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Renewable Energies Use for Hydrogen Production Powering Fuel Cell Vehicles in the Island of Crete, Greece

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Abstract

The possibility of using indigenous renewable energies for electrolytic hydrogen production in Crete has been investigated. Hydrogen can be used for de-carbonization of the transportation sector in the island replacing all existing conventional vehicles with fuel cell electric vehicles. The required H_2 has been estimated as well as the electricity needed for its production via water electrolysis. Solar and wind energy is currently used for electricity generation with solar-PV systems and wind farms in Crete generating a significant amount of the island's electricity consumption. The size and the cost of the solar-PV systems and the wind farms required for electricity generation, needed in electrolytic H_2 production, have been estimated. The hydrogen required for powering all fuel cell vehicles in Crete has been estimated at 53,037 tonsH_2/year and the electricity required for its electrolytic production at 3,826,563 MWh. The size of the solar-PV systems generating the electricity required in water electrolysis is estimated at 2,710 MW_p while their cost at bil. \$ 3.25. The size of the wind farms generating the electricity required in water electrolysis is estimated at 1,501 MW_{el} while their cost at bil.\$ 1.50. It is concluded that local renewable energies can be used for electrolytic H_2 production in Crete although their installation cost is high. The results can be used for the creation of a roadmap regarding the de-carbonization of the island's transportation sector.

Keywords: Crete-Greece; electric vehicles; electrolytic hydrogen; fuel cell; solar energy; wind energy.

1. Introduction

The urgent necessity to cope with climate change requires the transition from the "fossil fuels economy" to "zero carbon emissions economy" replacing fossil fuels with renewable energies (REs) and other zero carbon emissions energy sources.

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Hydrogen (H_2) is an energy carrier which is going to play an important role in the new era. European Union has decided to become "climate neutral" by 2050. Achievement of this goal requires the radical transformation of our current energy system which is mainly based on fossil fuels. H_2 can be produced with different technologies including water electrolysis using electricity generated from various renewable energy sources (RES). This technology route has the advantage of "green H_2" production without any carbon emissions. However the technology has not been commercialized so far since H_2 production from thermal processing of natural gas is cheaper than its production via water electrolysis. De-carbonization of the transport sector requires the replacement of conventional vehicles having internal combustion engines (ICEs) with electric vehicles using either rechargeable batteries or fuel cells using H_2. Island of Crete, Greece is rich in various REs, particularly in solar and wind energy, which could be used for electrolytic H_2 production. Electricity is currently generated in Crete with solar photovoltaic (solar-PV) systems and wind turbines covering approximately 20% of its annual consumption. De-carbonization of Crete's transportation sector using fuel cell electric vehicles (FCEVs) and H_2, as green fuel, requires the development of the necessary and complex infrastructure for H_2 production, storage, transportation and distribution. Current work is focused in the estimation of the H_2 required for fuelling FCEVs necessary for de-carbonization of the island's transport sector. Additionally the required size and cost of the solar-PV systems and wind farms, generating electricity, necessary for the electrolytic H_2 production are estimated. The results could be used for the development of a road map for Crete's transition to H_2 economy complying with the EU goal to become "Climate neutral" by 2050.

2. Literature review

2.1 Production of H_2 from renewable energies

An overview of technology options for H_2 production has been published [1]. The report mentioned seven promising technology options for H_2 production. These included four thermal processes, one electrolytic process and two photolytic processes. The H_2 production technologies have been overviewed [2]. The authors stated that some H_2 production technologies are commercially available while some others are under development while fossil fuels and non-fossil fuels are used for that. They also mentioned that water electrolysis can be combined with REs to co-produce carbon free H_2 while NH_3 decomposition process is under development and it could be commercialized soon. The current status and future developments in H_2 production technologies have been studied [3]. The authors mentioned that currently the most developed and used technology is hydrocarbon's reforming. They also stated that developments in H_2 production from REs could be commercialized in the future minimizing the environmental impacts during production of H_2. The green methods for H_2 production have been studied [4]. The author stated that energy for green H_2 production can be derived from renewable sources, nuclear energy and waste energy. He also mentioned that H_2 can be extracted from water, hydrogen sulphide, biomass and fossil fuels. The potential for H_2 production from REs and its use in transportation as well as in energy generation has been studied [5]. The author stated that H_2 production methods using REs include biomass-based methods, plasma involving processes and water splitting. She also mentioned that the creation of the required infrastructure for green H_2 storage is important for its future broad scale utilization in energy generation. The possibility of using hybrid wind energy-H_2 systems for consistent green energy generation in Ireland has been investigated [6]. The authors stated that the intermittent nature of wind energy is a drawback in its use for electricity generation. They mentioned that, in Ireland, excess wind electricity could be used for H_2

