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The role of green hydrogen in Cyprus's future energy mix

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Signed: Georgios Yiasoumas Date: 17 August 2021

Abstract

After the Paris Agreement in 2015 the European Union (EU) set its first emission target; to reduce its carbon emissions until 2020 by 20% in comparison to 2005. As a member of the EU, Cyprus failed to meet its goal for 2020 of reducing its emissions by 5%, despite surpassing the set goal for the share of renewable energy in the gross final energy consumption [1]. This is happening because Cyprus is isolated in terms of interconnections, and the small size of its grid cannot support the penetration of a large number of renewable energy systems (RES); mainly because it can cause technical and safety issues. In addition, Cyprus is heavily depended on imported fossil fuels as a primary energy source for electricity production and transport; as a result, approximately 70% of Cyprus's carbon emissions are related to transport and electricity production [2]. The aim of this dissertation is to investigate the role of hydrogen as part of future decarbonisation strategy by estimating the potential demand for hydrogen in Cyprus and determining the feasibility of producing this hydrogen from RES. Four different initial proposals were formed from the transport and electricity production sector based on future projections for the EU. Using an optimization software for energy systems, Homer Pro, an energy system was modelled in order to satisfy each proposal with different scenarios for renewable energy production. For the first scenario, it was determined that the RES used for the production of green hydrogen is solar energy, the primary RES in Cyprus. The second scenario suggests the production of green hydrogen from offshore wind energy, an energy source that is not yet implemented in Cyprus but shows great potential in other countries. The final scenario investigates the combination of solar and wind power for green hydrogen production. The process was repeated for 3 different time periods 2021, 2030 and 2050. Finally, a comparison between the different scenarios and time periods was carried out based on capital expenses, land requirements, profitability and needed RES capacity in order to determine the feasibility of each proposal and suggest changes.

Acknowledgements

I would like to take this opportunity to thank my supervisor, Dr William Dempster, for his guidance and feedback during the stages of this dissertation and the freedom he provided to form the theme of this dissertation around my interests.

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Nomenclature

Symbol	**Description**
RES	Renewable Energy Sources
EU	European Union
CAPEX	Capital Expense
OPEX	Operating Expense
GHG	Greenhouse Gas
NECP	National Energy Climate Plan
CERA	Cyprus Energy Regulatory Authority
IEA	International Energy Agency
CHIC	Clean Hydrogen in European Cities
TSOC	Transfer System Operator of Cyprus
GHI	Global Horizontal Irradiation
CHC	Carbon Capture and Storage
CEA	Cyprus's Electricity Authority

1.0 Introduction

The realization of climate change worldwide has forced countries to create strategies with the aim to reduce and eventually eliminate Greenhouse Gas (GHG) emissions. The need for these efforts to be global and to ensure that they will succeed has resulted in a number of international agreements starting from the Kyoto Agreement in 1997, with the latest being the Paris Agreement in 2015. Being collectively one of the largest polluters in the world with 22% of the total GHG produced worldwide the involvement of Europe is crucial [1].

In March 2020 the European Union (EU) has pledged to be carbon neutral by 2050 by submitting a long-term strategy to the United Nations Framework Convention on Climate Change (UNFCCC). All country members of the EU are required to form national long-term strategies in order to contribute in this objective. Every national plan is different and is based on the resources, size and geographical location of each country member. However, all countries have to form their plan in order to follow the five attributes that have been set by the EU; decarbonisation, energy efficiency, security of energy supply, internal energy market, and research, innovation and competitiveness.

Following the EU's directive and as a member of the EU in 2020 Cyprus has issued its own National Energy and Climate Plan (NECP) for the period of 2021-2030 [4]. The plan aims to form policies that will help Cyprus meet its goals set by the EU. More specifically the binding targets of Cyprus for climate and energy for 2030 are the reduction of GHG by at least 40%, increasing the efficiency to at least 32% and the increase of the share of renewable energy sources (RES) to at least 32% [4]. In addition, during the formation of the policies, an impact assessment was performed in order to make sure the new policies are enough for Cyprus to meet its targets for 2030. However, as mentioned in the conclusions of the impact assessment the successful implementation of the policies is not guarantee because a large amount of investment capital is required.

Being an island has some added difficulties for Cyprus. The absent of interconnections with other countries has ruled out the option of importing electricity and the use of fossil fuels to produce electricity is currently necessary. This has created the need for a more diverse plan that does not ignore new technologies. The global movement towards a carbon-free society has been the driving factor for new technologies in the energy sector and at the same time the creation of financial opportunities for countries. One of the emerging solutions for the energy sector is the production of green hydrogen. Despite being mentioned recently by high level officials, like the head of Cyprus Energy Regulatory Authority (CERA), as a good option for the future; hydrogen has not been included in any of the policies announced for 2030. Worth noting Cyprus has not yet released its long-term strategy for 2050.

The aim of this dissertation is to investigate the technical and financial feasibility of producing green hydrogen in Cyprus. In addition, the future demand of hydrogen is determined providing a direction for future strategies involving hydrogen and three different scenarios for RES are introduced. Based on the results the involvement of green hydrogen for the future policies targeting 2030 is examined and also suggestions are made for the policies for 2050.

2.0 Literature Review

As a member of the EU, Cyprus has to be carbon-free by the end of 2050. The fact that Cyprus is an island and isolated in terms of interconnections, makes the formation of an effective strategy more difficult. However, islands can play a crucial role in the efforts towards a carbon-free future. Many experts considered islands the perfect place to showcase and study the implementation of clean technologies at a small scale [5]. By embracing this role islands can solve their energy problems and at the same time become hubs of innovation for the energy sector. The EU has over 2200 populated islands. For the EU to be carbon neutral by 2050 the decarbonisation of islands cannot be ignored. In 2018 the EU has launched the Clean Energy for EU Islands Secretariat with the aim to help its members that have large island populations form sustainable energy solutions [6].

2.1 Energy Challenges for islands

The challenges that islands face are not new in the energy sector. They are the subject of research especially now that many islands are trying to reduce their GHG and eventually become 100% green. Islands have a small size electrical grid that technically does not support the penetration of a large number of RES due to the intermittent production that RES have [7]. As a result, the majority of islands are heavily depended on fossil fuels for electricity production [7][8]. However, as Ioannidis and Chalvatzis [9] mention in their research, with the present conditions it’s important for islands to develop RES in order to become more independent and have a sustainable future. On the other hand, as Giatrakos *et al* [10] suggest, to be able to have a high penetration of RES and exploit their full potential the use of storage systems and alternative fuels are required [7]. But today’s storage technologies are not sustainable to sustain a large penetration of RES [7].

The sustainability of any project is directly related to the financial aspect. Many current policies are based on the estimation that the prices of RES are going to drop significantly. A big problem for islands is the extra cost for logistics related to renewable energy deployment [11]. The need to transport the equipment with ships or planes adds an extra cost and difficulty to an already complex process. Moreover, usually islands do not have the local human resources and expertise to design, install and maintain RES; as a result in many cases, they are forced to hire experts from abroad adding more to the financial burden [11]. In addition as Kougias *et al* [12] suggests islands usually have outdated equipment and electrical infrastructure and before any RES is deployed they have to bear a large financial cost to upgrade and modernize their electrical grid.

One of the most promising solutions today is hydrogen. The EU recognized the potential of hydrogen and has issued on July 2020 a dedicated strategy for hydrogen [13]. In this strategy is stated that islands can become hydrogen clusters where hydrogen will have various implementations beyond the transport sector and electricity production and that local production using RES should be developed. Cyprus has not yet determined a strategy in regards to hydrogen at least not until 2030 [4]. Following the guidance of the EU Cyprus is expected to release its strategy for 2050 but is not yet determine if it will involve hydrogen.

2.2 The peculiarity of Cyprus

Beyond the isolated energy system Cyprus has other political issues to manage, that have an impact on all the policies of the island. It was considered important to briefly explain the political and military status quo of Cyprus and to mention some energy related plans of Cyprus that are affected by it. The political and military status quo is internationally known as the Cyprus Problem. In 1974 Turkey invaded Cyprus and occupied the north part of the island. To this day 38% of the island is still occupied by Turkish troops. Figure 1 shows the current political and military landscape. A more detailed explanation of the Cyprus Problem is given by the Ministry of Foreign Affairs of the Republic of Cyprus [14].

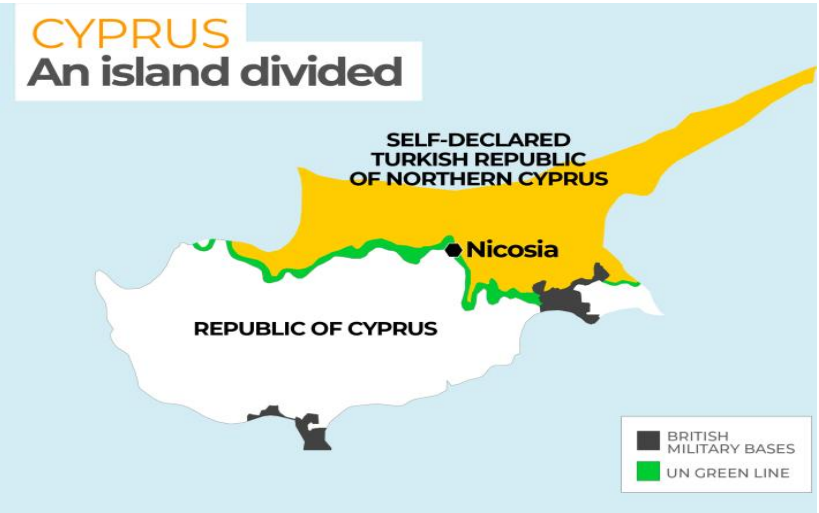

Figure 1: Current political and military landscape of Cyprus [15]

2.2.1 The effects on energy policies

With the division of Cyprus, the effect on energy policies and operation is inevitable. The electrical grid of Cyprus despite being connected between the two parts of the island as shown in Figure 2 is managed by two different operators [17]. As a result, the two operators follow different strategies on how to upgrade and develop each grid. In 2006 the Republic of Cyprus began the explorations for hydrocarbon; as a first step, the Exclusive Economic Zone (EEZ) was established. As it can be observed in Figure 3, due to the current situation the explorations could only be done only in the south EEZ. Since then hydrocarbon has been an object for political leverage and the cause for illegal explorations from Turkey [18]. This causes uncertainty for the future of hydrocarbon explorations and the long-term energy plan of Cyprus.

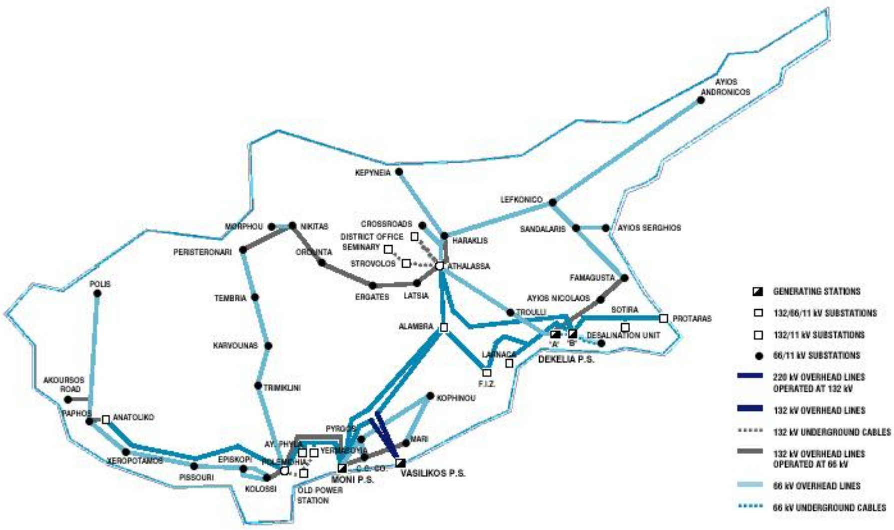

Figure 2: Cyprus Electrical grid [16]

Following the discovery o natural reserves of hydrocarbon Cyprus alongside Greece and Israel approved a gas pipeline project called Eastern Mediterranean (EastMed) which is also co-funded by the European Union. The main objective of the project is to transfer hydrocarbon to Europe by connecting via a pipeline to Israel, Cyprus and Greece. A big obstacle for the project is Turkey's efforts to stop the project from happening by disputing the right of the Republic of Cyprus to approve such a project [19]. The backlash from the dispute between Cyprus and Turkey can also be a threat to other 2 international energy projects EuroAfrica [20] and EuroAsia [21]. Both projects are electrical interconnections that with Cyprus as a substation will connect

Europe to Asia and Africa. The projects have the full support of the Republic of Cyprus but only the EuroAsia project has entered the construction face. The uncertainty that prevails in the area has caused the delay of the energy plans of Cyprus and nobody can be certain the projects will be completed.

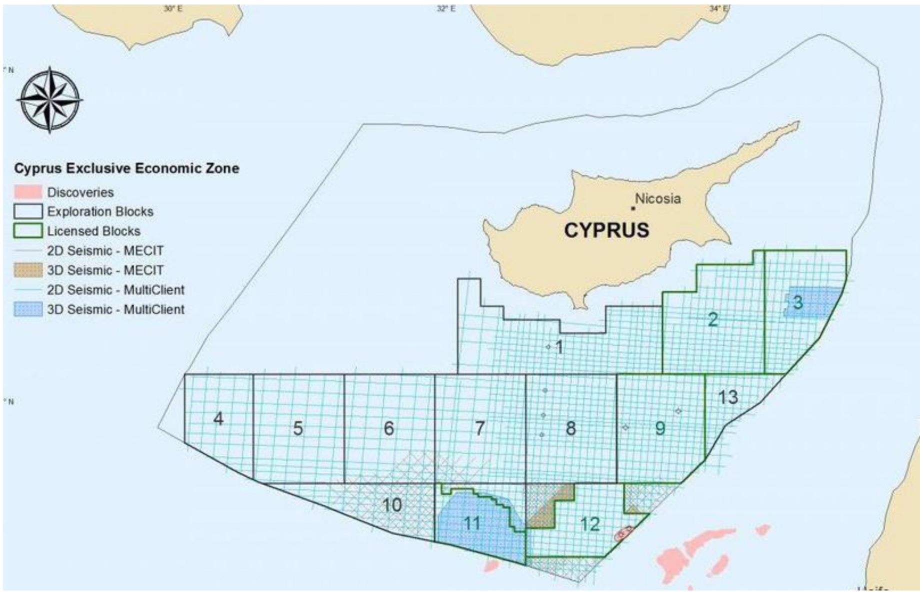

Figure 3: Cyprus's Exclusive Economic Zone (EEZ)[15].

2.3 Hydrogen research for islands

There are many examples of research for islands that suggest hydrogen implementations in their strategies. Morales *et al.*[22], among other green strategies, investigates the potential of hydrogen in the island of Cuba. In their research, they identify that hydrogen can cover some of the island's energy demand but also that there is an opportunity for countries with no fossil fuel reserves to use hydrogen to upgrade their role in the new fuel sector landscape. Moreover, they concluded that hydrogen has the prospect of being the energy storage element that can eliminate the intermittent energy production of RES. Similar research was performed for the Greek island of Karpathos; Giatrakos *et al* [6] form a sustainable strategy for the island to be self-sustain in terms of energy. Beyond the use of batteries as storage and the increase of RES, hydrogen is suggested as fuel for transport and the production of electricity using fuel cells.

Krajačić *et al* [5] investigates the use of hydrogen as storage in order to increase the penetration of RES in islands across Europe. The results showed the technical feasibility of hydrogen production and the important contribution of hydrogen in the energy mix of the examined islands. Moreover, the study suggests that the use of hydrogen on bigger islands can have a big impact if it's used in applications in the transport sector. In a study about another island member of the EU, Malta, one of the main policies proposed is the production of green hydrogen [23]. With the production of green hydrogen the study aims to decarbonise the energy sector of the island. The results showed a slide increase in the price of electricity due to the investment cost.

The majority of the studies are examining the use of hydrogen in the transport sector and suggest that is a sustainable way for islands to use hydrogen in order to achieve a carbon-neutral future.

2.4 Current hydrogen policies

In these early stages of green hydrogen development, countries need to provide a suitable environment for investments and development. The need for policies about hydrogen is crucial for the development of the hydrogen economy. In 2020 the European Commission issued its hydrogen strategy until 2030, setting the goal for at least 40 GW of electrolysis by 2030 collectively from all members of the EU [13]. In addition, it is estimated that by 2030 a total investment of up to €42 billion could be spent on the development of green hydrogen. Finally, the European Commission's strategy identifies the potential of offshore wind hydrogen production between its members and suggests the co-location of hydrogen plants with offshore wind farms. Some European Union members took a further step and release their hydrogen strategies.

The German government issued its hydrogen strategy in 2020 setting the goal to develop 10 GW of electrolysis by 2030 [24]. In their plan is highlighted that a hydrogen strategy has to have a holistic approach, taking into account all aspects related to hydrogen. Finally as mentioned in their strategy, Germany considered hydrogen a vital solution in their efforts towards a carbon-free society. Similar strategy was released by France, setting the goal of 6.5 GW of electrolysis by 2030 but also setting a more short-term goal of 0.87 GW by 2023 [25]. Both countries have measures in their strategy to increase the research around hydrogen realizing that the technology has to be improved in order for green hydrogen to be more sustainable. Other European countries like the Netherlands

[26] and Portugal [27] have released plans as well and other countries like Spain and Austria are planning to announce it in the near future [27].

Outside of Europe, many countries have published policies for hydrogen as well. Australia released its strategy in 2019 with the aim to be a supplier in the future and export large amounts of green hydrogen to South Korea and Japan [28]. China has the title of the biggest hydrogen producer in the world and it's an important developer for machinery related to hydrogen production. The government of China aims to have a 10% of its energy mix produced using hydrogen by 2040 [29]. Finally, the UK despite not officially releasing its strategy for green hydrogen it's being mentioned in several reports that the potential of offshore wind energy can create opportunities for green hydrogen production [30].

The impact of these policies can already be seen by the number of green hydrogen projects announced worldwide. Some of these projects are given in Table 1.

Table 1: Planned green hydrogen projects worldwide.

Name	Location	Power source	Electrolysis Capacity	H2 production (million tones/ year)	Completion
HyDeal Ambition [31]	Spain, France, Germany	Solar	67 GW	3.6	2030
Asian Renewable Energy Hub [32]	Australia	Onshore Wind, Solar,	14 GW	1.75	2028
NorthH2 [33]	Netherlands	Offshore wind	10 GW	1.00	2040
Aqua Ventus [34]	Germany	Offshore wind	10 GW	1.00	2035
Beijing Jingneng Inner Mongolia[35]	China	Onshore Wind, Solar,	5 GW	0.5	2021
Greater Copenhagen[36]	Denmark	Offshore	1.3 GW	0.250	2030

The literature review highlights the need of new technologies for the energy mix of Cyprus. Hydrogen is a promising solution that many EU countries have already incorporate in their policies and many green hydrogen projects are in construction stage. In addition, hydrogen shows great potential in islands and is considered as a credible energy solution that can help islands manage the challenges they face. By investigating the potential of hydrogen in Cyprus there is a high possibility to create a reliable alternative that will contribute in the GHG emission goals of Cyprus.

2.5 Hydrogen Energy Systems

2.5.1 Hydrogen

Hydrogen as a versatile energy carrier is considered to have an important role to play in the future energy mix and eventually replace fossil fuels [37][38]. The potential of producing hydrogen with RES and the fact that its consumption has minimum environmental impact has given hydrogen a lot of political and business momentum. As a result, hydrogen is often considered in future energy strategies and projects. A typical integrated green hydrogen system is illustrated in Figure 4. The main components of such system are analyzed further.

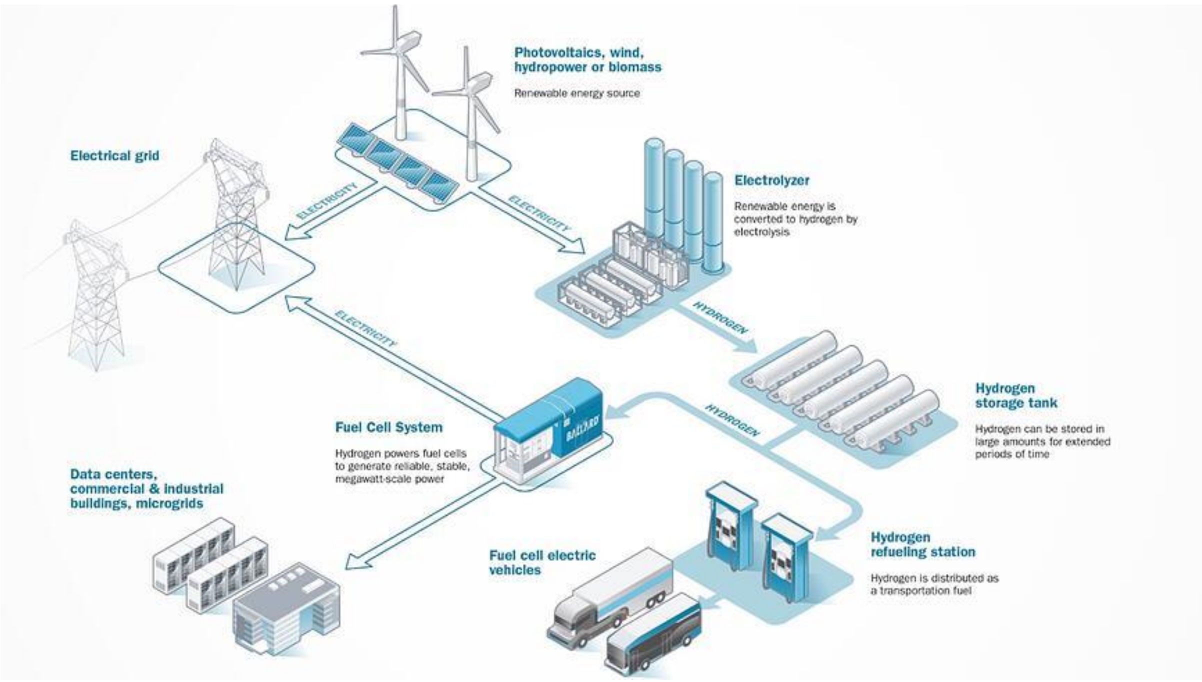

Figure 4: Integrated green hydrogen system [39].

2.5.1.1 Hydrogen Production

Despite existing in abundance in the universe, hydrogen cannot be found in pure form, therefore requires production [40]. The production of hydrogen was first mentioned in the 1800s and in the 18th and 19th centuries many energy implementations were made [41]. Based on the environmental impact of its production, hydrogen is divided into three main categories. When hydrogen is produced using fossil fuels is called grey hydrogen and is considered to be the most polluting type [42]. The most common type of fossil fuel used is natural gas. Blue hydrogen is called the grey hydrogen that during the production a method is used to capture the carbon dioxide and store it. The whole process is called Carbon Capture and Storage (CCS) [42]. Lastly, green hydrogen is called the hydrogen that is being produced using energy from RES.

There are two main methods of producing hydrogen that use different energy sources. For the grey and blue hydrogen, the technique that is usually used is Steam Methane Reforming. High-temperature steam reacts with methane and as a result we have the by-products of hydrogen and carbon dioxide [40]. The second method for hydrogen production uses electricity and is called electrolysis. Electrolysis uses electricity to split water into oxygen and hydrogen [40]. It can be used to produce all types of hydrogen depending on the source of electricity that is been used. As mentioned before for green hydrogen the source of electricity for the process needs to be from RES. For this dissertation the type of hydrogen that is been investigated is green hydrogen and so the method of electrolysis is farther analyzed.

Electrolysis

The machinery used to perform electrolysis is called electrolyzer. There are 3 types of electrolyzers:

- Alkaline Electrolyzer: The first type of electrolyzer to be made and the most used electrolyzers to this day [43]. Since is the most established type of electrolyzer is also the most affordable type [43]. Beyond the low capital cost, alkaline electrolyzers can operate in relatively lower temperatures than other types and some of its key parts can be manufactured with non-noble metals [44].

- Proton exchange membranes (PEM) Electrolyzer: A newer type of electrolyzer than the alkaline electrolyzer PEM electrolyzers have the advantage of working well under part-load conditions [43]. However the capital cost of PEM electrolyzers is considerably higher than the alkaline electrolyzer because some of its parts are very expensive to manufacture [44].

- Anion exchange membrane (AEM): A promising technology of electrolyzers which is the evolution of the alkaline electrolyzer [45]. It has the potential to reduce the capital cost and increase the efficiency of hydrogen production [45]. However, since is a new technology there are still questions regarding its chemical and mechanical durability [45].

With the data that exists today and according to many pieces of research, PEM electrolyzers are the best choice when coupling with RES [43][46]. The main reason for that is that as mentioned earlier PEM electrolyzers work better in part-load conditions than the other types. The stochastic nature of RES will force the electrolyzer to work in part-load conditions the maturity of its lifetime.

2.5.1.2 Storage, transmission and distribution

In an ideal situation, the produced hydrogen is consumed on-site in order to minimize the need for storage, transmission and distribution. According to the International Energy Agency (IEA) [41], about 85% of hydrogen today is produced and consumed on-site and the remaining 15% is transported by pipelines or trucks. The strategy of how to store, transmit and distribute the hydrogen can play a major role on the financial sustainability of the project. Most of the time the end use of the product determines the form of the hydrogen and in some cases requires reforming. Storage, transmission and distribution are considered as important as the production of hydrogen [48]. Research has shown that the best way to reduce the cost of hydrogen is to develop production and transmission at the same time [49].

2.5.1.2.1 Storage

Nowadays, hydrogen is stored in liquid or gas form. There is also research about storing it in a solid state but is still under development [48]. Depending on the form hydrogen requires a different storage environment. To store it in liquid form hydrogen needs to be liquefied, something that requires 11-15 kWh per kg of hydrogen [47], that's about 38% of its energy density (33,33 kWh), and stored in -252.87 ^{o}C and 1 bar pressure. On the other hand, it does not need to be compressed to be stored. Hydrogen at its gas form is compressed up to 700 bar in order to reduce its density but requires more space for storage than liquid. Today the main storage options are geological storage and storage caverns [41].

