N_2O), methane (CH_4) and five other pollutants for six fuels. They mentioned that bio-diesel and compressed natural gas had definite advantages regarding the emissions for the most pollutants. *Kugemman & Polatidis, 2020* have analysed the road transportation fuels and vehicles using multi-criteria decision analysis. The authors considered several economic, environmental, social and technological criteria using life-cycle sustainability assessment methodology. They stated that electricity and ethanol are good alternatives for light vehicles where gaseous fuels seem more appropriate for heavy vehicles like buses. *Fulton et al, 2015* have examined the need for bio-fuels as part of a low carbon future. The authors stated that the world needs bio-fuels largely due to aviation, ocean shipping and long-haul trucking. They also mentioned that there will be a large demand for dense liquid fuels in 2050 up to 80% of the total transportation fuels. First-generation bio-fuels are currently used in Greece according to the *Greek National Plan for Energy and Climate.* It is stated that bio-diesel is mixed at 7% with diesel oil while bio-ethanol at 5% with gasoline. Bio-diesel is produced in 18 plants in the country while bio-ethanol is imported. Second generation bio-fuels are not currently produced in Greece. It is also mentioned that by 2030 public re-charging stations with output at 1.3 KW per every passenger BEV should have been installed while for each PHEV the output of the required re-charging stations should be at 0.7 KW. *Lizbetin et al, 2017* have compared the alternative fuels used in road transportation. The authors examined the energy performance and the emissions of carbon monoxide (CO), CO_2, Sulphur dioxide (SO_2) and Nitrous oxides (NO_X) of unconventional fuels including liquid pressurized gas (LPG), bio-diesel, bio-ethanol and compressed natural gas (CNG). They mentioned that LPG, CNG and bio-ethanol had the best performance. *Prakash Sandaka & Kumar, 2023* have reviewed the challenges regarding the use of electricity, hydrogen and bio-fuels in vehicles. The authors stated that zero emission vehicles (ZEVs) powered by electricity and H_2 are the future in transportation. However, their market penetration is limited for several economic and technological reasons. Meanwhile bio-fuels can be used right away in the existing conventional vehicles until the problems related with the mass use of EVs will be solved. *The EU directive 2018/2021* is focused on the promotion of the use of energy from renewable sources. The directive stated that each member state is obliged to ensure that the share of renewable energy sources (RES) within the final consumption of energy in the transport sector is at least 14% by 2030. The directive also mentioned that the contribution of advanced bio-fuels as a share in final consumption of energy in the transport sector shall be at least 3.5% in 2030. *The EU directive 2023/2413* has amended previous EU directives related with the promotion of energy from RES. The directive stated that the share of renewable energy within the final consumption of energy in the transport sector should be at least 29% by 2030.

3. Conventional Transportation Vehicles in Crete

Conventional transportation vehicles using gasoline and diesel oil are mainly used in Crete. During the last years the number of BEVs is growing assisted by the governmental subsidies regarding their purchasing cost and the development of batteries' re-charging stations across the island. FCEVs powered by H_2 and refuelling stations do not exist currently in Crete. The number of vehicles in Crete are presented in table 1, the quantities of gasoline and diesel oil used by them in table 2 while their annual carbon emissions in table 3. The data in tables 1, 2 and 3 have been collected from www.statistics.gr and have been processed by the author.

Table 1. Number of vehicles in Crete (2021)

Type of vehicle	Number of vehicles
Passengers' cars	294 913
Trucks	136 951
Buses	1 175
Motorcycles	142 686

Source: www.statistics.gr

Table 2. Gasoline and diesel oil use in conventional vehicles in Crete and in Greece (2021)

Fuel	Consumption in Crete (tons/year)	Consumption in Greece (tons/year)	Consumption in Crete to consumption in Greece (%)
Gasoline	139 306	2 025 674	6.88
Diesel oil	170 460	2 657 533	6.41
Total	309 766	4 683 207	6.61

Source: www.statistics.gr and personal estimations

Table 3. Annual carbon emissions due to gasoline and diesel oil use in vehicles in Crete (2021)

Fuel	Annual CO_2 emissions ($tnCO_2$/year)	Annual CO_2 emissions per capita ($tnCO_2$/year)
Gasoline [1]	459 710	0.74
Diesel oil [2]	545 472	0.87
Total	1 005 182	1.61

Source: *www.statistics.gr* and personal estimations, [1]CO_2 emissions from gasoline = 3.3 $kgCO_2$/kg, [2]CO_2 emissions from diesel oil = 3.2 $kgCO_2$/kg