production. Hydrogen could be stored and used later in fuel cells providing constant electricity supply into the grid. The potential of green H_2 production in Pakistan has been estimated [7]. The authors mentioned that various REs in the country could be used for green H_2 production. They stated that the most promising source is biomass which can produce annually 6.6 mil tons H_2 followed by solar-PVs with 2.8 mil. tons while municipal solid wastes could produce 1 mil. tons H_2 annually. A study on H_2 economy has been reported [8]. The authors stated that H_2, as a clean energy source, can enable a revolution in our energy systems while industry has already started the market introduction of fuel cells. However using electricity generated with H_2 at grid scale requires solution of the problems related with clean H_2 production, bulk storage and its distribution. Production of H_2 from a small-scale solar photovoltaic thermal (solar-PV/T) system has been investigated [9]. The authors compared the H_2 production of a solar-PV/T system with the H_2 production of a conventional solar-PV system estimating that the first produced 4.49 kgH_2 compared with 3.96 kgH_2 of the solar-PV system. They also mentioned that the calculated levelized cost of H_2 production for the solar-PV system was at 4.87 \$/kgH_2 while for the solar-PV/T system was at 5.61 \$/kgH_2. The development of a hybrid solar-PV-battery-H_2 system used in stand-alone micro-grids has been studied [10]. The authors examined three case scenarios using simulation software for a solar energy based micro-grid system. They found out that a hybrid energy system based in H_2 and batteries is a cost-effective solution which could be used in electrifying remote communities. The resources for H_2 production in USA have been assessed [11]. The authors mentioned that the use of domestic low-carbon H_2 in vehicles equipped with fuel cells is a promising technological option for reducing both greenhouse gas (GHG) emissions and reliance on imported oil. They stated that 20 mil. tons H_2 per year are required for fuelling 100 mil. light-duty FCEVs. The authors concluded that the economic wind and solar energy resources in USA can produce more H_2 than the required quantities for fuelling the abovementioned electric vehicles The potential for H_2 production from key RES in U.S has been estimated [12]. The authors mentioned that 1 bil. tons of H_2 could be produced annually from on-shore wind energy, solar-PV and biomass in USA. The production of H_2 from renewable resources using biological methods has been estimated [13]. The authors mentioned that biological production of H_2 can be achieved with microbial processing of various biomass resources. They stated that biological H_2 production processes have diverse efficiencies while the efficiency of dark fermentation of biomass varies between 60-80% which is comparable with the efficiency of conventional H_2 production from fossil fuels. An analysis of H_2 production from RES has been published [14]. The authors stated that ample resources exist to produce transportation fuel from wind and solar power. However, they stated, in order to produce H_2 at $ 2/kg using electrolyzers the electricity prices would have to be less than $ 0.01/KWh. They concluded that various challenges should be overcome for H_2 production from solar and wind energy in a cost-effective way. The potential of renewable hydrogen production in Hong Kong has been estimated [15]. The authors stated that although renewable energy resources cannot entirely satisfy the energy demand in Hong Kong, solar energy, wind energy and biomass are available for significant H_2 production. They also mentioned that H_2 production from RES could cover up to 40% of Hong Kong’s energy consumption in transportation. The potential of Venezuela for H_2 production with “renewable” electricity has been estimated [16]. The authors stated that solar, wind and mini-hydro electricity could be used in the country for H_2 production with water electrolysis. They estimated that the total annual production could reach at $2.073X10^{10}$ kgH_2 using 95% solar-PV electricity while this quantity could cover all the annual demand in rural areas lacking electric grids. It could be also used as feedstock in industrial processes in Venezuela The potential of electrolytic H_2 production from