Geological storage

Geological storages can be considered old natural gas, oil reservoirs, salt caverns and aquifers [50][51]. This kind of storages are considered promising for large scale hydrogen long-term storage since there is not a new storage strategy; geological storages are already used to store natural gas [41]. Using this kind of storage can have a large impact on the sustainability of large-scale hydrogen projects because of the low operational cost and low land cost [41]. However geological storages are not always available and most of the time storage tanks are used instead.

Storage tanks

Storage tanks are mainly suggested for small to medium-scale hydrogen projects because of the high discharge rate and availability [41]. However the based on the form of hydrogen, the storage can require much more space than conventional fuels. For example, compressed hydrogen has 15% of the energy density of gasoline; an equivalent storage will require seven times the space [41]. On the other hand, storing hydrogen as liquid requires less space than compressed gas but as mention before a large amount of energy is required to maintain it at a specific temperature.

The storage of hydrogen is one of the main aspects of research today and has a major role to play for the future of hydrogen.

2.5.1.3 Transmission and distribution

The low density of hydrogen causes challenges in the transmission and distribution of hydrogen. Some solutions have been developed that include compression, liquefaction or incorporation of hydrogen into other molecules. In some cases where countries have the infrastructure for natural gas is suggested that it can be used to transport and distribute hydrogen and boost its development [41]. However, these gas networks have to fulfil certain requirements, like the piping, the joints the pressure used in these networks, in order to be safe [52]. New infrastructure can be developed as well but is still considered as a great financial risk since hydrogen has not yet established demand in many countries [41]. According to the IEA [41], the distance of transport is the main aspect of hydrogen transmission in terms of cost. Transmission of hydrogen by pipeline is the cheapest solution if the distance of transport is less than 1500 km, for longer distances the conversion of hydrogen into other forms like ammonia are considered to be more cost-effective. In smaller local projects the distribution of hydrogen is usually done with a pipeline network or with trucks according to the demand [41].

3.0 Methodology

This chapter describes the methodology that was created in order to produce the targeted outputs of the dissertation. Figure 5 shows a flowchart with the steps followed for the methodology.

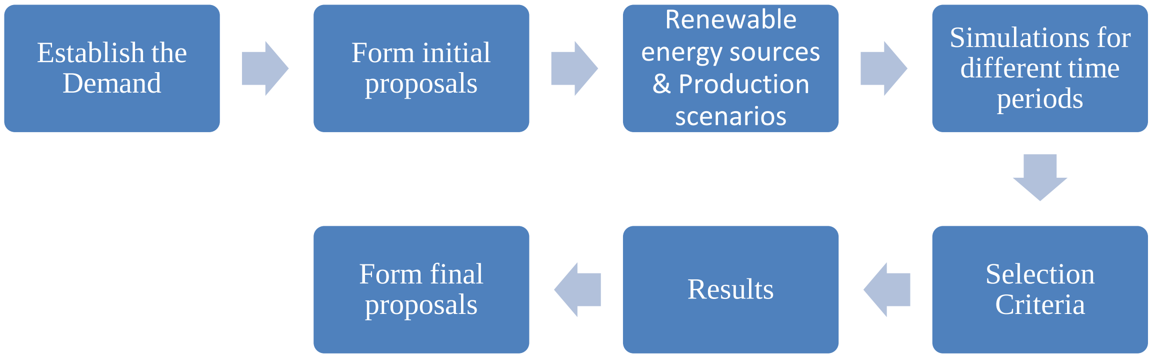

Figure 5: Flowchart of the methodology

3.1 Establishing the demand of hydrogen

Knowing that the main polluting sectors of Cyprus are the transport sector and the electricity production, the focus of establishing a future demand for hydrogen was focused on those two sectors. Four different proposals are identified as promising directions.

3.1.1 Transport

The transport sector is responsible for 30% of the carbon emissions of Cyprus. In 2020 the government has issued the National Climate Plan (NECP) of Cyprus [4], giving the profile of the transport sector and its projection until 2030, based on the planned policies and measures. The projections suggest that due to policies that promote public transport the number of vehicles in Cyprus will be reduced by approximately 34 thousand cars by the end of 2030. In addition, as shown in Figure 6 a rapid increase of electric vehicles is projected for 2030 that will replace vehicles that run alternative fuels. None of the mention policies in NECP suggest the use of hydrogen as an alternative fuel in the transport sector.

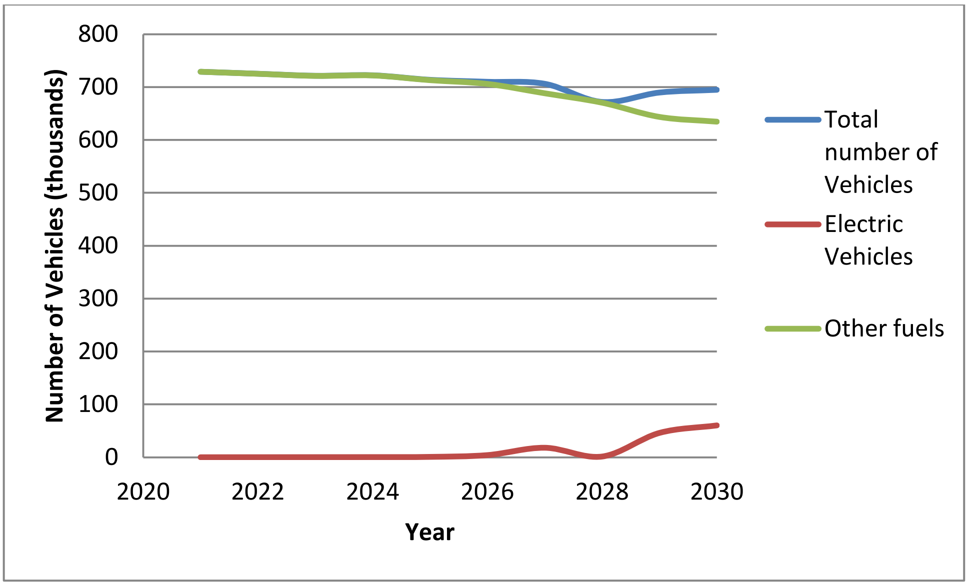

Figure 6: Changes in vehicles based on their energy source.

The NECP recognizes that the electrification of the transport sector has a major role to play in the effort to reduce emissions. However, as mentioned in the NECP the nature of the electrical grid of Cyprus could face issues in the future if the electric load of the island increases too much. This can be avoided if specific charging schedules can be imposed; something that at the moment and for the near future is very complicated to implement. The small distances in Cyprus favours the use of electric vehicles but hydrogen is a promising alternative that can help Cyprus decarbonizes the transport sector.

3.1.1.1 Public transport

One of the most promising ways to incorporate hydrogen in future policies in the transport sector of Cyprus is the public transport. The public transport of Cyprus only has bus routes and the large majority of buses in Cyprus are owned by the public transport. The NECP's projections suggest that in 2030 6010 buses will be needed, which is an increase of 181% in relation to 2021. Moreover, only 7.2% of those buses will be electric and the rest will still run using fossil fuels. Hydrogen buses already exist in Europe and European Union already financed projects related to hydrogen buses [53]. Based on the hydrogen roadmap of Europe [57], it's projected that hydrogen buses will have a 20% share of the total number of buses by 2050. Assuming that Cyprus will have the same share of hydrogen buses the estimation of the potential demand was calculated as follows:

- The first step was to determine the total distance covered by buses in the public sector. Since this information was not available from any public records a different approach was taken. According to Enerdata [54], the mobility of public transport per capita for 2018 was 1809 km/capita and the population of Cyprus for 2018 was 888000 [55]. As mentioned earlier the public transport in Cyprus consists only of buses. Therefore, by multiplying the public transport per capita with the population of Cyprus a rough estimation is made of the total distance covered by buses in the public sector for 2018 of 1606392000 km. It was assumed that the same distance will be covered in 2021.
- Next, the total distance estimated in the previous step was divided by the number of buses for 2021, to determine the distance covered per bus in 2021 at 484729.0284 km. The NECP's projections suggest that in 2030 5574 buses using fossil fuels will be needed; the share of 20% is 1115 buses. Assuming that the mobility of public transport per capita will remain the same at 1809 km/capita, the projection for the distance covered in 2030 was determined at 540472866.6 km.
- As mentioned in the Euro Transport magazine [56], one of the projects financed by the EU, the Clean Hydrogen in European Cities project (CHIC) uses hydrogen buses that have a consumption of 9 kg per 100 km. This determines the demand of hydrogen per year to 48.634 Mtonnes.

3.1.1.2 Passenger Cars

Many consider that hydrogen passenger cars are not the future of transport due to low efficiency rates [57]. However, it is believed that they will still have a small share of cars in the future. The hydrogen roadmap of Europe [57] mentions that is expected that 4.5% of passenger cars in Europe will be hydrogen passenger cars. Assuming that Cyprus will follow this trend, the potential hydrogen demand was calculated as follows:

- It was assumed that in 2030 Cyprus will have the same share of hydrogen passenger cars as Europe and according to the NECP of Cyprus, the total number of cars estimated for 2030 is 493724. This results to 22218 hydrogen passenger cars.

- The consumption of hydrogen for a typical hydrogen passenger car was found from literature at 0.76 kg/100 km [58].
- Due to lack of information about the distance covered by a passenger car per year, it was assumed that this value was the same as Malta which has approximately the same cars per capita as Cyprus [59]. The distance covered per passenger car was determined at 13587 km/year.
- The demand was calculated at 2.294 Mtonnes per year.

3.1.1.3 Trucks

Due to the high range that hydrogen provides, hydrogen trucks are expected to grow in numbers in the future. Cyprus has a small fleet of trucks of 13209 in 2021 and based on the projections of the NECP are expected to be 13441 by 2030. To investigate if is possible to replace the whole fleet of trucks with hydrogen trucks the demand of hydrogen was calculated as follows:

- According to Eurostat [60] the total tonnes carried by road freight transport in Cyprus for 2018 were 29308 and for every million km 892 tonnes (million tonne-kilometres) were carried.
- By dividing the total tonnes carried by the million tonne-kilometres, the total distance covered by trucks in 2018 was calculated at 32856502.24 km.
- The hydrogen consumption of a typical truck is 8 kg/100 km [61]. The demand of hydrogen was determined at 2.67 Mtonnes of hydrogen per year.

3.1.2 Electricity production

Electricity production has a major role to play in the efforts to reduce GHG emissions since electrification is the most used way to decarbonize the energy load. According to the Transfer System Operator of Cyprus (TSOC) for 2020 conventional fuels account for the 88.1 % of the electricity production of Cyprus [62].Moreover, the latest data given by the Cyprus government for 2021, to the United Nations Climate Change secretariat (UNFCCC) suggest that the emissions related to electricity production accounts for 28.7 % of GHG[63]. The NECP projections for 2030 show that if only the current policies are implemented the share of RES in the electricity sector will only be at 26 % of the total energy mix and natural gas will replace the conventional fossil fuels used today in thermal stations. None of these policies include the use of hydrogen in gas turbines or fuel cells. In addition, the analysis of the NECP suggests an increase on the demand of Cyprus by 2030 of 15.6% in comparison to 2021; that accounts for 533 ktoe or 6198.79 GWh per year.

3.1.2.1 Fuel Cells

Fuel cells are being widely used in hydrogen vehicles to produce electricity and power an electric motor. However, they can be used as an energy source to give electricity back to the grid. The most important characteristic of a fuel cell is the efficiency. Nowadays, efficiencies are about 40% and are expected to reach efficiencies of 60% in the future [41]. In addition, the European Commission mention in a recent report that hydrogen is projected to be account for 10% to 25% of the electricity production by 2050 [64]. Assuming that fuels cells will have a 10% share in the future energy mix of Cyprus the hydrogen demand was calculated using equation 1.

$$Hydrogen\ demand = \frac{Demand\ of\ Cyprus \times 5\%}{energy\ content\ of\ 1\ kg\ of\ hydrogen \times 60\%} \qquad (1)$$

The demand of hydrogen is 15.5 Mtonnes per year.

3.1.2.2 Hydrogen-fired gas turbines

Hydrogen is been used before in gas turbine plants in high hydrogen content gas fuels [65]. Many existing designs today have a hydrogen share of up to 30% and plants that are being designed are aiming to go even higher [4]. After realizing the potential of such hydrogen implementation the European gas and steam turbine industry (EUTutbine) committed in providing gas turbines that can be powered with 100% hydrogen as a fuel by 2030 [66]. Since this technology is still very new a rough estimation was made to calculate the demand of hydrogen in such implementations:

- Firstly, it was assumed that the percentage of the demand of Cyprus that is going to be covered by hydrogen-fired gas turbines will be 15% based on the estimation made in the hydrogen strategy of the EU [13].

- The energy content of hydrogen is 33.33 kWh/kgH_2 [41] and the efficiency of the gas cycle is assumed to be 60%, the same as other combined gas cycle projects that use other fuels [67].
- The demand was calculated using equation 2

$$\text{Hydrogen demand} = \frac{\text{Demand of Cyprus} \times 15\%}{\text{energy content of 1 kg of hydrogen} \times 60\%} \qquad (2)$$

The demand of hydrogen is 49.5 Mtonnes per year

3.1.3 Initial Proposals

Based on the analysis of the potential demand of Cyprus four initial proposals were formed in order to be investigated in more dept. The initial proposals are given below:

- Initial Proposal 1: Cover the demand of hydrogen to decarbonize 20% of the public transport. The demand was calculated in section 3.1.1.1.
- Initial Proposal 2: Cover the demand of hydrogen to decarbonize 4.5% of passenger cars. The demand was calculated in section 3.1.1.1.
- Initial Proposal 3: Cover the demand of hydrogen to decarbonize 100% of trucks. The demand was calculated in section 3.1.1.1.
- Initial Proposal 4: Cover the demand of hydrogen to produce 10% of the electricity production. The demand was calculated in section 3.1.1.1.

Despite being developed in other countries it was decided that hydrogen –fired gas turbines is not a vital solution for Cyprus. The main reason for this decision is that as mentioned by Ditaranto *et al* [65] the combustion of hydrogen has a harmful by-product; a gas called nitrogen oxides (NOx) that reacts with oxygen and forms nitrogen dioxide; one of the gasses that is considered as GHG. This gas can be limited using a procedure called Exhaust Gas Recirculation (EGR) but it cannot be eliminated completely. Investing in such projects will create more problems instead of eliminating GHG.

3.2 Renewable energy sources & Production scenarios

For the production of green hydrogen two main RES were selected based on the characteristics of Cyprus, future potential and the possibility of providing new approaches. Solar energy was selected as the most established energy source in Cyprus and offshore wind because is not yet implemented in Cyprus.

3.2.1 Solar Energy

Solar energy is one of the oldest forms of energy that humanity has harvest and today has established technologies for electricity production and thermal application. Like the majority of south European countries, solar energy is the most promising RES for Cyprus. In terms of solar thermal energy Cyprus has the highest solar capacity in operation per capita in Europe with 0.883 kW/cap, which is more than double than the country in second place [68]. However, solar power used for electricity production is not at the same level. Based on data released by the TSOC [69], in 2020 there was a total of 229.1 MW of installed capacity of photovoltaic but only 5.8 % of the total electricity produced in 2020 came from solar energy. Figure 7, taken from Solargis 0, shows the Global Horizontal Irradiation (GHI) potential of Cyprus. As it can be observed in general Cyprus has a great solar energy potential especially at the south shores of the island.

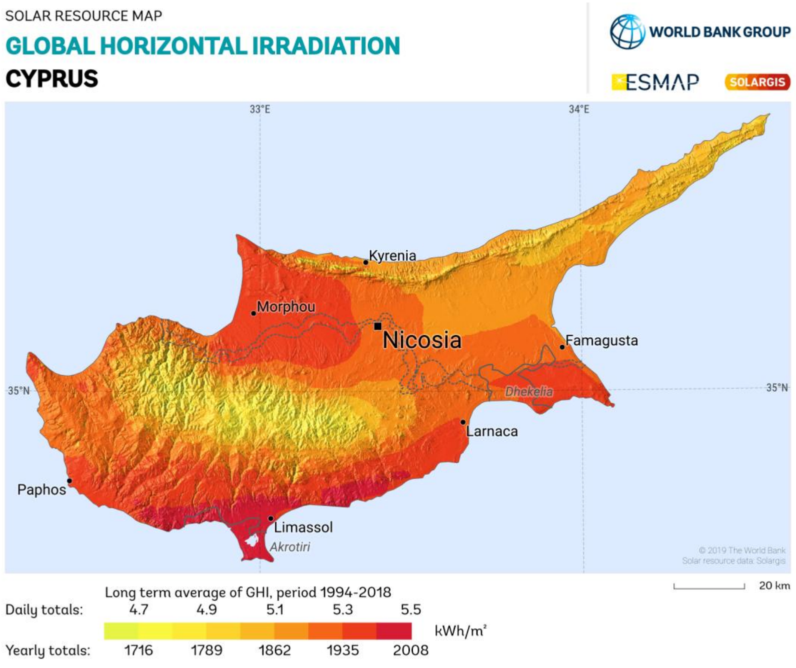

Figure 7: Irradiation potential of Cyprus [70]

3.2.2 Offshore Wind Energy

Wind energy is not as established RES as solar energy in Cyprus. However according to the TSOC despite having less installed capacity at 157.5 MW than photovoltaic 5.04 % of the total electricity produced came from wind energy [69]. As mentioned before there are still no offshore wind farms in Cyprus. Figure 8 illustrates the average wind speed in Cyprus at 100 m which is the common height for offshore wind turbines. As it can be observed there is great potential on the north and south of Cyprus. However, due to the current political landscape of the island, as it was explained in section 2.2, Cyprus can only exploit the south part of its EEZ.

Figure 8: Wind potential of Cyprus at 100m altitude [71]

Offshore wind energy is considered by many the best option among the RES to couple with hydrogen production. Moriary and Honnery [72] studied different scenarios of coupling RES with hydrogen production and concluded that offshore wind has the biggest potential. A similar analysis was performed by Acar and Dincer [73] but for a specific country, Turkey. The research had the same output.

3.2.3 Production scenarios

The scenarios determined for further research are given below:

- Scenario 1: Production of electricity using only solar energy.
- Scenario 2: Production of electricity using only offshore wind energy.
- Scenario 3: Production of electricity using both solar energy and offshore wind energy.

3.3 Simulations

In order to determine the best scenario for each proposal a software called Homer Pro was used. Homer Pro is an optimisation software that based on technical and financial criteria can give the best architecture for the modelled energy system. The modelled system can have one or more conventional power sources like gas turbines and RES like solar energy, wind energy, tidal energy and hydroelectric energy. In each power source different inputs are required from the user based on the specifications of the system. However, for the natural resources connected to each RES and based on the selected location, Homer Pro uses POWER Data Access Viewer which is a database made by NASA. In addition according to the purpose of the modelled system the user can add electric and hydrogen loads with specific hourly profiles and the machinery needed to satisfy the load.

After the determination of the inputs Homer Pro can perform three different tasks. Firstly, the simulation of the system calculates the technical feasibility of the system. Secondly, the optimization process begins based on the financial inputs for CAPEX and OPEX of each component. Finally, based on the inputs of the user it can perform sensitivity analysis for specific variables. The obtained results include the hourly production of electricity and hydrogen, if it's included, the total CAPEX and OPEX needed and based on the needs of the user can also calculate financial metrics and carbon emissions. For the purpose of this thesis Homer Pro was used for the optimization of the system and only to obtain the hourly production of hydrogen and electricity and not for the financial metrics.

3.3.1 Location

The initial proposals made in section 3.1.3 were not about a specific location. However, for the simulations, a specific location was determined based on the maps in Figure 7 and Figure 8. Figure 9 shows the selected location for the PV system; based on the potential of solar energy shown in Figure 7; the shores of Cyprus near Limassol are one of the best locations. In addition, the location is near the Vassiliko which is considered the energy centre of Cyprus.

Figure 9: Selected location for the PV system

Figure 10: Selected location for the offshore wind farm.

Figure 10 points the selected location for the offshore wind farm. The location is in the EZZ and according to Figure 8, the location has a great wind potential.

3.3.2 Natural Resources

Since it was not feasible to get official data for the wind and radiation of Cyprus the use of other resources was needed. The wind and solar data used were taken from the POWER Data Access Viewer of NASA. It's the database that is commonly used with Homer Pro and is available for free. Figure 11 shows the average daily radiation per month in the chosen location. As expected the months of June and July have the biggest daily radiation. In addition, the clearness index is illustrated per month; this index represents how clear the atmosphere is around the chosen location. Finally, Figure 12 shows the average wind speed per month in the area.

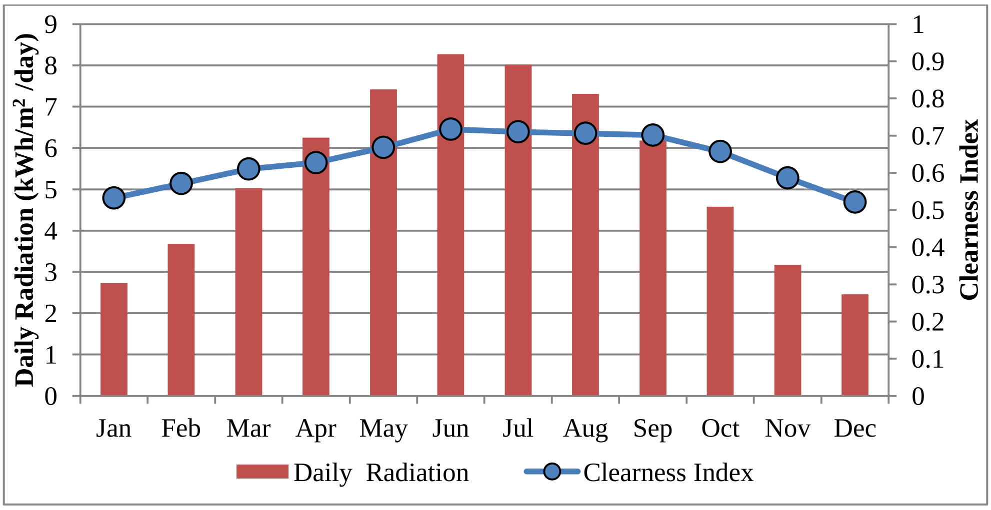

Figure 11: Daily radiation and clearness index for the selected location

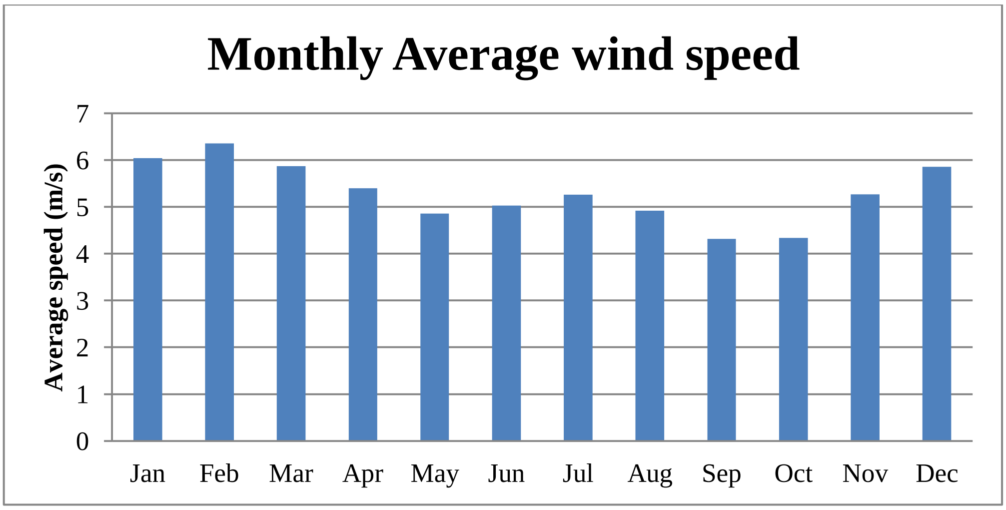

Figure 12 : Monthly average wind speed

The wind resource has some very important parameters that need to be determined before any simulations. The measurement of wind speed is usually done at a lower altitude, using an anemometer, than the altitude of the wind turbine's hub. To adapt the data Homer Pro uses equation 3.

$$\frac{U_{hub}}{U_{anem}} = \left(\frac{Z_{hub}}{Z_{anem}}\right)^{\alpha} \qquad (3)$$

where:

U_{hub}: wind speed at the altitude of the turbine's hub

U_{anem}: wind speed at the altitude of anemometer

Z_{hub}: Altitude of the turbine's hub

Z_{anem}: Altitude of anemometer

α : power law exponent

The power law exponent was determined at 0.11 since the wind turbine is located on seawater [74]. Another important parameter is the Weibull parameter k, which is the shape parameter of the Weibull density probability function given in equation 4. The Weibull density probability function is often used to analyze the distribution of wind for a specific location.

$$f(U) = \frac{k}{c}\left(\frac{U}{c}\right)^{k-1} exp\left[-\left(\frac{U}{c}\right)^{k}\right] \quad (4)$$

Where

U: wind speed

k: shape factor

c: scale factor

Parameter k and c was determined at 2.3749 and 6.3388 respectively with the use of MATLAB.

3.3.3 Components

In order to perform the simulations, the components selected were based on literature and components that are used today. The main components are given below:

3.3.3.1 Wind Turbine

The power output of a wind turbine is given from equation 5. In addition, wind turbines have limits in term of wind speeds; they have a cut-in speed when the turbine starts producing electricity and an upper limit cut-out speed. These specifications are given by the manufacture and they are very important in the selection of a wind turbine for a specific project.

$$P_{out} = \frac{1}{2} C_P A \rho U^3 \quad (5)$$

where:

P_{out}: Power Output

C_P: power coefficient

ρ: air density

A: frontal area

U: wind speed

As the main part of the offshore wind farm, the selection of a wind turbine is crucial. The selected turbine for the simulations is the Vestas 164-8.0; it's an 8 MW wind turbine manufactured by Vestas and it's mainly used for offshore wind farms. It's important to mention that turbines, as the technology evolves, tend to grow in capacity for offshore wind farms applications. Nowadays the capacity for commercially available wind turbines can be up to 8 MW and in the future, this value is expected to grow up to 12 MW [75]. Figure 13 shows the power curve of the selected turbine and Table 2 shows its key characteristics.

