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Wave energy a new energy mix to produce green hydrogen: a potential future maritime shipping fuel : a study on the Port of Ngqura, Southern Africa's "Green Status Port"

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World Maritime University
Malmö, Sweden

WAVE ENERGY A NEW ENERGY MIX TO PRODUCE GREEN HYDROGEN, A POTENTIAL FUTURE MARITIME SHIPPING FUEL

A study on the Port of Ngqura, Southern Africa's

"Green Status Port"

By

ZIMASA NTOMBEMVELI MACINGWANE

A dissertation submitted to the World Maritime University in partial fulfilment of the requirements for the reward of the degree of

MASTER OF SCIENCE

in

MARITIME AFFAIRS

(Maritime Energy Management)

2021

DECLARATION

I, ZIMASA NTOMBEMVELI MACINGWANE, certify that all the material in this dissertation that is not my own work has been identified, and that no material is included for which a degree has previously been conferred on me.

The contents of this dissertation reflect my own personal views and are not necessarily endorsed by the University.

(Signature): **...** **......**

(Date): **..............20./.09./.2021..................**

Supervised by: ..**......................................**

Supervisor’s affiliation**.................................**

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ABSTRACT

Title of Dissertation: **Wave Energy A New Energy Mix to Produce Green Hydrogen, A Potential Future Maritime Shipping Fuel.**

Degree: **Master of Science**

The study is based on the construction of wave farms in the Port of Ngqura, the energy generated from the wave farm will can be converted into green hydrogen through a process of electrolysis. The produced hydrogen will be used to supply the port with electricity, serve to refuel tug boats and provide the global shipping industry with green hydrogen bunkering fuel for commercial shipping vessel.

The Port of Ngqura is geographically well positioned to lead the production of zero carbon shipping fuel. The study will focus on exploring and evaluating the viability and potential of the production of renewable bunker fuels from wave energy in Nelson Mandela Bay Municipality at the Port of Ngqura. It will look at the other maritime shipping fuels. We will look into introducing a new energy mix from a renewable energy source which is wave energy and how wave energy can be used to produce green hydrogen through a process of electrolysis and the CAPEX and OPEX of a hydrogen plant, evaluate the current cost of hydrogen and hydrogen production and the selling price of hydrogen.

The results found showed that with wave energy convertors in a row of 3 next to each other the energy produced by the wave farm was 2 973 024MJ which is equivalent to 18.58 ton of produced hydrogen, when we consider the low heating value of hydrogen and if we assume hydrogen efficiency is 75%. With the produced hydrogen fuel we will be able to refuel 1.3 tug boats with hydrogen from the energy produced by the wave farm each month. It is predicted that the price of hydrogen is expected to drop and the price of fossil will gradually increase in the coming years. The fact coal electricity can be produced on demand and wind and solar energy are produced when the wind blows and the sun shines there is a need for energy storage and the efforts to study the production of hydrogen and ammonia. Hydrogen is still predicted to be more expensive that coal electricity, however, from this maybe a critical cost for a kg of CO_2 could be calculated which could make hydrogen competitive.

KEYWORDS: wave energy, wave farm, port of Ngqura, hydrogen, hydrogen plant, shipping fuel, LCOE, Nelson Mandela Bay, WEC, cost of hydrogen

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LIST OF ABBREVIATIONS

ATR	Automated Thermal Reforming
$C_{12}H_{22}O_{11}$	Table sugar
CAPEX	Capital Expenditures
CCS	Carbon Capture and Storage
CH_4	Methane
CO_2	Carbon dioxide
EEZ	Exclusive Economic Zones
GHG	Greenhouse gas
GW	Gigawatt
H_2	Hydrogen
H_20	Water
H_2O_2	Hydrogen peroxide
HCl	Hydrochloric acid
HSE	Health and Safety Environment
IMO	International Maritime Organisation
IPCC	Intergovernmental Panel on Climate Change
IPP	Independent Power Producer
IPPPP	Independent Power Producer Procurement Programme

kg	Kilogram
kg/l	kilogram per litre
kVA	Kilovolt-ampere
kWh	Kilowatt hours
LCOE	Localised Cost of Energy
LCOH	Localised Cost of Hydrogen
LNG	Liquid Natural Gas
LPG	Liquid Petroleum Gas
MJ/l	Mega Joule per litter
MSP	Marine Spatial Planning
MW	Megawatt
NH_3	Ammonia
NMB	Nelson Mandela Bay
NMBM	Nelson Mandela Bay Municipality
OPEX	Operation Expenditure
OWE	Offshore Wind Energy
PM	Particulate Matter
POX	Partial Oxidation
R	Rand South African currency

SAWEA	South African Wind Energy Association
SONA	State of the Nation Address
SR	Steam Reforming
TNPA	Transnet National Port Authority
TW	Terawatt
TWh	Terawatt-hour
UK	United Kingdom
UNEP	United Nations Environmental Programme
WEC	Wave Energy Convertors

CHAPTER 1

INTRODUCTION

1.1 Background

Since the dawn of the industrial revolution there has been an increase in demand for seaborne trade and transportation, including a significant increase in greenhouse gas emissions. As the world is moving away from fossil fuels and encouraging renewable energy projects to reduce carbon footprint, various forms of renewable energy are being explored to replace the existing energy generation facilities. The Paris Agreement is aiming to limit global warming to 1.5 degrees Celsius in comparison to preindustrial levels (UNEP, 2020). In a generation that depends highly on energy and power supply for production and sustainability, energy is a crucial component to sustain human life, economic growth and activities. South Africa has also shown that it is in support of the IMO emission reduction strategy, through finding new and innovative ways to supply reliable and environmentally friendly energy.

South Africa is the seventh largest coal producer in the world and around 77% of the country's electricity is generated from coal which has caused high levels of environmental degradation, it is said that South Africa's greenhouse gas emissions per capita is among the highest in the African continent. The country's dependency on fossil fuels and its inability to meet its energy demands, has promoted renewable energy projects such as wind power, solar energy and hydropower plants to address objectives of sustainable development and energy security. Renewable energy promises to be one of the viable and most accepted technologies when it comes to green power generation.

South Africa currently has an ageing coal fleet of thermal power stations, which will slowly be decommissioned in the next coming 30 years (Rae, 2020). This is the realisation that the country needs to transition to an alternative energy sources. The aim of the country is to reduce its dependence on coal power generation and increase its renewable energy potential to achieve its decarbonisation goals. With the country's energy crisis and load shedding which came about in 2007, it is still a pandemic that the country face affecting businesses and industries. It is inevitable that a new energy mix is urgently required to meet the country's energy demand.

Renewable energy has gained attention in a world that highly depends on energy for sustainability, renewable energy sources like wind, solar and hydropower are becoming popular due to environmental awareness and the advancement in technology (Acciaro, 2014). South Africa boast highly of its wind potential which is rather higher in the country's coastal regions, the average wind is between 6m/s with an altitude of 10m and the entire country has a high wind potential of 60 TWh of annual wind energy (Mostafaeipour et al, 2020). In the past 6 years it has been reported that there has been an increase in wind and solar production in the country by 8.5 times from 467 MW to 3 957 MW (Mostafaeipour et al, 2020). There is a prediction that by 2030 about 11 800MW up to 12 500MW of the country's energy will be produced by wind energy (Mukonza and Nhamo, 2018). The country's ports are perfectly positioned in areas embedded in abundant wind, opportunities are there to produce hydrogen from the excess wind located in the country's coastal regions.

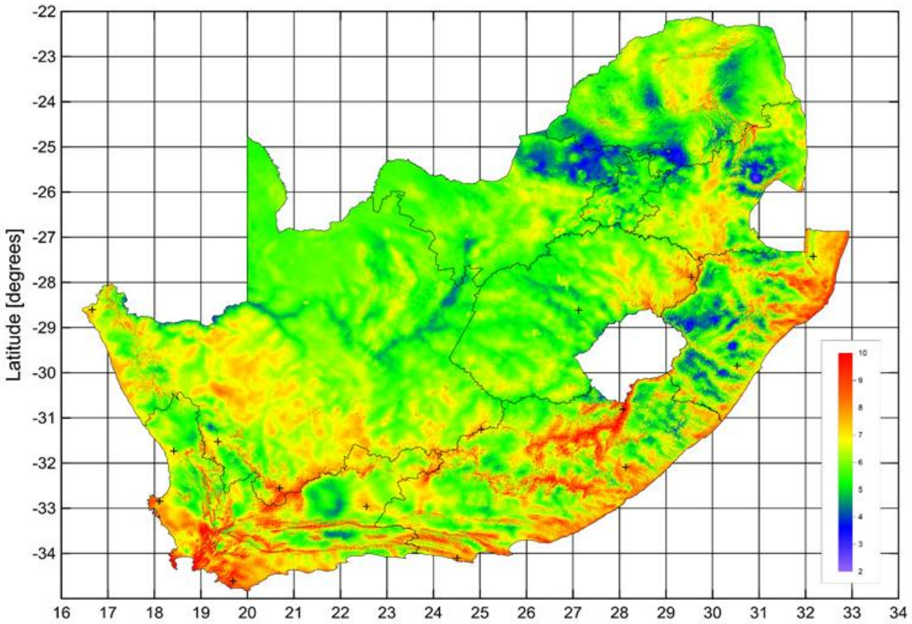


Figure 1: **South African Wind Atlas (mean wind speed [ms-1] at 100 m)**

(Source: SAWEA, 2017)

South Africa is geographically located at the most southern tip of Africa; it is geographically well positioned in exploring untapped offshore resources for energy generation. The South African coastline stretches more than 3 000 km from the boarder of Namibia on the Atlantic Ocean around the tip of Africa to the boarder of Mozambique in the Indian Ocean (South African Government, 2016). The Port of Ngqura is a deep-sea transhipment port which is capable of serving a Post Panamax (Africa Ports and Ships, 2021). The Port of Ngqura is located in Gqeberha formally known as Port Elizabeth the country's Windy City. There is abundant wind in the area, it is a perfect location not only for wind farms, however, for wave farms too.

Figure 2: Map of South Africa at the southern tip of the African Continent

(Source: Power Pointing.com, 2009)

South Africa is endowed with an abundance of mixed energy resources, it has the best models to tackle its energy challenges, through the use of wind, solar energy, wave and hydro power. The Port of Ngqura being the only port with a green status in Southern Africa (Daniels, 2019), has access to renewable energy to transition its current energy to a renewable energy mix for port operations and economic growth. The key to the success of the port is through a successful resolution of the country's energy crisis, combating climate change, sustainable development and economic growth.

In addition to wind power which is being developed, there exists a strong potential for harnessing wave power in South Africa. Offshore wind is regarded as the cleanest energy technology generation which holds significant resource potential in many coastal countries. However, (Elsner, 2019) piloted a continental offshore wind resource assessment in Africa and his findings showed a gross capacity of 26 968 GWh of Offshore Wind Energy (OWE) resource on an annual basis. The waves along the coastal waters of South Africa can produce between 25 MW/km and 50 MW/km of energy, it is estimated that the total power generation of 56 800 MW is available on the entire coast line (Fourie and Johnson, 2017). Therefore, OWE has a huge potential to play in South Africa’s large-scale aim of a new energy mix and decarbonisation. (Fourie and Johnson, 2017), also agree that wave energy can contribute 8 to 10 GW towards South Africa’s electricity supply.

(Pontes, 2007) estimated that 80 00TWh of electricity per year can be captured from ocean waves and this is sufficient to meet global demand by five times over (Waves for power, 2021). Wave energy just like solar and wind have one thing in common an origin from renewable energy which is continuously received from the sun. The reason to venture into harnessing wave energy is that wave energy has a higher power density compared to solar and wind energy and it is more consistent and predictable than solar and wind. Weather forecasts for wave heights and lengths can be predicated 48 to 72 hours in advance and it is more accurate (Waves for power, 2021).

Through the construction of wave farms in the country’s ports, the energy generated can be converted into green hydrogen through a process called electrolysis and bridge the gap by supplying the global shipping industry with green hydrogen as a bunkering fuel. The Port of Ngqura is geographically well positioned to lead the production of zero carbon shipping fuel.

Figure 3: **Port of Ngqura in the coast of South Africa. The location of instruments and berths**

(Source: Stuart et al, 2013)

Renewable energy technology such as wave farms can provide a non-polluting alternative in reducing emissions which are caused by fossil and nuclear fuels, when it comes to ocean power it ranges between 10-30gCO_2eq/kWh for wave power, tidal barrages and marine current turbines (IPPC, 2014). The Carbon Capture and Storage (CCS) has the potential to reduce GHG emissions to 70-290gCO_2eq/kWh and without CCS coal emits 98-396gCO_2eq/kWh (IPPC, 2014). Due to the geographical locations of the country, ports can transition and make use of tidal and wave energy in meeting some of its energy demands.

South Africa has an abundance of renewable energy potential; it is enough to supply the country's domestic energy demand as well as the production of zero carbon fuels to supply commercial vessels a refuelling service. The increased volatility and unsteadiness of renewable energy production requires suitable energy storage, in order to provide electricity when it is needed and to ensure grid stability.

The greatest concern that renewable energy power generation faces is the dependency on natural resources which humans have no control of, compared to fossil fuel (Maradiya, 2019). Solar power is generated when the sun shines, with wind on the other hand it solely depends on the wind availability, if the wind speeds are too low the wind turbines will not turn this results in zero power flowing to the main grid.

Energy storage is a crucial element in energy planning, in the renewable sector. Energy storage is mostly crucial in renewable energy technologies due to the nature of renewable energy sources and variability with the requirements of electricity loads (Bank and Schaffler, 2005). There are other technologies that are being developed including and not limited to batteries, super capacitors, compressed air options, super conductors and flywheels energy storage (Bank and Schaffler, 2005). According to (Maradiya, 2019), the uncertainty of energy production in renewable technologies is contributing in making integration a little more complex. When it comes to green hydrogen and ammonia they carry a potential of storing large amounts of renewable energy over long periods of time, while this form of energy storage is also the most suitable fuel for large commercial vessels for bunkering.

South Africa has the opportunity to provide the growing global demand, with bunkering services providing zero carbon fuels to all types of vessels. With the access to busy shipping routes, a combination of abundance of renewable energy potential and the experience of handling marine fuels, South Africa is in a great position to produce future shipping fuels and accessing a growing global market and introducing a new low carbon economy (Taylor, 2021).

1.2 Problem Statement

Ports are the heart of the country's economy, the Initial IMO Strategy is placing CO_2 emission reductions from shipping and with the Paris Agreement temperature goals, there is a greater need for an alternative and green energy in ports to curb greenhouse gas emissions. There is a dire need to better understand energy related activities which occur in ports and surrounding areas in order to monitor usage and the growing energy trends and demands.

Ports make use of enormous amounts of energy to perform their operations, with the port's current energy consumption of container terminals there is a great need to address the issue of climate change and energy security. The Port of Ngqura consumes on average 217 296 500 kWh and 6 718 467 kVA in electricity during the winter months and an average of 147 218 000 kWh and 3 350 761 kVA of electricity during the summer season (TNPA, 2021). There is a dire need for environmentally friendly energy to drive green hydrogen and ammonia as future fuels for international commercial vessels during bunkering.

Figure 4, demonstrates LCOE in South Africa Rand per kWh for various energy sources including wind, solar, coal, gas and nuclear. The energy option which we will investigate for the study is the potential of ocean wave energy.

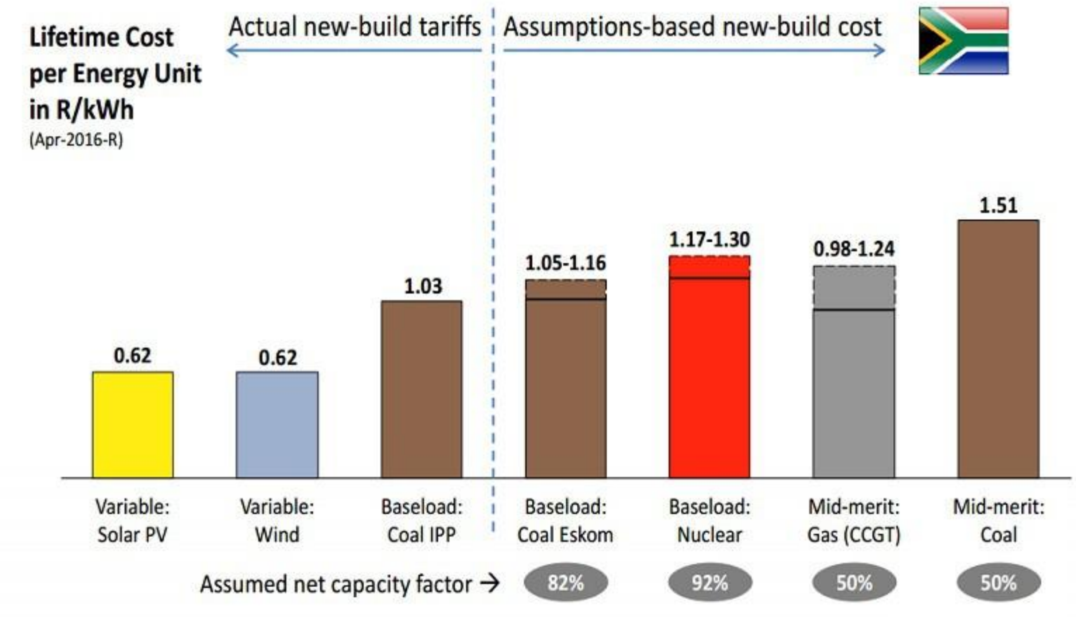


Figure 4: **LCOE potential in South Africa for various energy sources**

(Source: Yeneva, 2016)

The LCOE according to the above figure 4 is R0.62 per kWh for both wind and solar and R1.03 for coal IPP, coal IPP is slight expensive compared to wind and solar energy (Yeneva, 2016). Wind, solar PV and coal IPP in South Africa it is fully comparable as they are usually based on long term contracts with the same off taker which is Eskom and with the same consumer price index inflation (Yeneva, 2016).

1.3 Research Aim

- The study aims to investigate South Africa's energy potential of wave energy, by means of a case study. South Africa has a vast coastline and has a great potential to introduce wave energy into its renewable energy mix.
- The study aims to explore and evaluate the viability and potential of the production of renewable bunker fuels from wave energy in Nelson Mandela Bay Municipality at the Port of Ngqura. It will evaluate how wave farms technologies can be converted into energy to power commercial ports in the country. The aim to get the generated renewable energy converted into green hydrogen through a process of electrolysis in order to produce bunkering fuel for international commercial vessels.

1.4 Research Objectives

- Evaluate how capital intensive is the construction of a hydrogen plant at the Port of Ngqura.
- The research aims to interrogate the best technical and sustainable options for increasing renewable energy and energy efficiency in South Africa's commercial ports.
- The main objective of the study is to evaluate whether renewable energy is cost-competitive with fossil fuels.
- Establish the production cost of green hydrogen using electrolysis.
- To evaluate the potential energy production from a wave farm in Nelson Mandela Bay Municipality at the Port of Ngqura.
- To publish information on renewable energy efficiency.
- Provide ports with an alternative environmental-friendly energy source.

1.5 Research Question

- Is South African well positioned to supply hydrogen and ammonia as a potential renewable shipping fuels?
- Does South Africa have a potential of producing zero-carbon fuels?
- What significance does the geographic location of our ports have on renewable energy?
- What is the capital cost of constructing a hydrogen plant for bunkering fuel?
- How cost intensive are wave farms installation for the production of renewable energy to generate green hydrogen and ammonia?

1.6 Limitation

The greatest limitations encountered during the study is not having enough adequate training when it comes to working with the Python and QGIS program. Another limitation was when it came to acquiring data for capital and operational expenditure for a wind farm of any scale, companies were reluctant with the data as it was considered high level information.

CHAPTER 2

LITERATURE REVIEW

2.1 The need for renewable maritime fuels

The IMO (International Maritime Organization) has developed targets to reduce carbon emissions between 2020 and 2050, by 2030 an expected reduction of 40% in CO_2 emissions per transport work compared to 2008 levels, while aiming for 70% in CO_2 reduction per transport work by 2050 (IMO, 2018). Replacing fossil fuels with zero carbon alternative fuels is regarded as an ideal approach in achieving the carbon footprint reduction of the energy generation industry (Rahman and Wahid, 2021). The IMO also anticipates an annual total greenhouse gas (GHG) emission from ships will be halved by 2050 as part of their strategy to push towards full decarbonisation. In order to meet these caps, maritime companies are exploring clean alternative fuels from LPG (Liquid Petroleum Gas), methanol, LNG (Liquid Natural Gas), biofuels, hydrogen and ammonia (Marine & Offshore, 2019). The Paris Agreement has stipulated that each country must identify plans and conduct regular reporting regarding its contribution to undertake the reduction of global warming (Vrontisi et al, 2020).