REs in Ecuador has been calculated [17]. The authors stated that solar-PV energy, wind energy, geothermal and hydro energy have been considered for electricity generation while annual H_2 production could reach $4.55X10^8$ kgH_2. H_2 produced could cover a significant amount of vehicle's transportation, replacing gasoline and diesel oil, as well as the needs of rural communities for cooking replacing fire wood. A study on hydrogen production from renewable resources in EU has been published [18]. The study has evaluated eleven (11) green H_2 production pathways different than water electrolysis. The eleven technologies have been benchmarked using various criteria and performance indicators including H_2 production cost of water electrolysis (4-6 €/kgH_2) and steam methane reforming (3-5 €/kgH_2). The study has selected six (6) promising green H_2 production pathways including a) Biomass pyrolysis and gasification, b) Raw biomass reforming, c) Thermo-chemical water splitting, d) Photo-catalysis, e) Fermentation combined with raw biogas reforming, and f) Supercritical water gasification of biomass. The potential for H_2 production from REs in Algeria has been calculated [19]. The authors have considered solar-PV and wind energy for electricity generation and electrolytic H_2 production in various regions of the country. They stated that annual solar-PV-H_2 production could reach at $2.4X10^5$ $tonsH_2/Km^2$ while wind-H_2 could reach at $2.1X10^5$ $tonsH_2/Km^2$. A strategic agenda for European research and innovation in H_2 has been published [20].The report stated that mature and developing EU H_2 technologies could help in achieving a sustainable and de-carbonized energy system. It also mentioned that currently H_2 is produced worldwide by fossil fuels while water electrolysis is a key technology for green H_2 production using RE technologies. The GHG emissions reduction using solar and wind energy for H_2 production have been estimated [21]. The authors stated that using solar and wind energy for electricity generation is less costly for GHG emissions mitigation than using them for H_2 production. They also mentioned that the use of "renewable H_2" as vehicle's fuel is economically effective regarding GHG emissions only if the efficiency of FCEVs is more than two times higher than that of vehicles with ICEs. The environmental and economic aspects of various H_2 production methods have been studied [22]. The authors stated that carbon emissions during H_2 production from fossil fuels vary between 7.33 to 29.33 $kgCO_2$ per kgH_2 produced. They also mentioned that utilization of off-peak power for H_2 production would result in economic benefits while hydro and wind electricity are more favorable for H_2 production via electrolysis. Prediction of collapse of fossil fuels civilization by 2028 has been made [23]. The author urges that the transition from fossil fuels to REs is urgent and feasible. Implementation of this transition requires, among other changes, the replacement of conventional vehicles using internal combustion engines with electric vehicles using either rechargeable batteries or fuel cells powered by H_2. An investigation of hydrogen economy has been published [24]. The author stated that H_2 is going to be the fuel of the future replacing the polluting fossil fuels. He mentioned that carbon-free H_2 can be generated from water with solar and wind electricity creating a global non-polluting H_2 web. The alkaline water electrolysis process using renewable energies has been reviewed [25]. The authors stated that water electrolysis is a key technology for large scale H_2 production using REs. They mentioned that while solar-PV panels can be directly coupled with alkaline water electrolyzers wind turbines require the use of suitable converters.