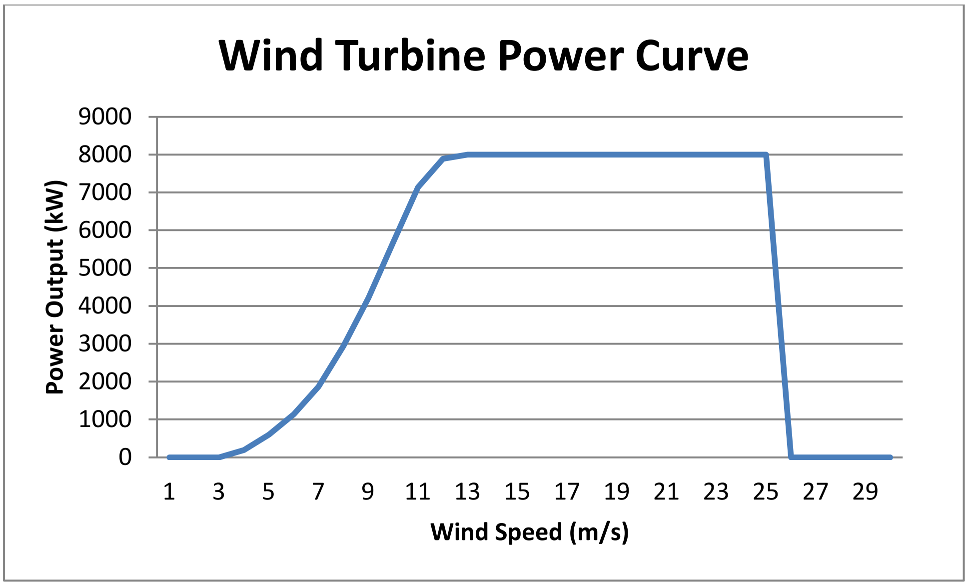

Figure 13: Vestas 164-8.0 power curve

Table 2: Key characteristics of the wind turbine

Wind Turbine	Vestas V164-8MW
Rated power	8000 kW
Hub height	100 m
Rotor diameter	164 m
Cut-in speed	4 m/s
Cut-out speed	25 m/s
Lifetime	25 years

3.3.3.2 Solar panels

For the production of electricity from solar energy, a generic solar panel was selected from Homer Pro's database. The key characteristics of the solar panel are given in Table 3.

Table 3: Key characteristics of the generic solar panel

Solar Panel	Generic
Rated power	1 kW
Lifetime	15 years
Efficiency	20%
Nominal Operating Temperature	47°C
Panel Slope	34.75°
Derating Factor	90%

3.3.3.3 Electrolyzer

As explained in section 2.5.1.1 the best electrolyzer for the production of green hydrogen is the PEM electrolyzer. For the simulations, the characteristics of the electrolyzer used are given in Table 4. Access to water is very important for the production of hydrogen through electrolysis. Is estimated that for every kg of hydrogen 10 litres are needed [76].

Table 4: Key characteristics of the electrolyzer

Electrolyzer:	PEM
Lifetime	15 years
Efficiency	67% [82]
Minimum load ration	10% [82]

3.3.3.4 Storage

Homer Pro does not have many features in modelling the storage system beyond its size. For the simulations, 4 options for the size of storage are given for the optimization process. The options are based on the hydrogen demand per day multiplied by 1,2,3 and 4; giving the option to the software to keep stored hydrogen for 1-4 days. A key assumption made for storage is that is stored in gaseous form so there is no need for liquefaction of hydrogen.

3.3.4 Different simulation time periods

One of the objectives of this dissertation is to determine a time period for each of the initial proposals. To decide that three different time periods were selected. The first time period is 2021 in order to have a picture of the current landscape for green hydrogen. Secondly, the year 2030 was set, which is the year the EU set its intermediate goals for each country. Finally, 2050 was selected as the final time period because is set as the end goal for the effort towards a carbon-free future. For each period changes were made in prices and technical characteristics of the components based on values from literature and technical reports. The changes are given in Table 5 for the cost and

Table 6 for the efficiencies of some components. For the cost, the Capital Expenditure (CAPEX) is given and as a percentage of the CAPEX for each year the Operating Expenditure (OPEX) is given as well.

Table 5: Changes made for each period

COMPOMENT	2021		2030		2050	
	CAPEX	OPEX (%)	CAPEX	OPEX(%)	CAPEX	OPEX (%)
Wind turbine (m£/MW)	4 [77]	1.31 [78]	1.65 [78]	1.94 [78]	1.5308 [78]	1.93 [78]
Solar Panels(m£/MW)	0.60242 [78]	1.99 [78]	0.5934 [78]	1.28 [78]	0.4816 [78]	1.32 [78]
Storage (£/kgH2)	795.77 [80]	5 [80]	228 [80]	2.5 [80]	192 [80]	2.03 [80]
Electrolyzer (£/kW)	337.65 [79]	3 [79]	560.94 [79]	4 [79]	344 [79]	4 [79]

Table 6: Changes in efficiency for each period

COMPOMENT	2021	2030	2050
Solar Panel (%)	20 [81]	23 [81]	26 [81]
Electrolyzer (%)	67 [82]	71 [86]	76 [86]

3.3.5 Space requirements

An important aspect of RES is the space required to create high capacity production systems. In addition, since the RES are for the production of hydrogen, additional space is needed for the production and storage. It was considered important to calculate the space requirements since Cyprus is an island and has limited available space. As explained in section 2.2 Cyprus can only exploit 62% of its land which is 5.73562 km^2. The space requirements for each main component are given in Table 7. The results were compared with the largest football stadium, GSP, which covers an area of 75068.14 m^2 to give context behind the numbers.

Table 7: Space requirements for main components

Component	Space Requirements
Solar farm	30352.5 m^2 / MW [87]
Offshore wind farm	365 W/m^2 [88]
Electrolyzer	80 m^2/MW [86]
Storage	42 m^3/kgH_2 [89]

3.3.6 Net Present Value

One of the main aspects of the sustainability of any project is the cost and profitability. In order to address that, the Net Present Value (NPV) was used. NPV is a financial metric that calculates the profitability of any project thought out its lifetime based on its cashflows. In addition, using NVP the return of the initial investment can be easily calculated. Equation 6 is the formula used to calculate NVP.

$$NPV = \sum_{i=1}^{n} \frac{Cashflow_i}{(i+r)^i} - CAPEX \qquad (6)$$

where:

i : years
r: future value discount rate
Cashflow: Hydrogen sold-Electricity sold-OPEX

The cash flow for each year represents the income from selling the produced hydrogen plus the income for selling the excess electricity from the RES (Appendix I, II &III), minus the cumulative OPEX of the project based on the data in Table 5. According to the EAC, the renewable energy purchase price is 0.061 pounds per kWh [84]. For the hydrogen price, it was recently reported that the production cost of green hydrogen in 2020 was 4.34 pounds per kg of hydrogen [85]. It was assumed that the selling price of hydrogen will be double that, at 8.68 pounds per kg. In addition, it was assumed that the prices of electricity and green hydrogen will remain the same for all three simulation periods. The period of 15 years was determined the best period to calculate the NVP were in theory none of components will need replacement.

4.0 Results

In this chapter, the results of the simulations are presented. The results are divided for each proposal and time period. The results are also given in Appendix I, II and III for simulation periods 2021, 2030 and 2050 respectively.

4.1 Proposal 1

Proposal 1 refers to the decarbonization of 20% of the public transport as calculated in section 3.1.1. After the simulations, the following results were obtained.

4.1.1 2021

Scenario 1: Production of hydrogen using only solar energy.

The CAPEX for scenario 1 is 3.079 billion pounds and the total space required is 106082107.3 m^2. As shown in Figure 14(b), 68% of the total CAPEX for proposal 1 is for the solar panels needed. In addition, as presented in Figure 14(a), in comparison to the electrolyzer and the storage, solar panels require the majority of space. The total land space for this scenario is equivalent to 1414 GSP stadiums.

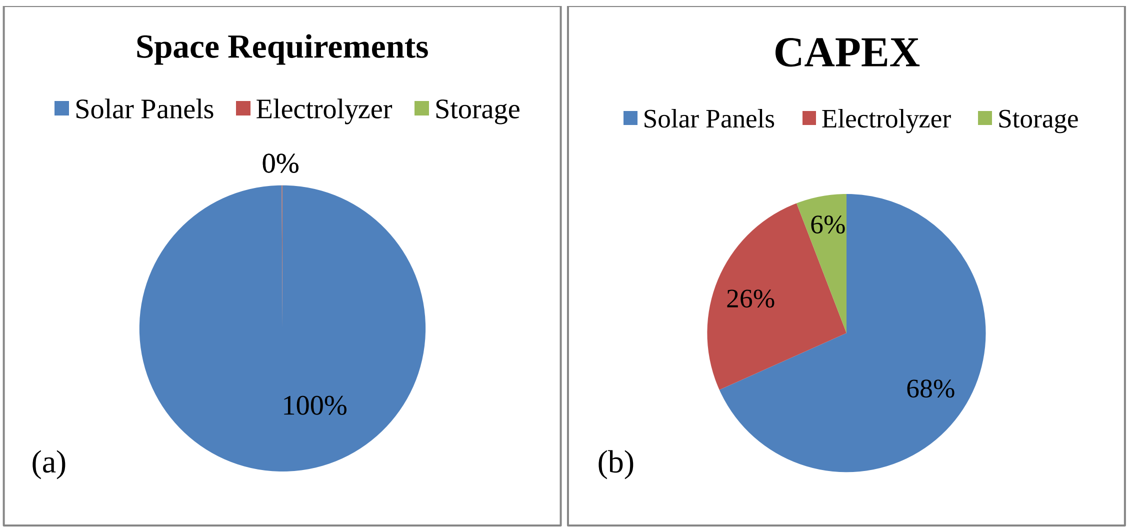

Figure 14: Space requirements (a) and CAPEX (b) for Proposal 1 in 2021, Scenario 1

Scenario 2: Production of hydrogen using only wind energy.

The CAPEX for scenario 2 is 9.283 billion pounds and the total space required is 6012692.19 m^2. As shown in Figure 15(b) 89% of the total CAPEX accounts for the wind turbines. In addition, as illustrated in Figure 15 (a) in comparison to the electrolyzer and the storage wind turbines require the majority of space. However, only 1% of that space is land. The total land space for this scenario is only for the electrolyzer and storage, and is equivalent to 1.23 GSP stadiums.

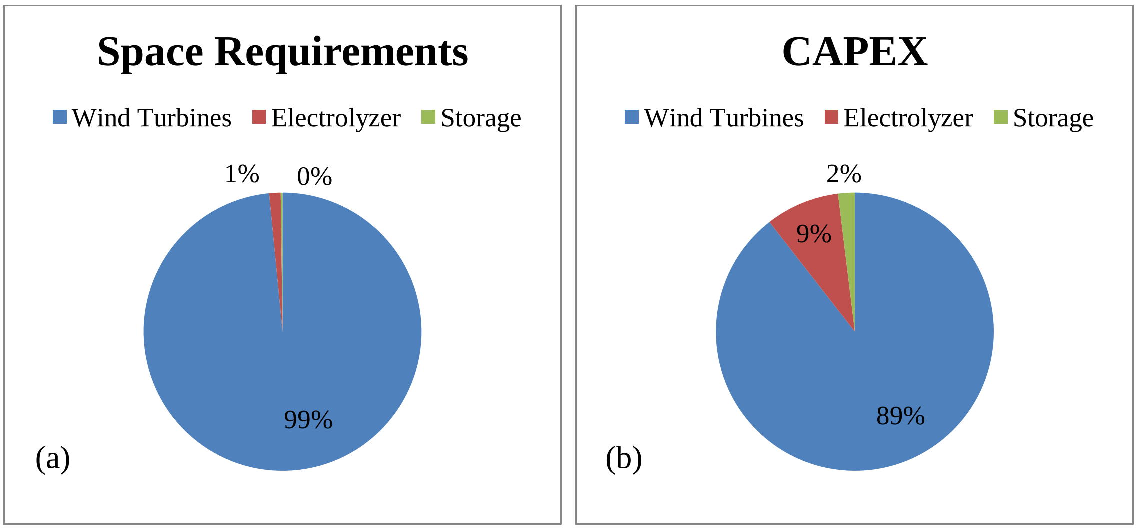

Figure 15: Space requirements (a) and CAPEX (b) for Proposal 1 in 2021, Scenario 2

Scenario 3: Production of electricity using both solar energy and offshore wind energy

The CAPEX for scenario 3 is 3.189 billion pounds and the needed space is 1113645576 m^2. As shown in Figure 16 (b) 22% of the total CAPEX for proposal 1 accounts for the wind turbines, 25% for the electrolyzer and 47% for the solar panels. Moreover, as illustrated in Figure 16 (a) the majority of space is needed for the solar panels, which is 76071865.71 m^2. The total land space for this scenario is only for the solar panels, the electrolyzer and storage and is equivalent to 1014 GSP stadiums. In terms of land use, the results are better than scenario 1 but still not practical.

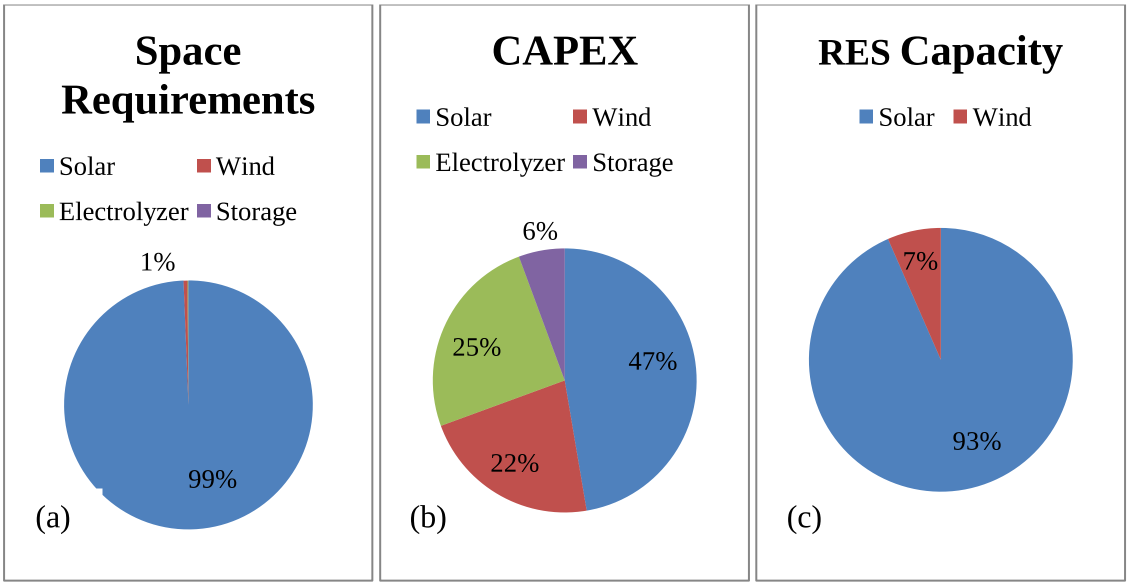

Figure 16: Space requirements (a), CAPEX (b) and RES Capacity (c) for Proposal 1 in 2021, Scenario 3

4.1.2 2030

Scenario 1: Production of hydrogen using only solar energy.

The CAPEX for scenario 1 is 2.080 billion pounds and the total space required is 64461897 m^2. As shown in Figure 17(b), 60% of the total CAPEX for proposal 1 is for the solar panels needed. In addition, as illustrated in Figure 17 (a) in comparison to the electrolyzer and the storage, solar panels require the majority of space. The total land space for this scenario is equivalent to 858.71 GSP stadiums.

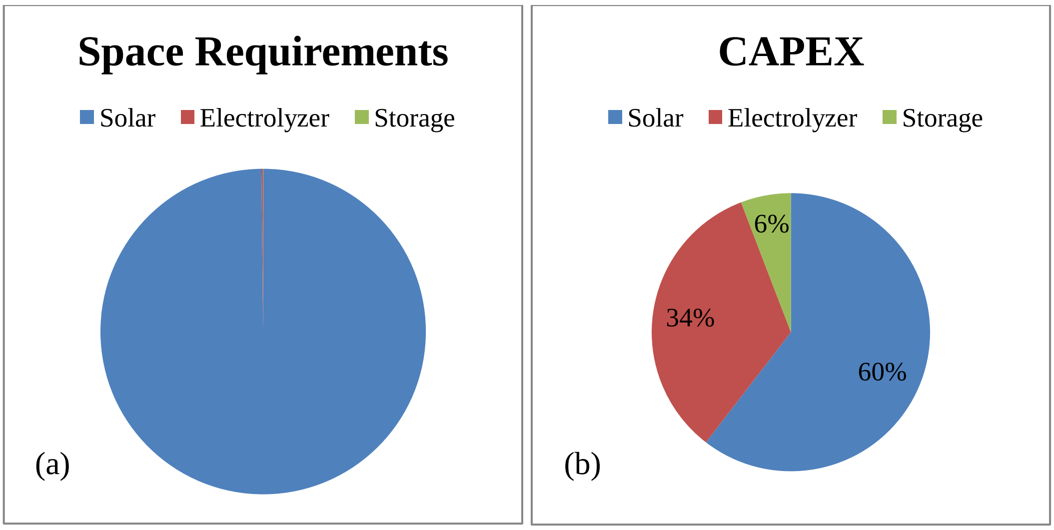

Figure 17: Space requirements (a) and CAPEX (b) for Proposal 1 in 2030, Scenario 1

Scenario 2: Production of hydrogen using only wind energy.

The CAPEX for scenario 2 is 3.665 billion pounds and the total covered space is 5258406.476 m^2. As shown in Figure 18 (b), 82% of the total CAPEX for proposal 1 accounts for wind turbines. As it can be observed in Figure 18 (a), in comparison to the electrolyzer and the storage, wind turbines require the majority of space. However, the total land space for this scenario is only for the electrolyzer and storage and is equivalent to 1.23 GSP stadiums.

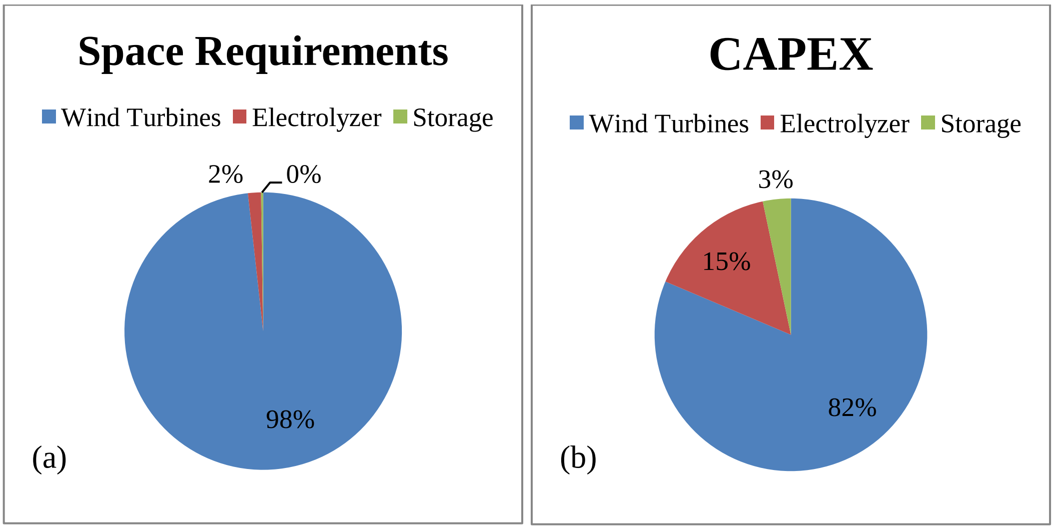

Figure 18: Space requirements (a) and CAPEX (b) for Proposal 1 in 2030, Scenario 2

Scenario 3: Production of electricity using both solar energy and offshore wind energy

The CAPEX for scenario 3 is 2.947 billion pounds and the total space required is 2734490616.9 m^2. As shown in Figure 19 (b) 72% of the total CAPEX for proposal 1 accounts for the wind turbines, 15% for the electrolyzer and 10% for the solar panels. In addition, as illustrated in Figure 19 (a) the majority of space is needed for the solar panels, which is 15817097.77 m^2. The total land space for this scenario is only for the solar panels, the electrolyzer and storage and is equivalent to 211.68 GSP stadiums. The results (Figure 19 (c)) showed that 71% of the RES capacity is for wind turbines. With the price drop of the wind turbines the optimizer of Homer Pro, chooses to pick more wind turbines than the 2021 time period.

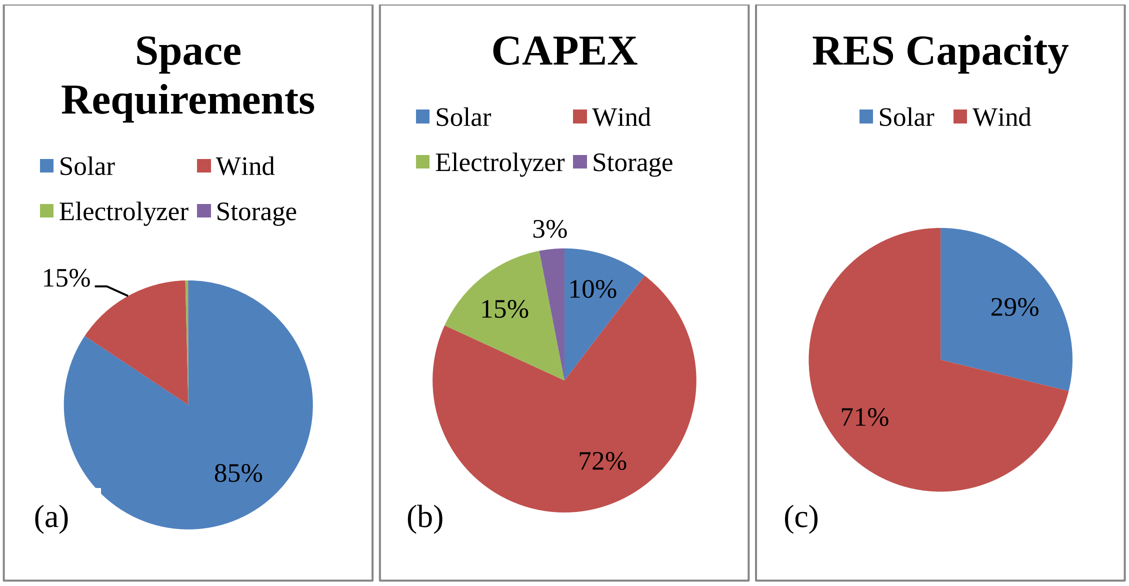

Figure 19: Space requirements (a), CAPEX (b) and RES Capacity (c) for Proposal 1 in 2030, Scenario 3

4.1.3 2050

Scenario 1: Production of hydrogen using only solar energy.

The CAPEX for scenario 1 is 1.437 billion pounds and the total space required is 57142226.87 m^2. As shown in Figure 20 (b) 63% of the total CAPEX for proposal 1 accounts for the solar panels needed. In addition, as illustrated in Figure 20 (a) the solar panels require the majority of space. The total land space for this scenario is equivalent to 761.2 GSP stadiums.

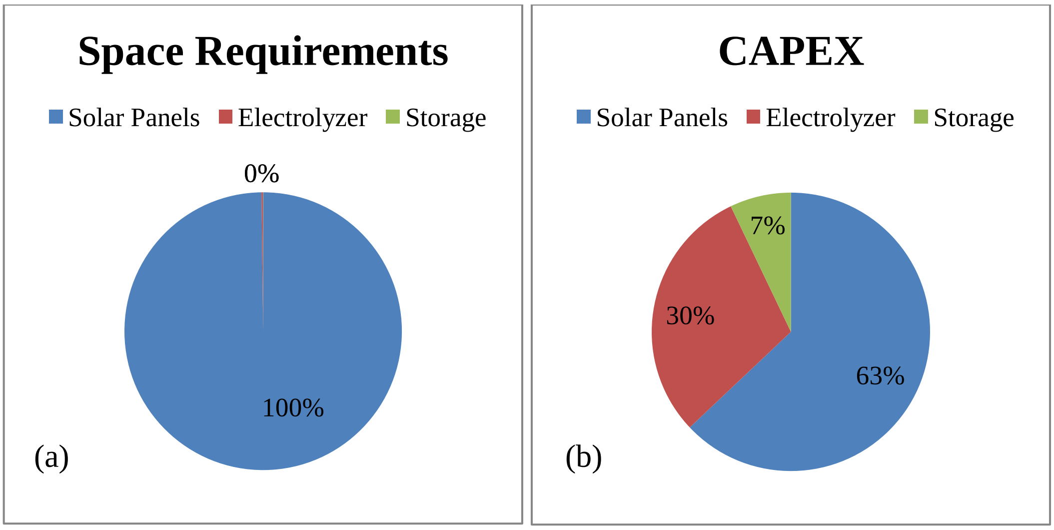

Figure 20: Space requirements (a) and CAPEX (b) for Proposal 1 in 2050, Scenario 1

Scenario 2: Production of hydrogen using only wind energy.

The CAPEX for scenario 2 is 3.312 billion pounds and the total space required is 5441263.619 m^2. As shown in Figure 21 (b), 87% of the total CAPEX for proposal 2 accounts for the wind turbines. In addition, as illustrated in Figure 21 (a) in comparison to the electrolyzer and the storage wind turbines require the majority of space. However, the total land space for this scenario is only for the electrolyzer and storage and is equivalent to 0.96 GSP stadiums.