South Africa is looking at other alternatives in combating carbon emissions, the country has a vast coastline which can be explored to introduce a new energy mix to its existing renewable energy production (Eskom, 2020). The South African energy sector is an important element due to the country’s advancement and innovations in the renewable sector. Renewable energy projects in South Africa are becoming more inexpensive, widely used and efficient. The country has an abundance of renewable resources which can effectively supply the country’s energy supply. According to (Winkler, 2005), South Africa has a vast renewable energy potential of about 280 TW, it possesses the most promising renewable source in Africa. Several studies have endorsed renewable technologies as a scalable resource with a strong output capacity and solar being the resource with the largest potential, wind and wave provide other viable alternatives (Krupa and Burch, 2011). With the geographical location of South Africa at the southernmost tip of Southern Africa there is a great potential for commercial wave farms to contribute to the country’s energy mix. According to the natural resource accounts report for minerals by the Statistics South Africa in 2004 (Report no. 04/05/02; 1980-2001), highlighted that in 2000 renewable energy was at (11.6%), coal (74.8%), nuclear power (3.2%) and oil (9%).

2.2 Hydrogen a future maritime fuel

In South Africa there is a positive acceptance of implementation of renewable energy projects which has been displayed by the introduction of various energy policies which are aimed at promoting renewable energy projects (Department of Mineral Resources and Energy, 2020). Sasol is one of the country’s integrated oil and gas company, supports the implementation of an alternative zero carbon fuels in South Africa and the interest of a zero-carbon alternative fuel is triggered by an environmental and economic issues, hydrogen is among the most promising carbon free alternative fuel as it can be produced by renewable sources (Rahman and Wahid, 2021). The integrated oil and gas company has developed an environment to advance the country’s green energy economy (SASOL, 2021). (Welch and Prasad, 2018) and (Rahman and Wahid, 2021) both agree that hydrogen is the future energy which could help to decarbonize the global energy use.

The development of the hydrogen industry in South Africa is a key enabler to transition into a decarbonized future, as hydrogen has the potential to decarbonize various sectors within the country. According to (SASOL, 2021) the green hydrogen industry in the country will provide an opportunity to create a new hydrogen ecosystem and become a credible exporter of sustainable energy and chemical products such as hydrogen, renewable aviation fuel and ammonia. The South African green hydrogen potential must support the energy transition by unlocking a new value chain by igniting the country’s economy. Carbon neutral production of hydrogen is a most critical factor in transitioning the energy sector towards a climate friendly energy supply (Pein et al, 2021). With time, technology advancement and our changing needs there is a constant demand of fuel and energy, hence our future fuels must be environmentally friendly and clean, this can only be achieved by sourcing it from renewable energy resources (Mondal, 2020).

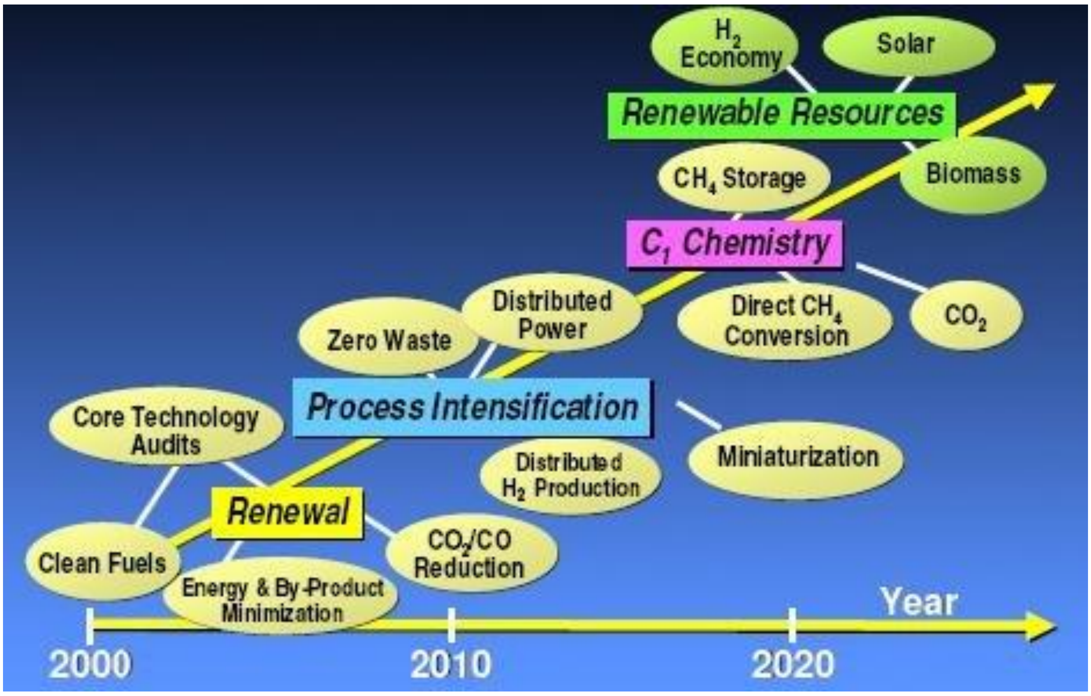


Figure 5: **Alternative fuel obtained from renewable sources, vision for future fuel technology**

(Source: Mondal, 2010)

2.3 Ammonia storage, a transportation medium for hydrogen

Ammonia is considered one of the most potential chemical in transporting and storing hydrogen, it contains high liquid density of 0.6 kg/l compared to hydrogen which is 0.071kg/l and the heat combustion of ammonia is 11.2MJ/l compared to 8.58MJ/l of hydrogen liquid (Jolaoso and Zaman, 2020). (Jolaoso and Zaman, 2020) and (Pein et al, 2021) are in agreement that hydrogen storage material will not only provide a short-term need, however it pose to bring a long-term solution to the transportation sector while producing zero carbon emissions. Hydrogen has also been reported to be a greenhouse gas, with a GWP100 around 5.8, this is one of the negative aspect which must to be considered when designing hydrogen infrastructure in order to avoid explosions and leakages.

Ammonia is a relatively effective and a viable chemical to be employed in hydrogen as a storage material (Jolaosoa and Zaman, 2020). “The advantage of ammonia is that it is one of the agents that can be used to transport hydrogen over long distance. Through marine transportation, ammonia can be combusted directly and utilized as a fuel.” (World Energy Council, 2019).

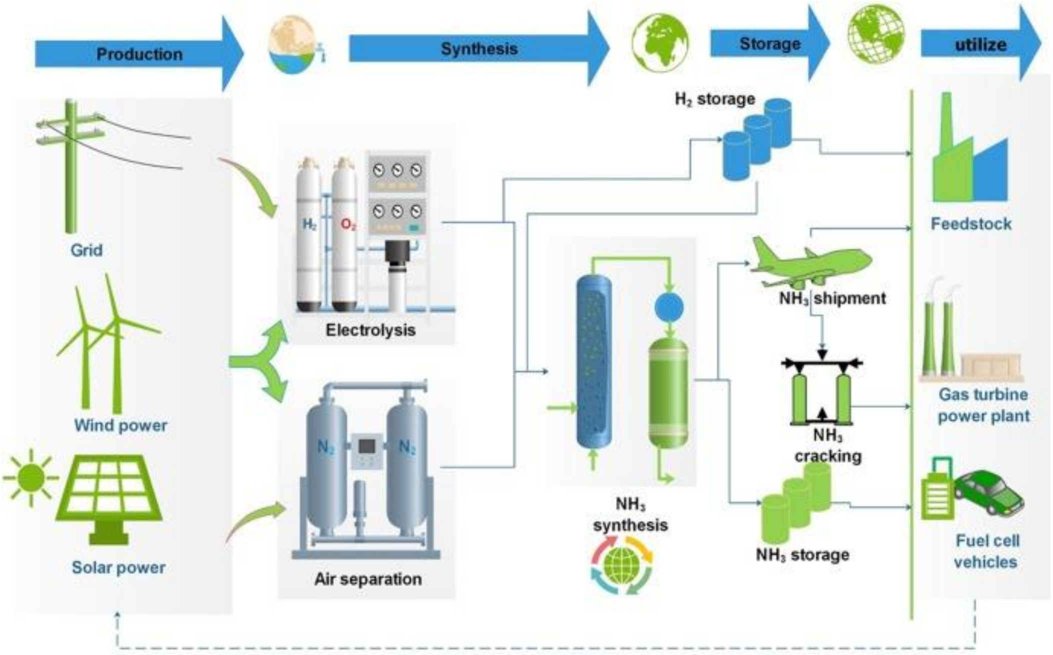


Figure 6: **Schematics of the green ammonia process from production to utilisation**

(Source: Chehade and Dincer, 2021)

(Bexter, 2020), strongly believes that the reason hydrogen is inefficient is due to the energy vector transition. He goes as far as making an example of 100 watts of electricity produced through a renewable source, the energy has to be converted into hydrogen passing through water using an electrolysis process. According to (Bexter, 2020), this is 75% energy efficient and 25% of electricity is lost, the produced hydrogen can be compressed, chilled and transported to a hydrogen station and the process is around 90% efficient. Once the hydrogen is inside the vehicle it must be converted into electricity which is 60% efficient and finally the electricity which is used to drive the vehicle is 95% efficient, in essence 38% of the initial electricity which is 38 watts out of the 100 watts is used. The same is true for ammonia, and indeed, conversion to ammonia will most probably involve more losses. However, this energy is then stored in a stable form, and we can release it when we need it. This is the final hurdle that needs to be taken in a renewable energy system, to match supply and demand in terms of timing, as we managed to do with fossil fuels.

2.4 Future Maritime fuels

2.4.1 LNG

LNG is still relatively a fossil fuel despite its emission reduction potential, it poses a challenge of methane slip which is caused by incomplete LNG combustion in the vessels engine (Schonborn, 2021). The price of LNG is falling making it competitive to Heavy Fuel Oil (HFO) the trend is expected to build up as the global LNG bunkering infrastructure develops (Marine & Offshore, 2019). According to (Kumar and Himabindu, 2019), while LNG gains momentum as an alternative marine fuel solution more LNG powered vessels are being constructed. Methane is compatible with LNG propulsion technologies, methane can be a carbon neutral, alternatively when used in carbon capture and fuel cell technology and current existing LNG fuel infrastructure can be used to serve both fuels (Marine & Offshore, 2019). Methane offers great environmental benefits by producing more heat and light energy by mass compared to other hydrocarbons (SoCalGas, 2021). In essence the more natural gas is used to replace coal in electricity generation for fuelling buses, cars and trucks in essence means less smog and GHG emissions emitted in the environment.

2.4.2 Biofuels

Biofuels is a carbon neutral solution which is increasingly becoming available as a marine fuel, the mass production of biofuels is not sustainable as industries already make use of biofuels (Marine & Offshore, 2019). This makes biofuels a partial solution to establishing a viable future maritime fuel (Hertel et al, 2010). Biofuels have the potential to replace fossil fuels and generate environmental benefits (Huang et al, 2013). According to academic studies through the use of economic model's biofuels can lead to reductions of lifecycle GHG emissions as compared to conventional fuels and land use remains a burning issue for some biofuels. (Hertel et al, 2010 and Huang et al, 2013).

2.4.3 LPG

LPG is another possible alternative fuel which is easy to store, handle and is relatively available, LPG has a lower CAPEX compared to LNG (Marine & Offshore, 2019). LPG limits the output of carbon; however, it does not eliminate CO_2 emissions. The levels of LPG production are relatively low to make this alternative fuel a solution for future maritime fuels, however it could be part of a larger solution starting with LPG carriers.

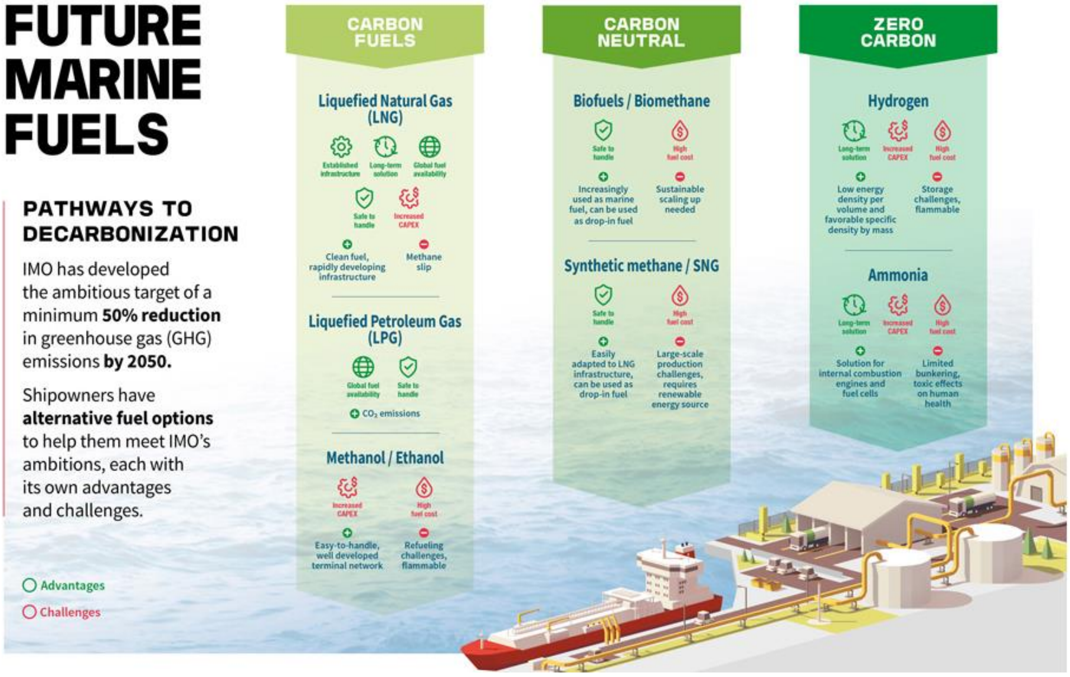
2.4.4 Ethanol and Methanol

Methanol and ethanol present other alternative fuels to LNG, they are both liquid and potentially produced as biofuels. LPG is quite rare as a biofuel and requires pressurized or cooled tanks. These fuels are easy to handle compared to LNG (Marine & Offshore, 2019). Methanol and ethanol fuelled ships are designed with special care as bunkering facilities are limited and considering the gases toxicity and flammable nature (Marine & Offshore, 2019). For safe usage additional CAPEX is required for handling and storage, the CAPEX gap is smaller for LNG fuel as costs tend to be less favourable compared with LPG and LNG (Hertel et al, 2010).

2.4.5 Hydrogen and Ammonia

Hydrogen and ammonia are considered the world’s cleanest fuels, as they are carbon free and produce zero CO_2 emissions when they are sourced from renewable energy. Hydrogen and ammonia are a clean fuel solution for internal combustion engines and fuel cells (Marine & Offshore, 2019). According to (Li et al, 2020) hydrogen energy can enrich renewable energy storage at low costs, this can assist renewable energy to regulate fluctuation and thus promoting energy diversification structures and the security of energy supply. (Pein et al, 2021) considers hydrogen as an attractive energy source for energy storage and an important industrial commodity, (Rahman and Wahid, 2021) also agrees with (Pein et al, 2021) that carbon free fuel has a potential in playing an important role in decarbonizing all economic sectors.

The developments which are associated with green hydrogen and green ammonia has been reviewed and is there to support an existing potential (Rahman and Wahid, 2021). Ammonia, acting as a hydrogen carrier shows an indication as a zero carbon fuel for shipping. Ammonia is a commonly used chemical around the world with global production levels of 190 million tons per annum, it is widely available hence the need of marine bunkering infrastructure needs to be developed (Marine & Offshore, 2019). Ammonia conveniently carries hydrogen and is an emerging clean fuel.


FUTURE MARINE FUELS

PATHWAYS TO DECARBONIZATION

IMO has developed the ambitious target of a minimum **50% reduction** in greenhouse gas (GHG) emissions **by 2050.**

Shipowners have **alternative fuel options** to help them meet IMO's ambitions, each with its own advantages and challenges.

Figure 7: Future maritime fuels, a pathway to decarburization.

(Source: Marine & Offshore, 2019)

2.5 Hydrogen economy

Hydrogen has been produced for years before it come to be recognized as an element, Robert Boyle produced hydrogen gas in 1671 while he was experimenting with iron and acids (Blaszczak, 2015). Hydrogen was first recognized as an element by Henry Cavendish in 1766, it is the most abundant element in the universe made from one proton and one electron. Hydrogen is nontoxic and light as an energy storage medium and it has a small negative impact on the environment when it is used as a fuel source (Burton et al, 2021). Hydrogen is known to be the most abundant element and the lightest gas in the universe with a gravimetric energy density of 141 kJ/g in comparison to fuels derived from fossil fuels, it also accounts for 75% of all matter (Jolaosoa and Zaman, 2020). Hydrogen is considered the cleanest burning fuel which burns more effectively than most petrochemicals (Rahman, Wahid, 2021), vehicles making use of hydrogen as an energy source carry low levels of environmental damaging emissions (Burton et al, 2021). Hydrogen has the lowest viscosity which has resulted to a decreased friction which contributes to the overall loss of efficiency in the form of heat (Burton et al, 2021). Hydrogen is a raw fuel which most stars use in a nuclear fusion reaction to produce energy, the sun's supply of hydrogen is expected for another 5 billion years (Blaszczak, 2015).

Large amounts of hydrogen are combined with nitrogen in the air to produce ammonia (NH_3) through a Haber process, liquid hydrogen when combined with liquid oxygen becomes an excellent component for rocket fuel (Blaszczak, 2015). There are primary energy sources such as wave energy, solar, hydropower, geothermal and wind, which the extraction of hydrogen can be conducted in a sustainable manner (Jolaosoa and Zaman, 2020). Hydrogen may combine with other elements to form ammonia (NH_3), water (H_2O), hydrochloric acid (HCl), table sugar ($C_{12}H_{22}O_{11}$), methane (CH_4) and hydrogen peroxide (H_2O_2) (Blaszczak, 2015).

The hydrogen energy system is based on the energy complementary to renewable energy which can improve the consumption of renewable energy and pose a characteristic of green, sustainable, low carbon which is currently a hot topic in global research (Li et al, 2020). In addition, hydrogen is by far less poisonous as a fuel compared to methane and gasoline which produce less harmful emissions after combustion and a higher ignition temperature, hence it is considered a safer fuel than methane and gasoline and ranks top in transportation industries as a future alternative fuel (Burton et al, 2021).

Produced with a green energy source or low carbon technology, hydrogen (H_2) presents a promising future for multidisciplinary decarbonisation (Tlili et al., 2020). It can act as a flexible energy bearer that reduces the negative effects of climate change by reducing global greenhouse gas emissions (Seo et al., 2020). Hydrogen has great potential to reduce its dependence on fossil fuels. It is a rich material, has the highest energy content by weight, and is almost three times the gasoline content (Blaszczak, 2015). Green hydrogen is also a sustainable option for renewable energy storage (Jafari et al., 2020).

Green hydrogen as a clean energy source makes use of electrolysis. However, critics argue that the production produces green H_2 and O_2, however, the process is energy intensive. The increased use of alternative renewable energies should be considered as counter measures to reduce GHG emissions, countries which fail to limit and reduce their carbon footprint should be issued with energy fines. There is another challenge that hydrogen is facing from an economics point of view, the manufacturing cost of electrolysis for green hydrogen is also higher than the established hydrogen manufacturing system of grey hydrogen by steam reforming (SR), partial oxidation (POX) and automatic thermal reforming (ATR) (Pozzi, 2017). The production of hydrogen by electrolysis costs around $10.3 per kg of H_2 this is five times more than the current established techniques which go by $1.5-2.3 per kg of H_2 (Kumar and Himabindu, 2019).

Failure to invest in green hydrogen plants which have a great potential in decarbonizing our economies is no longer an option and our reliance on fossil fuel for a wider power demand is increasingly being disputed as unrealistic. Hydrogen as a versatile energy carrier has a long-term potential to complement renewable generated energy and also provide solutions to decarbonize certain sectors and store energy.