2.2 H_2 and Fuel cells

A report on H_2 energy and fuel cells has been published [26]. The report stated that H_2 and fuel cells are strategic technologies for increasing energy security, mitigating climate change and improving air-quality. Europe must increase its efforts to promote and commercialize these technologies since the competition from

North America and Asian countries is currently strong. A study on the role of H_2 and fuel cells in the creation of energy communities has been made [27]. The authors stated that H_2 could play an important role as transportation fuel as well as for storing energy in 100% renewable energy communities. REs could provide clean electricity for water electrolysis and production of a clean energy carrier like H_2, used in energy generation. The performance of battery and fuel cell electric vehicles in China has been compared [28]. The comparison included fossil energy use, total energy use as well as GHG emissions. The authors found out that FCEVs using natural gas as energy source had better performance than battery electric vehicles (BEVs) in terms of energy use and GHG emissions The fuel cell vehicle development in China has been investigated [29]. The authors stated that although in the past decade China has made great progress in the H_2 and fuel cell industry there are still some technological and cost challenges hindering the commercialization of FCEVs. They mentioned that production of FCEVs requires the establishment of a flourishing H_2 industry as well as the reduction of the capital and operating cost of these vehicles. The scientific and technological knowledge of FCEVs has been studied [30]. The authors have researched the literature during the last twenty years regarding scientific and technological development in FCEVs. They found out that USA is most productive in patent jurisdiction, China in science development while Japan in technological development. They also mentioned that science is currently directed towards H_2 production and storage. The current status and future prospects of FCEVs have been studied [31]. The authors stated that FCEVs have significant advantages over BEVs while H_2 fuel cells will play an important role in transportation industry in the near future. They also mentioned that the prices of fuel cells will be reduced after their mass production and commercialization. The durability and fuel cell performance of FCEVs for assessing their commercial readiness have been studied [32]. The authors have evaluated 230 vehicles for a long time. They found out that fuel cells at 25% rated power have achieved 57% efficiency which is below the target at 65%. They also mentioned that fuel cell stacks have exceeded the time target at 5,000 hours of operation. However they have been degraded at 10% after 2,000-3,000 hours of operation.

2.3 Use of renewable energies in Crete

The electrification of the transport sector in the island of Crete, Greece has been investigated [33]. The author stated that REs like solar and wind energy could be used for electricity generation necessary for re-charging the batteries of all BEVs replacing conventional vehicles in Crete. He estimated that the required size of solar-PV plants for re-charging the batteries of all BEVs in the island should be between 728 MW_p to 874 MW_p while the size of wind turbines between 445 MW_{el} to 534 MW_{el} respectively. The autonomous electric power system in Crete has been reviewed [34]. The author stated that large scale introduction of RE technologies in the power system of Crete should be based in a different energy policy than the currently adopted. A report on electricity generation and consumption in Crete has been published by DEDDIE [35]. The report stated that during 2018 the total electricity generation in the island was at 3,043 GWh while 257 MWh were generated by small hydroelectric systems, 135 GWh from solar-PV systems and 510 GWh from wind parks. The installed power of small hydro systems was at 0.6 MW, of wind parks at 200.3 MW and of solar-PV systems at 95.5 MW. A report on islands as test beds for innovative energy solutions has been published [36]. The report mentioned that the island's transition to a low carbon economy is not only possible but also desirable. It will offer many opportunities for sustainable development in island's communities. The total number of vehicles in Crete as well as the annual consumption of transportation fuels, including gasoline and diesel oil, in the island has been recorded [37]. Current use of REs for energy generation in rural areas in Crete has been studied [38]. The author stated that solar-PV and wind energy systems are broadly used for power generation in the island. Additionally small hydro and biogas plants generate small amounts of electricity so far. He also mentioned that the future interconnection of the electric grid of Crete with the country's continental grid will take-off the electricity generation from REs in the island.