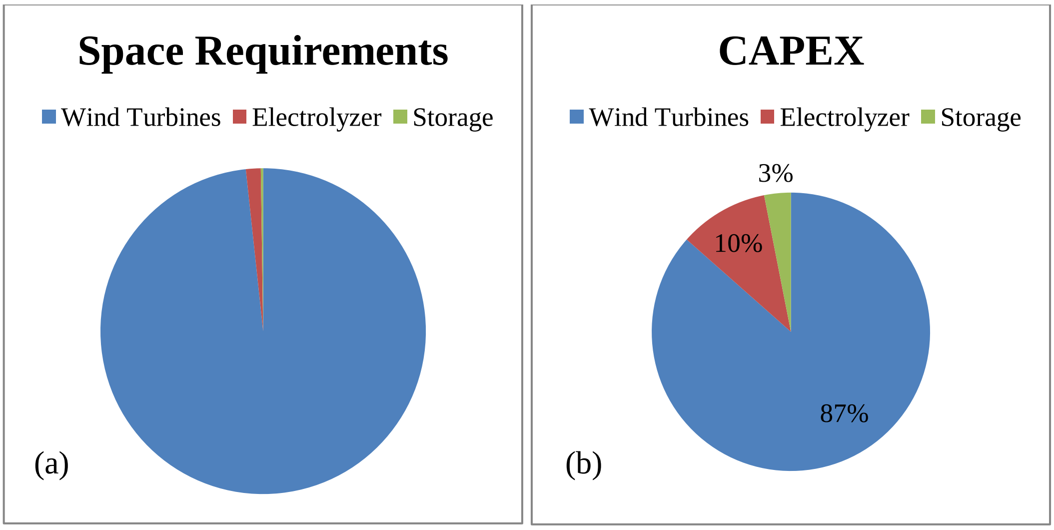

Figure 21: Space requirements (a) and CAPEX (b) for Proposal 1 in 2050, Scenario 2

Scenario 3: Production of electricity using both solar energy and offshore wind energy

The CAPEX for scenario 3 is 2.473 billion pounds and the total space required is 264553903.62 m^2. As shown in Figure 22 (b), 78% of the total CAPEX for proposal 2 accounts for the wind turbines, 11% for the electrolyzer and 8% for the solar panels. In addition, as illustrated in Figure 22 (a) the majority of space is needed for the solar panels. The total land space for this scenario is only for the solar panels, the electrolyzer and storage and is equivalent to 177.89 GSP stadiums. The results (Figure 19 (c)) showed that 74% of the RES capacity is for wind turbines. With the price drop of the wind turbines the optimizer chooses to pick more wind turbines than the 2021 time period.

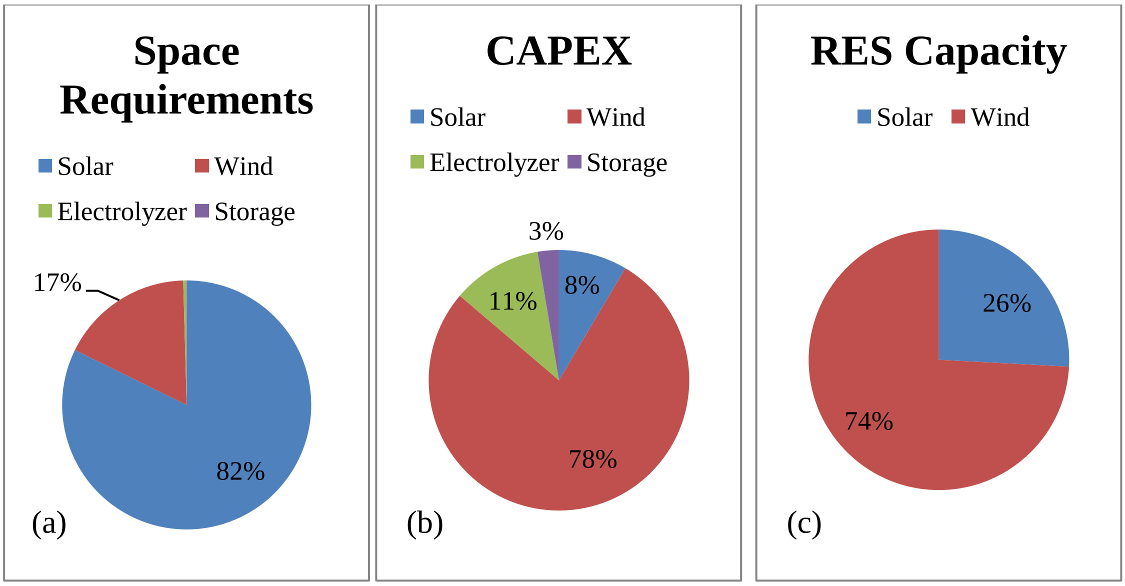

Figure 22: Space requirements (a), CAPEX (b) and RES Capacity (c) for Proposal 1 in 2050, Scenario 3

4.1.4 Overall Results

CAPEX

The overall results for the CAPEX of proposal 1 are given in Figure 23. All scenarios have a reduction on the CAPEX in all time periods. The most significant reduction is observed for scenario 2 from 2021 to 2030.

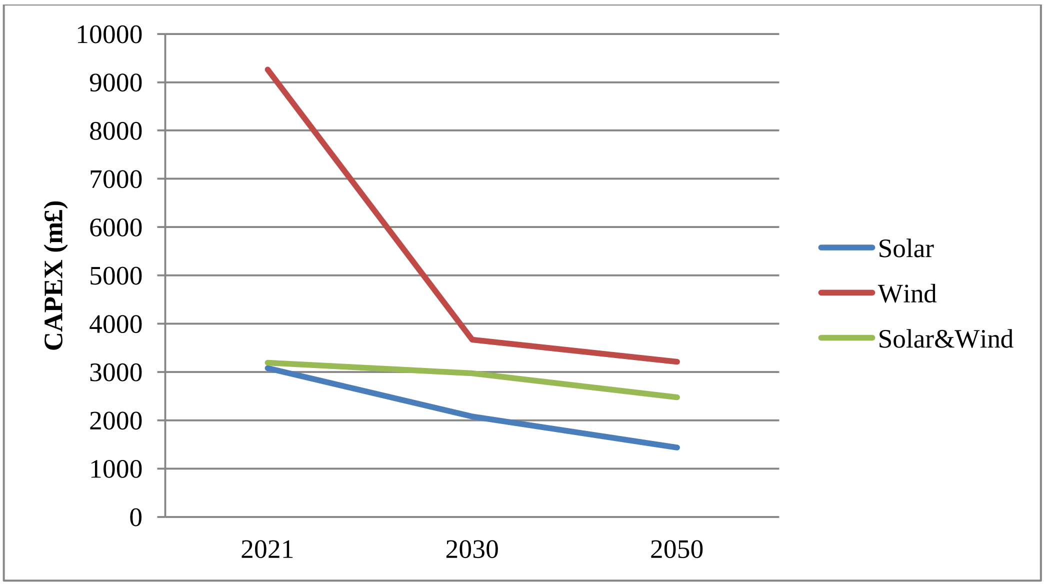

Figure 23: Overall results of CAPEX for proposal 1

Land space

In Figure 24 the land space requirements for each scenario are given. As expected scenario1 with only solar energy needs the most land and the wind energy scenario, since we have offshore wind, takes minimum land space. The combination of the two RES in scenario 3 in all three periods results in less space requirement than scenario 1. Moreover, the results of scenario 1 show that for the different time periods the needed space is decreasing. That's the result of the increase in solar panel's efficiency as mentioned in section 3.3.4.

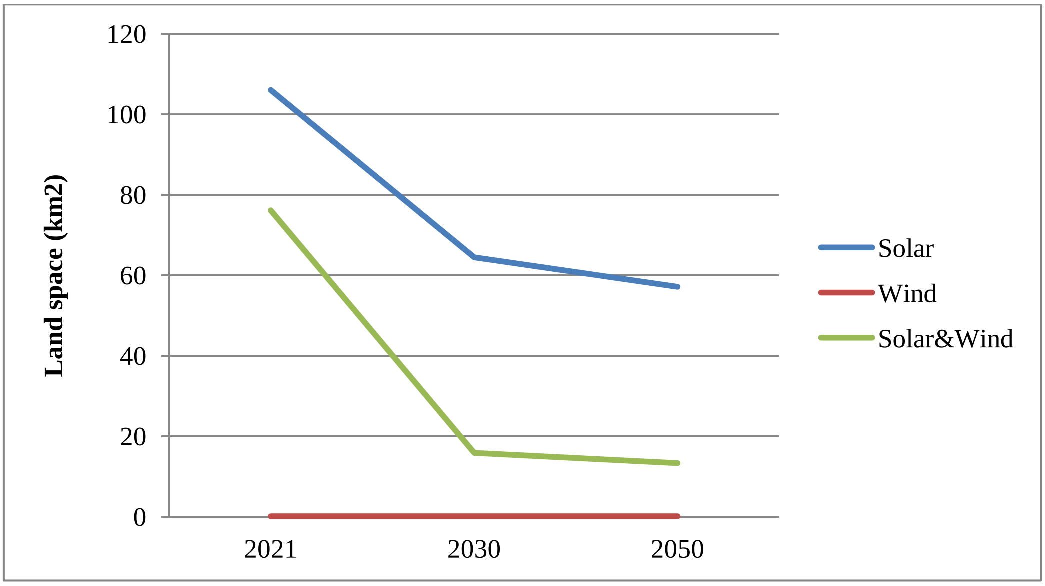

Figure 24: Overall results of land space requirements for proposal 1

RES Capacity

In Figure 25 the overall results of the RES Capacity requirements for proposal 1 are given. Scenario 1 and 2 with solar and wind respectively have a decrease in all three simulation periods. Especially solar energy has the biggest drop due to the increase of the solar panel's efficiency. The decline from 2021 to 2030 in the needed capacity of offshore wind energy is the result of the increase in the efficiency of the electrolyzer.

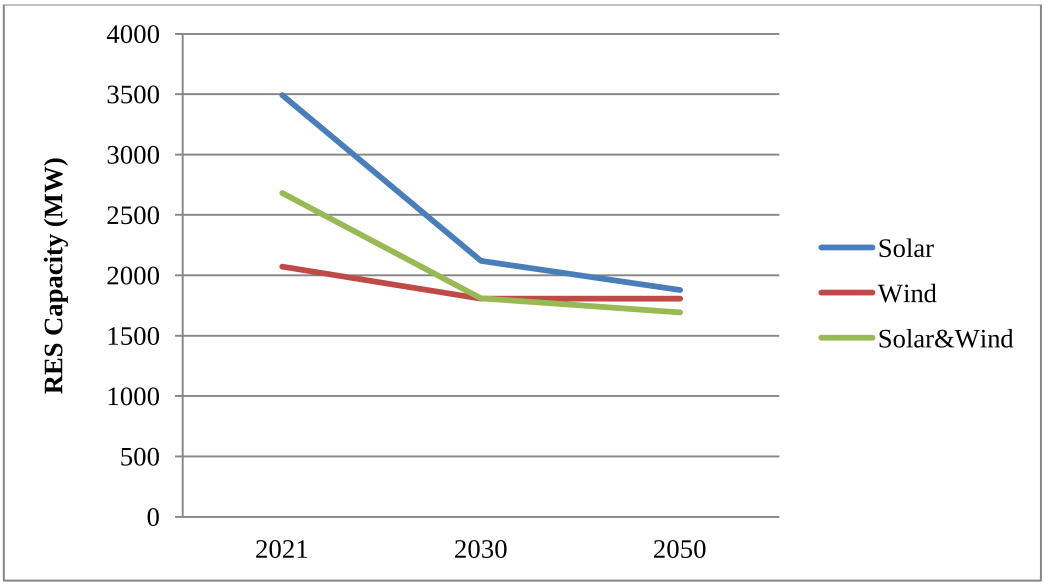

Figure 25: Overall results of RES Capacity requirements for proposal 1

Net Present Value

In Figure 26 the NVP for the first 15 years of the proposal for each scenario is given. All production scenarios have a positive NVP for 2030 and 2050. For 2021 only scenario 2 with the wind energy production is not profitable with a negative NPV. However, a significant increase is observed from 2021 to 2030. Based on the results scenario 1 would be more profitable for all time periods.

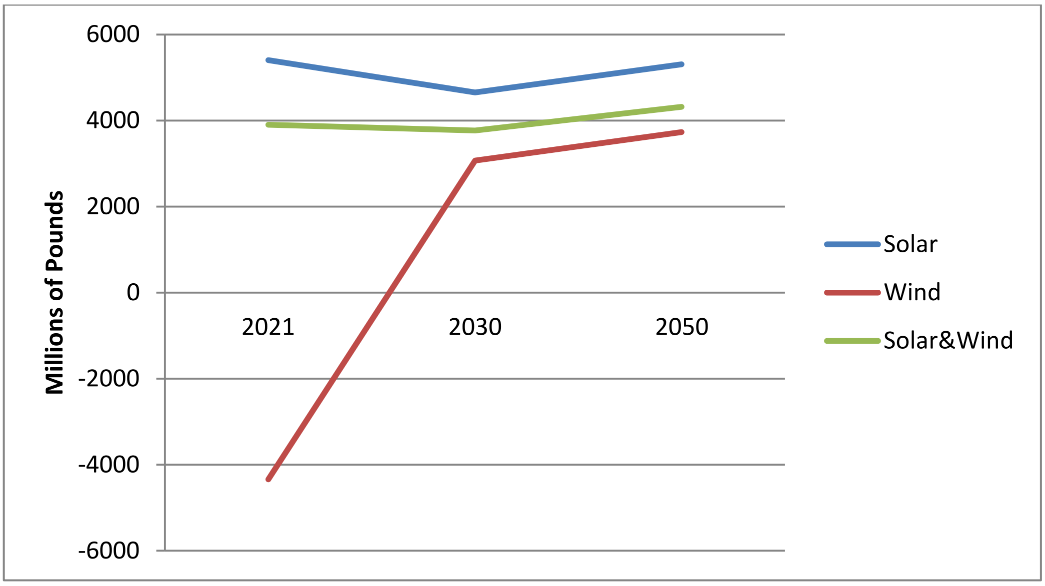

Figure 26: Overall results of NPV for proposal 1

Comments

- The results for the needed RES capacity show that the proposal is not feasible. Such capacities require large amounts of space on land and sea. This is confirmed by the land requirements for each scenario and the area needed for the offshore wind farms.

- In addition, the cost for each scenario is difficult to be supported. But as the NVP showed the profitability for each scenario is positive. The most realistic scenario would be scenario 2 because of the land requirement.

4.2 Proposal 2

Proposal 2 refers to the decarbonization of 4.5% of the passenger cars as calculated in section 3.1.1. After the simulations, the following results were obtained.

4.2.1 2021

Scenario 1: Production of hydrogen using only solar energy.

The CAPEX for scenario 1 is 123.058 million pounds and the total space required is 3370430.583 m^2. As shown in Figure 27 (b), 54% of the total CAPEX for proposal 2 accounts for the solar panels needed. In addition, as illustrated in Figure 27 (a) in comparison to the electrolyzer and the storage solar panels requires the majority of space. The total space for this scenario is equivalent to 44.89 GSP stadiums.

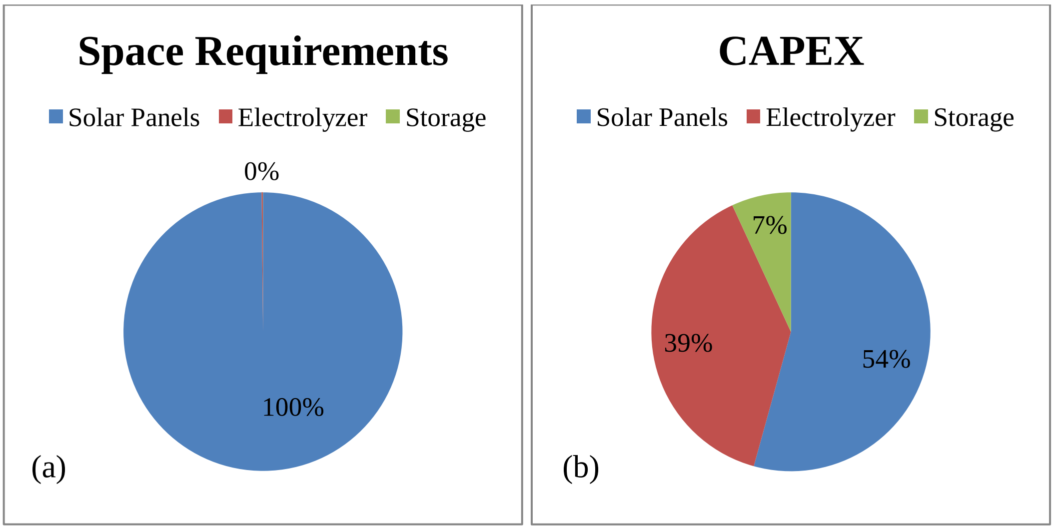

Figure 27: Space requirements (a) and CAPEX (b) for Proposal 2 in 2021, Scenario 1

Scenario 2: Production of hydrogen using only wind energy.

The CAPEX for scenario 2 is 462.156 million pounds and the total space required is 301591.857 m^2. As shown in Figure 28 (b), 90% of the total CAPEX for proposal 2 accounts for the wind turbines. In addition, as illustrated in Figure 28 (a) wind turbines require the majority of space. However, the total land space for this scenario is only for the electrolyzer and storage and is equivalent to 0.05 GSP stadiums. Looking at the results is easy to notice that this scenario is more practical in terms of space but it's very expensive since the CAPEX needed is approximately 4 times more than scenario 1.

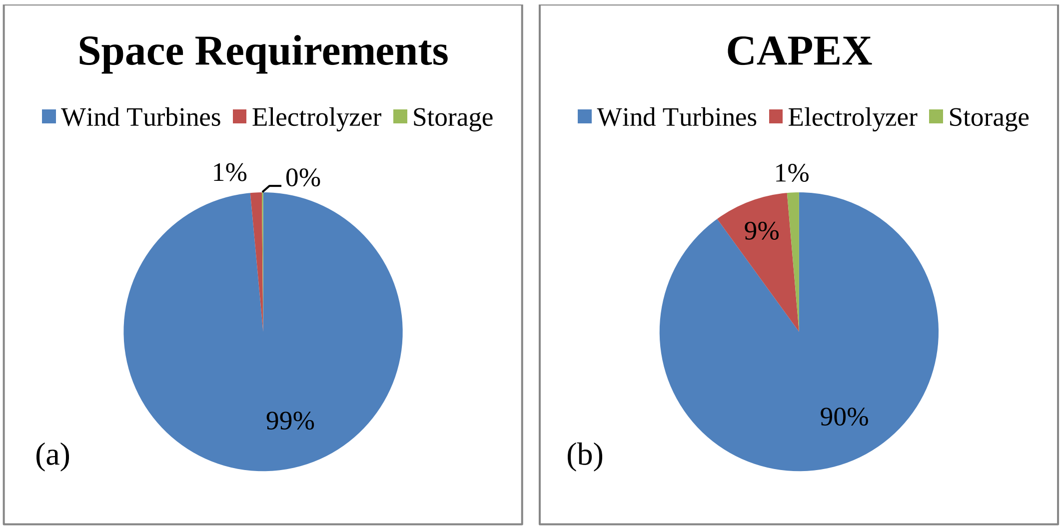

Figure 28: Space requirements (a) and CAPEX (b) for Proposal 2 in 2021, Scenario 2

Scenario 3: Production of electricity using both solar energy and offshore wind energy

The CAPEX for scenario 3 is 145.659 million pounds and the total space required is 30230552.481 m^2. As shown in Figure 29 (b), 22% of the total CAPEX for proposal 2 accounts for the wind turbines, 33% for the electrolyzer and 41% for the solar panels. In addition, as illustrated in Figure 29 (a) the majority of space is needed for the solar panels, which is 3000025.704 m^2. The total land space for this scenario does not include wind turbines and is equivalent to 40.03 GSP stadiums. In terms of land use, the results are better than scenario 1 but still not practical. The results (Figure 29 (c)) showed that only 7% of the RES capacity is for wind turbines that's because Homer Pro uses financial criteria to optimize the system. The high cost of wind turbines is a major constrain for the inclusion of more wind turbines and this can be seen when comparing the results of scenario 1. With only 7% share of wind energy, the CAPEX increased by 22.601 million pounds.

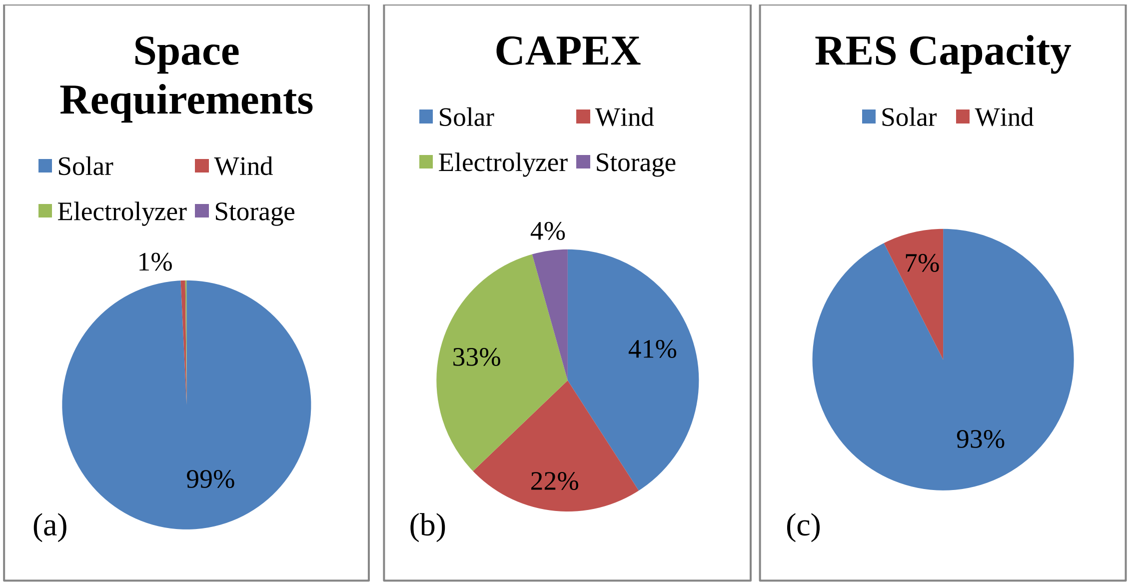

Figure 29: Space requirements (a), CAPEX (b) and RES Capacity (c) for Proposal 2 in 2021, Scenario 3

4.2.2 2030

Scenario 1: Production of hydrogen using only solar energy.

The CAPEX for scenario 1 is 97.968 million pounds and the total space required is 3001630.44 m^2. As shown in Figure 30 (b), 60% of the total CAPEX for proposal 2 accounts for the solar panels needed. In addition, as illustrated in Figure 30 (a) in comparison to the electrolyzer and the storage solar panels requires the majority of space. The total space for this scenario is equivalent to 39.99 GSP stadiums.

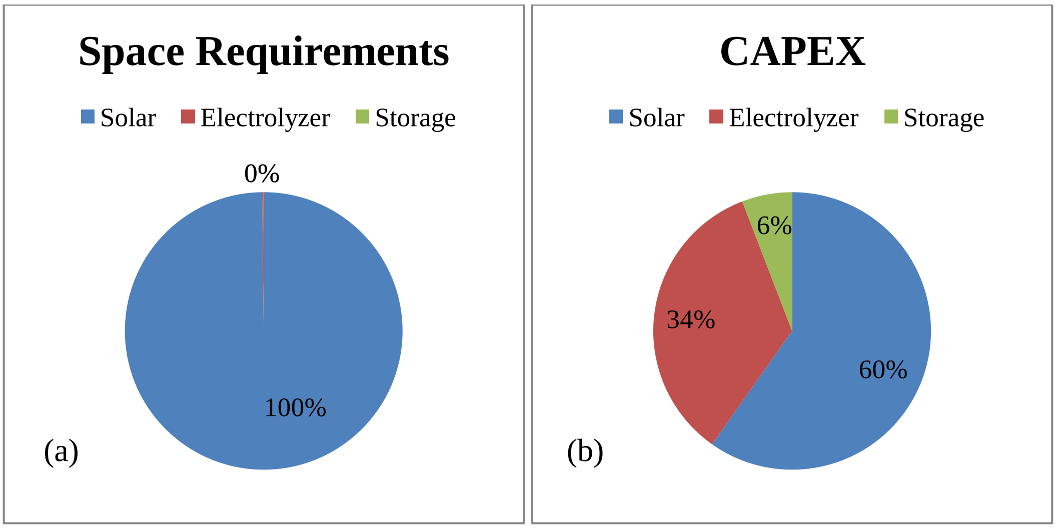

Figure 30: Space requirements (a) and CAPEX (b) for Proposal 2 in 2030, Scenario 1

Scenario 2: Production of hydrogen using only wind energy.

The CAPEX for scenario 2 is 192.18 million pounds and the total space required is 301591.857 m^2. As shown in Figure 31 (b), 82% of the total CAPEX for proposal 2 accounts for the wind turbines. In addition, as illustrated in Figure 31 (a) in comparison to

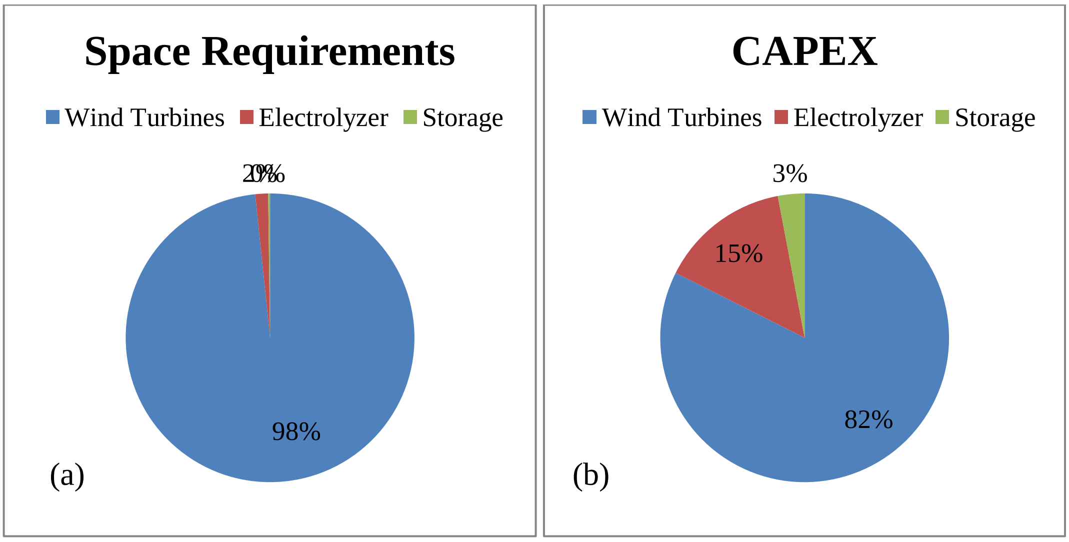

Figure 31 : Space requirements (a) and CAPEX (b) for Proposal 2 in 2030, Scenario 2

the electrolyzer and the storage wind turbines require the majority of space. However, land space is only needed for the electrolyzer and storage and is equivalent to 0.061 GSP stadiums. The results show that this scenario is more practical in terms of space but it's very expensive since the CAPEX needed is approximately 2 times more than scenario 1.