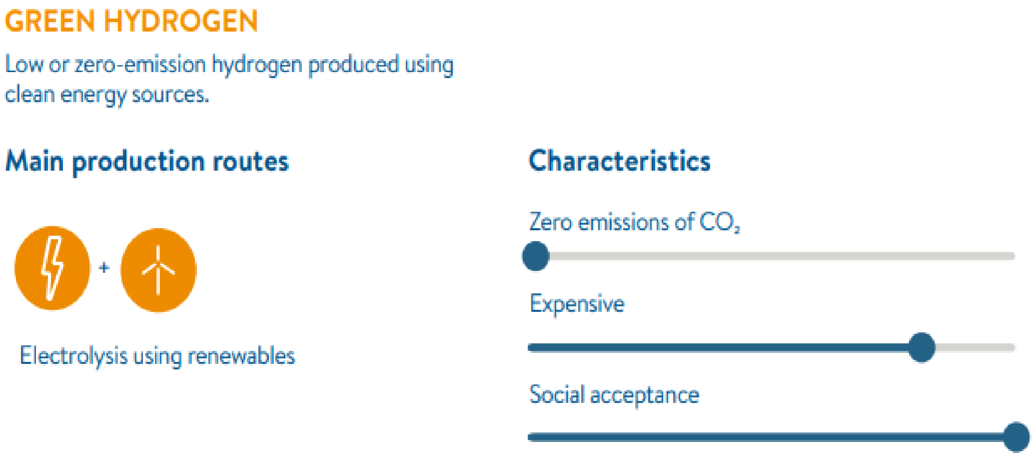
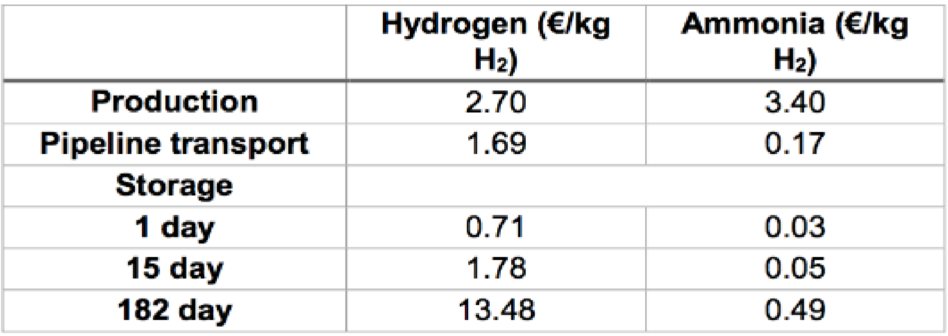


Figure 8: **Figure Production of green hydrogen**

(Source: World Energy Council, 2019)



	Hydrogen (€/kg H_2)	Ammonia (€/kg H_2)
Production	2.70	3.40
Pipeline transport	1.69	0.17
Storage		
1 day	0.71	0.03
15 day	1.78	0.05
182 day	13.48	0.49

Table 1: Cost of hydrogen and ammonia

(Brown, 2016)

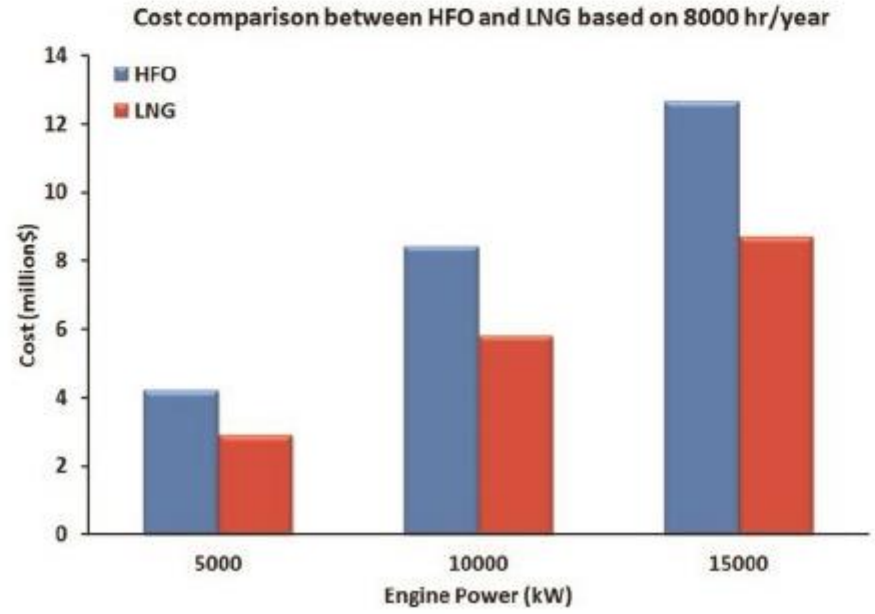


Figure 9: Cost comparison of HFO and LNG

(Source: Elgohary et al, 2021)

2.6 Future outlook of hydrogen

Many authors agree that hydrogen is a potential paradigm shifter, it has a great potential in playing a major role in the future of low carbon economies (World Energy Council, 2019). Whether hydrogen becomes the energy carrier of choice for decades to come or if it delivers specific energy services, it has a vital role to play in the future and development of future energy systems (World Energy Council, 2019). With the diversity of hydrogen production, consumption and transportation pathways a clear government strategy could have an impact on cost reduction in introducing fuel cell technologies and hydrogen. The cost and performance of hydrogen rely on the favourable economies which have been identified, mostly the continuous reduction of renewable prices, price drop of fuel cells and performance. With the cooperation of government support and technological progress and a large scale of investments in this could be a clear indication that hydrogen is here to stay (World Energy Council, 2019).

Renewable energy and fuel prices, followed by stringent climate change policies and the involvement of China are step changers. These factors are leading to realistic potential for hydrogen's role in the Grand Transition (World Energy council, 2019). Fuel cell and electrolysis technologies are maturing, with additional increased manufacturing and its wide spread availability is driving cost reduction. With cost reduction of renewable energy technologies currently leading opportunities to decarbonize the production of hydrogen. The pressure to meet climate change targets and air pollution concerns is leading private companies and governments to search for decarbonisation solutions which are different in application, time frame and scale (The Maritime Executive, 2018). The government must be at the forefront of the hydrogen and wave farms development. Hydrogen has a shorter refuelling time and the use of hydrogen without emitting any greenhouse gases has made mobility a capable field for fuel cells and hydrogen (Pozzi, 2017). These technologies encounter challenges in terms of costs, investment and infrastructure. Working on mainstreaming hydrogen as a decarburization pathway is required, this includes the safety of hydrogen and customer engagement (The Maritime Executive, 2018).

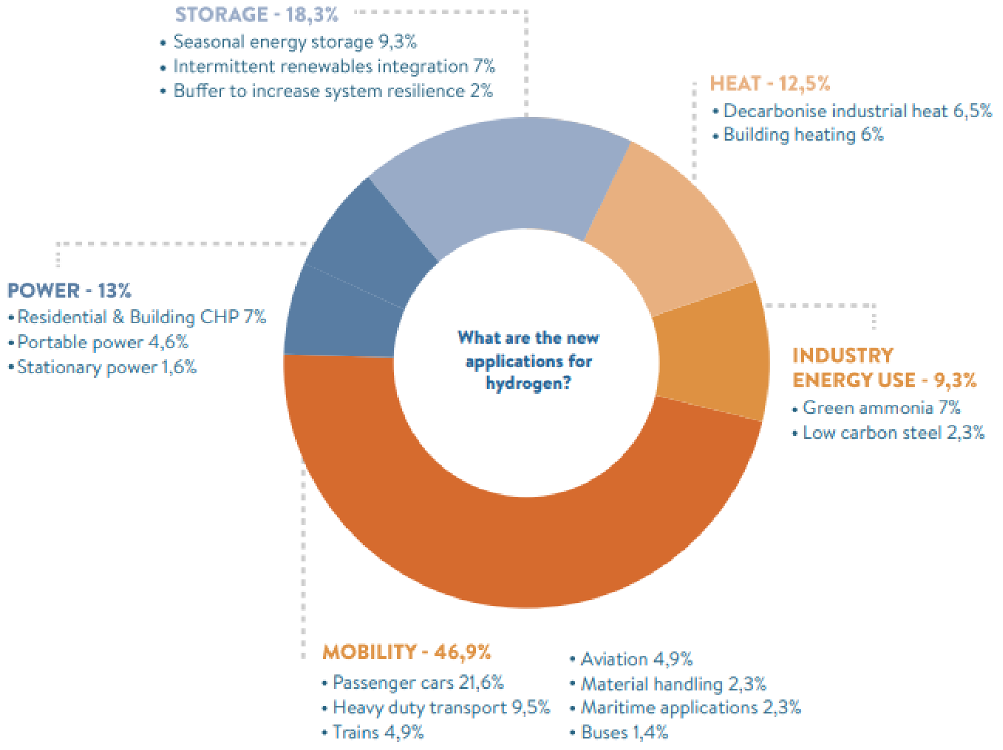


Figure 10: The new application for hydrogen

(Source: World Energy Council, 2019)

Decarbonizing applications by 2050 suggests investment for research and development and feasibility studies should be starting now. Installing hydrogen decarbonisation solution requires the involvement of the supply chain of national and local governments. The development of hydrogen application relies on continuous innovations and setting up projects at a higher scale than technological breakthrough. Renewable energy resources such as solar and wind tend to compare the current state of hydrogen before they can implement any supporting policies (World Energy Council, 2019), However, recent declines in electricity prices are driven by renewable energy which reflects a savings of up to 30% in production costs which is expected within 10 years (IEA, 2019c). In addition, the expansion of electrolysis capacity has other additional impacts in reducing the manufacturing cost of green hydrogen (Pozzi, 2017). Another issue when it comes to green hydrogen is its low energy efficiency of about 30% (The Maritime Executive, 2018).

There are also existing views in relation to the security of hydrogen when it comes to storing and transporting, very similar to the concerns in the early days of the LNG supply chain. In the case a leak is found that hydrogen fuel is safer than hydrocarbon fuels on hydrocarbon, such as gasoline, as they rise quickly and quickly derive into the atmosphere, limiting the burner capacity (Pozzi, 2017). The liquid and compression hydrogen is at a frozen temperature and thus the security effects of their release in the air in the process of the synthesis of the supply chain network should be considered (Tlili et al., 2020). In 2014, Japan has initiated a hydrogen plan worldwide and has developed strategies for the hydrogen supply chain to remove the transport industry, the supply chain will import hydrogen (Kawasaki, 2019).

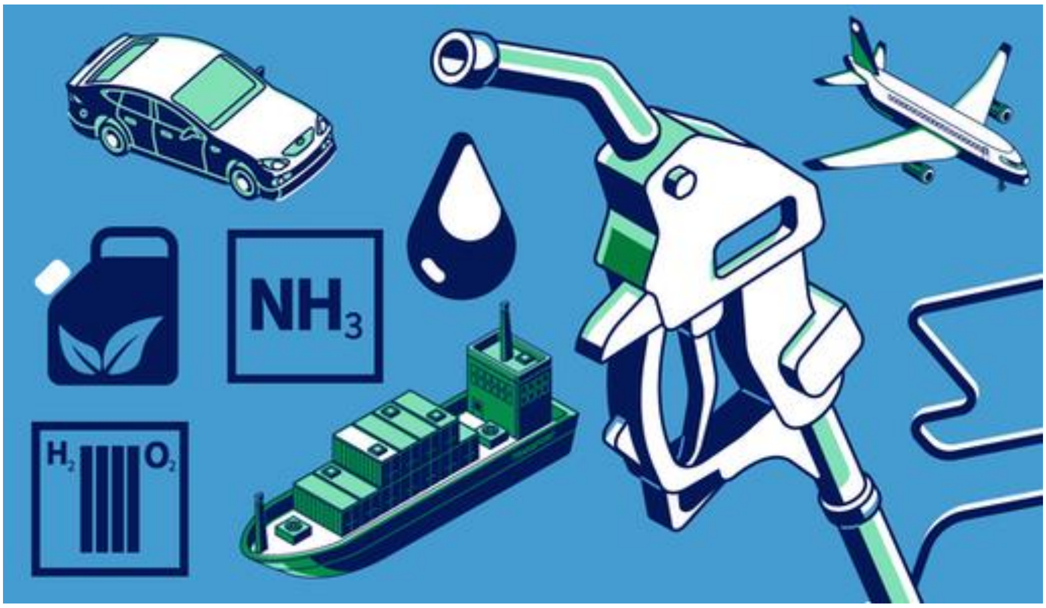


Figure 11: Future roles of sustainable fuels

(Source: Holland, 2021)

2.7 Waves and the South African coastline

There are three parameters which play a decisive role in marine operations which are waves, wind and current, the only one that is predicted by the weather is the wind. The wind is predicted by local and international weather organization and weather applications including South African Weather Services. Wave buoys within the South African coastline provides a valuable design of data for local maritime developments.

According to (Kumar and Himabindu, 2019), satellites for wave measurements are suited to supply information on wave height in remote offshore areas. The significant wave heights are vitally important for different problems in marine activities such as wave converters and marine structures, it is usually estimated by using buoys and record time series of wave elevation information (Cornejo-Bueno et al, 2016).

The availability and reliability of wave data plays a crucial role to better understand statistical and numerical wave models (Casas-Prat et al., 2014; Durrant et al., 2013), although wave focusing has been installed for the safety of ship navigation, for the design of marine structures, for wave energy convertors, wave overtopping volumes and for calculating wave heights for research purposes (Comola et al., 2014; Kim and Suh, 2014). According to (Kumar and Himabindu, 2019), waves generally have an impact on energy production, human safety and economics.

Wave is an abundant and a sustainable energy resource which is created by wind over the ocean surface, the more the distance the higher and longer the wave will be formed (Eskom, 2020). The World Energy Council has estimated that 2TW of energy can be harvested from the world's ocean and the United Kingdom (UK) has estimated that recoverable wave energy exceeds the total UK electricity demand (World Energy council, 2019). (Eskom, 2020), coastlines with an ocean catch greater than 400 km are most suitable to invest in offshore energy such as wind, wave and tidal farms. However, greater resources are also available between latitudes of 300 and 600 in the Southern and Northern hemispheres.

According to (World Energy Council, 2019), if less than 0.1% of the renewable energy within the oceans could be converted into electricity, it will satisfy the current world energy demand by more than five times. The involved technology is the collector which is used to capture the wave data and power take off (PTO) which is employed to transform the wave power into energy.

Currently Eskom is looking into available resources of wave power along South Africa's east and west coastal regions, this is in order to capture wave data and manipulate the data to determine the viability of investing economically into exploiting wave energy and investing in new technologies. Many countries in the world are currently looking to invest in wave energy, Canada has announced the opening of new wave energy generation systems. (Eskom, 2020) added that once the resource assessment of investing in wave energy has been completed and the results are relatively positive, the country's utility energy provider will conduct laboratory tests on various ocean conversion technologies. The test will assist Eskom to identify the best technologies to be used.

Offshore wind is regarded as the cleanest energy technology generation which holds significant resource potential in many coastal countries. However, wave power has a far greater energy density compared to wind and solar, as it generates up to 24-70kW per meter of wave and with a peak near shore power which ranges from 40-50kW per meter (King and Spalding, 2021). The world's total wave potential is estimated at 2 TW of energy, according to (King and Spalding, 2021) this is equivalent to the world's electricity consumption. Therefore, OWE and wave energy has a huge potential to play in South Africa's large-scale aim of a new energy mix for energy security, decarbonisation and emission reduction.

According to the Pacific Wave Atlas the cost of energy is a measure to generate electricity keeping in mind the life time energy production and costs involved. The cost of energy depends on installation, maintenance and device costs and the amount of energy extracted. An important element to consider is that, it does not consider profits meaning it does not reflect the actual price of electricity which consumers pay.

Type	Cost range
Device	US$ 3 - 4 million
Moorings	US$ 0.3 - 0.4 million
Installation	US$ 1.2 - 1.6 million
Shipping	US$ 0.18 - 0.24 million
Total	**US$ 4.74 - 6.3 million**

Table 2: An estimate of capital costs of a wave convertor

(Source: Bosserrelle et al, 2015)

The below table represents operational and maintenance costs of technology device used for a wave farm project which has a life span of 25 years.

Type	Cost range
Annual Operation and maintenance	US$ 0.049 - 0.272 million
Mid-life refit	US$ 0.49 - 0.68 million
Decommissioning	US$ 0 - 1.0 million
Total for the device lifetime (25 years)	**US$ 1.72 - 8.48 million**

Table 3: Operation and maintenance cost of a wave farm devices (25 years)

(Source: Bosserrelle et al, 2015)

CHAPTER 3

METHODOLOGY

3.1 Purpose of the study

South Africa is a country highly dependent on fossil fuel mainly coal for economic growth and electricity generation. It has introduced a new energy mix for electricity power supply from renewable sources such as wind and solar. South Africa has a great potential of generating electricity from wave power due to its coast line. South Africa has a potential market for offering bunkering fuel services as many vessels including huge commercial vessels passing through the Cape point during trading routes. In this chapter we look into the potential of wave energy as an alternative energy source being introduced in the current energy mix, as South Africa is geographically well positioned in Southern Africa with a coast line stretching from 2 800 km from the boarders of Namibia to Mozambique and has a high potential to unlock the offshore renewable energy sector. We will look into the installation of a wave farm with three-point convertors in the Eastern Cape in Nelson Mandela Bay (NMB) and the construction of a hydrogen plant which will be located at the Port of Ngqura to offer bunkering services to international commercial vessels. We will also evaluate the viability of constructing a hydrogen plant through using Capital Expenditure (CAPEX) and Operational Expenditure (OPEX). The hydrogen plant will make use of electrolysis to produce green hydrogen, we will take a look at the current market costs of electricity for businesses and the current cost of hydrogen per kilogram in South African Rand. We will also investigate when the hydrogen plant starts making profit. Through the use of Monte Carlo simulation, we will predict the price of electricity from 2021 to 2025 using data from ESKOM tariffs in order to calculate the possible future value of electricity. The price of electricity is the determining factor towards the price of green hydrogen.

3.2 Method Approach

The research method we will use is a mixed methodology research design, according to (Creswell, 2012), it is a procedure for collecting, analysing, and “mixing” both quantitative and qualitative research methods in a single study to understand a research problem. For one to utilise this type of methodology more effectively, it is essential that both qualitative and quantitative methods are well understood. Research that takes a positive approach is likely to work primarily with data in terms of it being facts or values which can be observed, counted and measured (Mathews, 2010).

3.3 Research Approach

In the study we will identify a suitable location for our wave farm which will consist of three-point convertors working simultaneously to generate energy from wave power.

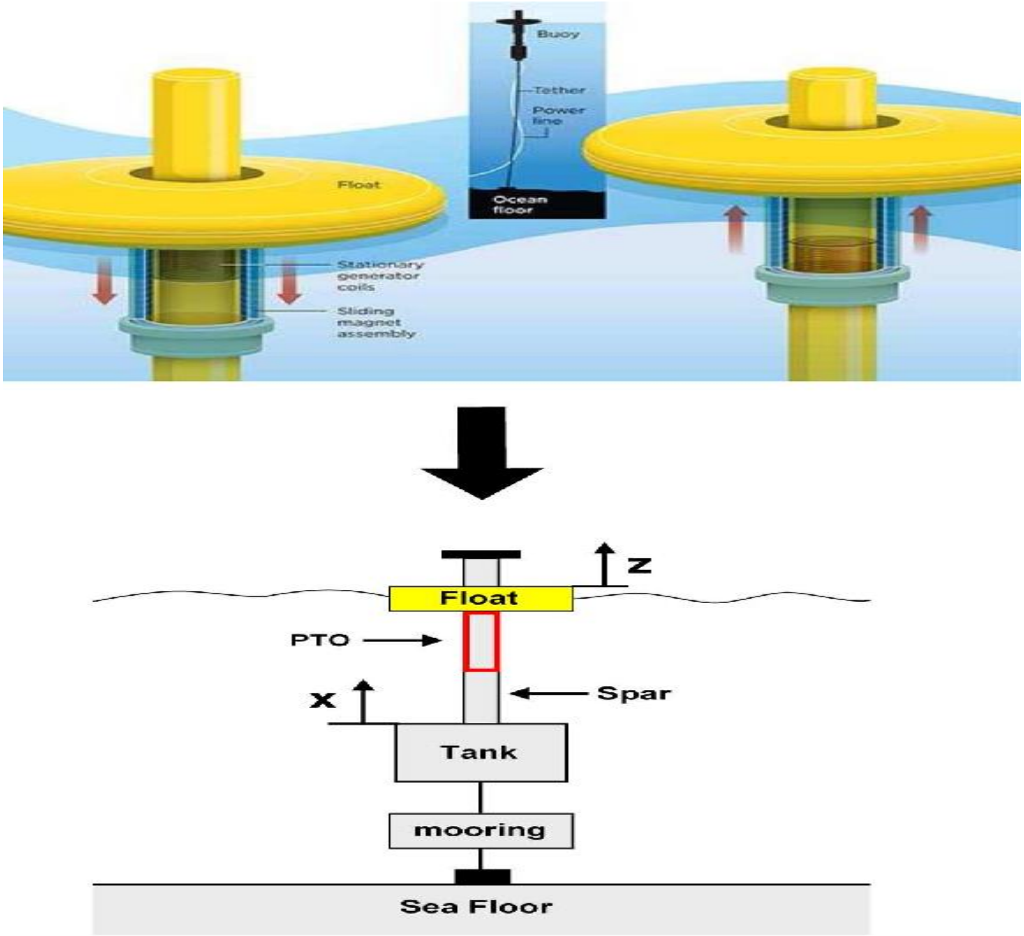


Figure 12: Schematic of a point convertor

(Source: Richter et al, 2021)

The location for wave farm, the coordinates are 34.16° S and 25.83° E where the wave farm will be located in (NMB). The wave data is extracted from E.U Copernicus Marine Service, Global Analysis Forecast WAV_001_027.