Aims of the current work are:

a) *The investigation of using solar and wind electricity for H_2 production with water electrolysis in Crete,*
b) *The estimation of H_2 quantities required for powering all vehicles in Crete assuming that the existing conventional vehicles with ICEs will be replaced with FCEVs, and*
c) *The estimation of the size and the cost of solar-PV and wind energy systems required to produce electricity for electrolytic H_2 production for fuelling all FCEVs in Crete.*

After the literature review the current use of solar and wind energy for electricity generation in Crete is presented while the number of existing conventional vehicles and the transportation fuels consumed are stated. Next the technology of H_2 production with water electrolysis using green electricity is mentioned followed by an estimation of the H_2 required for powering all FCEVs in Crete replacing existing conventional vehicles. In the following sections the electricity needs for producing the required H_2 are estimated as well as the size and the cost of the solar-PV systems and wind farms generating the required electricity for electrolytic H_2 production in the island. Finally discussion of the findings and the conclusions drawn are presented closing with proposals for future research. Limitations in current research are related with: a) The fact that most probably electric vehicles with rechargeable batteries will co-exist in the future in Crete with electric vehicles equipped with fuel cells using H_2, b) The uncertainty regarding achievement of the required reduction in the cost of H_2 production, storage and distribution in the future in order to be competitive with other zero carbon emissions vehicle fuels, and c) The assumptions made regarding transportation with various types of vehicles in the future in the island.

3. Use of solar and wind energy for electricity generation in Crete

Island of Crete has abundant solar and wind energy resources and it is considered as a privileged region for application of RES. Solar energy is currently used for heat and electricity generation while wind energy for electricity generation. Electricity generation from solar and wind energy in Crete is currently profitable and there is a high interest for additional investments in solar and wind electricity generation systems. The electric grid in the island is currently autonomous and this fact restricts the higher use of local REs for electricity generation. However its future interconnection with the Greek continental grid is expected to take-off the investments in solar and wind electricity generation systems in Crete. The installed power and the generated electricity of the solar-PV systems and wind parks in the island are presented in table 1 together with the annual productivity of the solar-PV systems and the capacity factor of the operating wind parks. Current solar and wind electricity generation in Crete corresponds approximately at 20% of its annual electricity generation which was at 3,043 GWh in 2018.

Table 1: Installed capacity and electricity generation from solar-PV systems and wind parks in Crete (2018)

Energy source/Technology	Installed capacity	Annual generated electricity (MWh)	Annual productivity/capacity factor
Solar photovoltaic	95.5 MW_p	134,808	Annual productivity=1,412 MWh/MW_p
Wind parks	200.3 MW_{el}	510,059	Capacity factor = 0.291
Total	-	644,867	-

Source: HEDNO, 2018, Own estimations

4. Existing vehicles with ICEs in Crete

The vehicles which are currently used in Crete are equipped with ICEs while the number of electric cars using re-chargeable batteries is negligible. Small is also the number of vehicles using either gaseous fossil fuels like natural gas and LPG or biological fuels like bio-ethanol and bio-diesel. The number of existing vehicles in the island, in 2019, is presented in table 2.

Table 2: Vehicles in Crete (2019)

Type of vehicle	Number
Cars	280,280
Tractors	132,884
Buses	1,163
Motorcycles	134,991

Source: www.statistics.gr

5. Consumption of transportation fuels in Crete

Conventional vehicles equipped with ICEs in Crete are using fossil fuels including gasoline and diesel oil. The annual consumption of vehicle's fuels in the island during 2019 is presented in table 3.

Table 3: Consumption of vehicle's fuels in Crete (2019)

Fuel	Annual consumption (tones)
Gasoline	157,477
Diesel oil	215,420
Total	372,897

Source: www.statistics.gr

6. Hydrogen production with water electrolysis and green electricity

Hydrogen can be produced with various thermo-chemical, bio-chemical and electro-chemical methods. Currently it is mainly produced from thermo-chemical processing of natural gas with high efficiency and low cost. However this technology route implies carbon emissions during H_2 production. Electrolysis of water using electricity is an old and well known technology which produces H_2 with higher cost. However the electricity required in water electrolysis could be generated from REs like solar, wind or hydro energy. In this case H_2 production is not related with atmospheric carbon emissions. A lot of research is currently carried out worldwide for achieving H_2 production from water electrolysis with competitive cost. Low cost H_2 production through a sustainable technology route, avoiding carbon emissions, will allow its mass use as a green transportation fuel in FCEVs replacing conventional vehicles using ICEs and fossil fuels. Low cost green H_2 could be also used in many other applications including electricity and heat generation. It could be also used for bulk electricity storage. Developing commercial processes of green H_2 production with affordable cost would be a necessary step in moving to H_2 economy which is necessary for reducing carbon emissions into the atmosphere and mitigating climate change. The efficiency and maturity of various H_2 production processes is presented in table 4.