Scenario 3: Production of electricity using both solar energy and offshore wind energy

The CAPEX for scenario 3 is 99.414 million pounds and the total space required is 1748801 m^2. As shown in Figure 32 (b), 40% of the total CAPEX for proposal 2 accounts for the wind turbines, 33% for the solar panels and 23% for the electrolyzer. In addition, as it can be observed in Figure 32 (a) the majority of space is needed for the solar panels, which is 1691818 m^2. The total land space for this scenario is only for the solar panels, the electrolyzer and storage and is equivalent to 22.59 GSP stadiums. In terms of land use the results are better than scenario 1 but still not practical. The results (Figure 32 (c)) showed that only 30% of the RES capacity is for wind turbines.

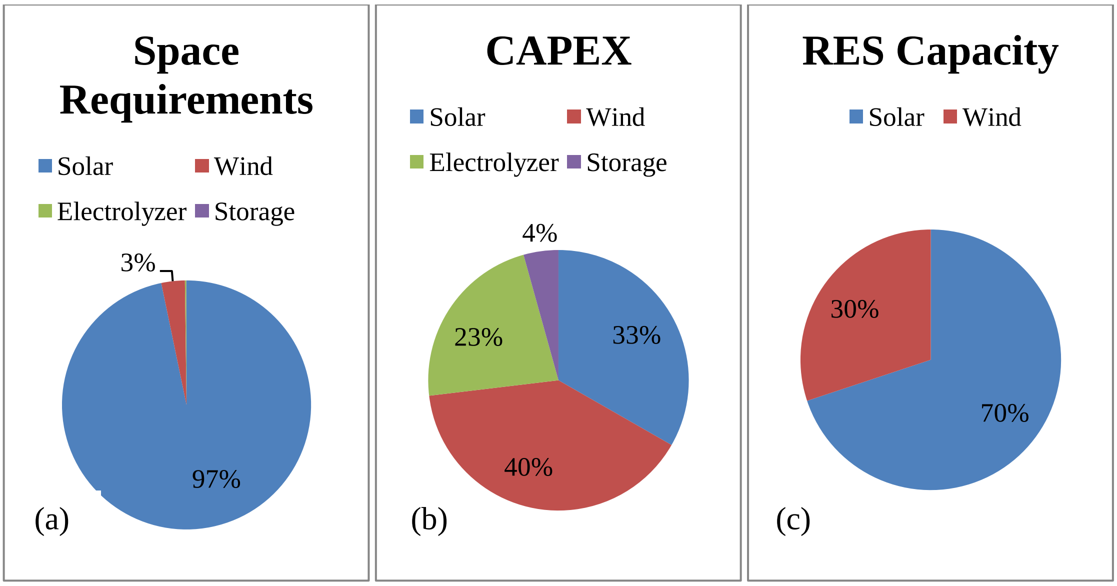

Figure 32: Space requirements (a), CAPEX (b) and RES Capacity (c) for Proposal 2 in 2030, Scenario 3

4.2.3 2050

Scenario 1: Production of hydrogen using only solar energy.

The CAPEX for scenario 1 is 67.389 million pounds and the total space required is 2647369 m^2. As shown in Figure 33 (b), 62% of the total CAPEX for proposal 2 accounts for the solar panels needed. In addition, as illustrated in Figure 33 (a) in comparison to the electrolyzer and the storage solar panels requires the majority of space. The total land space for this scenario is equivalent to 35.27 GSP stadiums.

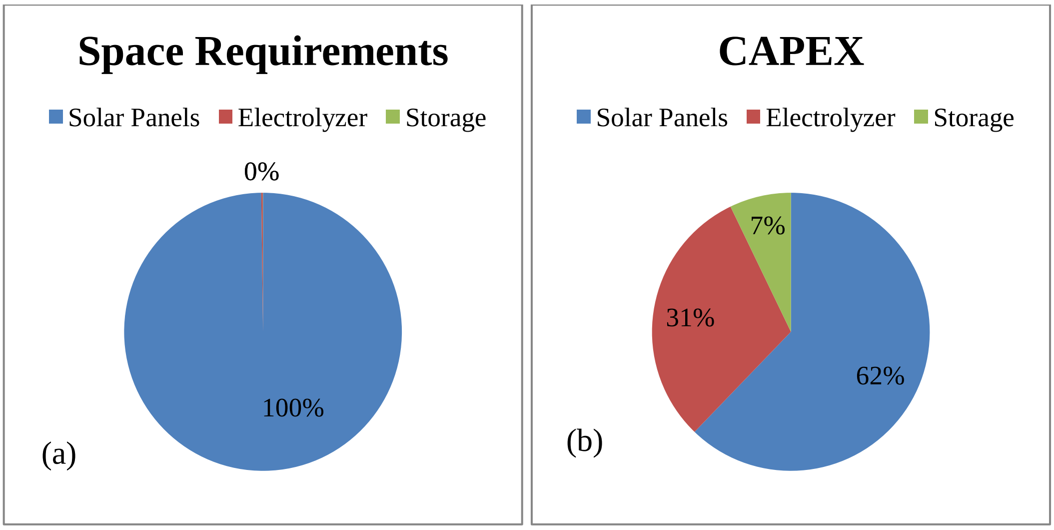

Figure 33: Space requirements (a) and CAPEX (b) for Proposal 2 in 2050, Scenario 1

Scenario 2: Production of hydrogen using only wind energy.

The CAPEX for scenario 2 is 156.738 million pounds and the total space required is 256027.2 m^2. As shown in Figure 34 (b), 82% of the total CAPEX for proposal 2 accounts for the wind turbines. In addition as illustrated in Figure 34 (a) in comparison to the electrolyzer and the storage wind turbines require the majority of space. However, land space is only needed for the electrolyzer and storage and is equivalent to 0.061 GSP stadiums.

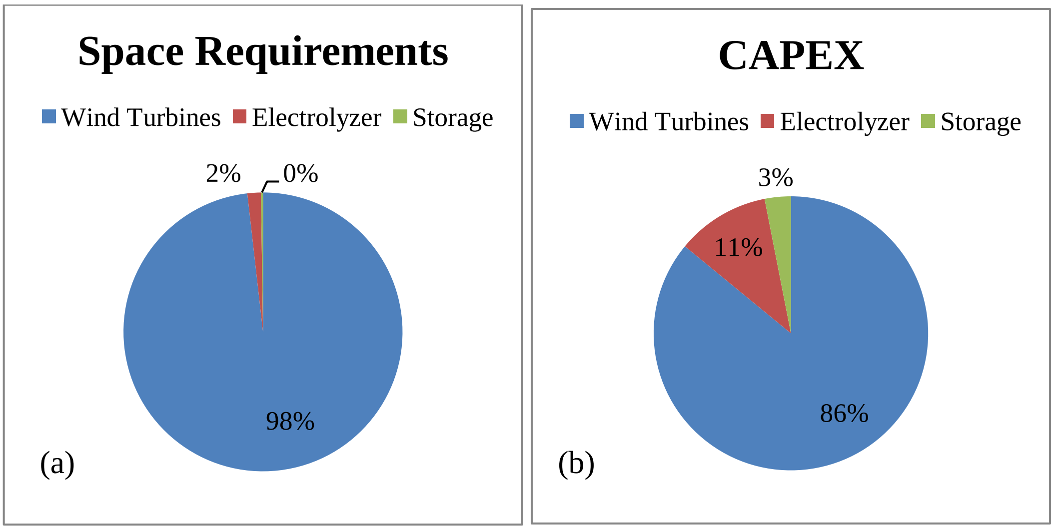

Figure 34: Space requirements (a) and CAPEX (b) for Proposal 2 in 2050, Scenario 2

Scenario 3: Production of electricity using both solar energy and offshore wind energy

The CAPEX for scenario 3 is 73.564 million pounds and the total space required is 2113361 m^2. As shown in Figure 35 (b) 33% of the total CAPEX accounts for the wind turbines, 45% for the solar panels and 19% for the electrolyzer. In addition as illustrated in Figure 35 (a) the majority of space is needed for the solar panels, which is 2073305.705 m^2. The total land space for this scenario is only for the solar panels, the electrolyzer and storage and is equivalent to 22.59 GSP stadiums. The results (Figure 35 (c)) showed that only 19% of the RES capacity is for wind turbines.

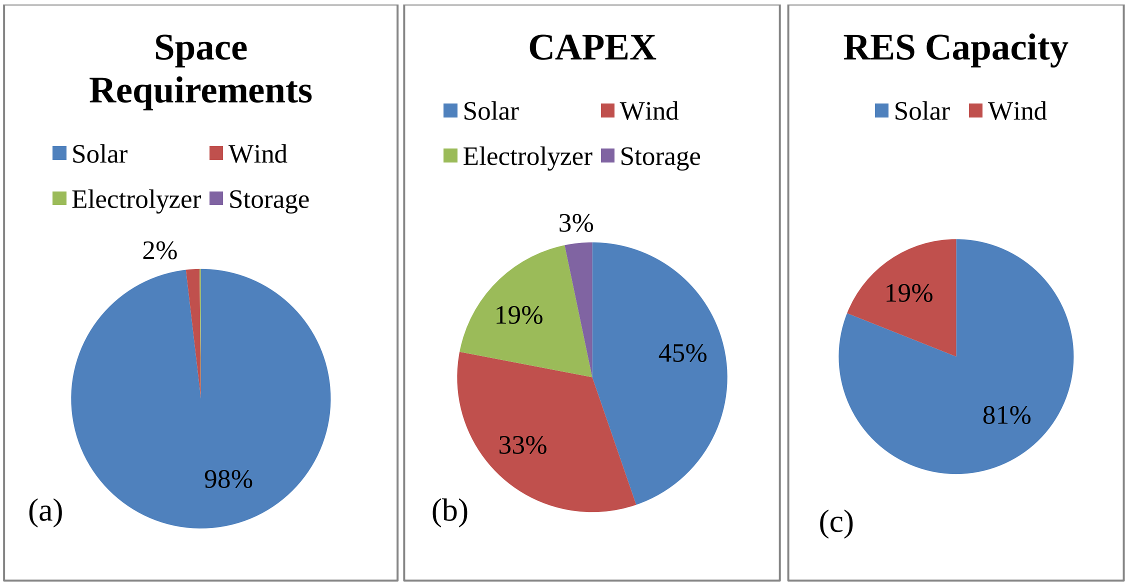

Figure 35: Space requirements (a), CAPEX (b) and RES Capacity (c) for Proposal 2 in 2050, Scenario 3

4.2.4 Overall Results

CAPEX

The overall results for the CAPEX of proposal 2 are given in Figure 36. As it can be observed in all three scenarios of RES the CAPEX has a significant reduction. The biggest reduction is made in the CAPEX of scenario 2 with the exclusive production of hydrogen with only wind energy.

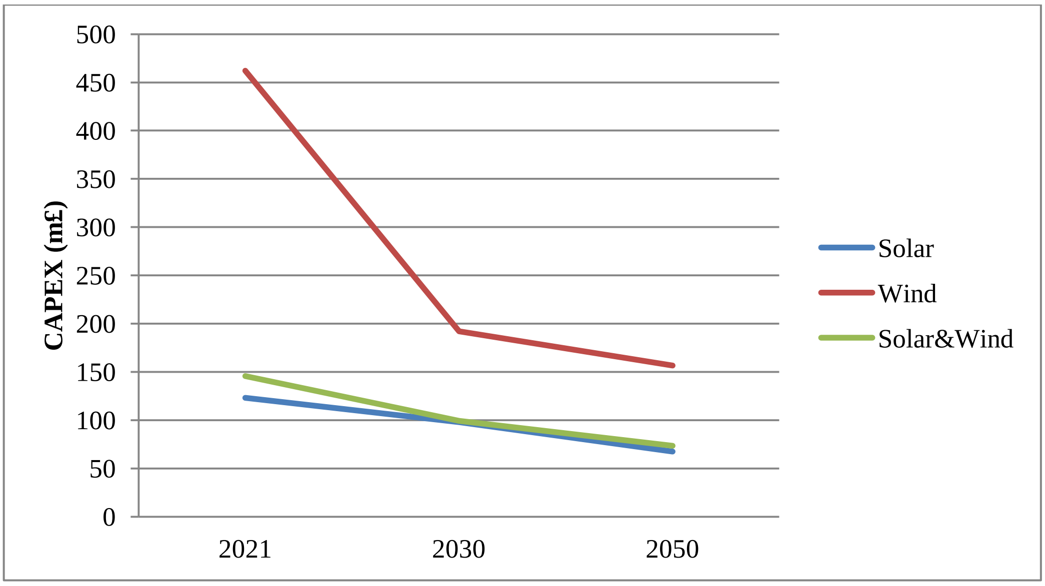

Figure 36: Overall results of CAPEX for proposal 2

Land space

In Figure 37 the land space requirements for each scenario are given. As expected scenario1 with only solar energy needs the most land and wind energy since we have offshore wind takes minimum land space. The combination of the two RES in scenario 3 in all three periods results in less space requirement than the solar scenario. The results of scenario 1 show that for the different time periods the needed space is reducing. That's the result of the increase in solar panel's efficiency as mentioned in section 3.3.4.

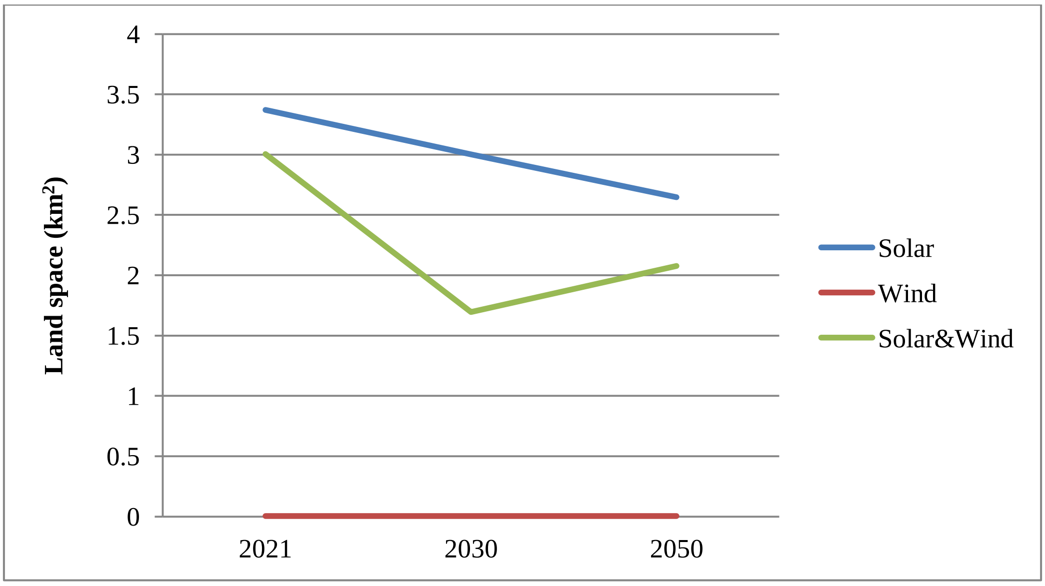

Figure 37: Overall results of land space requirements for proposal 2

RES Capacity

In Figure 38 the overall results of the RES Capacity requirements for proposal 2 are given. Scenario 1 and 2 with solar and wind respectively have a steady decrease in all three simulation periods. Especially solar energy has the biggest drop due to the increase of the solar panel's efficiency. The decline in the needed capacity of wind energy is the result of the increase in the efficiency of the electrolyzer.

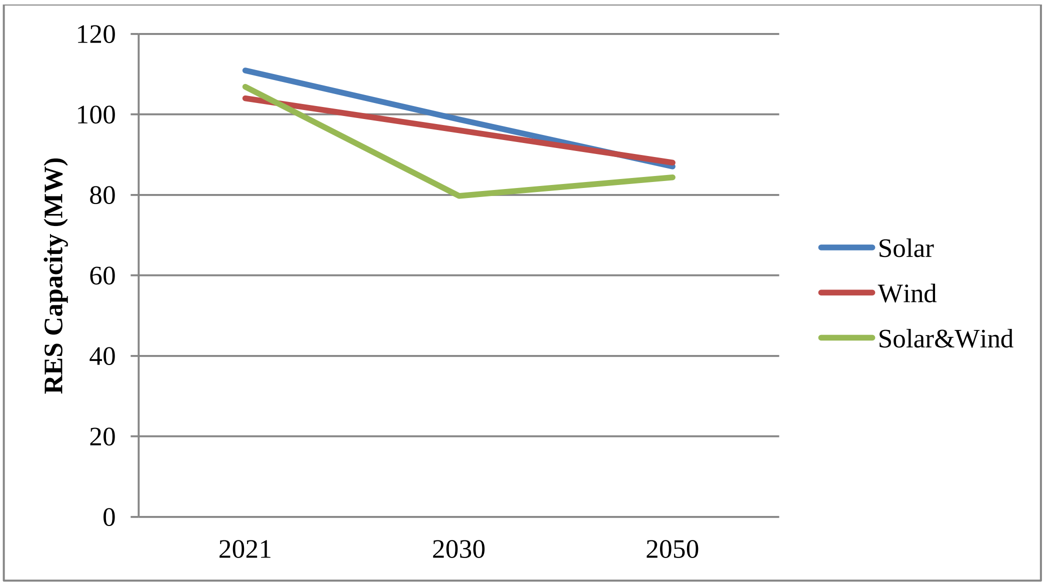

Figure 38: Overall results of RES Capacity requirements for proposal 2

Net Present Value

In Figure 39 the NVP for the first 15 years of the project for each scenario is given. In all of the scenarios an increase in NVP is observed. For 2021 only scenario 3 with the wind energy production is not profitable with a positive NPV. For the 2030 and 2050 time periods all scenarios have a positive NVP with wind energy having a significant increase. Based on the results scenario 1 would be more profitable for all time periods.

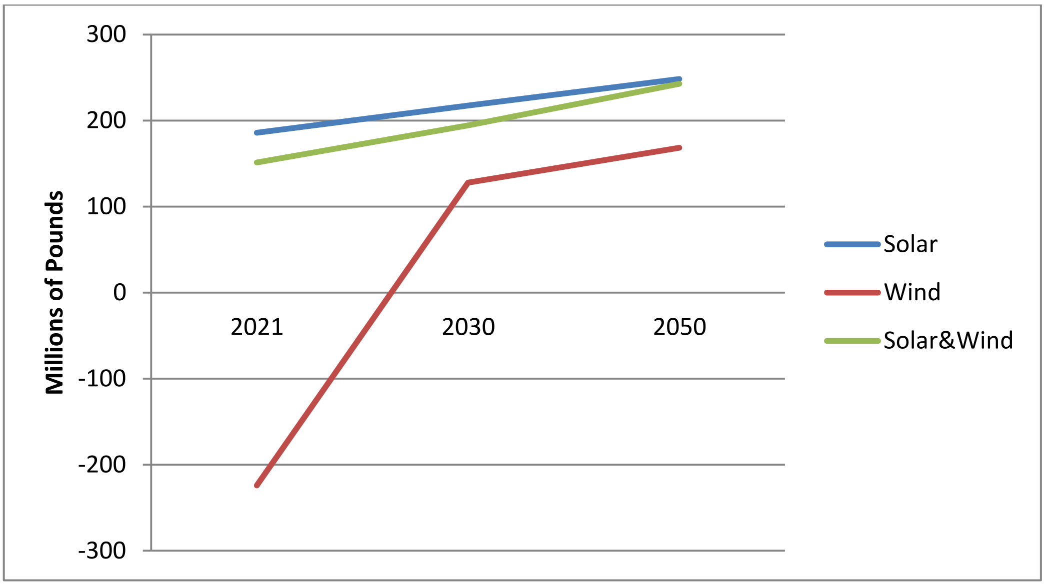

Figure 39: Overall results of NPV for proposal 2

Comments

- Based on the results for the CAPEX and NVP scenarios 1 and 3 are more profitable than scenario 2. However, due to the land requirements, they are not practical to implement.
- The most realistic scenario to implement is the second scenario which despite the higher CAPEX for the time periods of 2030 and 2050 has a significant NVP.
- As mentioned before Homer Pro does not take into account the required space for each RES so another realistic scenario would be scenario 3 but with higher share of wind energy.

4.3 Proposal 3

Proposal 2 refers to the demand of hydrogen to decarbonize 100% of trucks. The demand was calculated in section 3.1.1. After the simulations the following results were obtained.

4.3.1 2021

Scenario 1: Production of hydrogen using only solar energy.

The CAPEX for scenario 1 is 142.773 million pounds and the total space required is 3894345.64 m^2. As shown in Figure 40 (b), 54% of the total CAPEX for proposal 2 accounts for the solar panels needed. In addition, as illustrated in Figure 40 (a) in comparison to the electrolyzer and the storage solar panels requires the majority of space. The total space for this scenario is equivalent to 51.88 GSP stadiums.

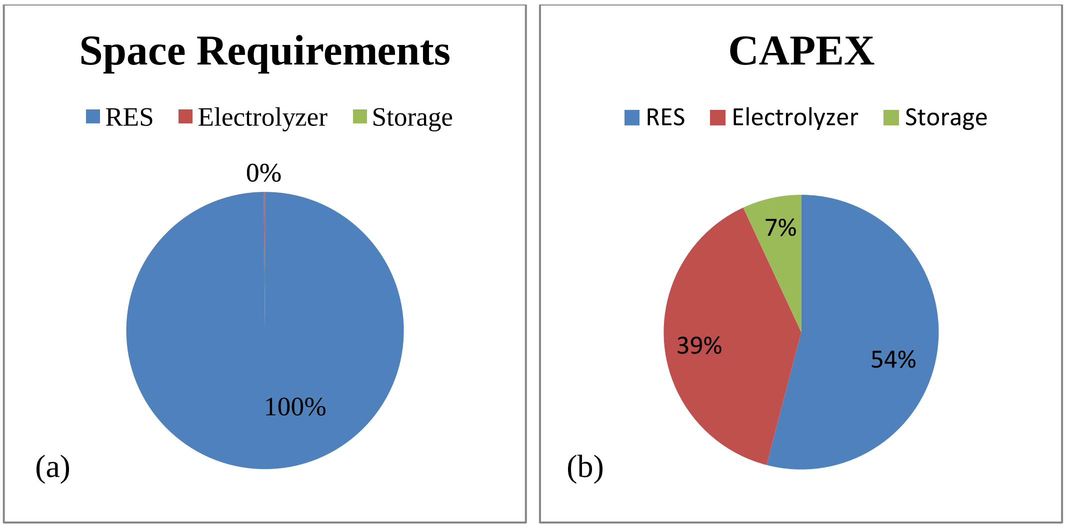

Figure 40: Space requirements (a) and CAPEX (b) for Proposal 3 in 2021, Scenario 1

Scenario 2: Production of hydrogen using only wind energy.

The CAPEX for scenario 2 is 559.214 million pounds and the total space required is 370237.785 m^2. As shown in Figure 41 (b), 90% of the total CAPEX for proposal 2 accounts for the wind turbines. In addition, as illustrated in Figure 41(a) in comparison to the electrolyzer and the storage, wind turbines require the majority of space. The total land space for this scenario is only for the electrolyzer and storage and is equivalent to 0.06 GSP stadiums.

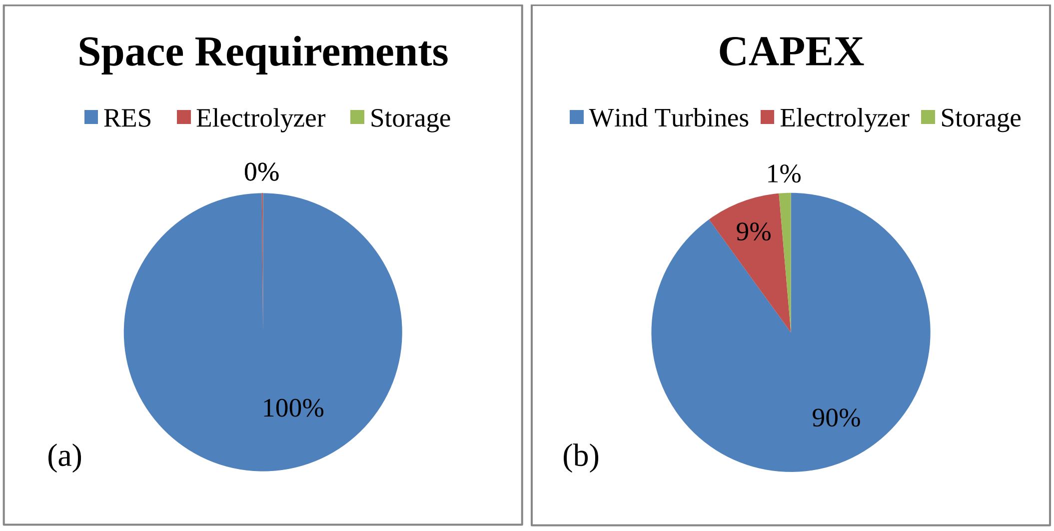

Figure 41: Space requirements (a) and CAPEX (b) for Proposal 3 in 2021, Scenario 2

Scenario 3: Production of electricity using both solar energy and offshore wind energy

The CAPEX for scenario 3 is 175.39 million pounds and the total space required is 6037900.45 m^2. As shown in Figure 42(b,) 22% of the total CAPEX for proposal 3 accounts for the wind turbines, 33% for the electrolyzer and 41% for the solar panels. In addition, as illustrated in Figure 42 (a) the majority of space is needed for the solar panels, which is 2832576.903 m^2. The total land space for this scenario is only for the solar panels, the electrolyzer and storage and is equivalent to 37.8 GSP stadiums. In terms of land use, the results are better than scenario 1 but still not practical. The results (Figure 42 (c)) showed that only 7% of the RES capacity is for wind turbines that's because Homer Pro uses financial criteria to optimize the system.