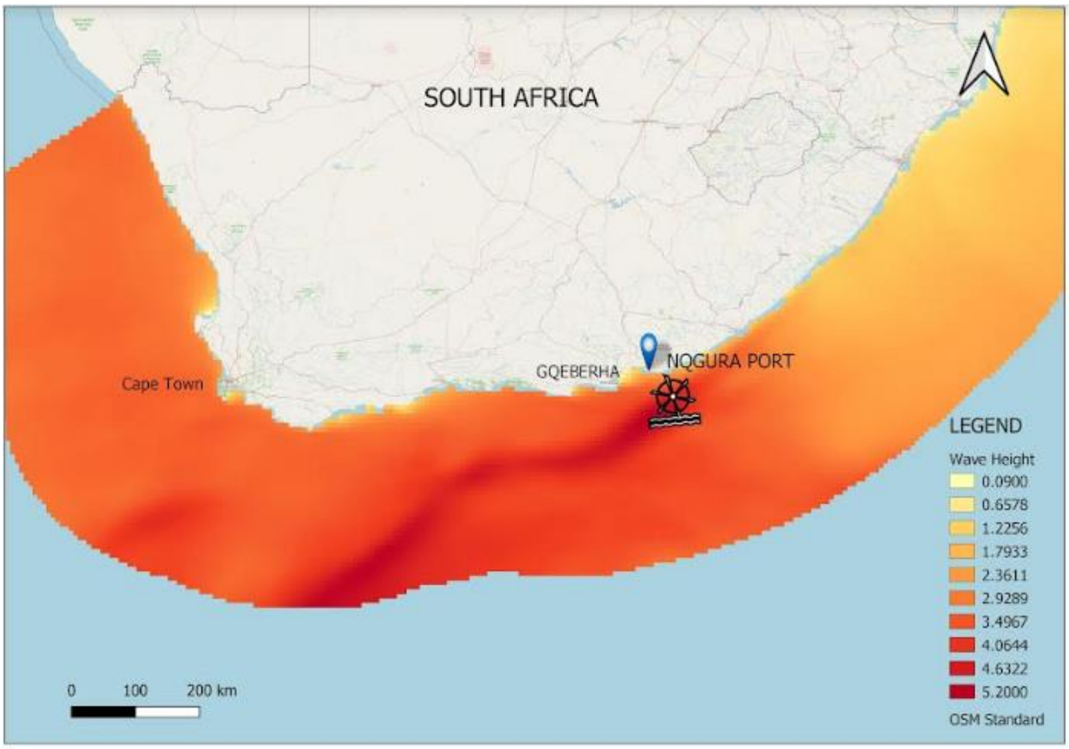


Figure 13: **Location of the Wave Farm in Nelson Mandela Bay Municipality with the average wave height in (m)**

The wave data extracted from E.U Copernicus was used in QGIS to provide the reader with a visual representation for the location of the wave farm which is roughly 5km from the coastline of Port of Ngqura. The data was downloaded from E.U Copernicus global high-resolution wave model (CMES GLOBAL_ANALYSIS_ FORECASTWAV_ 001_027). It was then loaded into QGIS and was used to map the location of the wave farm in Nelson Mandela Bay Municipality. A symbology was used to air mark the location of the wave farm, and to process data to visualise and illustrate the distribution of wave heights within the (Exclusive Economic Zones) EEZ of the Port of Ngqura. Through using QGIS and E.U Copernicus we managed to identify a suitable location for the wave farm and provide a visual representation.

Selecting a suitable location for a wave farm various factors need to be considered from identifying EEZ, shipping lanes leading to the Port, water depth, Marine Spatial Planning (MSP), fisheries and breakwater where the Wave Energy Convertors (WEC) will be installed. The installation of the wave farm is located in an industrial area more than 2km from the coastline where there is little or no environmental impacts (Cascajo et al, 2019). There are various commercial activities occurring in the South African Maritime Zones, which are not limited to tourism, mining, agriculture, fishing, coastal geoengineering, shipping and renewable energy (Ramulifho, 2014). The exploitation and exploration of natural resources and coastal developments undermines and disrupts the ability of natural cycles to sustain its natural form hence the need for MSP Planners and Environmental Specialists to conduct the necessary studies to prevent disruption of marine natural habitat. Further studies should be conducted by MSP and Environmental specialists regarding the suitable location of the wave farm we are aware of the need for zoning the area before any projects or work can take place. Relevant stakeholders and community members to be consulted and engaged regarding the development of a wave farm in their Municipality to get their views and opinions regarding the development.

The Port of Ngqura was identified as the port choice to spear head the hydrogen plant. The Port of Ngqura is a deep-sea transhipment port and is the youngest commercial port in South Africa, it started operations in 2012. Looking at the below figure 14 it indicates vessels passing through the southernmost tip of Africa and the need to capture the market through offering vessels with environmentally friendly green fuel. This bunkering service will not only make the Port of Ngqura more attractive and competitive; however, it will be a Port of choice and will have an edge of being a one stop shop.

The study will demonstrate the advantages of the captured power in energy absorption and investigate the effect of WEC devices on a power capture performance, creating a foundation of developing an optimized performance method in the future. The study will also provide a reference for future studies in South Africa costal zones and EEZ on wave energy capture.

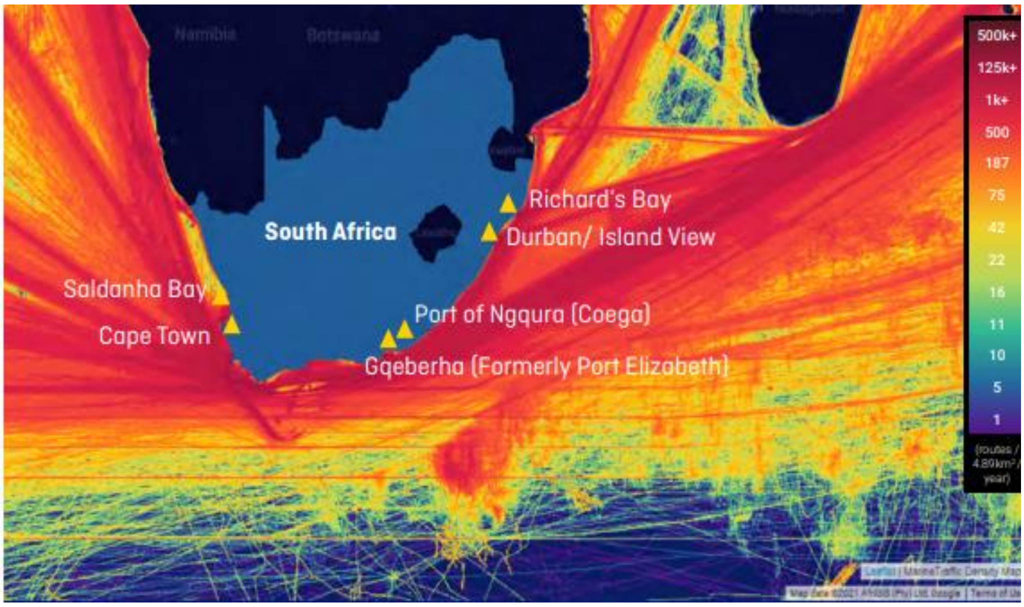
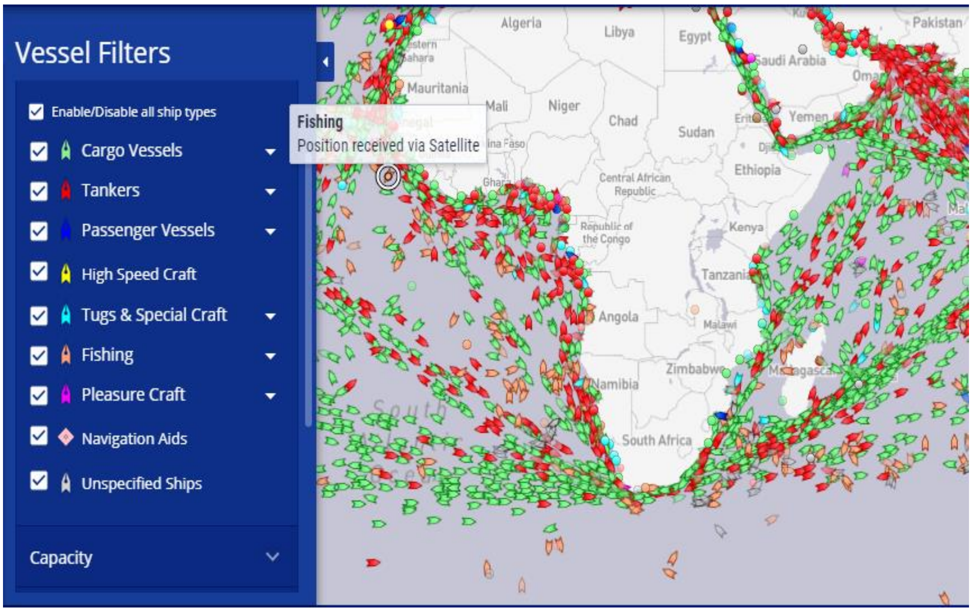


Figure 14: **Illustration of vessel traffic in South Africa's busiest ports**
(Source: Ricardo and Environmental Defence Fund, 2021)

Figure 15 shows marine traffic and the types of vessels passing through the southern tip of Southern Africa. Having identified the opportunity to offer hydrogen bunkering fuel, future research can possibly investigate retrofitting commercial vessels at the Port of Ngqura. A ship yard to be built to offer commercial vessels an opportunity of retrofitting with an aim of decarbonising and using environmentally friendly fuel. However, for our study we investigate introducing a new energy mix from a renewable energy source which is wave energy and how wave energy can be used to produce green hydrogen through a process of electrolysis and the CAPEX and OPEX of a hydrogen plant, the current cost of hydrogen and hydrogen production and selling price of hydrogen and the profits made.



Vessel Filters

☑ Enable/Disable all ship types
☑ Cargo Vessels
☑ Tankers
☑ Passenger Vessels
☑ High Speed Craft
☑ Tugs & Special Craft
☑ Fishing
☑ Pleasure Craft
☑ Navigation Aids
☑ Unspecified Ships

Capacity

Fishing
Position received via Satellite

Figure 15: **Vessels passing through the Southern tip of Africa**

(Source: Marinetraffic.com, 2021)

3.4 Research Instruments

3.4.1 E.U Copernicus Marine Service (Wave height database)

The Global analysis forecast provides an aggregated analysis which are updated weekly with a 10-day forecast (updated daily). The data contains 3D potential temperatures, currents and salinity information from top to bottom and 2D sea surface level and bottom potential temperature. The data set used for this research is the Global analysis forecast phy 001-024 hourly merged uv (SMOC) Surface and Merged Ocean Currents that contains one data set. The global high-resolution wave model (CMES GLOBAL_ANALYSIS_FORECAST_WAV_001_027) was used. the data distributes zonal surface velocity fields for three components which is for waves, tides and general circulation on a 1/12° regular grid. The E.U Copernicus data is a combination between data assimilated models which describe the oceans circulation, wave and tides. On our study the data extracted from E.U Copernicus is an average power of three hours. We used E.U Copernicus to acquire wave data and the data extracted is from three hours intervals which validated the accuracy of the wave data at the location zoned for the wave farm.

3.4.2 Euler method simulation

In this work, a Euler-method dynamic simulation illustrates the dynamic response and power capture obtained by three wave energy converters in series. The simulation was implemented using the acceleration, velocity and position simulated using the equations of motion (Giordano & Nakanishi, 2006). The force acting on an induction generator was simulated and quantified using this computational model. The code is provided in Appendix 1.

3.4.3 Monte Carlo simulation

A Monte Carlo Simulation is a probability simulation; it is a mathematical technique which is used to estimate the possible outcome of an uncertain conditions. Monte Carlo simulation is used to assess the impacts of risks in scenarios such as stock prices, sales forecasts, prices, project management and artificial intelligence. It has the ability to predict models with fixed inputs and conduct sensitivity analysis and calculate correlation of inputs. Monte Carlo Simulation is used for long term prediction due to its accuracy. The reason the researcher used of Monte Carlo Simulation was to predict the probable price of electricity in 2021 to 2025 as it will give us an indication for the future price of green hydrogen, as the electricity price determines the price of green hydrogen.

3.4.4 QGIS (Quantum Geographic Information System)

QGIS is an open source of geographic information system which supports geospatial vectors, database formats and raster file types. QGIS was used as it offers a variety of mapping features and data editing, it supports plugin which expands functionality through providing additional tools such as data support, mapping tools and geo referencing.

3.4.5 Data analysis Programming (Python)

A wave data analysis program was written (Python programming language), to simulate three wave energy converters operating at sea wave, the data was extracted from the wave height database (E.U Copernicus Marine Service). Python is a powerful programming language which has an efficient high level data structure and an effective approach to object oriented programming. It can interpret data and translates it into an ideal language scripting and rapid application development in many areas. In the study we made use of python programming to evaluate the percentage change in wave height and calculated the monthly power produced by wave energy at a certain time period.

3.4.6 Microsoft Office (Excel)

MS Excel is part of Microsoft Office it is a spreadsheet program that consists of a powerful program for data analysis containing rows and columns, by means of organising the information in various cells it becomes easier to find, calculate and populate into graphs, bars and charts for visual representation. In the study we made us of MS Excel to calculate the LCOE of a solar plant and created charts from our data results.

CHAPTER 4

WAVE ENERGY CONVERTORS

4.1 Wave heights in the Port of Ngqura

Gqeberha is a medium sized city on the South Coast of South Africa, it is well known for its high wind conditions. It boasts of two sister ports the Port of Port Elizabeth and the transhipment Port of Ngqura which are 20km apart. For the bases of the study the port of choice is the Ngqura port and the wave farm will be installed on these coordinates 34.16° S and 25.83° E. the below figure 16, represents the location of the wave farm through data extracted from E.U Copernicus Marine Environment Monitoring Service 2021.

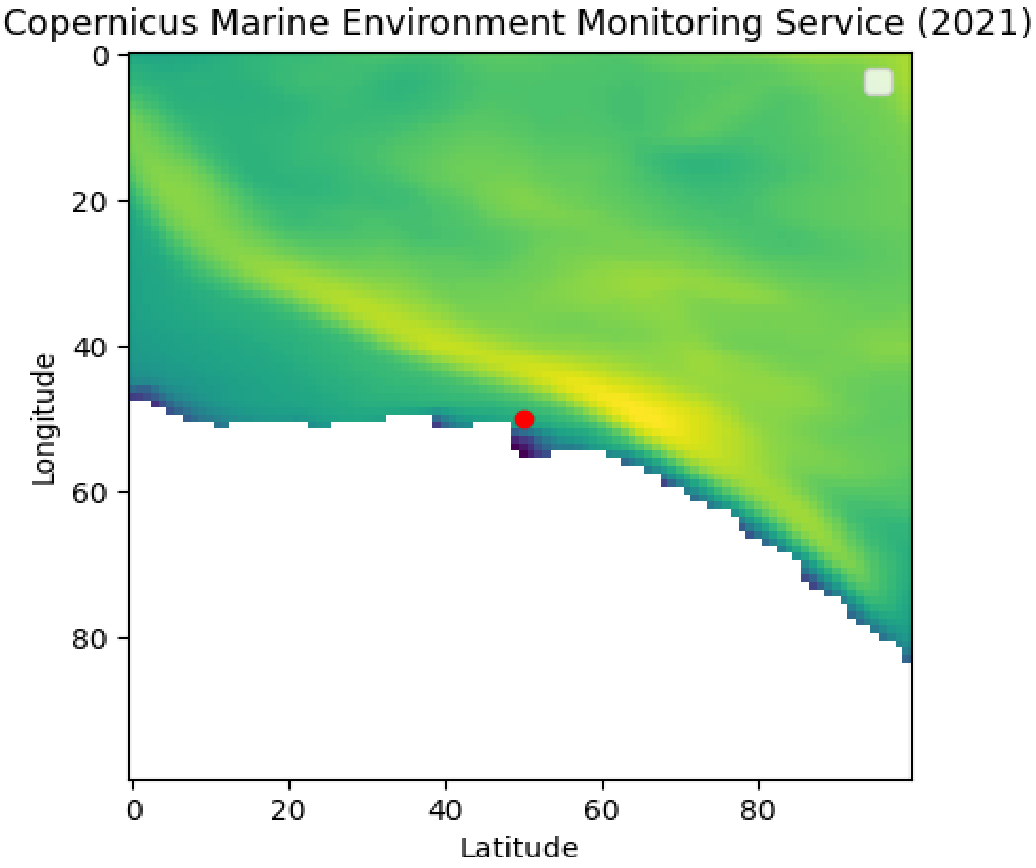


Figure 16: Location of the wave farm in Nelson Mandela Bay

Figure 17 represents an average wave height for August 2020, through data obtained from E.U. Copernicus Marine Service Information (wave height data).

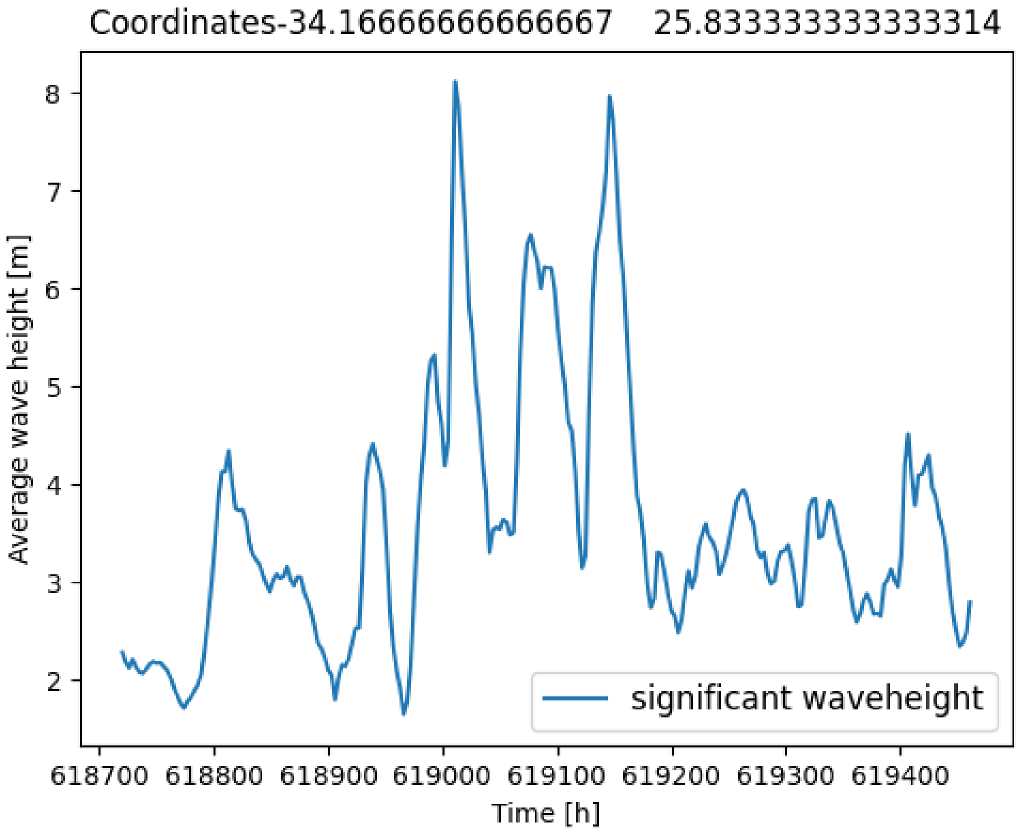


Figure 17: Average wave height (August 2020)

In the period of June 2020 to July 2021 we managed to calculate the amount of power produced in the zoned location for the wave farm. Figure 17, is a comparison of the power produced from January 2019 to August 2021. However, for best and accurate results we will need to evaluate recurrent weather and wave patterns for a prolonged period.

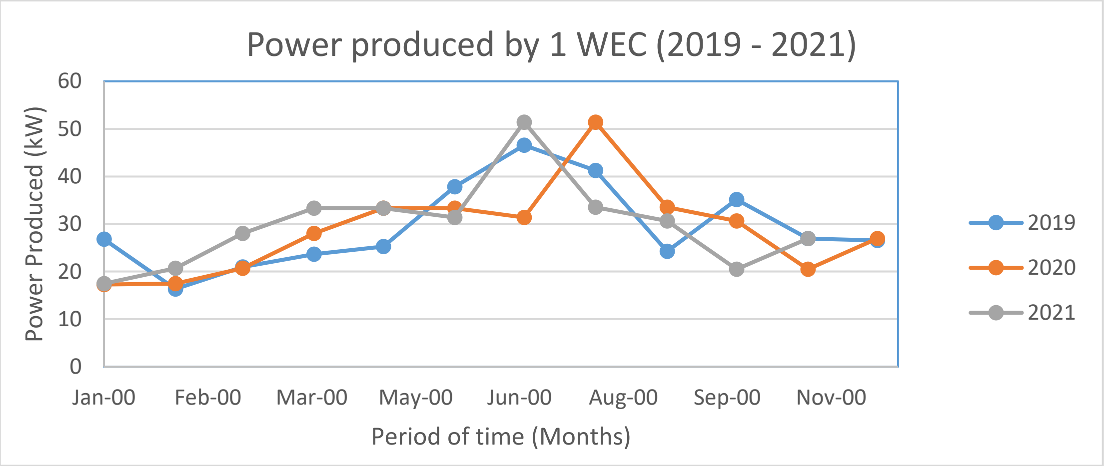


Figure 18: **The monthly power produced from Jan 2019 - August 2021 using one energy wave convertor**

4.2 Wave Energy Convertors (WEC) point absorbers

Ocean wave energy as a renewable source which has a greater power density compared to wind and solar energy. Point absorbers move up and down by the force of the waves and generators and convert wave energy into electrical energy. Wave Energy Convertors point absorbers can be simulated using a Euler-method dynamic simulation to illustrate the dynamic response and power capture obtained. Point absorbers consist of low construction costs, simpler structure and can effectively capture wave energy in offshore areas. Wave energy can easily be obtained through point absorbers in all directions, in essence point absorbers have drawn and attracted more attention.