Table 4: Efficiency of various hydrogen production processes

Production method	Raw material	Efficiency (%)	Process maturity
Steam reforming	Natural gas	70-85	Commercial
Partial oxidation	Natural gas	60-75	Commercial
Dark fermentation	Biomass	60-80	Non-commercial
Biomass gasification	Biomass	35-50	Commercial
Alkaline electrolysis	Water	50-60	Commercial
PEM electrolysis	Water	55-70	Non-commercial
Solid oxide electrolysis	Water	40-60	Non-commercial

Source: Kalamaras and his colleagues 2013, El-Shafie and his colleagues 2019

7. Estimation of H_2 required for powering all FCEVs in Crete

De-carbonization of the transport sector in Crete requires the replacement of all existing vehicles with ICEs using fossil fuels with either BEVs or FCEVs. In order to estimate the H_2 required annually for powering the FCEVs in Crete the following assumptions have been made:

a) All types of existing conventional vehicles in Crete using liquid fossil fuels will be replaced by FCEVs,
b) Electric vehicles will cover annually the same distance like the existing conventional vehicles,
c) Efficiencies of vehicles with ICEs and FCEVs will be the same as in table 5,
d) The energy content of vehicle's fuels is the same as in table 6.

The energy content of gasoline used in 2018 has been estimated at 1,999,958 MWh while of diesel oil at 2,778,918 MWh, totally at 4,778,876 MWh. The annual required H_2 for powering the FCEVs, replacing existing vehicles in Crete with ICEs using gasoline, has been estimated at 22,196 tonsH_2/year and its energy content at 739,115 MWh/year. The required H_2 for powering the FCEVs, replacing existing vehicles in Crete with ICEs using diesel oil, has been estimated at 30,841 tonsH_2/year and its energy content at 1,026,991 MWh/year. The total H_2 required, for powering all FCEVs in Crete, has been estimated at 53,037 tonsH_2/year and its energy content at 1,766,106 MWh/year. The tank to wheel efficiencies of conventional and electric vehicles are presented in table 5 while the energy content of various vehicle fuels in table 6.

Table 5: Tank to wheel efficiencies

Type of vehicle	Fuel used	Efficiency (%)
Conventional vehicle with internal combustion engine	Diesel or gasoline	17
Electric vehicle with rechargeable battery	Electricity	73
Electric vehicle with fuel cell	Hydrogen	46

Source: Li and his colleagues 2016 [27]

Table 6: Energy content of vehicle's fuels

Fuel	Type of vehicle using the fuel	Energy content (KWh/kg)
Hydrogen	Electric vehicle with fuel cell	33.3
Diesel oil	Conventional vehicle with ICE	12.9
Gasoline	Conventional vehicle with ICE	12.7

Source: El-Shafie and his colleagues 2019

The quantity and the energy content of H_2 required for powering FCEVs replacing conventional vehicles using gasoline in Crete are presented in table 7 as well as the quantity and the energy content of H_2 required for powering FCEVs replacing conventional vehicles using diesel oil.

Table 7: Quantity and energy content of H_2 required for powering FCEVs in Crete.

	Quantity of H_2 required	Energy content of H_2 required
FCEVs replacing conventional vehicles using gasoline	22,196 tonsH_2/year	739,115 MWh/year
FCEVs replacing conventional vehicles using diesel oil	30,841 tonsH_2/year	1,026,991 MWh/year
Total	53,037 tonsH_2/year	1,766,106 MWh/year

Source: Own estimations

8. Estimation of electricity requirements for electrolytic H_2 production and its liquefaction

Water electrolysis produces gaseous H_2 which needs liquefaction in order to be used in the tanks of FCEVs. In order to estimate the electricity requirements for H_2 production via alkaline water electrolysis as well as its needs for liquefaction the following assumptions have been made:

a) The energy efficiency of water electrolysis is 60% (table 4). The electricity requirements for producing via water electrolysis the necessary gaseous H_2 are estimated at 2,943,510 MWh, and
b) The energy requirements for producing the liquid H_2 used in FCEVs in Crete correspond approximately at 30% of its energy content and they are estimated at 883,053 MWh.