4. Required Low- or Zero-carbon Fuels for De-carbonizing Vehicles' Transportation in Crete

De-carbonization in vehicles' transportation in Crete can be achieved using conventional vehicles equipped with internal combustion engines fuelled by bio-fuels or by other carbon-free liquid or gaseous fuels. It can be also achieved with EVs equipped either with re-chargeable batteries or with fuel cells. BEVs should use green electricity generated from solar or wind energy in Crete. FCEVs should use H_2 produced locally by water electrolysis using green electricity generated from solar or/and wind energy. The generation of green electricity is going to increase substantially in Crete after the finalization of the grid interconnection with continental Greece in the next 1-2 years. The generated green electricity can re-charge the batteries of the BEVs and used in water electrolysis producing green H_2. Use of BEVs in Crete requires new infrastructure concerning the creation of many re-charging stations which are gradually developing in the island. Use of FCEVs requires the development of new infrastructure including H_2 storage, transportation and fuelling stations which does not exist in Crete. According to the *Greek National Plan of Climate and Energy (2023)* the share of new BEVs and PHEVs vehicles in 2022 in Greece was corresponding at 5.4% of the total new passengers' vehicles in the country. The forecast regarding the share of BEVs and FCEVs in new passengers' cars in Greece is presented in table 4. According to the *Greek National Plan of Climate and Energy, 2023*, the installed power of batteries' re-charging stations should be 1.3 KW per BEV and at 0.8 KW per PHEV. Assuming that the one third (1/3) of the existing passengers' vehicles will be BEVs the power of the necessary re-charging stations in Crete should be at 126.5 MW. Assuming also that another one third (1/3) will be PHEVs the power of the necessary re-charging stations in Crete should be at 77.9 MW.

Table 4. Forecast of the share of BEVs and FCEV in new passengers' cars in Greece (2025-2050)

	2025	2030	2035	2040	2045	2050
BEVs (excluding trucks)	6%	33%	78%	75%	79%	83%
FCEVs	0%	0%	7%	31%	27%	23%

Source: Greek National Plan of Climate and Energy (2023)

The forecast for green H_2 production in Greece during the period 2025-2050 is presented in table 5.

Table 5. Forecast for green H_2 production in Greece during 2025-2050

	2025	2030	2035	2040	2045	2050
Green H_2 production (mil. tons)	9	135	522	1 012	1 978	2 300
Water electrolysis capacity (MW)	115	1 739	6 958	13 474	26 352	30 643

Source: Greek National Plan of Climate and Energy (2023)

According to the existing regulations the gasoline and diesel oil which are currently used in vehicles' transportation in Crete contain liquid bio-fuels. Diesel oil contains 7% per volume bio-diesel while gasoline contains 5% per volume bio-ethanol/bio-ether. Bio-diesel is currently produced in 18 factories in Greece while bio-ethanol is imported in the country (*Greek National Plan of Climate and Energy, 2023)*. Increase in the production of liquid bio-fuels in Greece is not desired in order to avoid land conflicts with food and animal feed production.

5. Possibilities of Producing the Necessary Green Fuels for Unconventional Vehicles in Crete

5.1 Generation of Electricity from Renewable Energies 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. The installed power of various renewable energy systems and the energy generation in Crete are presented in table 6. Since the electric grid of Crete is autonomous there are technical constraints, related to the stability of the grid, which do not allow the installation of many wind farms and solar-PV plants although they are profitable and the interest of the investors is very high. The integration of renewable energies in the electricity system of the island requires the development of energy storage systems including pumped hydro energy storage systems and large-scale electric batteries. The advances in various renewable energy technologies like off-shore wind farms and solar thermal power plants will also allow the development of more benign carbon-free energy generation systems on the island.

Table 6. Green electricity generation in the island of Crete (2018)

Renewable energy	Installed power (MW)	Generated electricity (GWh)	%, of total electricity generation in Crete (3 043 GWh)
Solar energy	95.5	134 808	4.43
Wind energy	200.3	510 059	16.76
Hydropower	0.6	257	0.01
Total	296.4	645 124	21.20

Source: Vourdoubas, 2023

5.2 The Interconnection of the Electric Grid of Crete with the Grid of Continental Greece

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 *(Vourdoubas, 2023)* as follows:

a) A small-scale grid interconnection between the prefecture of Chania and the region of 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) A large-scale grid interconnection between the prefectures of Heraklion and Attica, DC interconnection capability 2 × 350 MW. This project is currently under implementation, and it will be hopefully finalized in the next 1–2 years.