Using the python program, the researcher managed to calculate the power produced by 1, 3 and 9 WEC for a period of 3 months from January 2019 to March 2019. In the beginning the researcher indicated the comparison of the measurements from the wave tank and the simulations.

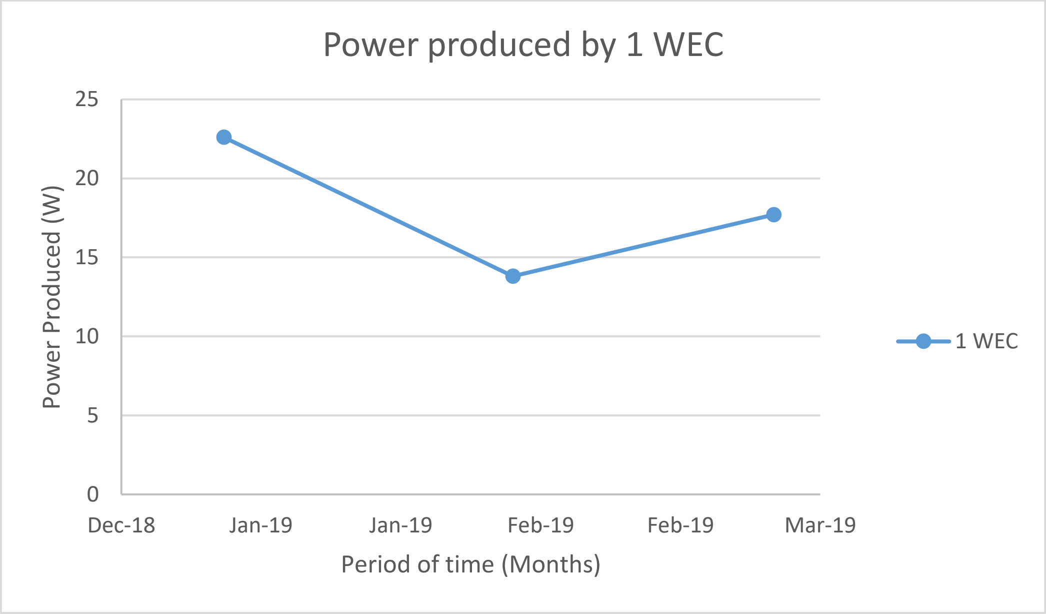


Figure 19: The power produced by 1 WEC

In figure 19 and all the other figures of the program going forward used wave energy converted with a diameter of 2.5 m and a height (L) of 4 m, meanwhile figure 18 made use of a diameter of 5 m and with a height of 3 m.

The 1 WEC, 2 WEC and 3 WEC does not refer to the total number of WECs used in the array, however, this refers to the position of the WEC within the same row of 3 WECs.

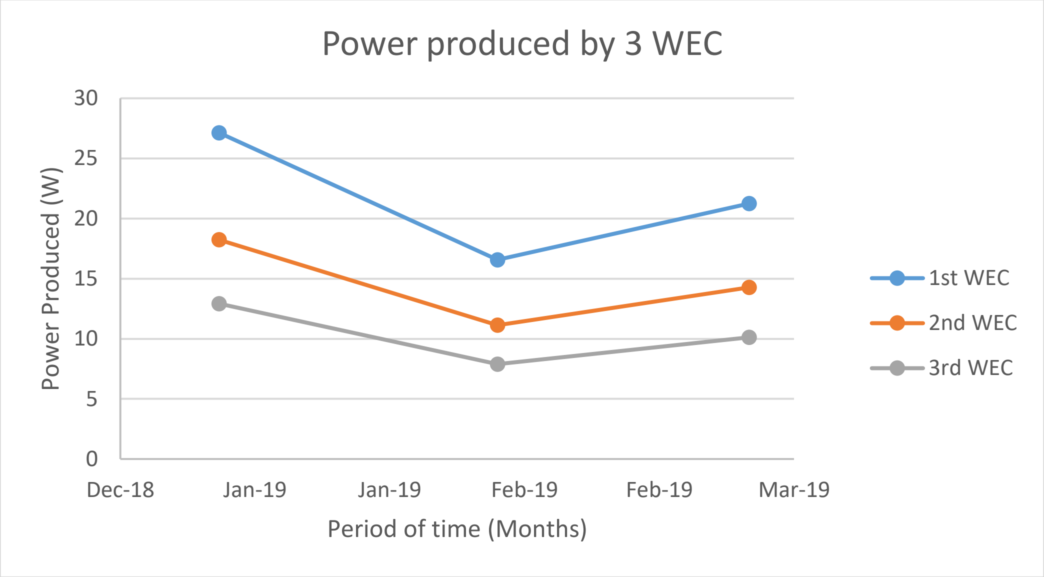


Figure 20: **The power produced by 3 WEC**

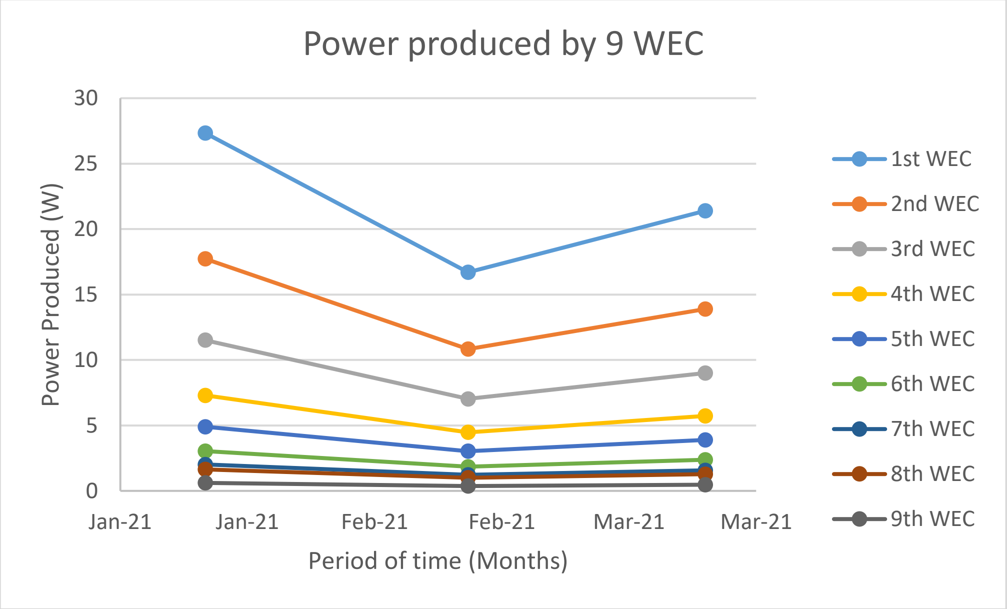


Figure 21: **The power produced by 9 WEC**

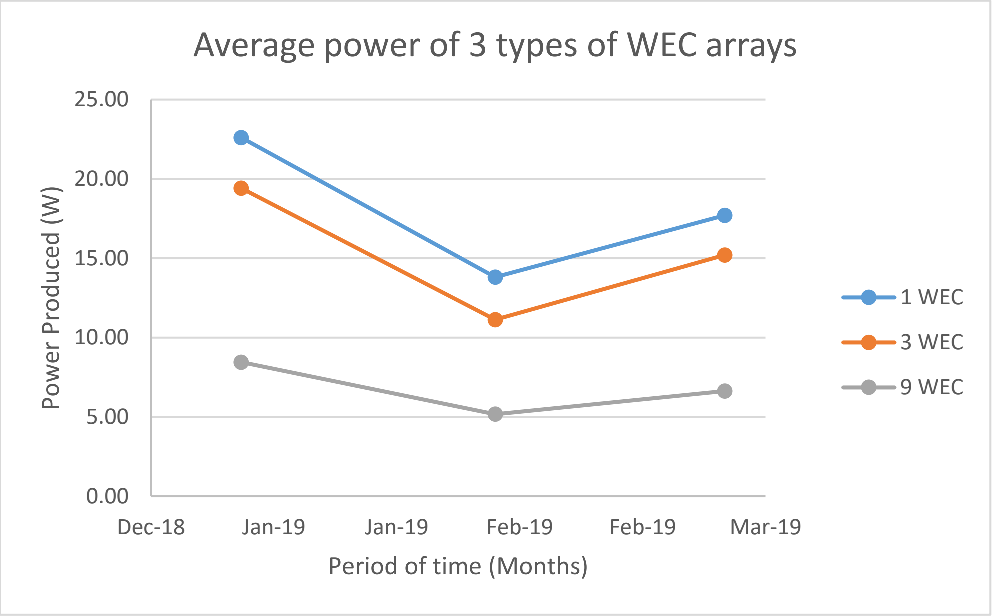


Figure 22: **The average power of the 3 types of WEC**

Through the python program the researcher managed to compare the results of 3 types of WEC which was the first WEC, second WEC and third WEC. The average of each convertor for a period of 3 months was used to compare the power produced by each convertor, Figure 22 indicates the results.

The below figure 23 is a wave basin experiment with a large wave energy converter arrays to study interactions between the converters and effects on other users in the sea and the coastal area.

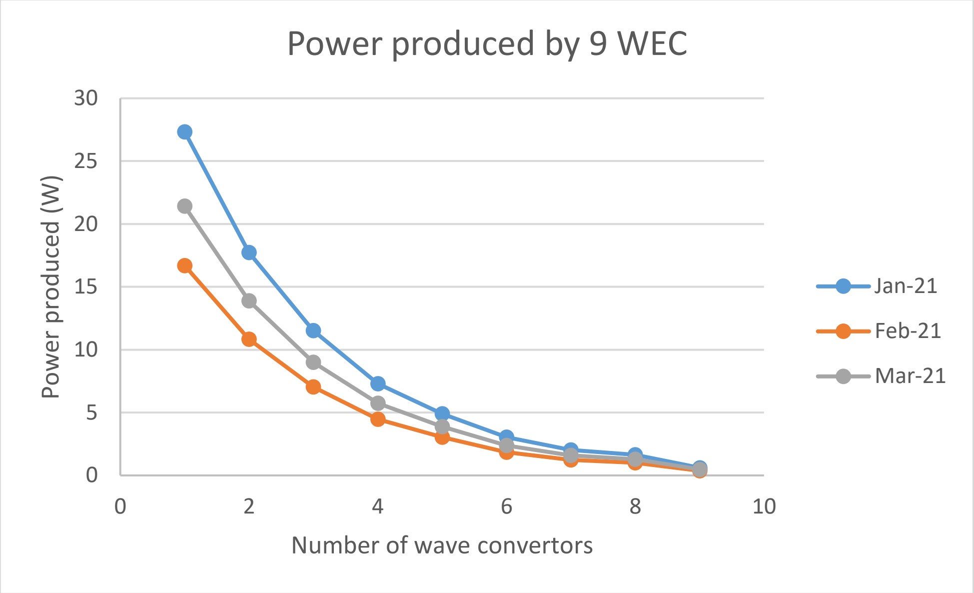


Figure 23: **The power produced by 9 WEC**

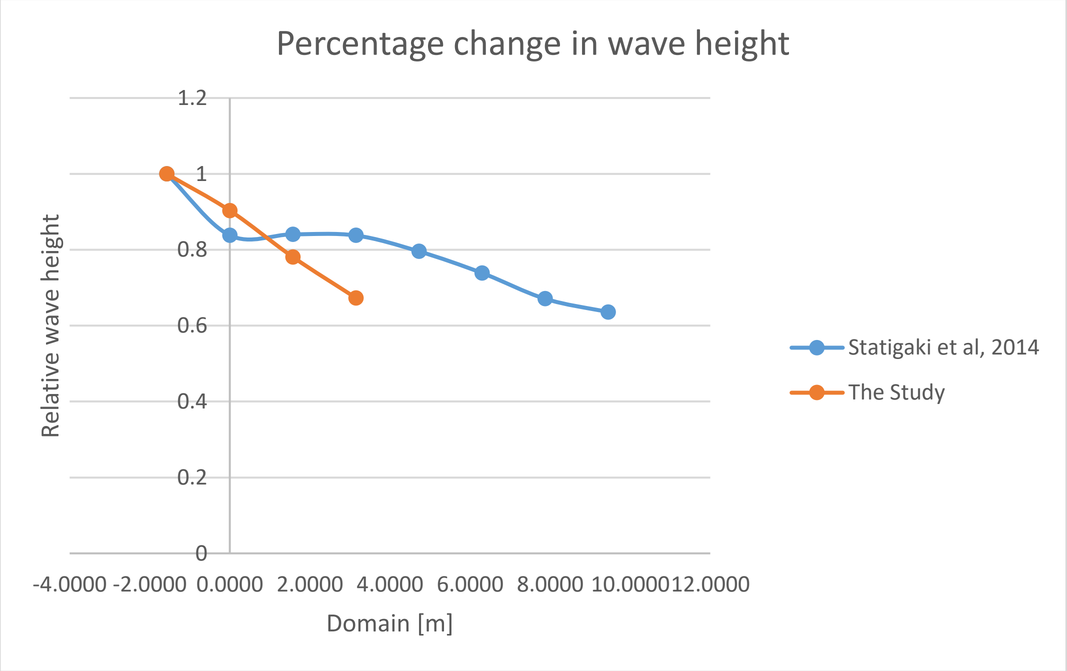


Figure 24: **The percentage change in wave weight**

In Figure 24. The change in relative wave height throughout the wave domain for the experimental study of Statigaki et al., 2014 and the wave simulations performed using the Euler model wave energy converter array in this study, adapted to the same physical dimensions as the Statigaki et al., 2014 experiments.

The reasons for wave basin experiments which use large WEC arrays to study the interactions between convertors and the efforts of various users at sea and in coastal areas (Zhang et al, 2021). In figure 24 the wave attenuation was 0.016 of the total wave height per wave energy converter passed. The Capture Width Ratio (CWR) according to (Zhang et al, 2021) was around 1% (0.827) and similar to the 1.75 modelled by this work.

When it comes to the South African Electricity grid, there are limitations as only Metropolitan areas along the South African coast line are connected to a high capacity transmission lines. Offline mini grids are practical solutions for coastal cities, for the wave farm an offline mini grid will be constructed to distribute electricity to the Port of Ngqura and the hydrogen plant. The advantage of an offline mini grid is that it is not connected to the country's main electricity grid in the case one system is damaged it shakes the entire network.

Figure 25: South Africa's transmission network

(Source: Energydata.info, 2017)

4.3 Wave farm in the Port of Ngqura

For our study the researcher assumed that the wave farm consists of 30 independent wave convertors. According to our calculation from the Python program (Appendix 1) running on the computer utility IDLE 3.9 (64-bit) the average power for the wave farm is 1 110 kW. The calculation for the amount of WECs which could generate this output as 1 110kW / 51.43kW = 21.58 units, this essentially means on this wave farm 21 WEC were used which were arranged independently only one per row. The energy produced by the wave farm is 2 973 024 MJ, with a low heating value of hydrogen at 120 MJ per kg the total mass of hydrogen produced during the month is 24 775 kg of hydrogen. Assuming that the efficiency of hydrogen production is 75% (Bexter, 2020), therefore, 18 581.40 kg of hydrogen is produced which is 18.58 tons of hydrogen produced a month. With the amount of produced hydrogen from the wave farm it is assumed that the study will able to supply the port and provide tug boats with hydrogen fuel from the port's hydrogen fuelling station.

According to (Walsh, 2008), modern tug boats have a power rating of 3 000 to 5 000 hp and tend to burn a large amount of fuel when operating at full rpm, this can be anywhere between 100 to 200 gallons of diesel fuel per hour for a tug pushing against a ship or between 3 000 to 5 000 gallons per day when under constant operation. Assuming that a tug may operate 10% of the time, we may assume a consumption of 400 gallons of diesel fuel per day will be used. Assuming that 1 ton of hydrogen is equivalent to the ratio of gravimetric lower heating values of hydrogen to diesel fuel, i.e. 120 / 42.7 = 2.81 tonnes of diesel fuel in terms of energy content. Assuming that 1 tonne of fuel has a volume of 313 gallons, then 2.81 tonnes of diesel fuel is equivalent to 880 gallons of diesel fuel. If we take the amount of hydrogen produced a month which is 18.58 tons and we multiply it by the gallon of diesel fuel per ton of hydrogen which is 880 x 18.58 to get a value of 16 350 gallons a month. If a tug boat uses 400 gallons of diesel fuel per day we will therefore, be able to fuel 1.3 which in essence is one tug boat with hydrogen fuel at this rate of fuel consumption, produced by the wave farm each month (31 days).

According to the study for vessels we will need more power meaning a wave farm at a greater scale will be required example a wave farm with 40 rows and a 10-meter distance of 3 turbines (40*10 m) = 400 m. Since we assumed there will be 3

WEC point absorbers in line, the wave farm consists of a 3x40 matrix, i.e. 120 WECs at a shore length estimated at 400 m. The study highlights the importance of Marine Spatial Planning and the engagement of relevant stakeholders, before any work can be done on the areas zoned must first be signed off by MSP and Environmental Specialists.

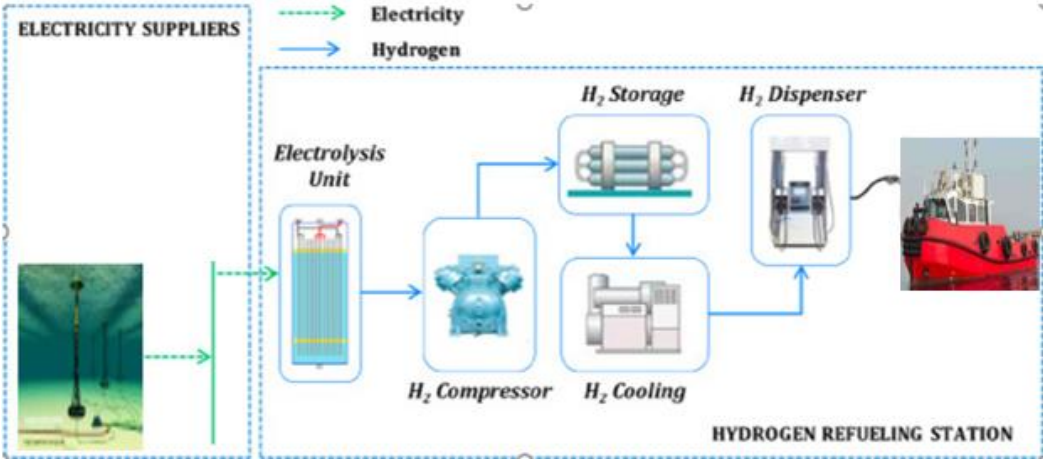


Figure 26: Hydrogen refuelling station

In the case we include another renewable energy mix in our study such as wind as the city is embedded with abundant wind, we will be able to down scale on the size of our wave farm while having sufficient energy to meet our hydrogen demand and targets. If we decide to add wind energy, we will win by a third of the power. The aim of the study is to be able to provide commercial vessels with bunkering fuel, in the coming years we will need to upscale the refuelling station in order to accommodate commercial vessels. If we change locations of the wave farm, however, still within close proximity to the Port of Ngqura and upscale in energy convertors we can expect fairly high amount of energy production from the wave farm which will go a long way in providing commercial vessels with bunkering fuel.

To evaluate how much hydrogen fuel we will need to for a vessel we need to identify a vessel type, for this study we will use DWT Shuttle Tanker Built in 1997, IMO Number 91311357, Cameroon flagged. With a Gross Tonnage of 71 850, Engine speed of 14.60kts at 65.00 tons per day, intermediate fuel oil very low sulphur, Horse power of 27 160 and power type of Diesel 2 stroke (information courtesy of Clarkson). According to calculation from the Python Programme from the 3-point convertors of the wave farm we can only produce 18.58 tons of hydrogen, which is equivalent to 2.81 tonnes of diesel fuel, i.e. 52.21 tonnes of diesel fuel. This is less than the required fuel for the Orion bulk tanker in one day.

To be able to produce at 65 tons of fuel for the bulk carrier for at least a day we will need to upscale the size of our wave farm. The researcher assumed that with 120 rows with a distance of 15 meters from each other (120*15m) = 1 800m, we can install 3 WEC in a row, the wave farm will consist of 120*3 matrix e.g. 360 WEC installed at the shoreline with an estimated length of 1 800m. According to the Python program (Appendix 1) running on the computer utility IDLE 3.9 (64-bit) the average power for the wave farm is 1 110 kW, we will assume that our wave farm is 12 times the size of the initial wave farm which consisted of 30 WEC in a row of 3. We will take the energy produced by the wave farm and multiply it by 12 (2 973 024 MJ * 12) = 35 676 288MJ, keeping in mind the heating value of hydrogen is 120 MJ per kg the total mass of produced hydrogen 297 302 kg. We shall assume that the efficiency of hydrogen is 75% as per (Bexter, 2020), therefore, the amount of produced hydrogen is 222 977 kg which is 233 tons. The amount of hydrogen produced will be able to propel the Orion tanker for 3.4 days per month with an engine speed of 14.6 knots. The size of the wave farm would thus have to be increased by a further factor in order to provide monthly hydrogen fuel for the vessel.