Therefore the total electricity requirements for producing the necessary electrolytic gaseous H_2 and liquidizing it are 3,473,363 MWh. The energy requirements for H_2 production in Crete are presented in table 8.

Table 8: Annual energy requirements for H_2 production in Crete

Process	Annual energy requirements (MWh)
Energy content of electrolytic H_2	1,766,106
Water electrolysis	2,943,510
H_2 liquefaction	883,053
Total electricity required in water electrolysis and H_2 liquefaction	3,826,563

Source: Own estimations

9. Estimation of the size and the cost of the solar-PV systems and wind turbines generating all the electricity required for the electrolytic H_2 production fuelling FCEVs in Crete

Electricity required in electrolytic H_2 production and its liquefaction can be generated in Crete with solar-PV systems and wind farms. In order to size the solar-PV systems and the wind farms necessary to produce all the H_2 required for fuelling the FCEVs in Crete the data of table 1 regarding the annual productivity of solar-PV systems and the capacity factor of wind farms in Crete are used. The nominal power of solar-PV systems is estimated at 2,710 MW_p while the electric power of wind farms is estimated at 1,501 MW_{el}. Assuming that the installation cost of solar-PV systems is at 1,200 €/KW_p the total installation cost of the required solar-PV systems is 3.25 bil. €. Assuming that the installation cost of wind farms is 1,000 €/KW_{el} the total installation cost of the required wind farms is 1.50 bil. €. The size and the cost of the renewable energy systems generating the required green electricity for the electrolytic H_2 production in Crete is presented are table 9.

Table 9: Size and installation cost of the solar and wind energy systems generating annually the required green electricity for electrolytic H_2 production.

	Solar-PV system	Wind farm
Annual electricity generation	3,826,563 MWh	3,826,563 MWh
Annual productivity of the solar-PV system/Capacity factor of wind farms	Annual productivity=1,412 MWh/MW_p	Capacity factor = 0.291
Size	2,710 MW_p	1,501 MW_{el}
Unit cost	1,200 €/KW_p	1,000 €/KW_{el}
Total installation cost	3.25 bil. €	1.50 bil. €

Source: Own estimations

10. Discussion

De-carbonization in the transportation sector in Crete can be achieved using instead of conventional vehicles: a) electric vehicles equipped with fuel cells using H_2, b) electric vehicles using rechargeable batteries and c) conventional vehicles with ICEs using bio-fuels including bio-ethanol and biodiesel. Bio-ethanol and bio-diesel are not currently produced in Crete and their broad use in Crete in the future is not foreseen. Use of electric vehicles with rechargeable batteries is currently promoted by the government offering financial subsidies to potential consumers. These types of electric vehicles are considered as the cost optimal solution for zero carbon transportation in the island. An advantage regarding their promotion consists of the fact that users can recharge the electric batteries of their vehicles at their homes using grid or solar electricity. Apart from electrolytic H_2 production in Crete other zero/low carbon emissions production methods have not been investigated so far. Various parameters regarding the de-carbonization of the transportation sector in Crete using FCEVs instead of the currently used conventional vehicles with ICEs have been estimated. These include the H_2 required for powering the FCEVs, the electricity needed for its electrolytic production, the required size of the solar-PV systems and the wind farms for generating the required electricity in electrolysis as well as the cost of the RE systems. The results indicate that "green H_2" production is technically feasible in Crete due to abundant solar and wind energy resources in the island. Renewable energies are the only "green energy resources" available for H_2 production since there are not any nuclear energy and waste energy resources. Estimations are useful in assessing the feasibility of island's transition, during the next decades, to climate neutral economy as well as for the creation of a roadmap for that. They could be used by Regional and National policy makers in their planning to comply with the current EU policy and targets regarding mitigation of climate change. Our results do not indicate the economic feasibility of the transition of Crete's transportation sector to H_2-based economy neither the necessary infrastructure needed for the transition. The infrastructure includes the production, storage, transportation and distribution of H_2 which requires new investments. There are though various technical and economic problems related with de-carbonization of the transport sector in Crete. These include: a) The high cost of FCEVs, b) The high cost of electrolytic H_2 production compared to its production with hydrocarbon's reforming, c) The high cost for creating the necessary infrastructure for broad H_2 utilization in Crete, and d) The technical problems and the necessary costly investments related with H_2 storage, transportation and distribution in vehicle's filling stations.