The interconnection of the island's electric grid will allow the installation of more wind farms and solar-PV plants accelerating the green energy transition.

5.3 Use of Green Electricity for Re-charging the Batteries of BEVs

The batteries of BEVs require re-charging which can be achieved either in charging stations installed in several public places or individually in the residential buildings of the vehicles' owners. If carbon-free electricity generated by solar and wind energy in Crete will be used for batteries' re-charging then zero-emissions vehicles' transportation would be achieved in Crete.

5.4 Production of Carbon-free Hydrogen with Water Electrolysis and Green Electricity

Hydrogen which is used in electric vehicles equipped with fuel cells can be produced via water electrolysis, an old and well-known technology co-producing also oxygen. The required electricity can be generated from solar and wind energy without any carbon emissions. Use of solar-PV systems and wind farms generating green electricity to power water electrolysis systems results in the production of green, carbon-free H_2 in Crete. Therefore, the abundant solar and wind energy resources in the island can be used for the production of carbon-free H_2 used in FCEVs.

5.5 Production of Bio-ethanol and Bio-diesel in Crete

Agricultural crops rich in sugars and rapeseed are not currently cultivated in Crete while bio-ethanol and bio-diesel are not produced in the island. Previous studies regarding the use of carob fruit, which is rich in sugars and grows in Crete, for bio-ethanol production have indicated that the process is not economically viable since the annual quantity of carob fruit currently produced in Crete is very low *(Vourdoubas, 2002)*. Production of bio-diesel from fried vegetable oils in Crete has been also investigated *(Vourdoubas, 2002)*. Although tourism industry is growing rapidly in the island the quantities of fried vegetable oils produced in hotel restaurants are low and they do not justify their processing in large plants for bio-diesel production. Currently, fried vegetable oils produced in Crete are collected, transported and used in plants operating in continental Greece for bio-diesel production. Taking into account the extensive cultivation of olive tree in the island production of second-generation bio-fuels based on olive-tree by-products and residues could be a viable option for bio-fuels production in the future.

6. The Cost of Green Energy Transition in the Transportation Sector in Crete

The green energy transition of the transportation sector in Crete has positive and negative economic impacts. The oil-based fuels used in conventional vehicles will be reduced or completely eliminated while new electric vehicles will be bought. The investments in green electricity generation from RES and in green electrolytic H_2 production in Crete will be increased. Additionally, new investments will be realized in the creation of the necessary infrastructure related with the development of batteries re-charging stations and in H_2 storage, transport and fuelling stations. The high governmental revenues due to taxes imposed on oil-based fuels used in vehicles will be decreased while the imports of oil in Greece will be also decreased. The investments in green electricity generation, in green H_2 production as well as in the necessary infrastructure for re-charging stations of BEVs and refuelling FCEVs with H_2 will be realized from private investors. However, the government should support financially the low- and middle-income households to purchase electric vehicles while it should find other ways to replace the significant reduction of revenues related with the taxes of oil-based transport fuels. Conclusively, the green energy transition of vehicles' transportation in Crete requires new private investments in various sectors and higher spending of households for purchasing new electric vehicles. Additionally, the state revenues due to transportation fuels taxes will be reduced while the expenses related to subsidies in households for purchasing new electric vehicles' will be increased. The impacts of the green transition of vehicles transportation in Crete on several stakeholders are summarized in table 7.

Table 7. Impacts of the green transition of vehicles transportation in Crete on several stakeholders

Stakeholder	Impacts
State	Reduction of the revenues related with taxes in oil-based vehicles fuels, increase of the expenses related with subsidies for purchasing electric vehicles, reduction of expenses for oil imports
Investors	Opportunities for investing in solar-PV systems and in wind farms in Crete, opportunities for investing in green hydrolytic H_2 production, opportunities for investing in batteries re-charging stations, opportunities for investing in H_2 storage, transport and vehicles fueling stations
Citizens	Increasing expenses for purchasing electric vehicles equipped either with re-chargeable batteries of with fuel cells
Environment	Reduced GHG emissions, reduction of emissions of various pollutants from conventional fuels used in vehicles' transportation

Source: Own estimations

7. Advantages and Drawbacks of Unconventional Vehicles and Fuels Which can be Used in Crete

The unconventional vehicles using electricity, hydrogen, bio-ethanol and bio-diesel have several advantages and disadvantages compared to conventional vehicles using oil-based fuels. The advantages and drawbacks of BEVs, FCEVs and vehicles with ICEs using bio-fuels are presented in table 8.