CHAPTER 5

HYDROGEN PRODUCTION

5.1 Hydrogen production

Hydrogen has been identified as a potential fuel of the future, due to its abundance and clean nature as it emits only water vapour. Green hydrogen seems to be a promising solution towards a decarbonised energy system as it can be used for long term energy storage from various renewable sources. The drive towards zero carbon emission has led to an increase in technology investments which are contributing to making hydrogen power more attractive. According to (Paddison, 2021) electrification is the most effective way to decarbonise many sectors and green hydrogen has the potential to fill the gaps. Currently the global supply of hydrogen is a vital economic activity worldwide, the demand for hydrogen has grown substantially more than three-fold since 1975 (Janke et al, 2020). Hydrogen is still rising and is mostly produced from fossil fuel which is grey hydrogen, 2% of coal and 6% of natural gas goes in the production of hydrogen (Janke et al, 2020). As countries are building up renewable energy power capacity and green hydrogen is becoming lower in costs per unit (Lawlor, 2021), renewable plants produce more than what the grid requires extra power can be used to produce green hydrogen.

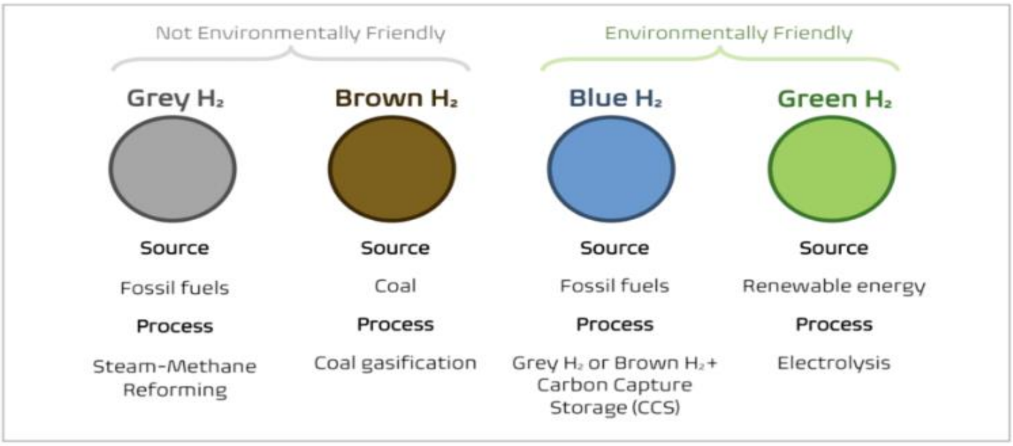


Figure 27: Various types of hydrogen and their production
(*Source: Bowden and Kassier, 2021)*

There are various processes that can be used to produce hydrogen. However, for the purpose of our study the researcher will make use of electrolysis for the production of green hydrogen.

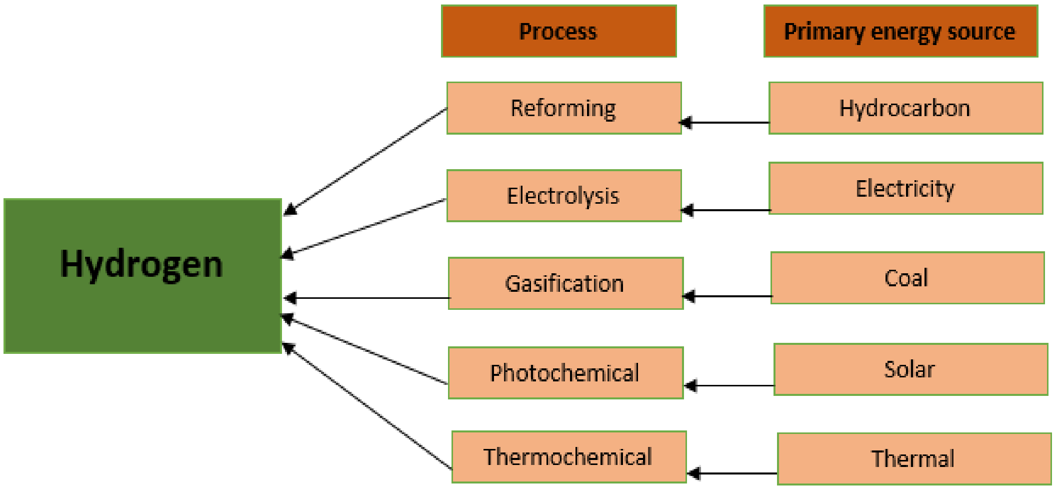


Figure 28: **General processes used for hydrogen production**

Green hydrogen is produced through splitting water using a process of electrolysis, this creates hydrogen and oxygen, the oxygen is released and does not impact the environment in any way. In the case of using electricity from a renewable source during the electrolysis process reduces our carbon footprint. An electrolyser operates through splitting water to its elemental components of hydrogen and oxygen, this reaction is represented below.

$$2H_20 \longrightarrow 2H_2 + O_2$$

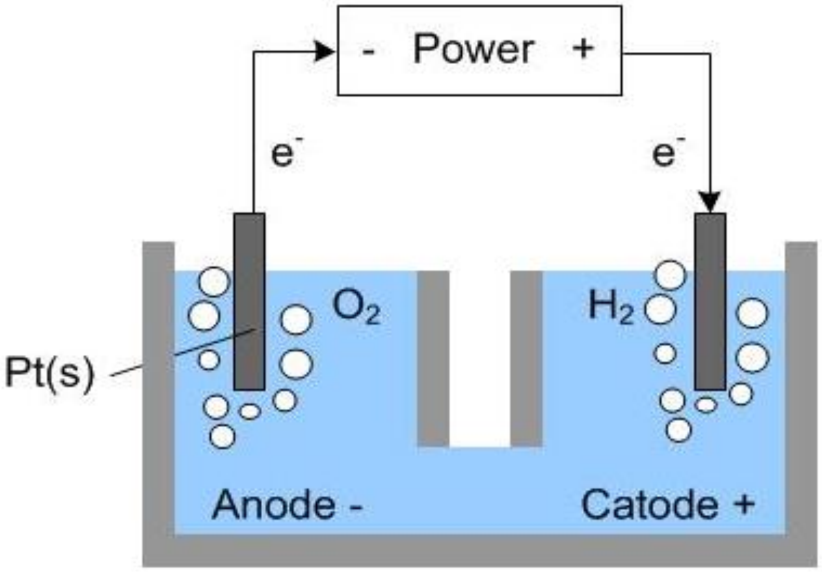


Figure 29: The process of splitting hydrogen and oxygen through electrolysis

(Source: Nebb Group, 2020)

Renewable energy will be used to split water in an electrolyze in order to produce green hydrogen, which can replace fossil fuels without emitting carbon emissions. Green hydrogen is produced through electric energy and water electrolysis from renewable energy sources, the system converts hydrogen by electrolysis. Nelson Mandela Bay is water stressed, for the purpose of the study the researcher made use of seawater during the water electrolysis process. Seawater electrolysis is a potential solution for carbon neutral hydrogen energy without relying on freshwater, however, the challenge is high costs and detrimental chlorine chemistry. Chlorine electrochemistry is avoided by low cell voltages without anode protection, seawater electrolysis is done by integrating low voltage direct hydrazine fuel cells (Sun et al, 2021). This process allows for efficient conversion of seawater into hydrogen fuel, through the removal of harmful pollutants. In addition, if the researcher makes use of too high voltages chlorine gas will be produced this is to be avoided.

Green hydrogen is relatively expensive compared to blue and grey hydrogen this is due to the price of technological equipment for green hydrogen production, distribution and storage. Blue hydrogen is considered as a clean version of hydrogen as emissions are captured and stored, however, it is still produced using gas. Due to production, distribution and storage of hydrogen it has led to high capital expenditure based on hydrogen technologies, which has resulted in escalating prices of generated green hydrogen which has reduced hydrogen's economic competitiveness in comparison to other fuels (Jovan and Dolanc, 2020). To accelerate the adoption of green hydrogen and technologies conditions need to be identified where green hydrogen can be competitive due to its low environmental impacts.

Another method of producing hydrogen is through steam reforming using natural gas, Appendix 2 provides a full detail of the plant, consumption data, hydrogen generation and methanol reforming. Hydrogen which is generated from steam reforming is represented by the below reactions:

$$H_2O\ (g) + CH_4\ (g) \rightleftharpoons 3H_2\ (g) + CO\ (g)$$

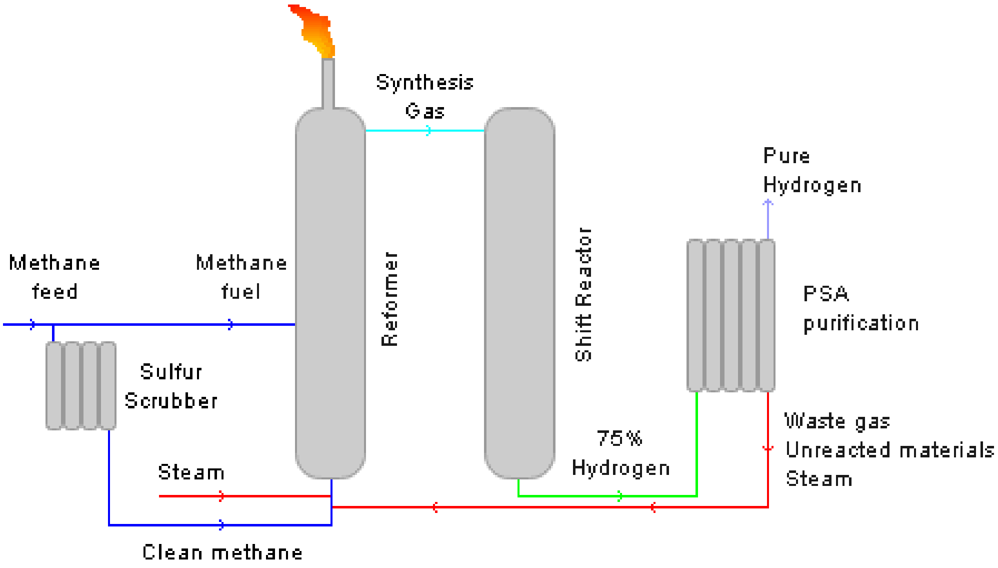


Figure 30: **Production of hydrogen through steam reforming using natural gas**

(Source: Digipac, n.d)

5.2 Cost and predicted cost of hydrogen

It is evident the major hurdle that green hydrogen has been faced with are production costs, storage and transportation and the energy that is required to produce hydrogen. The price of hydrogen highly depends on the location of the customer; this determines how the hydrogen will be delivered. The storage, transport and distribution of hydrogen is important during large scale production and a dedicated central production plant for deliveries and ensuring remote users also have access to hydrogen (Jovan and Dolanc, 2020). The price of hydrogen can vary from 10 to 60 €/kg which is roughly R173.70 to R1 042.20 South African Rands, the price of hydrogen with high purity levels is R1 042.20 this type of hydrogen is used for semiconductors and speciality applications (Jovan and Dolanc, 2020). It is evident that the price of hydrogen will be highly influenced by production and distribution costs. With electrolysers and renewables predicted to decrease in costs and fossil fuel prices rising, capital costs can be expected to fall by 64% by 2030 (Paddison, 2021). Some studies have analysed and predicted the future of retail hydrogen prices, the retail price of hydrogen will gradually decrease and will potentially drop down to around R86.85 to R121.59 per kg (of hydrogen by 2030 (Jovan and Dolanc, 2020).

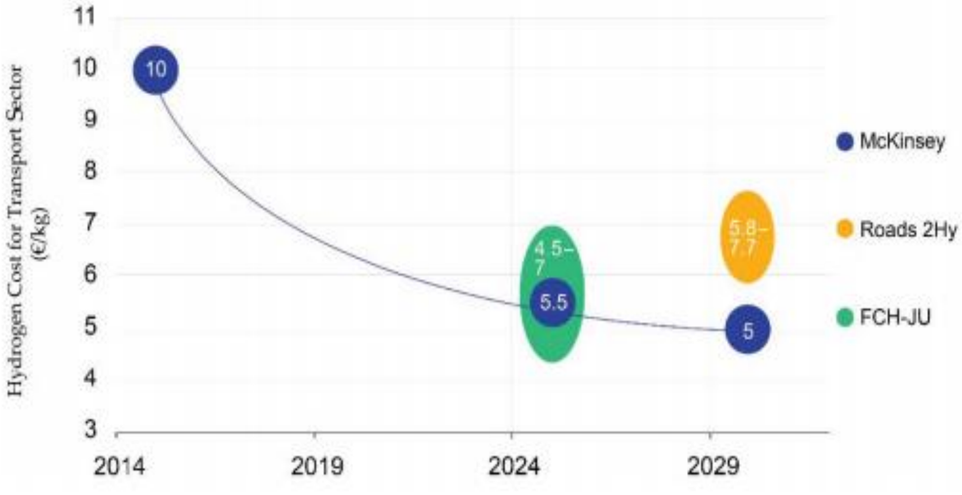


Figure 31: According to researchers estimated hydrogen cost development from 2015 – 2030

(Source: Jovan and Dolanc, 2020)

Electrolyser manufactures are in agreement of rapidly reducing investment costs mainly through economies of scales. There are devises that can produce hydrogen for R116.28/kg, before 2030 manufactures want to bring down the cost to R24.48/kg (Linchner, 2020). In 2018 an estimated cost of electrolyser produced a standard cubic meter of hydrogen in an hour at R116 280, currently prices have fallen between R91 800 to R74 970 (Linchner, 2020).

The water quality is a great influencer on the service life of an electrolyser, as impurities accumulate in the pores of the membrane and blocks them. Another factor which mess up electrolysis cells is the temperature; excess load tends to lead to high temperatures and unevenly coated electrodes have the potential to create hot spots (Linchner, 2020). NMB is one of the Municipalities in South Africa that is regarded as a water stressed municipality, in 2014 fresh water consumption per capita was just over 1 200 kilolitres per person per year (CSIR, 2004). It is important to note the state of water resources in NMB to identify future needs and water availability, hence for the purpose of this study it would be ideal to make use of seawater instead of freshwater due to water challenges the municipality faces. The researcher is aware that this will have an impact on the life span of an electrolyser. However, an alternative would be the use of a water purification plant combined with the hydrogen production, this process goes without say it would require more energy.

5.3 Factors influencing the price of electricity

There are many key factors which influence the price of electricity, from power plant costs, government regulations, transmission and distribution system, fuel to weather conditions. The price of electricity is generally reflected by the cost to finance, maintenance, building and operating power plants and electricity grids, in the basis of adding profit utilities which include financial return of shareholders and owners in their electricity prices.

The below are some factors that influence electricity prices:

- Power plant cost – power plants have financing, maintenance, construction and operating costs.

- Government regulations – Public services and utility commissions fully regulate prices.
- Weather conditions – Extreme weather temperature can increase demand for cooling and heating and an increase in electricity demand can push electricity and fuel prices up. When wind speeds are high, wind can provide low costs of electricity generation.
- Fuels – the price of fuels mainly natural gas and petroleum increase during high electricity demand and where there are fuel supply constraints, accidental damage to transportation infrastructure and extreme weather conditions pushes fuel prices and result in higher electricity prices.
- Transmission and distribution system – Electricity distribution and transmission system which connects power stations and plants with consumers include operations, maintenance and construction costs including damage repairs to systems from extreme weather conditions, accidents and improving cybersecurity.

The below table 4 are Eskom tariffs from 1994 – 2020, the electricity price for 2021 – 2025 was predicted using Monti Carlo simulation.

Year	Average (c/kWh)	Average price increase	Inflation	Inflation adjusted price (c/kWh)
1994	10.32	7.55	8.84	44.75
1995	11.15	8.04	8.75	44.18
1996	11.30	1.38	7.35	41.88
1997	11.85	4.87	8.63	40.28
1998	12.29	3.72	6.98	39.12
1999	12.44	1.19	5.08	37.81
2000	13.23	6.35	5.39	37.91
2001	13.76	4.06	5.64	37.47
2002	15.00	9.01	9.15	37.22
2003	16.09	7.27	5.87	37.96
2004	16.04	-0.03	1.43	37.31
2005	17.79	10.15	3.35	40.00
2006	18.70	5.10	4.62	40.01
2007	19.80	5.90	7.15	39.63
2008	12.24	27.50	10.99	44.55
2009	33.14	31.30	7.12	55.59
2010	41.57	24.80	4.26	67.18
2011	52.30	25.20	4.99	80.45
2012	60.66	24.80	5.62	88.90
2013	65.51	16.00	5.76	90.25
2014	70.75	8.00	6.09	91.65
2015	76.41	8.00	4.58	94.30
2016	82.53	8.00	6.34	96.08
2017	89.13	8.20	5.27	99.23
2018	93.79	5.20	4.62	99.32

2019	106.80	13.90	4.13	108.79
2020	11.93	3.90	2.43	110.93
2021	**59.75**	**5.75**	**4.08**	**113.45**
2022	**49.50**	**7.07**	**3.90**	**115.25**
2023	**42.60**	**8.01**	**3.72**	**116.67**
2024	**37.96**	**8.68**	**3.54**	**117.80**
2025	**34.83**	**9.16**	**3.36**	**118.69**

Table 4: Eskom Electricity Tariffs 1994 – 2020 and 2021 – 2025 predictions

The below figure 32 represents the predicted electricity prices in the next coming years from 2021-2023 using Monte Carlo simulation to determine the future electricity pricing for Eskom. With the momentum of increased renewable energy projects in the country, it has played a role in the predicted decreased price of electricity. With the government regulations and the country's aim to reduce carbon emissions and decarbonize, the IPP sector has accepted the Minister of Energy's call to purchase more electricity from IPP's (Takouleu, 2020).

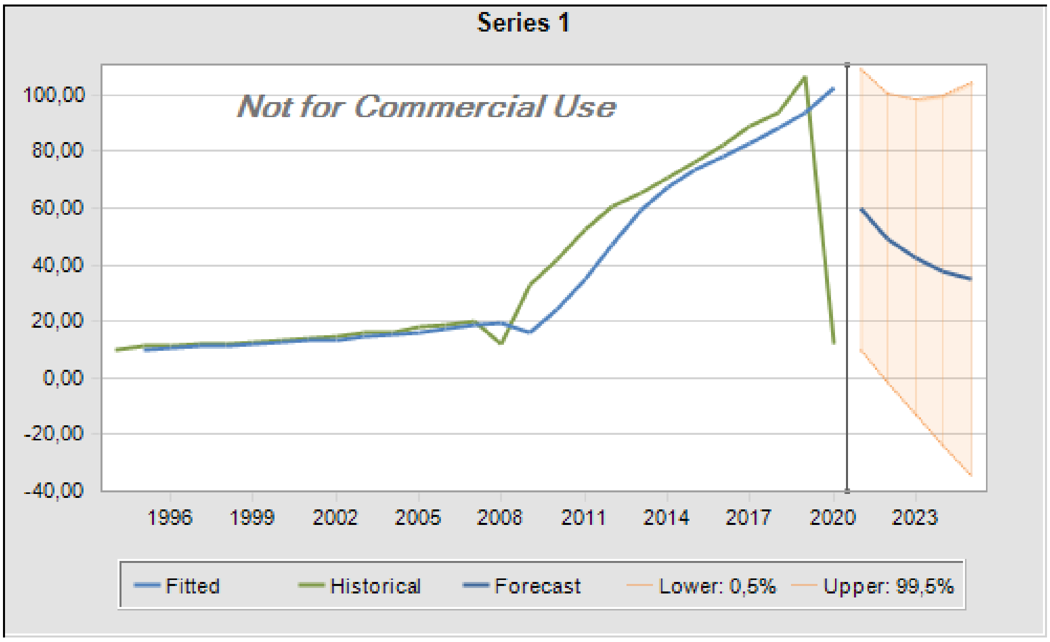


Figure 32: Predicted price of electricity in 2021-2023 in South African Rands

5.4. Levelised cost of hydrogen

The cost of hydrogen production considers the initial investment from plant construction, operational and management costs over its entire lifetime. These costs vary depending on the plant size and the energy source used for the production of hydrogen. The researcher made assumptions that the maximum daily hydrogen production can be calculated at 27kg/h or 594kg per day on a 2-shift system of 12 hours with all the Health and Safety Environmental (HSE) measures in place. The power consumption is estimated at 40.99kWh/kg. The hydrogen plant is estimated to operate at 8 000 hours a year over a period of 20 years with the current hydrogen price estimated at R300/kg is estimated against the current price of electricity for industries and businesses is R1.051/kWh. In the long term it is estimated that the price of hydrogen production in South Africa will drop down to R26.50/kg.