11. Conclusions

Hydrogen is a clean energy carrier which is expected to play an important role in the new carbon-neutral economy following the fossil fuels era. It can be produced with various methods including thermo-chemical, bio-chemical and electro-chemical processes. Hydrocarbon's reforming is currently the most commonly used and cheapest method for H_2 production. Water electrolysis is an old and well known technology producing H_2 with higher cost than hydrocarbon's reforming. However H_2 production via water electrolysis requires electricity which can be generated by REs. This technology route produces free-carbon "green H_2" which is highly desirable. Current work is focused in de-carbonization of the transportation sector in Crete. This can be achieved with replacement of all existing vehicles equipped with ICEs with FCEVs powered with green electrolytic H_2. Our results indicate that solar and wind energy resources in Crete can be used for green electricity generation and electrolytic H_2 production. Solar-PV systems and wind farms already generate a significant amount of electricity consumption in the island. The required H_2 for powering FCEVs replacing all existing vehicles using gasoline has been estimated at 22,196 tons H_2/year while the H_2 for replacement of all vehicles using diesel oil is estimated at 30,841 tons H_2/year. The total amount of H_2 is estimated at 53,037 tons H_2/year while its energy content at 1,766,106 MWh. The electricity needed for electrolytic H_2 production is estimated at 3,826,563 MWh/year. The size of the solar-PV plants generating the electricity used in hydrolytic H_2 production is estimated at 2,710 MW_p and their cost at 3.25 bil. €. The size of the wind farms generating the electricity used in hydrolytic H_2 production is estimated at 1,501 MW_{el} and their cost at 1.50 bil. €. The estimated size of the solar-PV systems are approximately twenty eight (28) times higher than the existing solar-PV installations in the island while the size of wind farms seven and half (7.5) times higher than the current installations. The cost of the required wind energy systems is approximately half than the cost of the required solar-PV systems. The estimated size of the solar-PV plants and wind farms generating the necessary electricity for green H_2 production in Crete is approximately three (3) times higher than the corresponding size of the same solar and wind energy plants generating the necessary electricity for recharging the batteries of BEVs replacing conventional vehicles in Crete (Vourdoubas, 2018). The results indicate the amount of the required H_2 for powering all FCEVs in Crete and the electricity requirements for its electrolytic production. Additionally the size and the cost of the required solar-PV systems and wind farms generating the electricity needed in hydrolytic H_2 production used in FCEVs for de-carbonization of the transportation sector in Crete. The results could be useful for the creation of a roadmap for de-carbonization of the energy sector in the island complying with the EU requirements for a climate neutral continent by 2050.

12. Recommendations

Further research should be focused in sizing of the required installations as well as their cost regarding the necessary infrastructure for electrolytic H_2 production, storage, transportation and distribution in Crete. For achieving island's carbon neutrality in the next 30 years electrification of the transport sector is required. Multicriteria analysis between electric vehicles using rechargeable batteries and fuel cells is necessary. Production of H_2 with other low/zero carbon emissions methods in parallel with water electrolysis in Crete should be investigated. Additionally the investigation of using H_2 for energy production in other sectors in Crete is also required for achieving the target of carbon neutral Europe by 2050.

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