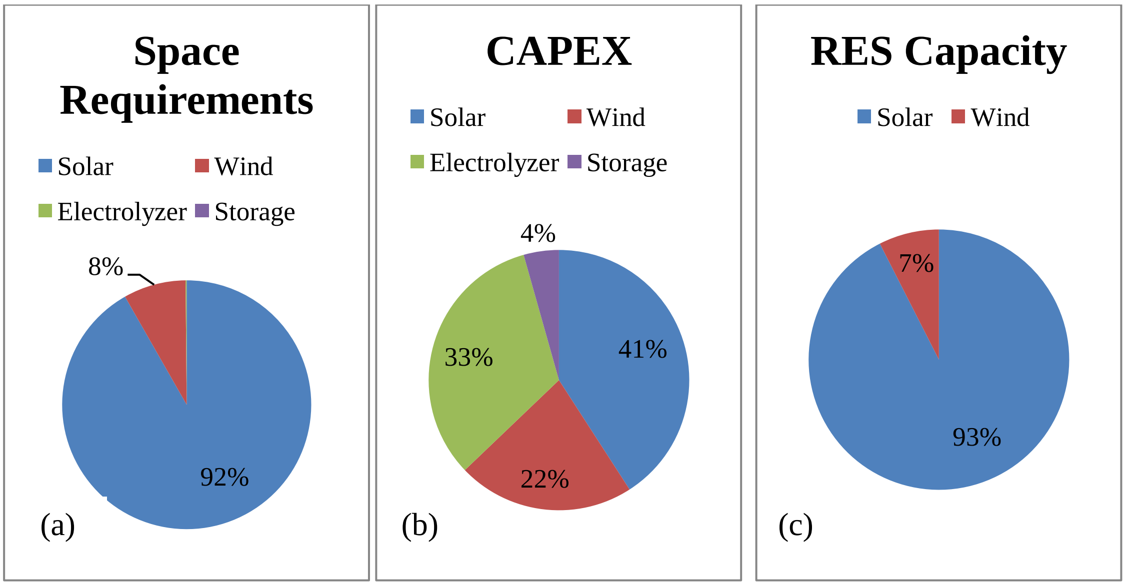

Figure 42: Space requirements (a), CAPEX (b) and RES Capacity (c) for Proposal 3 in 2021, Scenario 3

4.3.2 2030

Scenario 1: Production of hydrogen using only solar energy.

The CAPEX for scenario 1 is 114.44 million pounds and the total space required is 3509337.742 m^2. As shown in Figure 43 (b), 60% of the total CAPEX for proposal 3 accounts for the solar panels needed. In addition, as illustrated in Figure 43 (a) in comparison to the electrolyzer and the storage solar panels requires the majority of space. The total space for this scenario is equivalent to 46.75 GSP stadiums.

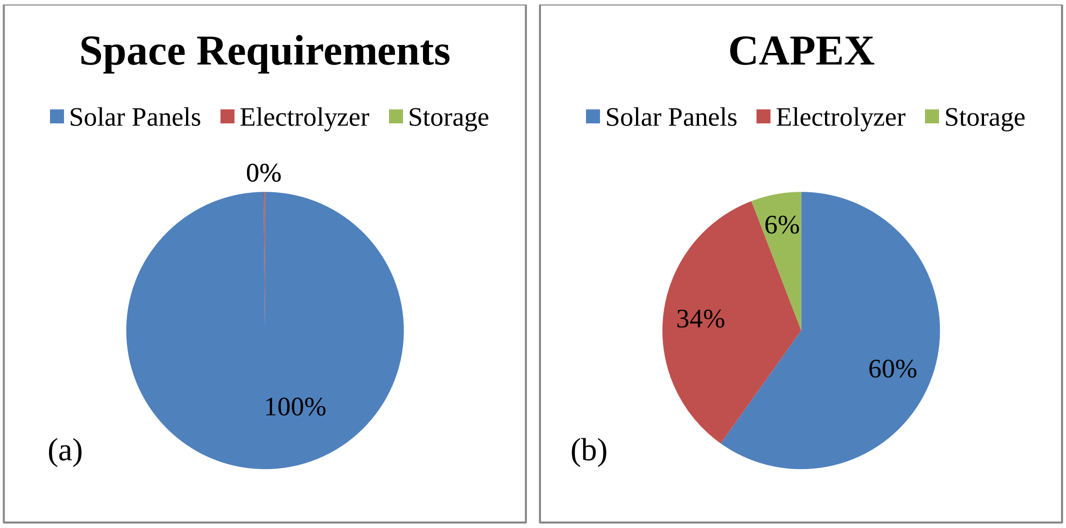

Figure 43: Space requirements (a) and CAPEX (b) for Proposal 3 in 2030, Scenario 1

Scenario 2: Production of hydrogen using only wind energy.

The CAPEX for scenario 2 is 206.33 million pounds and the total space required is 301840.76 m^2. As shown in Figure 45 (b), only 82% of the total CAPEX for proposal 3 accounts for the wind turbines. In addition, as illustrated in Figure 45 (a) in comparison to the electrolyzer and the storage wind turbines require the majority of space. However, land space is only needed for the electrolyzer and storage and is equivalent to 0.061 GSP stadiums. The results suggest that this scenario is more practical in terms of space but it's very expensive.

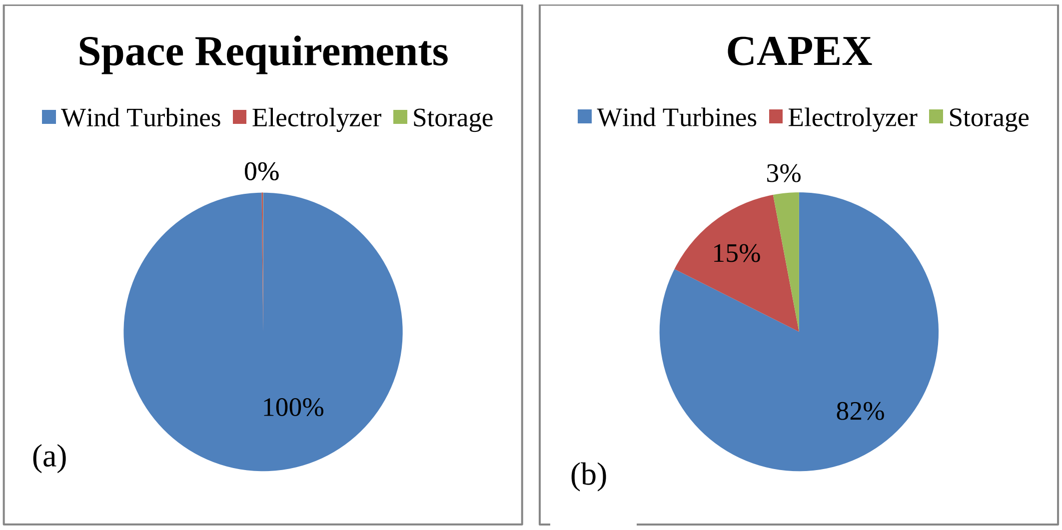

Figure 44 : Space requirements (a) and CAPEX (b) for Proposal 3 in 2030, Scenario 2

Scenario 3: Production of electricity using both solar energy and offshore wind energy

The CAPEX for scenario 3 is 114.7 million pounds and the total space required is 6954952 m^2. As shown in Figure 45 (b), 40% of the total CAPEX for proposal 2 accounts for the wind turbines, 33% for the solar panels and 23% for the electrolyzer. In addition, as illustrated in Figure 45 (a) the majority of space is needed for the solar panels, which is 2150428.67 m^2. The total land space for this scenario is only for the solar panels, the electrolyzer and storage and is equivalent to 28.71 GSP stadiums. The results (Figure 45 (c)) showed that only 30% of the RES capacity is for wind turbines.

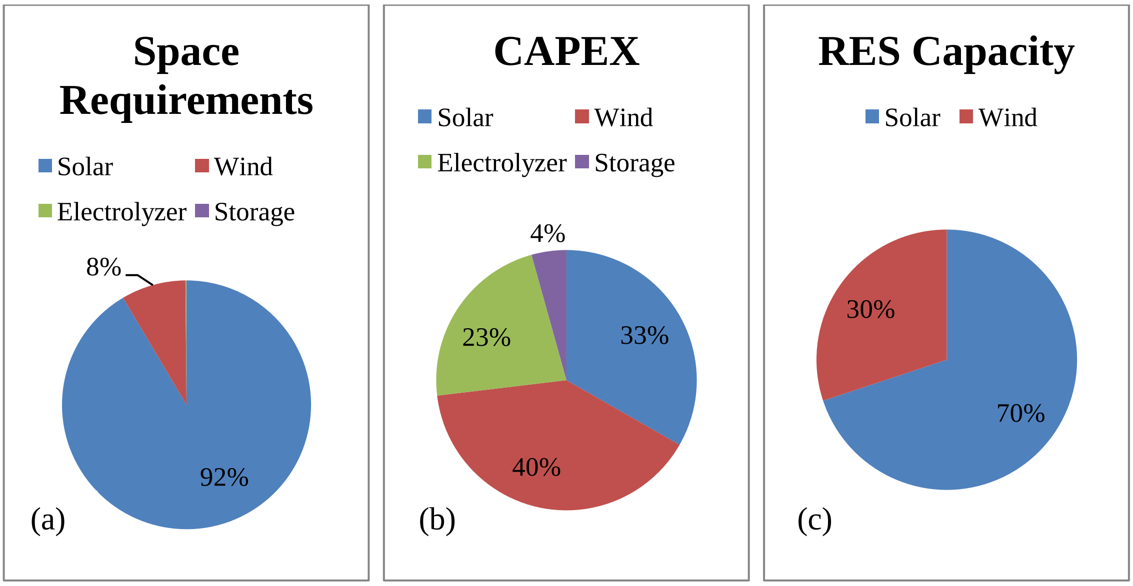

Figure 45: Space requirements (a), CAPEX (b) and RES Capacity (c) for Proposal 3 in 2030, Scenario 3

4.3.3 2050

Scenario 1: Production of hydrogen using only solar energy.

The CAPEX for scenario 1 is 78.52 million pounds and the total space required is 3084504.59 m^2. As shown in Figure 46(b) 62% of the total CAPEX for proposal 3 accounts for the solar panels needed. In addition, as illustrated in Figure 46 (a) in comparison to the electrolyzer and the storage solar panels requires the majority of space. The total land space for this scenario is equivalent to 41.09 GSP stadiums.

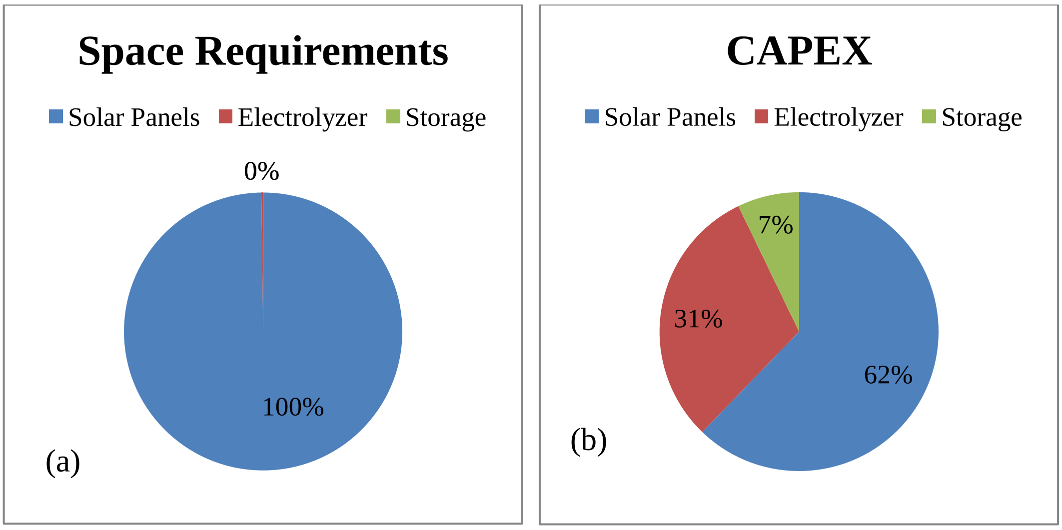

Figure 46: Space requirements (a) and CAPEX (b) for Proposal 3 in 2050, Scenario 1

Scenario 2: Production of hydrogen using only wind energy.

The CAPEX for scenario 2 is 168.38 million pounds and the total space required is 278809.14 m^2. As shown in Figure 47(b) 86%, of the total CAPEX for proposal 3 accounts for the wind turbines. In addition, as illustrated in Figure 47 (a) in comparison to the electrolyzer and the storage wind turbines require the majority of space. However, land space is only needed for the electrolyzer and storage and is equivalent to 0.06 GSP stadiums.

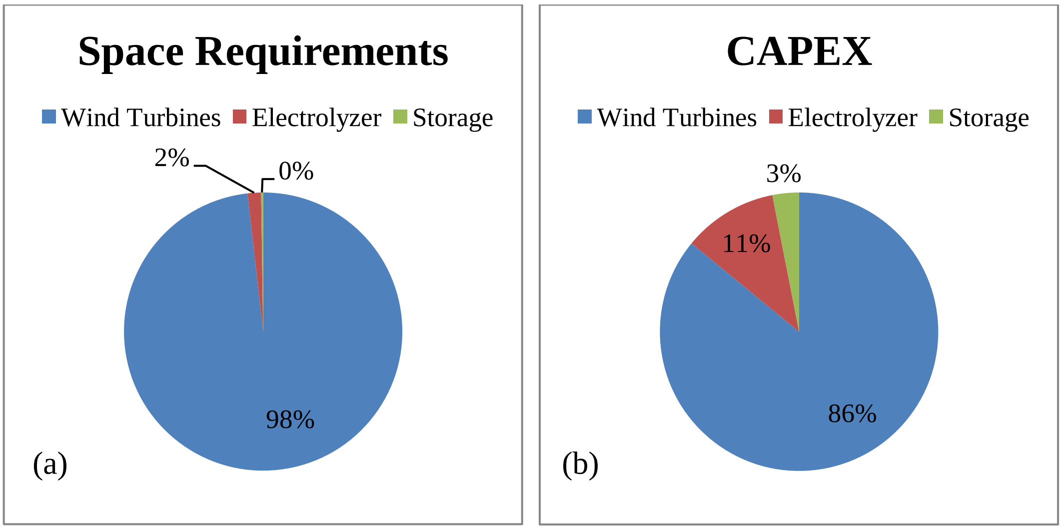

Figure 47: Space requirements (a) and CAPEX (b) for Proposal 3 in 2050, Scenario 2

Scenario 3: Production of electricity using both solar energy and offshore wind energy

The CAPEX for scenario 3 is 84.49 million pounds and the total space required is 5635793.82 m^2. As shown in Figure 48(b), 33% of the total CAPEX accounts for the wind turbines, 45% for the solar panels and 19% for the electrolyzer. In addition, as illustrated in Figure 48 (a) the majority of space is needed for the solar panels, which is 2431270.39 m^2. The total land space for this scenario is only for the solar panels, the electrolyzer and storage and is equivalent to 32.45 GSP stadiums. The results (Figure 48 (c)) showed that only 19% of the RES capacity is for wind turbines.

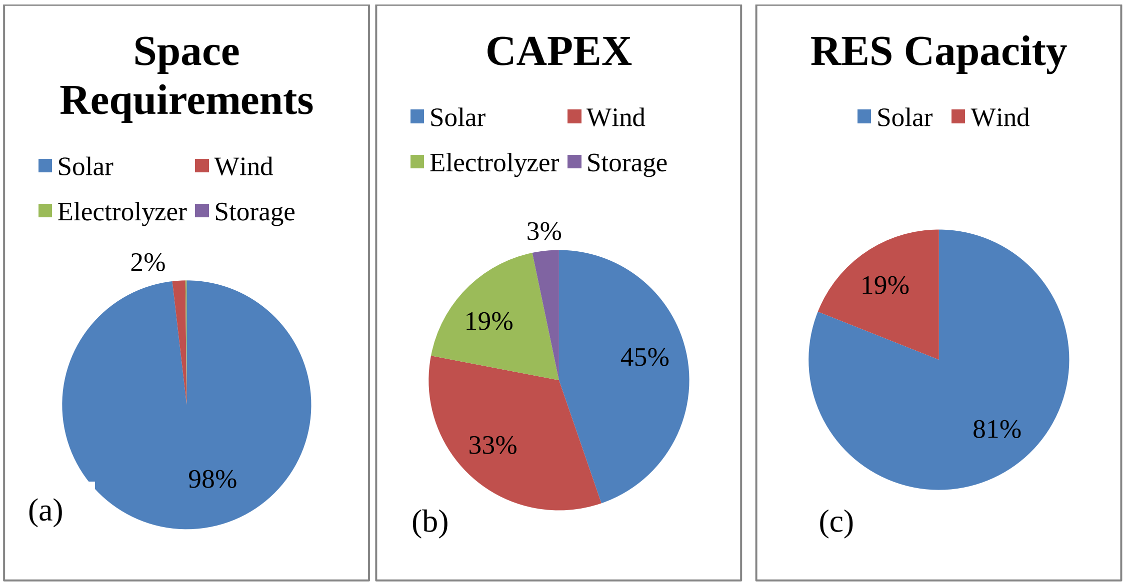

Figure 48: Space requirements (a), CAPEX (b) and RES Capacity (c) for Proposal 3 in 2050, Scenario 3

4.3.4 Overall Results

CAPEX

The overall results for the CAPEX of proposal 3 are given in Figure 49. As it can be observed in all three scenarios of RES the CAPEX has a significant reduction. The biggest reduction is made in the CAPEX of scenario 2 with the exclusive production of hydrogen with only wind energy. The results are similar to proposal 2.

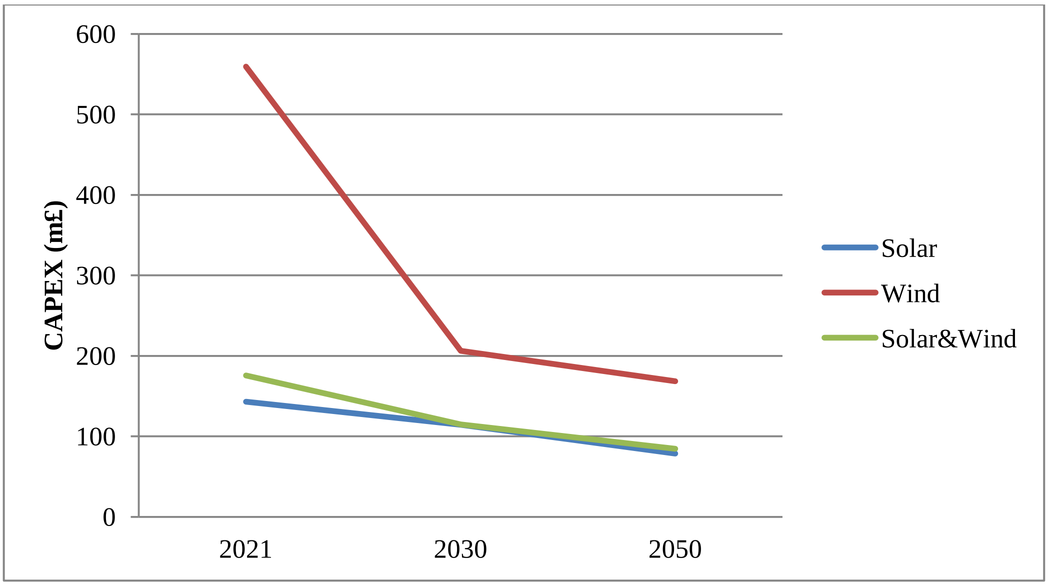

Figure 49: Overall results of CAPEX for proposal 3

Land space

In Figure 50 the land space requirements for each scenario are given. As expected scenario1 with only solar energy needs the most land and wind energy since we have offshore wind takes minimum land space. The combination of the two RES in scenario 3 in all three periods results in less space requirement than the solar scenario. The results of scenario 1 show that for the different time periods the needed space is reducing. That's the result of the increase in solar panel's and electrolyser's efficiencies as mentioned in section 3.3.4.

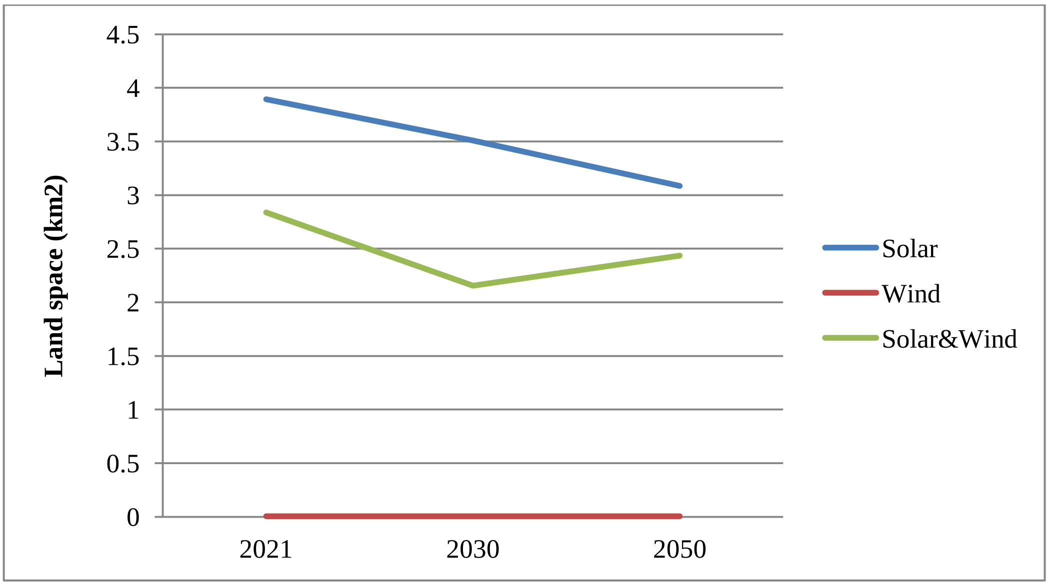

Figure 50: Overall results of land space requirements for proposal 3

RES Capacity

In Figure 51 the overall results of the RES Capacity requirements for proposal 2 are given. Scenario 1 and 2 with solar and wind respectively have a steady decrease in all three simulation periods. Especially solar energy has the biggest drop due to the increase of the solar panel’s efficiency. The decline in the needed capacity of wind energy is the result of the increase in the efficiency of the electrolyzer.

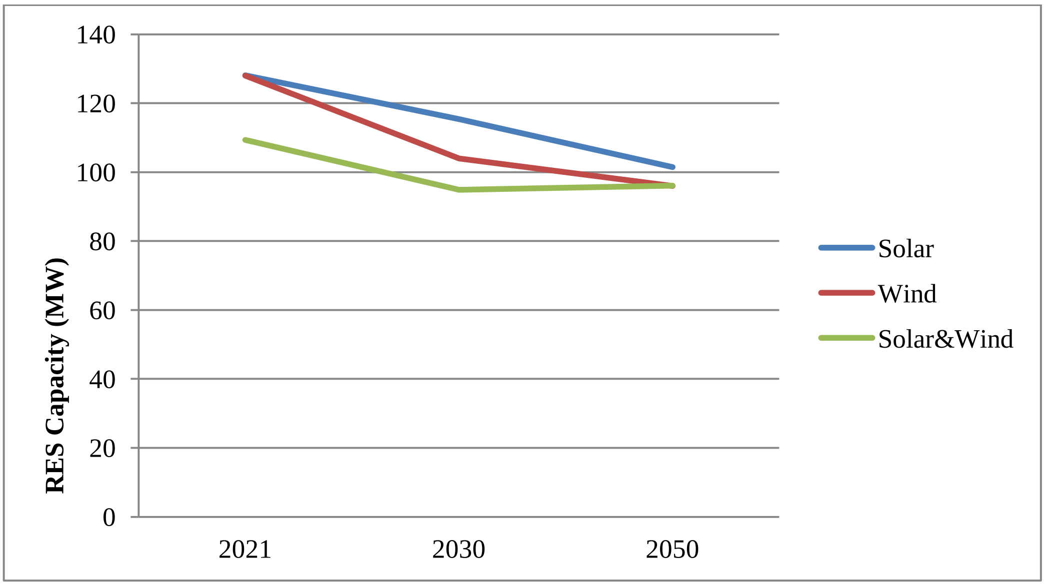

Figure 51: Overall results of RES Capacity requirements for proposal 3

Net Present Value

In Figure 52 the NVP for the first 15 years of the project for each scenario is given. In all of the scenarios an increase in NVP is observed. For 2021 only scenario 3 with the wind energy production is not profitable with a negative NPV. For the 2030 and 2050 time periods all scenarios have a positive NVP with wind energy having a significant increase. Based on the results scenario 1 would be more profitable for all time periods.

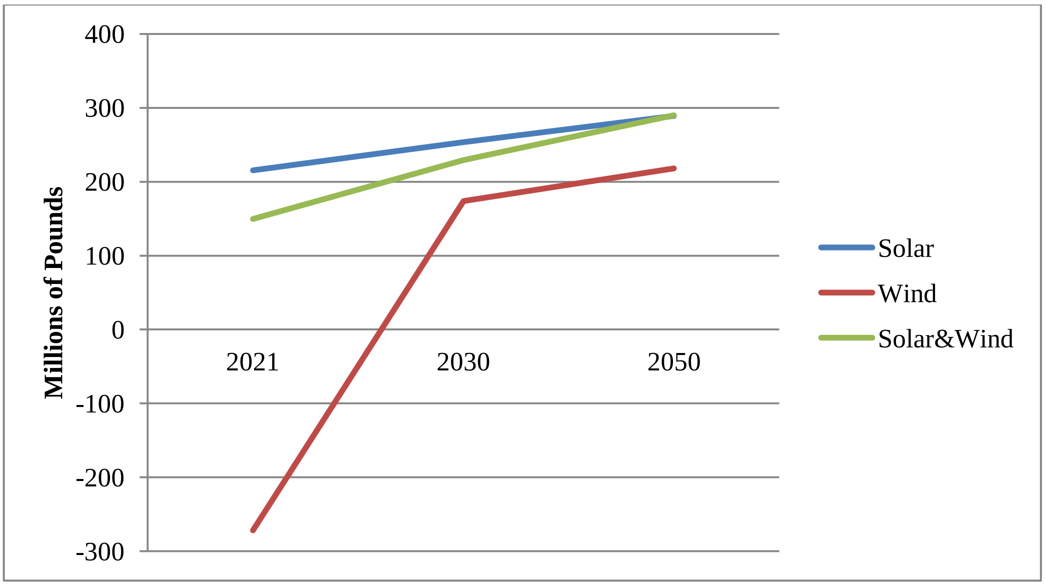

Figure 52: Overall results of NPV for proposal 3

Comments

- Based on the results for the CAPEX and NVP scenarios 1 and 3 are more profitable than scenario 2. However, due to the land requirements they are not practical to implement.
- The most realistic scenario to implement is the second scenario which despite the higher CAPEX for the time periods of 2030 and 2050 has a significant NVP that can attract investments.
- As mentioned before Homer Pro does not take into account the required space for each RES so another realistic scenario would be scenario 3 but with a higher share of wind energy

4.4 Proposal 4

Proposal 4 refers to the demand of hydrogen to decarbonize 10% of the electricity production. The demand was calculated in section 3.1.1 . After the simulations, the following results were obtained.