The below formula is used to calculate the Levelised cost of hydrogen.

$$\text{LCOH} = \frac{\text{Total Costs (R)} - \text{Electrical Revenue (R)}}{\text{Hydrogen Annual Production (kg)}}$$

$$= \frac{38\ 214\ 000 - 327\ 920}{216\ 000}$$

$$= 175.39$$

Calculating the LCOH evaluates the overall economic performance of the hydrogen plant and identifies the lowest hydrogen production costs. Through the Levelised Costs of Energy (LCOE) the researcher evaluated that the competitiveness of energy producers, the researcher also determined that the minimum electricity price which a project needs to use in order to start making profit. The CAPEX and OPEX is commonly used to calculate capital expenditure and operational expenditure of projects.

5.5 Selling cost and profit price of hydrogen

The cost of setting a hydrogen plant is relatively high today. However, it is projected that capital and operating costs will steadily drop as hydrogen becomes more competitive while the price of fossil fuel increases and the prices of renewable energy decreases. The below Table 5 is an assumption of the main estimated costs of implementing a hydrogen plant of about 1 MW. The CAPEX and OPEX costs for installing and operating a hydrogen plant is estimated. The respective value of CAPEX is assumed to be R38 214 000.

CAPEX Capital cost Expenditure of a hydrogen plant	**Estimated Cost in RAND**
Project documentation	1 737 000
Electrolyser	27 792 000
High pressure storage	3 474 000
Components	2 084 400
Electric connections	1 737 000
Construction and assembly works	1 389 600
TOTAL COSTS	**38 214 000**

Table 5: Capital Expedite of a hydrogen plant

According to Investec the current cost of hydrogen is estimated at R300 per kg in South Africa and the current cost of electricity is estimated against the current price of electricity for industries and businesses is R1.051 per kWh and for households R2.172 per kWh these are electricity prices for 2020. In the long term it is estimated that the price of hydrogen production in South Africa will drop down to R26.50 per kg.

South Africa electricity prices	**Household, kWh**	**Business, kWh**
South African Rand	2.172	1.051
U.S. Dollar	0.147	0.071

Table 6: The price of electricity in South Africa in 2020

The price of hydrogen production is mainly depended on the price of electricity. The value of the South African Rand versus the Euro on the 15th of August 2021 was R17.37 which is the value the researcher used in the calculations. It is assumed that through the use of an efficient electrolyser at 39 kWh multiple by the electricity cost of R1.051kWh for industries to produce 1 kg of hydrogen will cost R40.99 of electricity. The income is calculated by subtracting the selling price of hydrogen and the cost of producing hydrogen (R300 – R40.99 = R 259.01).

Number of KG	Selling price hydrogen (R/kg)	Cost of producing hydrogen (R/kg)	Income in RAND
1	300	40.99	259.01
2	600	81.98	518.02
3	900	122.97	777.03
4	1200	163.96	1036.04
5	1500	204.95	1295.06
6	1800	245.93	1554.07

Table 7: The income of hydrogen per kilogram sold in South African Rand

The cost of hydrogen is mainly calculated through assuming the purchasing price of business grid electricity.

Estimated KG of hydrogen	Estimated Selling price hydrogen (R/kg)	Estimated cost of producing hydrogen (R/kg)	Estimated Income in RAND
150 000	450 000 000	61 483 500	38 851 650

Table 8: Estimated income of 150 000kg of produced hydrogen

The production price and the selling price becomes more profitable. If 150 000 kg of hydrogen is produced, the estimated income is R38 851 650 which means all overhead costs (capital costs) are covered and profit can be generated. The capital costs for the hydrogen plant is R38 214 000, therefore, after producing 150 000kg of hydrogen, R637 650 profit is made.

CHAPTER 6

LEVELISED COST OF ELECTRICITY

6.1 Renewable Energy Economies

Subsidies and energy policies have led to a progressive expansion of renewable energy capacity being constructed in the world starting from 4 GW in 2000 to 74 GW in 2013 for both solar and wind (Roos and Wright, 2021). This has managed to drive down the costs, in 2014 a new build renewable power plants become more competitive with fossil fuel new built plants. In South Africa the prices for wind and solar has declined from between 60% to 80% between 2011 and 2015, reaching R0.62 per kWh (Roos and Wright, 2021). Offshore wind energy will expand in the coming years with an expected growth rate of 13% per year of installation capacity. According to (Reis, 2021), it is expected more than 10% of the total installed wind capacity will be from offshore energy generation by 2025, this is the year which 100GW mark will be reached this growth will be led by Europe and Asia.

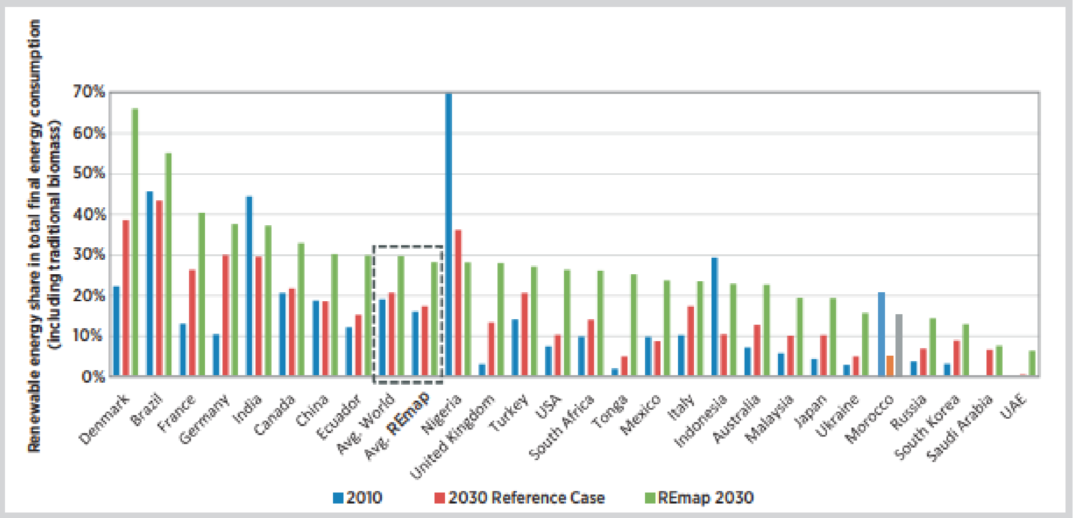


Figure 33: Projected share of renewable energy in final energy consumption by country 2010 – 2030

(Source: Roos and Wright, 2021)

According to (Vestas Wind Systems A/S, 2018), over the next decade the renewable capacity will have grown significantly. It is expected that Renewable energy will surpass the production of coal and other fossil fuels, which will make renewable energy a dominant energy generation source. The below figure 34 shows the Global Electricity Consumption with nuclear, coal, renewable energy, hydro power and other fossil fuels. It clearly indicates an increase in the potential of renewable energy between 2017 and 2035 and the decline in coal generation in 2035 compared to 2017. With these figures in mind it is evident that renewable energy will be a dominant energy generator in the coming years.

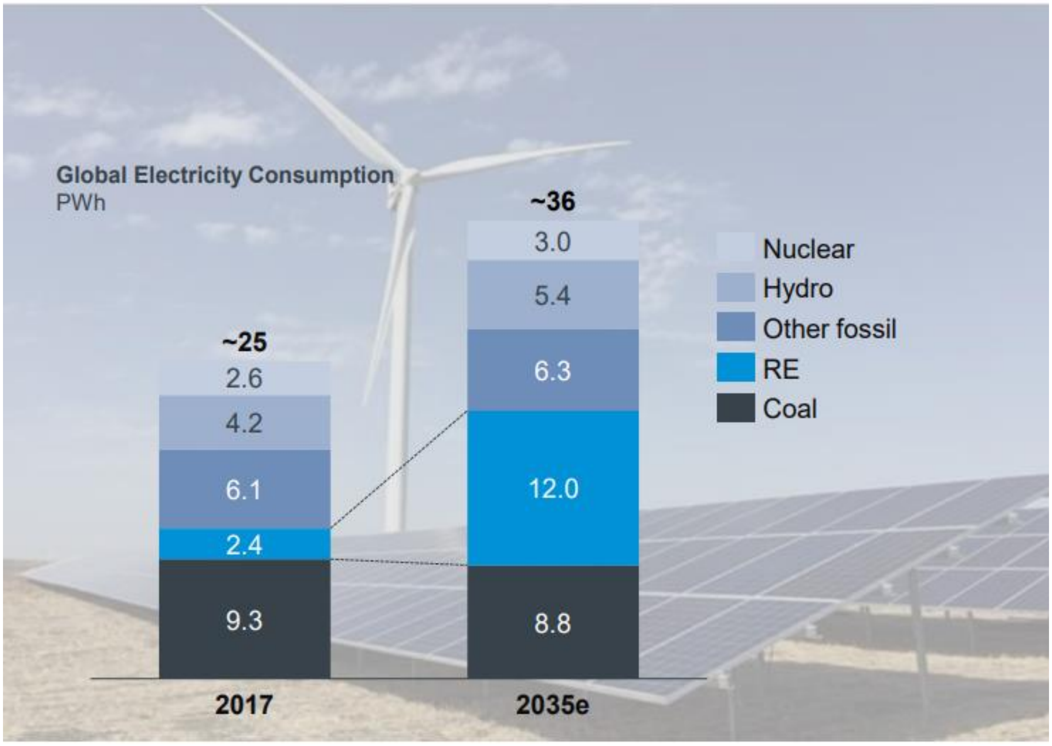


Figure 34: Global Electricity Consumption

(Source: Vestas Wind Systems A/S, 2018)

6.2 Levelised Cost of Electricity

The purpose of LCOE is there to compare and evaluate the cost of electricity production from various technologies and locations, it is useful when comparing the cost of a unit of energy produced. The LCOE hardly ever considers the cost which relates to balancing demand and supply. The LCOE is essential for utilities and policy makers, in the renewable electricity sector cost estimates are highly essential. High costs can bear a negative impact for the final consumer, stakeholders and policy makers, hence LCOE is used as an indicator to compare various technologies and economic enactment of an electricity source in various locations. LCOE can easily be translated as an economic measure of total average cost in operating and building a lifetime of electricity generation. The LCOE is much easier when you compare energy produced through different technologies example solar and wind. The LCOE electricity generation asset is estimated based on present value of OPEX and CAPEX over the expected electricity production over its life time. The CAPEX includes capital expenditure and development expenditure, while the DEPEX is the decommission expenditure when it comes to the renewable energy projects.

The below is a formula of LCOE over lifetime.

$$\boxed{LCOE = \frac{CAPEX + OPEX_{lifetime}}{AEP_{lifetime}}}$$

Figure 35: The LCOE formula and its lifetime

There are various potential trade-offs which must be considered when developing an LCOE model, the approache used in this study is simple as it is applied to only two technologies which is wind and wave energy. The more detailed the LCOE analysis model, this will present an impression of greater accuracy when the model cannot robustly be populated with assumptions and if the assumptions are not differentiated or based on real world data this usually leads to an accuracy approach and this approach will be considered misleading (IRENA, 2020).

6.3 LCOE Model of a Solar PV project cost calculator

The LCOE is a term which describes the costs of the power produced by solar over a period of time, which is typically the life warranty or life span of the system. Through the purchase of solar one is creating a hedge against the rising costs of electricity. My calculation is an example of simple calculations which takes into account the net present value (NPV) which is one of the crucial components when calculating the true LCOE. When calculating LCOE it requires one to know the two main key variables which are the system costs which include capital costs, financing, deducting tax credits and incentives. The other variable is the amount of power that the solar array will produce over the period which will be calculated between 20 – 25 years.

In the calculation of the solar PV project the researcher established that the size of the Solar PV plant is a 10 000 kW this is a small size project of a PV solar plant. The first year of production 52 417 000 kWh of energy is produced to supply the local grid, with an annual degradation of 0.50% and with a capital expenditure of $ 747 000. The below table indicates the project's projected life span which is between 20 – 25 years for a 10 000-kW plant. With the plants capital expenditure at $ 747 000 the production cost of electricity over 20 years is $ 947 589 491.09 per kWh and over a period of 25 years $ 1 234 732.07 per kWh and the operation and maintenance for 20 years is $ 403 055.62 and for 25 years is $ 546 888.96.

Year	Production (kWh)	Capital Expenditure ($)	Operation and Maintenance Cost ($)	PPA Escalator (%)	PPA Cost ($)
0		$ 747,000.00		-	
1	$ 52,417,000.00		$ 15,000.00	$ 0.03	$ 762,000.00
2	$ 52,154,915.00		$ 15,450.00	$ 0.03	$ 780,935.70
3	$ 51,894,140.43		$ 15,913.50	$ 0.03	$ 800,341.95
4	$ 51,634,669.72		$ 16,390.91	$ 0.03	$ 820,230.45
5	$ 51,376,496.37		$ 16,882.63	$ 0.03	$ 840,613.18
6	$ 51,119,613.89		$ 17,389.11	$ 0.03	$ 861,502.41
7	$ 50,864,015.82		$ 17,910.78	$ 0.03	$ 882,910.75
8	$ 50,609,695.74		$ 18,448.11	$ 0.03	$ 904,851.08
9	$ 50,356,647.27		$ 19,001.55	$ 0.03	$ 927,336.63
10	$ 50,104,864.03		$ 19,571.60	$ 0.03	$ 950,380.95
11	$ 49,854,339.71		$ 20,158.75	$ 0.03	$ 973,997.91
12	$ 49,605,068.01		$ 20,763.51	$ 0.03	$ 998,201.76
13	$ 49,357,042.67		$ 21,386.41	$ 0.03	$ 1,023,007.07
14	$ 49,110,257.46		$ 22,028.01	$ 0.03	$ 1,048,428.80
15	$ 48,864,706.17		$ 22,688.85	$ 0.03	$ 1,074,482.26

16	$ 48,620,382.64		$ 23,369.51	$ 0.03	$ 1,101,183.14
17	$ 48,377,280.73		$ 24,070.60	$ 0.03	$ 1,128,547.54
18	$ 48,135,394.32		$ 24,792.71	$ 0.03	$ 1,156,591.95
19	$ 47,894,717.35		$ 25,536.50	$ 0.03	$ 1,185,333.26
20	$ 47,655,243.76		$ 26,302.59	$ 0.03	$ 1,214,788.79
21	$ 47,416,967.54		$ 27,091.67	$ 0.03	$ 1,244,976.29
22	$ 47,179,882.71		$ 27,904.42	$ 0.03	$ 1,275,913.95
23	$ 46,943,983.29		$ 28,741.55	$ 0.03	$ 1,307,620.41
24	$ 46,709,263.38		$ 29,603.80	$ 0.03	$ 1,340,114.78
25	$ 46,475,717.06		$ 30,491.91	$ 0.03	$ 1,373,416.63
20 years	$ 947,589,491.09		$ 403,055.62		$ 18,220,876.78
25 years	$ 1,234,732,305.07		$ 546,888.96		$ 25,977,707.63

Table 9: LCOE Model of a Solar PV project

6.4 Evaluation of offshore projects

Evaluation of offshore projects mainly wind and wave farms. The researcher looked at the all the costs involved in detail from construction phase to decommissioning, service and maintenance. Appendix 3 has an in-depth detail on the costs involved in constructing an offshore wind farm.

6.5 Evaluating a wave farm project

For the purpose of my LCOE Model for a wave farm I had challenges accessing data for the CAPEX and OPEX. This led in consulting literature Journals and other energy publications to build my study. The CAPEX of a wave farm includes project development, construction and commissioning, balance of plant, wave energy convertor structure and the decommissioning phase at the end of the project life cycle.

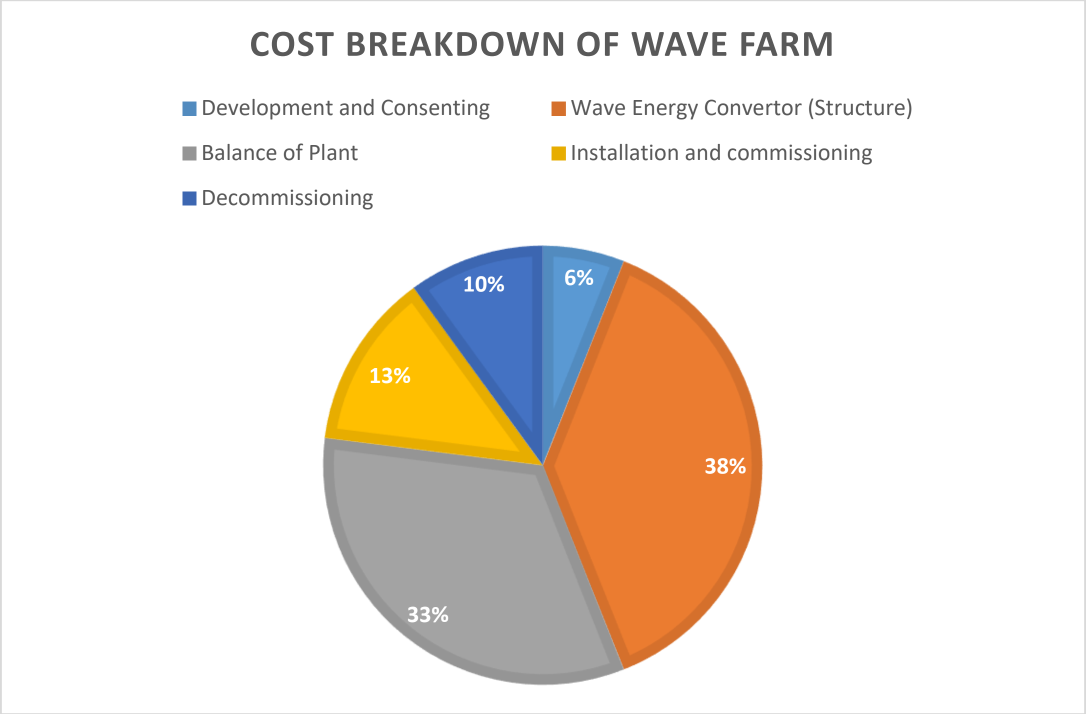


Figure 36: The cost breakdown of a wave farm

The OPEX are all the expenditure when it comes to operating the wave farm from the time a handover certificate is issued, this also includes all the operating and maintenance activities and all the costs relating to the leasing of the site including insurance. The below Table 10 summarises the OPEX cost breakdown with the site lease and insurance representing 6% of the total OPEX costs and the O&M is represented by the remaining part of the OPEX.

OPEX breakdown costs	
Items	OPEX Percentage (%)
Operation and maintenance (O&M)	94
Site lease and Insurance	6

Table 10: The OPEX break down costs

The wave farm is assumed to be a 20 MW plant; the CAPEX of the wave farm is €2 116 000 per MW this amount will be distributed over the years leading up to the first energy production. As with all projects there are various elements which will change due to project timing, local politics, competition, contracting conditions and exchange rate. The costs of a wave farm project include WEC, warranty costs, insurance costs, leasing costs, construction costs.

6.5.1 *Phase 1 Project planning and development of a wave farm*

The inception of a wave farm includes resource monitoring, environmental studies which includes zoning and MSP and issuing of certification when the work is approved by various specialists. The environmental impacts include the planning, engineering, assessment design and contract negotiations.

Project Planning and Development		
Items	Price in €	Unit
Resource monitoring	50 000	Year
Environmental studies	8 000 000	-
Certification	6 500 000	-

Table 11: Wave Farm project planning development

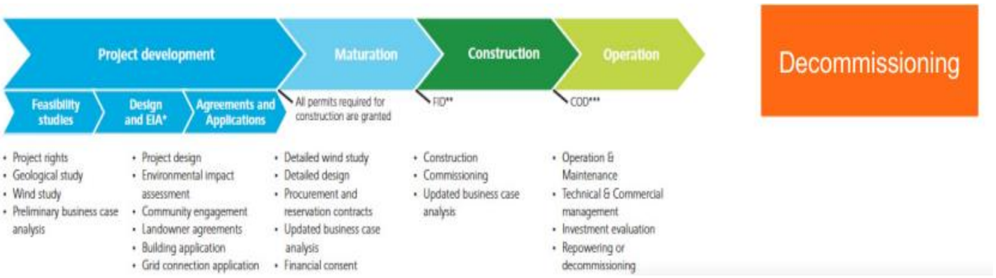


Figure 37: **Various phases of a wave farm**

(Source: Ballini, 2021)

6.5.2 Phase 2 Production phase of a wave farm

This phase includes the design, supply and production of including components from mooring, port delivery of components.

Mooring Total Cost in € (m)					
Water depth (m)	100	80	50	30	20
100	55 800	55 240			
50			54 400		
30				53 840	
20					53 560

Table 12: **The costs of mooring service in various water depth in meters**

The below Table 13 represents the structural material which make up the wave energy convertor.