Table 8. Advantages and drawbacks of unconventional vehicles and fuels

Type of vehicle	Type of fuel	Advantages	Drawbacks
Battery electric vehicle	Electricity	Battery re-charging can be achieved with carbon-free electricity generated in Crete Powerful and energy efficient Reduced maintenance expenses No tailpipe emissions, Smooth and silent driving	Demand for rare metals Recharging batteries takes long Lack of public charging facilities Not suitable for long-distance travel High cost of purchase Higher toxicity level to humans due to metal use Limited milage autonomy
Fuel cell electric vehicle	Hydrogen	H_2 can be produced from RES by water electrolysis in Crete Highly efficient No tailpipe emissions Reduced refueling time Smooth and silent driving Higher milage autonomy compared to BEVs	Higher cost of raw materials Requires H_2 production High cost of H_2 production Lack of H_2 refueling infrastructure Highly flammable High cost of purchase
Vehicle with ICE using bio-fuels	Bio-ethanol or bio-diesel	There is no need for purchasing new vehicles The infrastructure for vehicles' refueling exists Good fuel combustion They can reduce carbon emissions until the mass use of EVs	Tailpipe emissions There are limitations in biofuels production Bio-fuels are not produced in Crete Lower heating value

Source: Sacid Endiz, 2023, Own estimations

8. Discussion

The results indicate that low- and zero-carbon fuels can be used in de-carbonizing vehicles' transportation in Crete including electricity, H_2 and bio-fuels. They also analyse the cost dimension of the green transition as well as the advantages and drawbacks of different types of vehicles and fuels that can be used for that. It is indicated that the green energy transition will have negative impacts on state revenues and expenses while it is going to create opportunities for the creation of new infrastructure and for green energy investments. Use of electricity generated by RES in Crete for battery's re-charging in BEVs can eliminate all the emissions in these vehicles while the use of electrolytic H_2 produced by RES can eliminate all the emissions in FCEVs. Use of bio-ethanol and bio-diesel in vehicles equipped with ICEs can partly eliminate their carbon emissions. Our results indicate that the green energy transition in vehicles transportation in Crete is technically feasible while it is facilitated from the rich solar and energy resources in the island. They also indicate that the net-zero emission target in vehicles transportation in Crete by 2050 can be achieved with the existing technologies regarding unconventional vehicles and fuels. Although the feasibility of the green energy transition is adequately supported in the current study the temporal dimension for this achievement and the required cost have not been analysed and discussed. Types of unconventional vehicles with low or zero emissions such as PHEVs and FCHEVs have not analysed. Future work should be focused on a study regarding the development of a time plan for the green energy transition in vehicles transportation in Crete during the period 2025-2050 estimating the required financial resources for purchasing new unconventional vehicles and the creation of new infrastructure supporting their use.

9. Conclusions

The possibility of de-carbonizing the vehicles transportation in the island of Crete, Greece has been investigated. The replacement of conventional vehicles fuelled by oil-based fuels with unconventional vehicles and alternative fuels has been examined. Electric vehicles equipped either with re-chargeable batteries or with fuel cells can replace conventional vehicles in Crete. BEVs can use green electricity generated by RES in Crete for re-charging their batteries. The abundant solar and energy resources in the island can generate low-cost carbon-free electricity. Green electricity can also generate green electrolytic H_2 which can fuel FCEVs. The use of electricity generated by RES in Crete for re-charging electric batteries and producing carbon-free hydrogen for FCEVs can eliminate all the carbon emissions in vehicles transportation. Additionally, the use of bio-ethanol and bio-diesel in conventional vehicles equipped with ICEs can significantly reduce their carbon emissions. The green transition in vehicles transportation in Crete has several positive and negative economic impacts to all stakeholders. The use of the abovementioned types of unconventional vehicles and fuels has several advantages and disadvantages regarding their purchasing and maintenance cost, the required infrastructure, the environmental impacts, the driving autonomy of the vehicles et cetera. The results could be useful to public authorities, energy companies and to all stakeholders while they can facilitate the planning for the elimination of carbon emissions by 2050 in Crete.

Competing interests

There are no competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Informed consent

Obtained.

Ethics approval

The Publication Ethics Committee of the Macrothink Institute.

The journal's policies adhere to the Core Practices established by the Committee on Publication Ethics (COPE).

Provenance and peer review

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Data sharing statement

No additional data are available.

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