4.4.1 2021

Scenario 1: Production of hydrogen using only solar energy.

The CAPEX for scenario 1 is 1.663 billion pounds and the total space required is 47481538.25 m^2. As shown in Figure 53 (b), 57% of the total CAPEX for proposal 4 accounts for the solar panels needed. In addition, as illustrated in Figure 53 (a) in comparison to the electrolyzer and the storage solar panels requires the majority of space. The total space for this scenario is equivalent to 632.51 GSP stadiums.

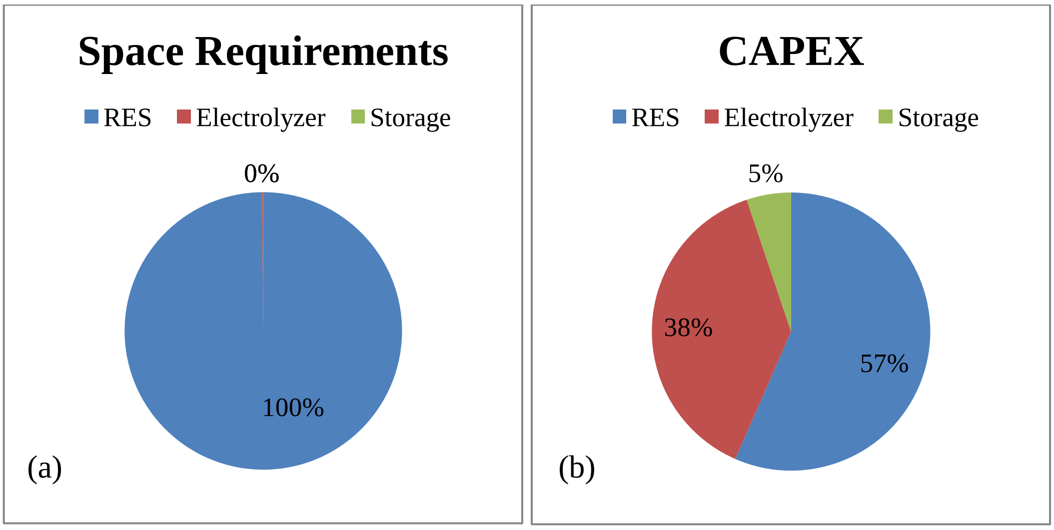

Figure 53: Space requirements (a) and CAPEX (b) for Proposal 4 in 2021, Scenario 1

Scenario 2: Production of hydrogen using only wind energy.

The CAPEX for scenario 2 is 5.295 billion pounds and the total space required is 3317802.286 m^2. As shown in Figure 54(b), 86% of the total CAPEX for proposal 2 accounts for the wind turbines. In addition, as illustrated in Figure 54 (a) in comparison to the electrolyzer and the storage, wind turbines require the majority of space. However, the total land space for this scenario is only for the electrolyzer and storage and is equivalent to 0.96 GSP stadiums.

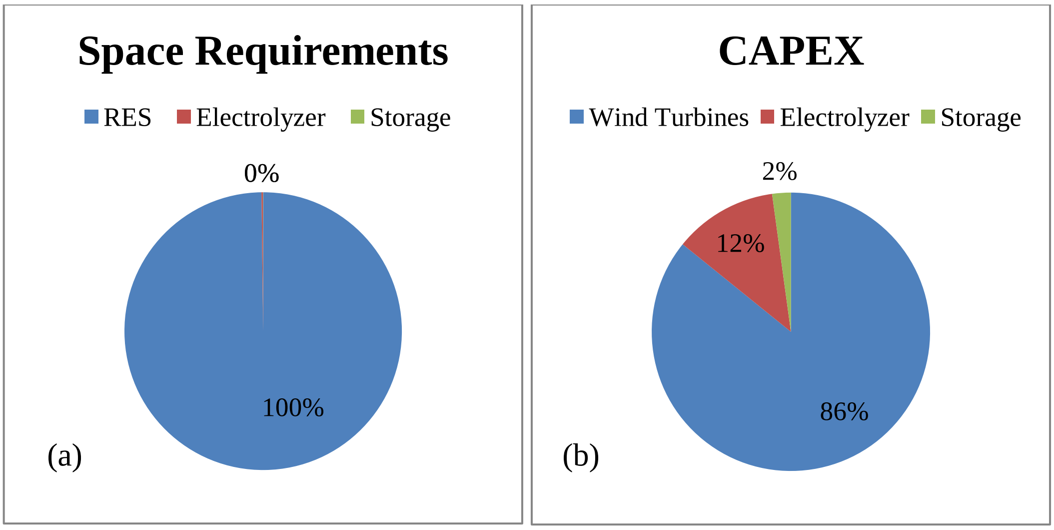

Figure 54: Space requirements (a) and CAPEX (b) for Proposal 4 in 2021, Scenario 2

Scenario 3: Production of electricity using both solar energy and offshore wind energy

The CAPEX for scenario 3 is 1.723 billion pounds and the total space required is 50493152.28 m^2. As shown in Figure 55(b), 22% of the total CAPEX for proposal 4 accounts for the wind turbines, 25% for the electrolyzer and 47% for the solar panels. In addition, as illustrated in Figure 55 (a) the majority of space is needed for the solar panels, which is 48823086.58 m^2. The total land space for this scenario is only for the solar panels , the electrolyzer and storage and is equivalent to 651.32 GSP stadiums. In terms of land use the results are better than scenario 1 but still not practical. The results (Figure 55 (c)) showed that only 7% of the RES capacity is for wind turbines, that's because Homer Pro uses financial criteria to optimize the system.

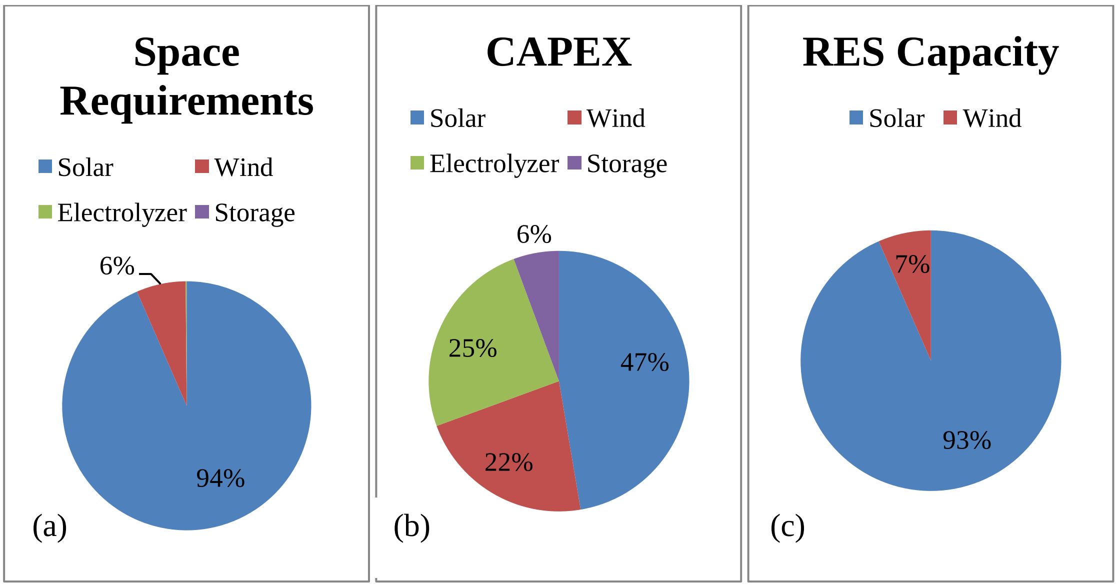

Figure 55: Space requirements (a), CAPEX (b) and RES Capacity (c) for Proposal 4 in 2021, Scenario 4

4.4.2 2030

Scenario 1: Production of hydrogen using only solar energy.

The CAPEX for scenario 1 is 1.323 billion pounds and the total space required is 40835141.74 m^2. As shown in Figure 56 (b), 60% of the total CAPEX for proposal 2 accounts for the solar panels needed. In addition, as illustrated in Figure 56 (a) in comparison to the electrolyzer and the storage solar panels requires the majority of space. The total space for this scenario is equivalent to 543.97 GSP stadiums.

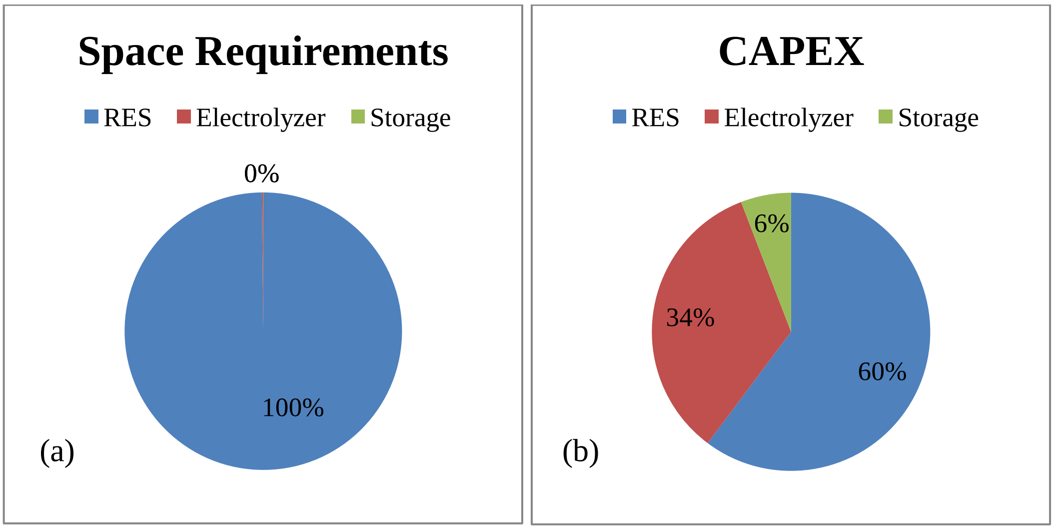

Figure 56: Space requirements (a) and CAPEX (b) for Proposal 4 in 2030, Scenario 1

Scenario 2: Production of hydrogen using only wind energy.

The CAPEX for scenario 2 is 2.578 billion pounds and the total space required is 3804659.426 m^2. As shown in Figure 57(b), 84% of the total CAPEX for proposal 2 accounts for the wind turbines. In addition, as illustrated in Figure 57 (a) in comparison to the electrolyzer and the storage wind turbines require the majority of space. However, land space is only needed for the electrolyzer and storage and is equivalent to 0.74 GSP stadiums. The results show that this scenario is more practical in terms of space but it's very expensive since the CAPEX needed is approximately 2 times more than scenario 1.

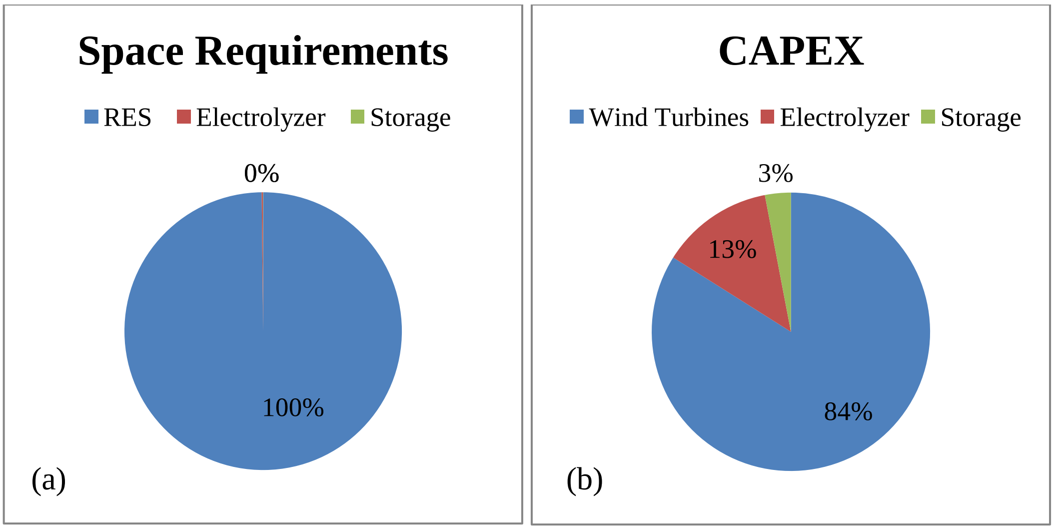

Figure 57 : Space requirements (a) and CAPEX (b) for Proposal 4 in 2030, Scenario 2

Scenario 3: Production of electricity using both solar energy and offshore wind energy

The CAPEX for scenario 3 is 2.196 billion pounds and the total space required is 221213094.31 m^2. As shown in Figure 58(b), 72% of the total CAPEX for proposal 4 accounts for the wind turbines, 10% for the solar panels and 15% for the electrolyzer. In addition, as illustrated in Figure 58 (a) the majority of space is needed for the solar panels, which is 8375050.26 m^2. The total land space for this scenario is only for the solar panels, the electrolyzer and storage and is equivalent to 93.27 GSP stadiums. In terms of land use the results are better than scenario 1 but still not practical. The results (Figure 58 (c)) showed that 71% of the RES capacity is for wind turbines.

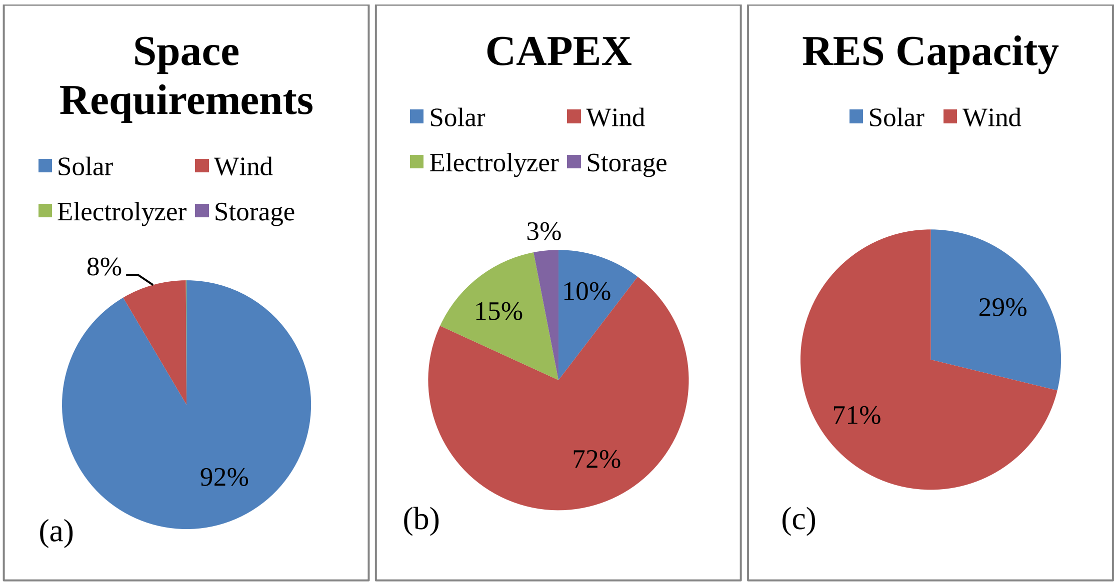

Figure 58: Space requirements (a), CAPEX (b) and RES Capacity (c) for Proposal 4 in 2030, Scenario 3

4.4.3 2050

Scenario 1: Production of hydrogen using only solar energy.

The CAPEX for scenario 1 is 0.910 billion pounds and the total space required is 36015760.69 m^2. As shown in Figure 59(b) 63% of the total CAPEX for proposal 2 accounts for the solar panels needed. In addition, as illustrated in Figure 59 (a) in comparison to the electrolyzer and the storage solar panels requires the majority of space. The total land space for this scenario is equivalent to 479.77 GSP stadiums.

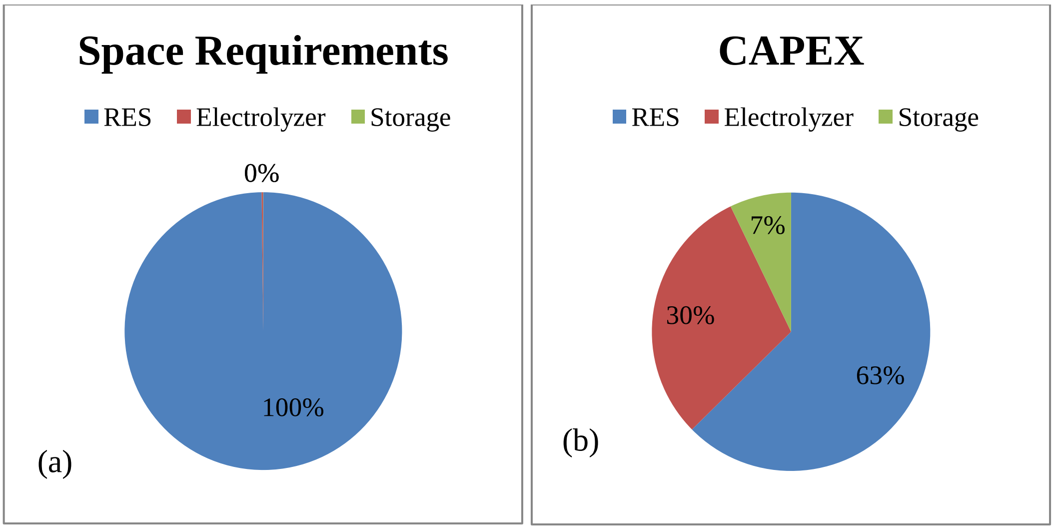

Figure 59: Space requirements (a) and CAPEX (b) for Proposal 4 in 2050, Scenario 1

Scenario 2: Production of hydrogen using only wind energy.

The CAPEX for scenario 2 is 2.045 billion pounds and the total space required is 3309802.29 m^2. As shown in Figure 60(b) 85% of the total CAPEX for proposal 2 accounts for the wind turbines. In addition, as illustrated in Figure 60 (a) in comparison to the electrolyzer and the storage wind turbines require the majority of space. However, land space is only needed for the electrolyzer and storage and is equivalent to 0.85 GSP stadiums.

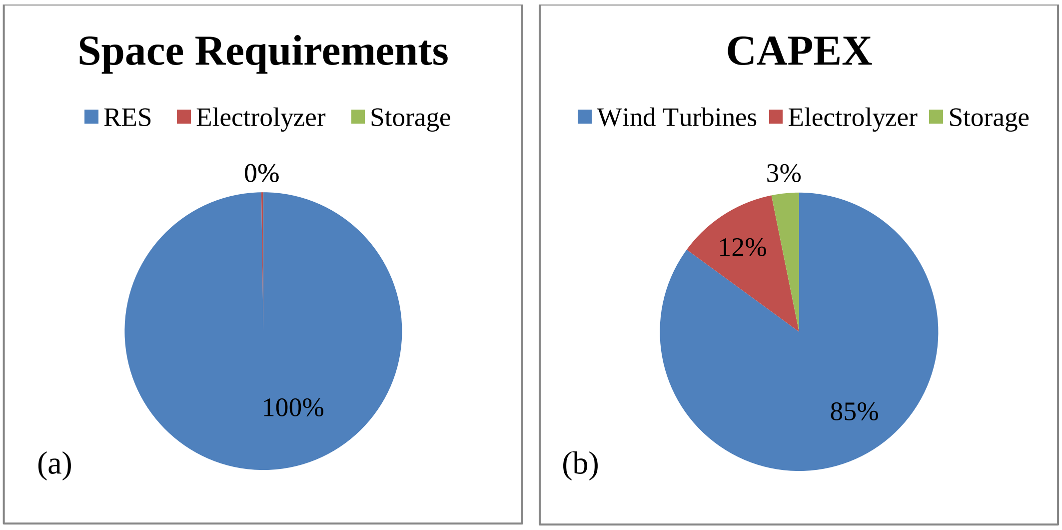

Figure 60: Space requirements (a) and CAPEX (b) for Proposal 4 in 2050, Scenario 2

Scenario 3: Production of electricity using both solar energy and offshore wind energy

The CAPEX for scenario 3 is 1.881 billion pounds and the total space required is 215001540.6 m^2. As shown in Figure 61 (b) 78% of the total CAPEX accounts for the wind turbines, 8% for the solar panels and 11% for the electrolyzer. In addition, as illustrated in Figure 61 (a) the majority of space is needed for the solar panels, which is 6963496.63 m^2. The total land space for this scenario is only for the solar panels, the electrolyzer and storage and is equivalent to 93.27 GSP stadiums. The results (Figure 61 (c)) showed that only 26% of the RES capacity is for solar panels.

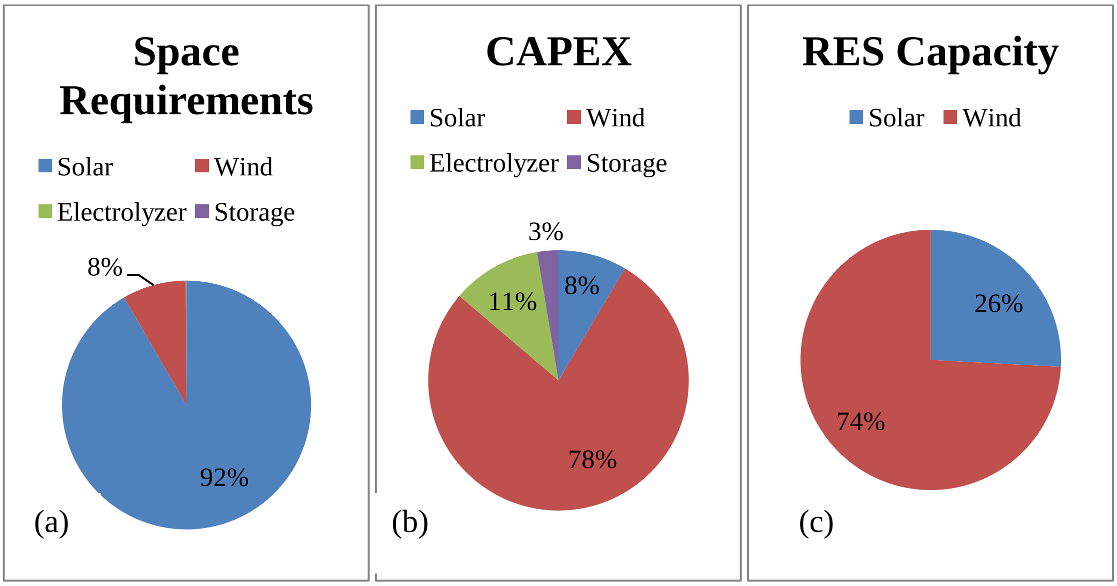

Figure 61: Space requirements (a), CAPEX (b) and RES Capacity (c) for Proposal 4 in 2050, Scenario 3

4.4.4 Overall Results

CAPEX

The overall results for the CAPEX of proposal 4 are given in Figure 62. As it can be observed for scenarios 1 and 2 the CAPEX has a significant reduction. The biggest reduction is made in the CAPEX of scenario 2 with the exclusive production of hydrogen with only wind energy. Scenario 2 has fluctuations since for 2030 and 2050 wind turbines had the biggest share of capacity.

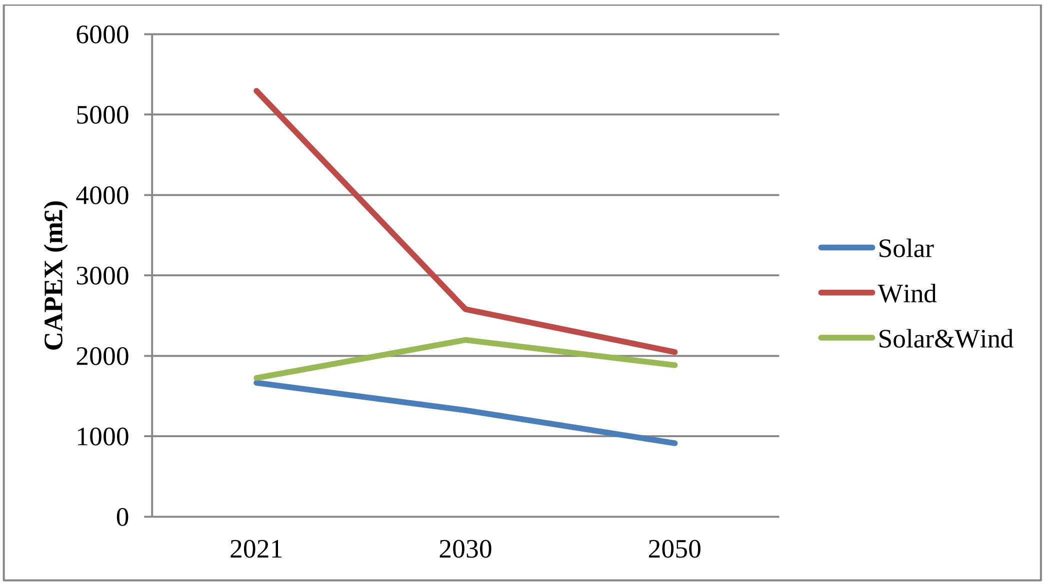

Figure 62: Overall results of CAPEX for proposal 4

Land space

In Figure 63 the land space requirements for each scenario are given. As expected scenario1 with only solar energy needs the most land space; wind energy since we have offshore wind takes minimum land space. The combination of the two RES in scenario 3 in all three periods results in less space requirement than the solar scenario. The results of scenario 1 show that for the different time periods the needed space is reducing. That's the result of the increase in solar panel's efficiency as mentioned in section 3.3.4. As the price of wind turbines drops in scenario 3 the percentage of wind turbines in the cumulative capacity becomes higher and as a result the land requirements drop.

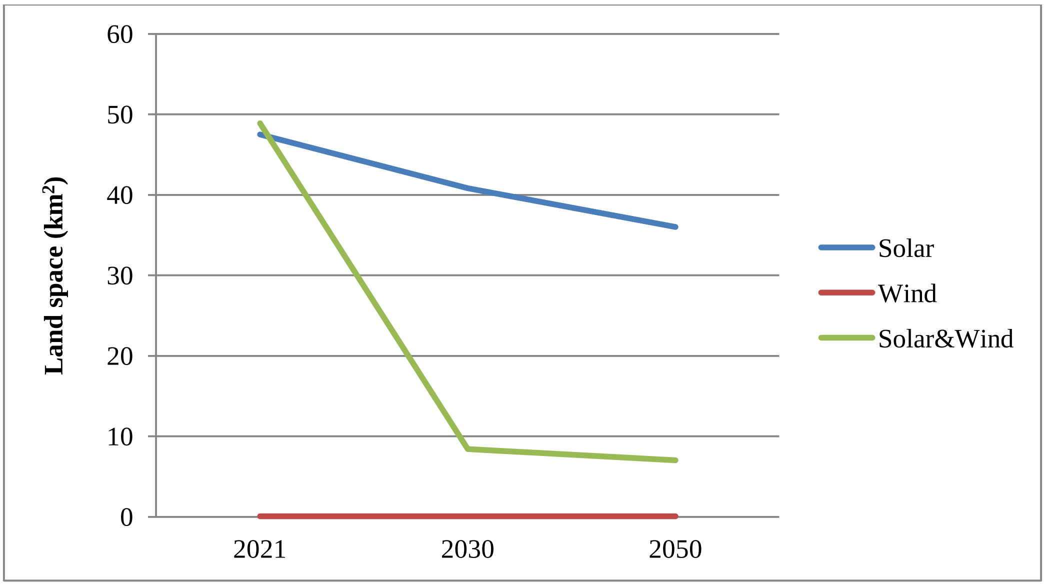

Figure 63: Overall results of land space requirements for proposal 4

RES Capacity

In Figure 64 the overall results of the RES Capacity requirements for proposal 4 are given. Scenario 1 and 2 with solar and wind respectively have a steady decrease in all three simulation periods. Especially solar energy has the biggest drop due to the increase of the solar panel's efficiency. The decline in the needed capacity of wind energy is the result of the increase in the efficiency of the electrolyzer. Scenario 3 has fluctuations since for 2030 a bigger storage and electrolyzer capacity was selected by the optimizer of Homer Pro.

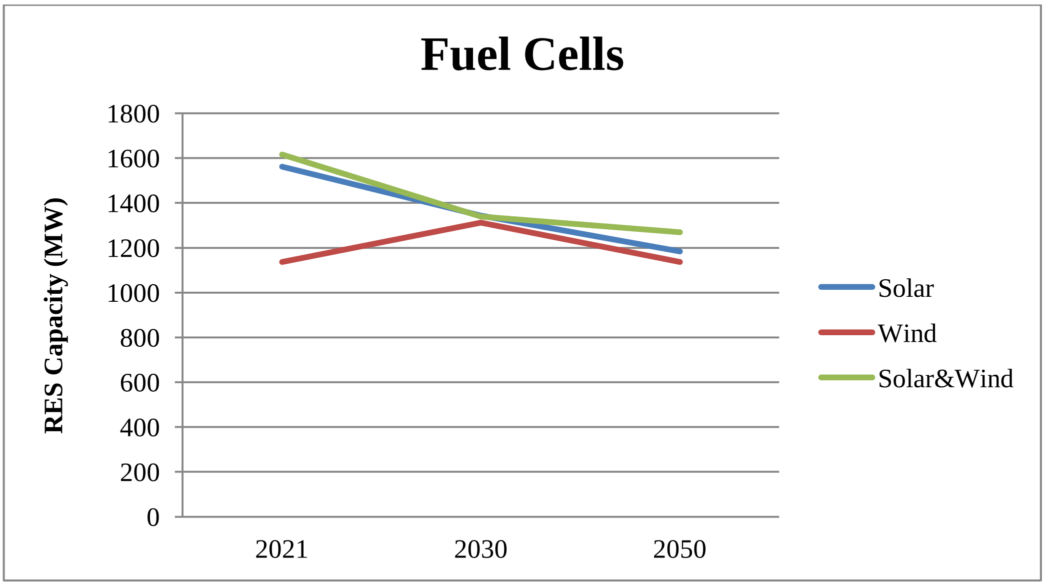

Figure 64: Overall results of RES Capacity requirements for proposal 4

Net Present Value

In Figure 65 the NVP for the first 15 years of the project for each scenario is given. In all of the scenarios an increase in NVP is observed. For 2021 only scenario 3 with the wind energy production is not profitable with a positive NPV. For the 2030 and 2050 time periods all scenarios have a positive NVP with wind energy having a significant increase from 2021 to 2030. Based on the results scenario 1 would be more profitable for all time periods.

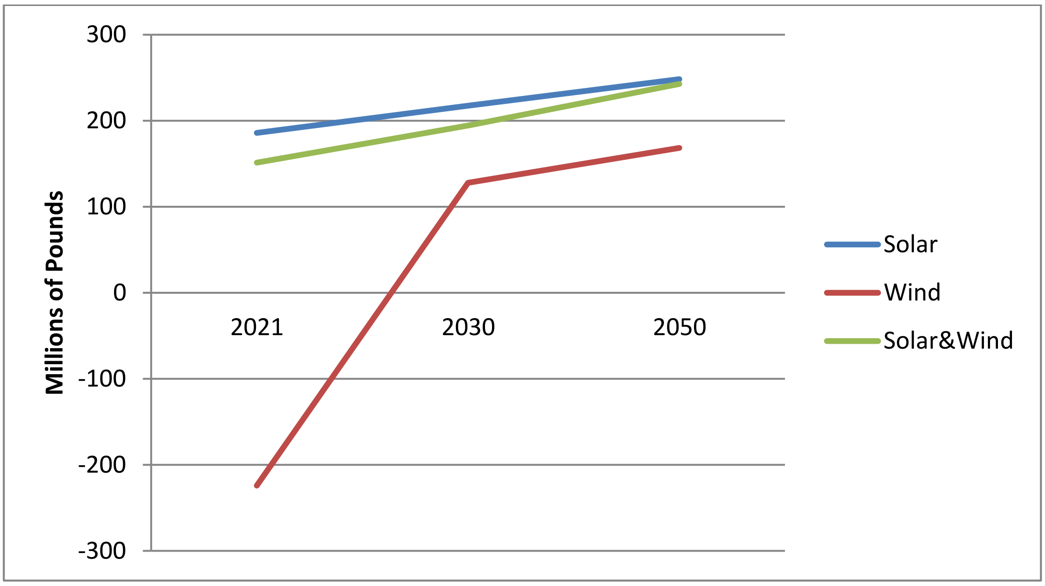

Figure 65: Overall results of NPV for proposal 4

Comments

- Based on the results for the CAPEX and NVP scenarios 1 and 3 are more profitable than scenario 2. However, due to the land requirements they are not practical to implement.

- The most realistic scenario to implement is the second scenario which despite the higher CAPEX for the time periods of 2030 and 2050 has a significant NVP.

- As mentioned before Homer Pro does not take into account the required space for each RES so another realistic scenario would be scenario 3 but with a higher share of wind energy.

4.5 Final Proposals

Based on the analysis on the results, suggestions are made in order to make the proposals feasible and more realistic.

4.5.1 Proposal 1

Initially proposal 1 was to cover the demand of hydrogen to decarbonize 20% of the public transport. Due to the high land requirements scenario 1 and 2 are not realistic for none of the simulation time periods. Scenario 2 is more realistic in terms of land space but has the highest CAPEX for all three time periods. It's clear that 20% of the public transport is not a realistic goal and needs to be adjusted. Based on the results of other proposals, a demand close to the initial proposals 2 and 3 is more realistic. That corresponds approximately to 0.95% of the public transport or else to 52 buses. The demand can be covered with scenario 2 or an adjusted scenario 3.

4.5.2 Proposal 2

The initial proposal 2 was to satisfy the potential demand of hydrogen to decarbonize 4.5% of passenger cars. Scenario 1 and 3 showed great financial potential in all time periods. On the other hand scenario 2 had a bad NVP for 2021 but showed a big rise on profitability for 2030 and 2050. The most feasible scenario was determined to be scenario 2. The need for large portions of land rules out scenario 1 and 3. However, an adjusted scenario 3 with the majority of RES to be wind turbines can be possible and can reduce the initial CAPEX. The best time period for this proposal would be 2030 or 2050.

4.5.3 Proposal 3

The initial proposal 3 was cover the demand of hydrogen to decarbonize 100% of trucks. The results were close to proposal 2 with slide differences due to the small difference in the potential demand. Like proposal 3, the most feasible scenario was determined to be scenario 2. The need for large portions of land rules out scenario 1 and 3. However, an adjusted scenario 3 with the majority of RES to be wind turbines can be possible and can reduce the initial CAPEX. The best time period for this proposal would be 2030 or 2050.

4.5.4 Proposal 4

The initial proposal 4 suggested the production of hydrogen to cover the demand to produce 10% of the electricity production. Like proposal 1, the high land requirements rules out scenario 1 and 2 for all simulation time periods. Scenario 2 is more realistic in terms of land space but has the highest CAPEX for all three time periods. It's clear that the 10% of the electricity production public is unrealistic. Based on the results of other proposals and specifically, a demand close to the initial proposals 2 and 3 is more realistic. That corresponds approximately to 1% of the electricity production. The demand can be covered with scenario 2 or an adjusted scenario 3.

4.5.5 All proposals in one

Two final simulations were made where it was assumed that all three proposals will be done at the same time. Only scenario 2 and 3 were simulated since scenario 1 was rule out for all proposals, the results are given in Table 8. As it can be observed following the same trend from the previous simulations, scenario 2 is the most realistic and the most expensive. Assuming that the cost of the 2 adjusted proposals would be the same as proposals 2 and 3 it would be cheaper to implement all four proposals at the same time. However, the upfront cost would be greater and that's why is suggested that the proposals should be done in stages from 2030 to 2050. In addition, implementing the proposals in stages can save money in the long term if the prices drop bellow what it was assumed or better components could be manufacture.

Table 8: Final simulations for a cumulative implementation of the proposals

2030				
Scenario	CAPEX (m£)	Land requirements (m^2)	Capacity (MW)	NPV(m£)
1	784.88	18703.90	392	666.77
2	761.50	3183586.66	456.34	730.51
2050				
Scenario	CAPEX (m£)	Land requirements (m^2)	Capacity(MW)	NPV(m£)
1	715.17	18703.90	408	776.21
2	392.38	8488607.98	399.13	1065.97

5.0 Conclusions

This dissertation investigates the potential of producing green hydrogen in Cyprus. An in-depth literature review was performed on the following aspects that were considered important. Firstly, the energy challenges that islands face were analysed and the peculiarity of Cyprus was explained; mentioning how it affected the energy policies of Cyprus until now. Secondly, hydrogen research for islands and some current hydrogen policies were reviewed. Finally, some background reading was reported on key aspects of hydrogen.

A methodology was formed in order to analyse the potential of hydrogen. Starting from the demand, four different initial proposals were identified based on projections for the EU for the transport and production of the electricity sector. Moreover, using Homer Pro different simulations were performed with different RES production scenarios and different time periods. Finally, the results were analysed based on financial, land use, capacity and NVP, and final proposals were formed.

In terms of the time periods all four proposals showed the same trends in their results. However, the deciding factor for the feasibility of each proposal was the land space requirements. Scenario 1 who was the production of hydrogen from solar energy required unrealistic, for the environment of Cyprus, amounts of land despite being the RES with the biggest potential. The results highlight the importance of land space for Cyprus and how it can affect the design process of RES projects. In addition, the results for scenario 2 show that a solution for the land limitations of Cyprus can be the offshore wind farms. Even if the production of hydrogen is not implemented the use of offshore wind farms is essential for Cyprus to hit its emission goals. Finally, scenario 3 that combines solar and offshore wind energy showed great potential in limiting the land requirements and reducing the cost. Homer pro optimizes its modelled energy system with technical and financial criteria it does not take into account the space requirements. That’s the reason in the majority of scenario 3 simulations solar energy had the biggest percentage of the capacity needed. An adjusted scenario 3 based on land use that uses more offshore wind energy can have great potential.

Time periods, 2030 and 2050 seemed ideal for the implementation of the proposals, especially because of the rapid drop that it was assumed for the price of wind turbines. Two last simulations were performed in order to see if the proposals should be done cumulative or separated. The results demonstrate that such strategy would require less CAPEX. However it was determined that since hydrogen technology is relatively new, the proposals should be implemented in stages, to take advantage of further drops in prices or better components. The first two proposals to be implemented should be proposal 1 and proposal 4 which refer to the public transport and electricity production respectively; the implementation of those proposals should be easier than the others because they don't depend on the response of the public. They can be easily initiated by the government if the needed funds are found. This way the public will slowly become aware of hydrogen technologies and the other 2 proposals that required the public's participation could be more successful.

As the results of the simulation suggest, an important factor for any hydrogen project is the financial aspect. The CAPEX for every proposal requires a substantial initial investment which for the size of Cyprus's economy will be difficult to find. However, this problem can be confined with the use of subsidy programs and the creation of favorable investing conditions. In addition, in the early stages the government can undertake projects with government funds in order to reassure potential investors on its commitment to hydrogen technology. Another financial aspect, OPEX, indicates a different problem that can occur which is a common problem for islands as mentioned in the literature review; the limitations in local human resources. The funding for research for hydrogen needs to be increased and specific training programs should be formed in order to limit this problem, which is more likely to increase the OPEX significantly.

It has to be noted that the assumptions about the efficiencies and prices of the components could be invalid because they were based on projections from research papers and technical reports. The main purpose of the dissertation was to investigate a different route that Cyprus can take for the future using an emerging technology. Overall green hydrogen has great potential for Cyprus especially for the period 2030-2050 were the technology would be more established. To be able to meet its goal Cyprus and all countries need to investigate opportunities for new technologies and not relay only on current technologies. That's the key to a carbon-free future.

5.1 Future work

In order to have a more holistic view further research is required. The financial aspect of the proposals needs to be investigated more in order to have a more specific picture for Cyprus. That would involve research around the logistics of transporting machinery related to the project and the cost that this would add to the project. In addition, a detailed analysis of the personnel needed for each proposal should take place in order to have a clear picture of the specializations needed.

As the results showed, for each implementation a large amount of space in land and sea is required. An Environmental Impact Assessment (EIA) should be carried out in order to make sure the environmental impact is mitigated and the proposals are within the regulations of the EU. Based on the results of the EIA adjustments on the design of the projects will be made.

As mentioned previously the public participation is crucial for some of the proposals. There is a need for research around public opinion for hydrogen. Based on the results specific proposals should be made to promote hydrogen. Finally, the investigation of other scenarios for renewable energy production like tidal energy and floating solar energy can be investigated.

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7.0 Appendices

7.1 Appendix I

The results of the simulations for 2021.

2021		Proposals			
		Passenger Cars	Trucks	Buses	Fuel Cells
Hydrogen Demand (kg)	Per year	2294213.972	2674686.935	48642558	30997049.7
	Per day	6285.517732	7327.909411	133267.2822	84923.42384
RES Capacity (MW)	Solar	110.869	128.101	3492.074	1562.084
	Wind	104	128	2072	1136
	Solar&Wind	106.843	109.326	2682.369	1616.593
	Solar	98.843	93.326	2506.369	1608.593
	Wind	8	16	176	8
Electricity produced (kWh)	Solar	202437679	233915410	6376246474	2852240119
	Wind	239640041	294541568	4767891638	2817102889
	Solar&Wind	197467324	206300112	4955403148	2938363658
Excess Electricity (kWh)	Solar	68644594	78058509	3542873770	1045381283
	Wind	105054835	136928592	1907572620	993533929
	Solar&Wind	63438106	50483658	2123703155	1130113026
Space for RES (m2)	Solar				
	Total land area	3365031.917	3888047.638	105989415.1	47411472.25
	Direct area	2602291.349	3006756.84	81965147.69	36664871.87
	Wind	297142.8571	365714.2857	5920000	3245714.286
	Solar&Wind	3017803.481	6032576.903	111271865.7	50423086.58
	solar	3000025.704	2832576.903	76071865.71	48823086.58
	wind	17777.77778	35555.55556	391111.1111	17777.77778
Cost of RES (m£)	Solar	66.78970298	77.17060442	2103.695219	941.0306433
	Wind	416	512	8288	4544
	Solar&Wind	91.54500006	120.2214489	2213.886813	1001.048595
	solar	59.54500006	56.22144892	1509.886813	969.0485951
	wind	32	64	704	32
Electrolyzer's Capacity (MW)	Solar	60	70	1000	800
	Wind	50	50	1000	800
	Solar&Wind	60	60	1000	800
Space for Electrolyzer (m2)	Solar	4800	5600	80000	64000
	Wind	4000	4000	80000	64000
	Solar&Wind	4800	4800	80000	64000
Cost of electrolyzer (m£)	Solar	47.7462	55.7039	795.77	636.616
	Wind	39.7885	39.7885	795.77	636.616
	Solar&Wind	47.7462	47.7462	795.77	636.616

Water usage (liters/day)		62855.17732	73279.09411	1332672.822	849234.2384
Needed Storage (kg)	**Solar**	25144	29316	533072	254772
	Wind	18858	21987	533072	339696
	Solar&Wind	18858	21987	533072	254772
Space for storage (m3)	**Solar**	598.6666667	698	12692.19048	6066
	Wind	449	523.5	12692.19048	8088
	Solar&Wind	449	523.5	12692.19048	6066
Cost of storage (m£)	**Solar**	8.4898716	9.8985474	179.9917608	86.0237658
	Wind	6.3674037	7.42391055	179.9917608	114.6983544
	Solar&Wind	6.3674037	7.42391055	179.9917608	86.0237658
CAPEX(m£)	**Solar**	123.0257746	142.7730518	3079.45698	1663.670409
	Wind	462.1559037	559.2124106	9263.761761	5295.314354
	Solar&Wind	145.6586038	175.3915595	3189.648574	1723.688361
OPEX (m£)	**Solar**	3.516951257	4.09308634	72.74666019	46.7390144
	Wind	10.45884711	12.40094232	210.1194528	50.5573098
	Solar&Wind	3.995171612	4.620128297	78.97737007	47.74284957
Land requirements (m2)	**Solar**	3370430.583	3894345.638	106082107.3	47481538.25
	Wind	4449	4523.5	92692.19048	72088
	Solar&Wind	3005274.704	2837900.403	76164557.9	48893152.58

7.2 Appendix II

The results of the simulations for 2030.

2030		Proposals			
		Passenger Cars	Trucks	Buses	Fuel Cells
Hydrogen Demand (kg)	Per year	2294213.972	2674686.93	48642558	30997049.7
	Per day	6285.517732	7327.90941	133267.282	84923.42384
RES Capacity (MW)	Solar	98.718	115.416	2120.138	1343.036
	Wind	96	104	1808	1312
	Solar&Wind	79.741	94.851	1809.132	1339.936
	Solar	55.741	70.851	521.132	275.936
	Wind	24	24	1288	1064
Electricity produced (kWh)	Solar	181034952	211656139	3888019987	2462929517
	Wind	222013195	259247731	4506922095	3034180333
	Solar&Wind	156701689	184188735	3915858409	2953665962
Excess Electricity (kWh)	Solar	54781864	64409346	1211799812	757831635
	Wind	94422506	110480885	1806626679	1313281979
	Solar&Wind	30572716	37106648	1223126842	1242185599
Space for RES (m2)	Solar				
	Total land area	2996231.776	3503039.83	64349205.2 6	40763053.74
	Direct area	2317085.907	2709017.47	49763385.4	31523428.23
	Wind	274285.7143	297142.857	5165714.28	3748571.429
	Solar&Wind	1745152.003	6950428.67	273417097	221175050.3
	solar	1691818.669	2150428.67	15817097.7	8375050.257
	wind	53333.33333	53333.3333	2862222.22	2364444.444
Cost of RES (m£)	Solar	58.5792612	68.4878544	1258.08988	796.9575624
	Wind	158.4	171.6	2983.2	2164.8
	Solar&Wind	72.6767094	81.6429834	2434.43972	1919.340422
	solar	33.0767094	42.0429834	309.239728	163.7404224
	wind	39.6	39.6	2125.2	1755.6
Electrolyzer's Capacity (MW)	Solar	60	70	1250	800
	Wind	50	50	1000	600
	Solar&Wind	40	50	800	425
Space for Electrolyzer (m2)	Solar	4800	5600	100000	64000
	Wind	4000	4000	80000	48000
	Solar&Wind	3200	4000	64000	34000
Cost of electrolyzer (m£)	Solar	33.6564	39.2658	701.175	448.752
	Wind	28.047	28.047	560.94	336.564
	Solar&Wind	22.4376	28.047	448.752	238.3995
Water usage (liters/day)		62855.17732	73279.0941	1332672.82	849234.2384

Needed Storage (kg)	**Solar**	25144	29312	533072	339696
	Wind	25144	29312	533072	339696
	Solar&Wind	18858	21984	399804	169848
Space for storage (m3)	**Solar**	598.6666667	697.9047619	12692.19048	8088
	Wind	598.6666667	697.9047619	12692.19048	8088
	Solar&Wind	449	523.4285714	9519.142857	4044
Cost of storage (m£)	**Solar**	5.732832	6.683136	121.540416	77.450688
	Wind	5.732832	6.683136	121.540416	77.450688
	Solar&Wind	4.299624	5.012352	91.155312	38.725344
CAPEX(m£)	**Solar**	97.9684932	114.4367904	2080.805305	1323.16025
	Wind	192.179832	206.330136	3665.680416	2578.814688
	Solar&Wind	99.4139334	114.7023354	2974.347041	2196.465266
OPEX (m£)	**Solar**	2.239391343	2.614354936	47.18906098	30.087404
	Wind	4.3381608	4.6179984	83.3501904	28.92353671
	Solar&Wind	2.19661648	2.553578988	47.46603133	37.12265101
Land requirements (m2)	**Solar**	3001630.442	3509337.742	64461897.45	40835141.74
	Wind	4598.666667	4697.904762	92692.19048	56088
	Solar&Wind	1695467.669	2154952.1	15890616.91	8413094.257

7.3 Appendix III

The results of the simulations for 2050.

2050		Proposals			
		Passenger Cars	Trucks	Buses	Fuel Cells
Hydrogen Demand (kg)	Per year	2294213.972	2674686.93	48642558	30997049.7
	Per day	6285.517732	7327.90941	133267.2822	84923.4238
RES Capacity (MW)	Solar	87.046	101.419	1878.974	1184.25
	Wind	88	96	1808	1136
	Solar&Wind	84.31	96.104	1693.601	1269.429
	Solar	68.31	80.104	437.601	229.429
	Wind	16	16	1256	1040
Electricity produced (kWh)	Solar	160327407	186799973	3460815420	2181228277
	Wind	203512096	239305598	4329257304	2831782909
	Solar&Wind	161674940	183222235	3693638122	2943475222
Excess Electricity (kWh)	Solar	42452636	49378766	959658717	588906078
	Wind	84434247	100989656	1805632927	1110972870
	Solar&Wind	43874614	45928764	1176556384	1229654394
Space for RES (m2)	Solar				
	Total land area	2641969.966	3078210.96	57029534.68	35943672.6
	Direct area	2043123.441	2380483.15	44102840.15	27796440.2
	Wind	251428.5714	274285.714	5165714.286	3245714.28
	Solar&Wind	2108861.261	5631270.38	264481813.1	214963496.
	solar	2073305.705	2431270.38	13281813.06	6963496.62
	wind	35555.55556	35555.555	2791111.111	2311111.11
Cost of RES (m£)	Solar	41.9213536	48.8433904	904.9138784	570.3348
	Wind	134.7104	146.9568	2767.6864	1738.9888
	Solar&Wind	57.390896	63.0708864	2133.433442	1702.52500
	solar	32.898096	38.5780864	210.7486416	110.493006
	wind	24.4928	24.4928	1922.6848	1592.032
Electrolyzer's Capacity (MW)	Solar	60	70	1250	800
	Wind	50	50	1000	700
	Solar&Wind	40	50	800	425
Space for Electrolyzer (m2)	Solar	4800	5600	100000	64000
	Wind	4000	4000	80000	56000
	Solar&Wind	3200	4000	64000	34000
Cost of electrolyzer (m£)	Solar	20.64	24.08	430	275.2
	Wind	17.2	17.2	344	240.8
	Solar&Wind	13.76	17.2	275.2	146.2

Water usage (liters/day)		62855.17732	73279.0941	1332672.822	849234.238
Needed Storage (kg)	**Solar**	25144	29132	533072	339696
	Wind	25144	21984	533072	339696
	Solar&Wind	12572	21984	339804	169848
Space for storage (m3)	**Solar**	598.6666667	693.619047	12692.19048	8088
	Wind	598.6666667	523.428571	12692.19048	8088
	Solar&Wind	299.3333333	523.428571	8090.571429	4044
Cost of storage (m£)	**Solar**	4.827648	5.593344	102.349824	65.221632
	Wind	4.827648	4.220928	102.349824	65.221632
	Solar&Wind	2.413824	4.220928	65.242368	32.610816
CAPEX(m£)	**Solar**	67.3890016	78.5167344	1437.263702	910.756432
	Wind	156.738048	168.377728	3214.036224	2045.01043
	Solar&Wind	73.56472	84.4918144	2473.87581	1881.33582
OPEX (m£)	**Solar**	1.476963122	1.72147763	31.22256462	19.8604184
	Wind	3.385911974	3.60995107	69.25404895	20.6394616
	Solar&Wind	1.506366534	1.06762661	41.21411878	32.8467248
Land requirements (m2)	**Solar**	2647368.633	3084504.58	57142226.87	36015760.6
	Wind	4598.666667	4523.42857	92692.19048	64088
	Solar&Wind	2076805.038	2435793.81	13353903.63	7001540.62

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