Wave energy convertor		
Structural material (items)	Price in €	Unit
Concrete	250	ton
Ballast concrete	70	ton
Steel	3400	ton
Glass fiber	9500	ton

Table 13: **The costs that make up a WEC**

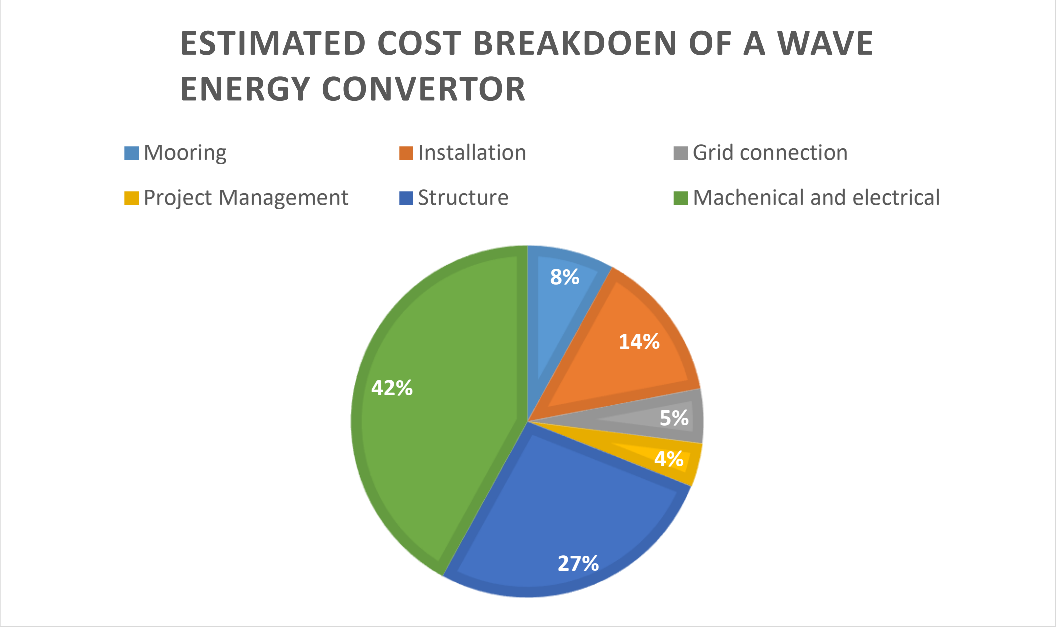


Figure 38: The estimated cost breakdown of a wave energy convertor (WEC)

6.5.3 *Phase 3 Installation and construction phase of wave farm*

In this phase the project includes installation of WEC, some of the installation costs are driven by charted costs and various installation methods require smaller and cheaper vessels.

Mooring installation (foundation)		
Items	Cost in €	Unit (day / km)
Renting cost for an anchor handler vessel	140 000	day
Single WEC, renting cost	10000	day
Single WEC, mooring installation for a single device	100000	-

Table 14: Estimated costs of foundation installation (Mooring)

WEC installation		
Items	Cost in €	Unit (day / km)
Towing vessel	7500	day
Diving work	2500	day

Table 15: Estimated costs of wave energy installation

Cable installation		
Items	Cost in €	Unit (day / km)
Cable laying trenched	282000	km
Cable laying entrenched	100000	km
Cable coverage (rock coverage)	939000	km

Table 16: Estimated costs of cable installation

Operations / Construction costs		
Items	Cost in €	Unit (day / year / trip)
Towing boat	12500	day
DP HLV	100000	day
Crane barge	220000	day
Sheerleg barge	50000	day

Table 17: Estimated Operations and construction costs

6.5.4 Phase 4 The commissioning phase of a wave farm project

In this phase of the project the costs of installations include WEC on site and commissioning to ensure they are commissioned into a fully operational state, up until handover and issuing of handover certificate.

Maintenance and service costs	
Items	Cost in €
Turbine maintenance and service	33 000
Balance of plant maintenance and service	18 000

Table 18: Estimated maintenance and service costs of a wave farm.

Service and Maintenance		
Items	Cost in €	Unit (day / year / trip)
Operation small vessel	100	trip
Multicat workboat	3 400	day
Travel and subsistence of personnel	36 000	year

Table 19: The estimated costs for human resource, vessels and boats used to ensure service and maintenance.

6.5.5 Phase 5 The decommissioning phase of a wave farm project

The decommissioning phase this phase usually includes all the costs that are related to the removal of WEC including the mooring systems, foundations electrical cables and everything which was agreed upon in the contract.

Decommissioning	
Items	Cost in €
Single WEC	200 000
based on real experiences at sea	176 000
offshore floating wind	140 000
offshore bottom-fixed wind	100 000

Table 20: The estimated costs of decommissioning a wave farm.

CHAPTER 7

CONCLUSION AND RECOMMENDATIONS

7.1 Conclusion

With South Africa being a coal producing country, plans are in place to decommission its coal powered plants in the next coming years, a new energy mix is urgently needed to meet the country's energy demand to ensure energy security. South Africa has a high renewable energy potential due to its geographical location and an extensive coastline it has a potential to unlock offshore wind and wave energy. Due to its geographic location South African has a potential to unlock the hydrogen industry and provide bunkering shipping fuel to large commercial vessel, it is well positioned to tap into this market. South Africa is a water stressed country when it comes to producing hydrogen through electrolysis, however, seawater electrolysis is a potential solution for carbon neutral hydrogen energy without relying on freshwater, this is a clear indication that South Africa can lead the green hydrogen industry. A new energy mix is no doubt needed in South Africa hence more energy policies are in place with an inclusion of renewable energy and hydrogen to promote a diverse energy mix to the local grid. Currently the price of hydrogen in South Africa is relatively high, however, the price of hydrogen is expected to drop and it is predicted that the price of fossil fuel will gradually increase in the coming years. The LCOE of wind and solar PV is currently sitting at R0.62 per kWh while the price of coal IPP is R1.03, this is a clear indication that the price of fossil fuel is relatively more expensive compared to the LCOE of wind and solar PV. The fact that coal electricity can be produced on demand and wind and solar energy are produced when the wind blows and the sun shines, there is a dire need for energy storage and the efforts to study the production of hydrogen and ammonia. Hydrogen is still predicted to be more expensive that coal electricity, however, from this maybe a critical cost for a kg of CO_2 could be calculated to make hydrogen competitive. The mass of CO2 produced per kg of carbon burnt is 44/12=3.66 times the amount of carbon burnt.

7.2 Recommendation

Extensive research is needed in South Africa to promote and raise awareness regarding its offshore energy potential. It is important to understand there is no sufficient research conducted in NMB and at the Port of Ngqura to install a wave farm and a hydrogen plant. There has been similar research conducted in the past in Europe and Asia on wave farms and green hydrogen production through electrolysis, however, projects in this field of research needs to be highly evaluated in order to understand the core of the research and the purpose of the research paper. The introduction of green hydrogen as a maritime fuel has the potential to decarbonize and reduce emissions in the Port of Ngqura, the produced hydrogen will power the port and provide tug boats and commercial shipping vessels with fuel. This will promote an environmentally friendly port and boost the port status, the Port of Ngqura is the only Port in Southern Africa holding a Green port status. The findings established must be investigated and put into practice and a more in depth conclusive research to support this study must be conducted in order to conclude the findings of the study.

7.3 Future work

Extensive models can be conducted on wave farms with an inclusion of solar and wind energy to evaluate the amount of energy a hybrid system can produce. With the hydrogen plant and hydrogen fuelling station in the Port of Ngqura, future studies can investigate the viability of a shipyard for retrofitting purposes. With the maritime sector aiming to decarbonise the industry large commercial vessels which pass by the Southmost tip of Africa will have an opportunity to be retrofitted with the necessary technologies in order to use hydrogen as a bunkering fuel.

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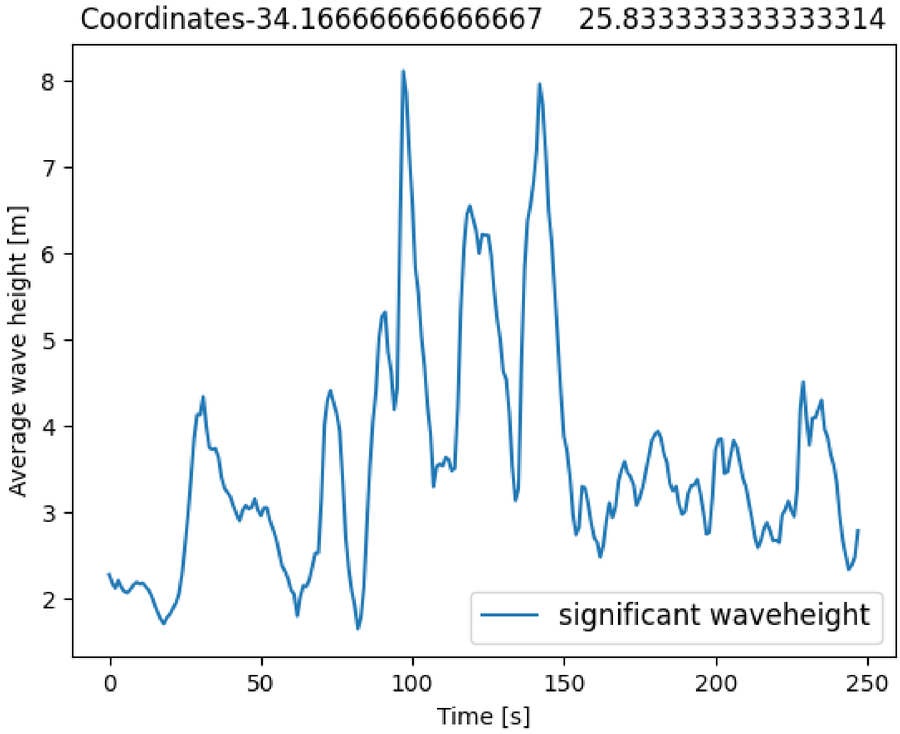
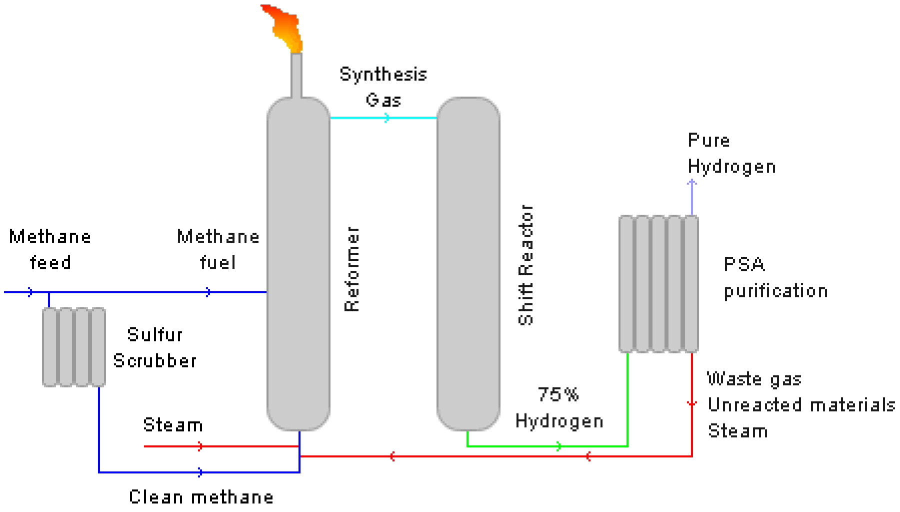
APPENDICES

Appendix 1: Average wave height in August 2020





Appendix 2: Production of hydrogen through steam reforming using natural gas

Production of Hydrogen gas by Steam Reforming (SR) using Natural gas, LPG and naphtha as feed.

The use of nickel as a catalyst the feedstock is desulphurised, it is mixed with steam and converted into synthesis gas in the top-fired reformer furnace. The synthesis gas is cooled in the heat recovery section and then fed to the high temperature co-conversion reactor. Post cooling the synthesis gas is purified through the use of Hydro swing PSA (Pressure Swing Absorption).

Plant data

Feedstock:	Natural gas, LPG, naphtha
Hydrogen capacity:	200 to 10.000 Nm³/h
Hydrogen product pressure:	10 – 30 bar(abs)
Hydrogen purity:	up to 99,9999 vol.-%

Typical consumption data for 1000 Nm³/h hydrogen:

Natural gas:	430 Nm³/h
Demineralized water:	900 kg/h
Cooling water:	38 m³/h
Electric power:	38 kW

Hydrogen Generation by Methanol Reforming

Hydrogen production using methanol reforming in conjunction with subsequent purification produces hydrogen with good efficiency and it is considered an alternative method for hydrocarbon in accessible locations. During production the Methanol-water mixture is vaporised and transformed to hydrogen rich synthesis gas over the copper catalyst in the tubular thermal-oil heated reactor. Synthesis gas from reactor outlet is cooled down and condensate is recycled under Hydro swing PSA technology.

With the use of thermal oil, the hydrogen production plant will keep its operating temperature extremely stable and can be restarted at short notice e.g. if a power failure occurs. With Mahlers' technology and design an overheating of the reactor and the low temperature catalyst, which is highly temperature sensitive is prevented by using a heat transfer media (thermal oil) buffering any temperature peaks. This helps to protect the catalyst for its entire lifetime.

Process

The HYDROFORM-M system is based on steam reforming of methanol as feed to produce a hydrogen-rich gas. The purification of the hydrogen-rich gas is done by means of the subsequent Hydro swing system.

Pre-treatment of the feed mixture

Methanol and fully demineralised water are fed to a storage vessel. Continuous measuring of density and level ensures the availability of the correct ratio of methanol and water. This feed mixture is pumped up and then preheated by heat recovery from raw hydrogen-rich gas. Vaporization of the feed and superheating to the optimal reactor inlet temperature is done by means of thermal-oil in the subsequent heat exchanger.

Methanol reforming reactor

The vaporized methanol-water mixture is catalytically reformed within the tubular thermal-oil heated reactor over copper catalyst into a hydrogen-rich synthesis gas. The reaction is endothermic and the required heat is transferred to the process by means of thermal-oil which ensures an even temperature distribution inside the reactor. The thermal-oil is heated by combustion of purge gas from the Hydro swing system.

Gas cooling by heat recovery

The hydrogen-rich synthesis gas coming from the methanol reactor is cooled down in heat exchangers by simultaneous economical preheating of the feed mixture. The process condensate is separated and sent back to the feed storage vessel to be reused.

Gas purification – HYDROSWING

The hydrogen-rich gas is sent to the HYDROSWING system which usually consists of four or five absorbers filled with different adsorbents. This process is based on pressure swing adsorption by which the impurities are separated to obtain hydrogen with purities up to 99.9% volume. The purge gas from depressurisation and purging during the regeneration step is used as fuel gas in the thermal-oil system.

Applications

Hydrogen generation based on methanol reforming with subsequent purification is a well-established process for hydrogen production and the alternative method at locations with limited access to hydrocarbons (e.g. natural gas, LPG or naphtha).

- Metallurgical and steel industry
- Petrochemical and refining industry
- Glass and float glass manufacturing
- Chemical and pharmaceutical industry
- Production of H_2O_2
- Food industry
- Electronics industry
- Technical gases

Plant data

Feedstock:	Methanol

Hydrogen capacity: 200 to 5.000 Nm³/h

Hydrogen product pressure: 10 – 30 bar(abs)

Hydrogen purity: up to 99,9999 vol.-%

Typical consumption data for 1000 Nm³/h hydrogen:

Methanol: 630 kg/h

Demineralized water: 340 kg/h

Cooling water: 20 m³/h

Electric power: 45 kW

Appendix 3: Evaluation of a wave farm (Babar, 2020)

According to (Miceli, 2019), the cost of a wind turbine is less then yesterday and probably tomorrow it will cost less than today. In 2019 the price of a turbine was around 700 000 € per MW, one can expect to pay 3 million€ for a 4 MW wind turbine. (Miceli, 2019), adds this is a huge reduction considering a few years ago the price of a turbine would cost 1 million€ for 1MW. There are huge pressures on the prices of wind turbines, these driving factors result in wind turbines being cheaper than ever. Vestas reported a 9.5% in 2018 and Siemens Gamesa a 7.6% pre PPA and Installation and Repairs (I&R) costs for the same year and with a 2019 range sitting between 7% and 8.5% (Miceli, 2019). Manufacturers are having more luck in the maintenance department of the business as the margins have slightly improved.

In 2019 it was calculated that 1 megawatt wind turbine produced $61 320 at 35% energy capacity, at 50% $87 600 energy capacity and $114 880 at 65% energy capacity. While a 4-megawatt wind turbine produced $245 280 at 35% energy capacity, $350 400 at 50% energy capacity and $455 520 at 65% energy capacity (Anemoi Energy Services, 2020). Wind turbines are expected to perform between 35% - 65% of its capacity due to varying wind conditions, the cost of a wind turbine will go up due to the size of the turbine meaning there are more benefits when it comes to using larger wind turbines.

For the purpose of my LCOE Model for a wind farm I had challenges accessing data from my employer for the CAPEX, OPEX and DEPEX as the data was considered high level information and not easily available for our disposal. This led in consulting literature Journals, IRENA, IEA and a few other energy publications to build the study. The CAPEX for the wind farm is £2 370 000 per MW this amount is spread out realistically over the years which leads up to the first energy production. The annual OPEX is £76 000 per MW over a lifetime of 27 years, with the Weighted Average Capital Cost (WACC) at 6% and the net average energy production at 4 471 MWh per year (Anemoi Energy Services, 2020). The prices of various elements many change due to local politics, timing of project, contracting conditions, exchange rate and competition. The prices for large wind turbine components includes and is not limited to warranty costs, delivery to the nearest port to supplier, developer costs which includes insurance, project and construction costs, overheads and typical spent contingency costs (Anemoi Energy Services, 2020). The below table is an assumption of a commercial scale wind farm at 1 000 MW.

PARAMETER	DATA
Wind farm rating (MW)	1000
Wind turbine rating (MW)	10
Water depth at site (m)	30
Annual mean wind speed at 100m height (m/s)	10
Distance to shore, grid, port (km)	60
Date of financial investment decision to proceed (FID)	2019
First operation date	2022

Table 21: Commercial scale wind farm at 10 MW

Cost Breakdown

This is a more detailed account of the cost breakdown, the figures which are presented are rounded. As it has been highlighted earlier in the study that there is usually a large variation in costs between projects which is influenced by various factors, therefore the values which are represented should only be considered as indicative. The breakdown is for an offshore wind farm, keeping in mind there are 5 phases of constructing any wind farm be it offshore or onshore they consist of the following phases the development phase, production phase, installation phase, operation and maintenance phase and decommissioning phase. The breakdown will display a costs of each of these phases the breakdown is adopted from (BVG associates, 2019).

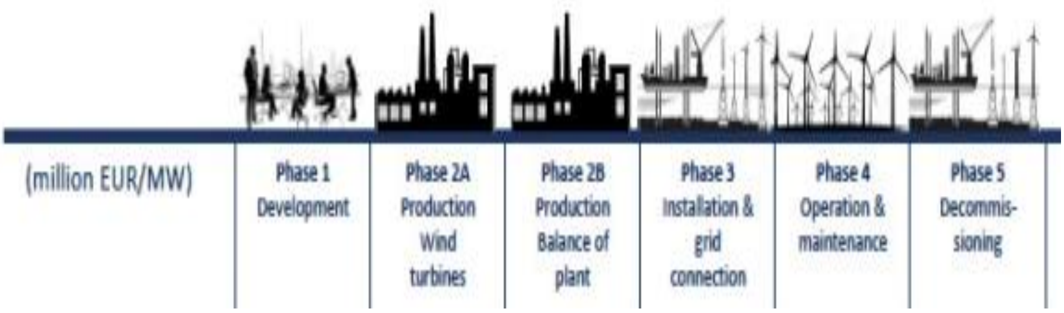


Figure 37: The five phases of constructing a wind farm. (Ballini, 2021)

Phase 1. The development of a windfarm

This is the most complex phase of a wind farm project, when the project progresses in the various stages of development mistakes usually get unravelled which can seriously affect the final success of the wind farm project. Major mistakes when it comes to wind development usually occurs in the early stages and can become very challenging to overcome. The below are the estimated costs of the development of a wind farm.

Items	**Estimated cost in (£/MW)**
Development and project management	120 000
Development and consenting services	50 000
Environmental impact assessments	8 000
Developer, employee hours and subcontract works	42 00
Environmental Surveys	4 000
Benthic environmental surveys	450
Fish and shellfish surveys	400
Ornithological environmental surveys	1000
Marine mammal environmental surveys	1000
Onshore environmental surveys	550
Human impact studies	350
Resource and met ocean assessment	4 000
Structure	3 000
Sensors	650
Maintenance	300
Geological and hydrological surveys	4 000
Geophysical surveys	700
Geotechnical surveys	2 500
Hydrographic surveys	800
Engineering and consultancy	4 000
Lost project which incurred development expenditure	54 000

Table 22: The Estimated costs of phase 1 of a wind farm project

Phase 2. The production phase of a wind farm.

There are no project costs break down associated with this phase of the project, however, the below are the costs of the main components which are used in the production phase such as turbines, rotor and towers, which makes up the complete tower of the wind turbine.

Items	**Estimated cost in (£/MW)**
Turbine	1 000 000
Nacelle	400 000
Bedplate	20 000
Main bearing	20 000
Main shaft	20 000
Gear box	70 000
Generator	100 000
Power take-off	70 000
Control system	25 000
Yaw system	17 000
Yaw bearing	7 000
Nacelle auxiliary systems	7 000
Nacelle cover	10 000
Small engineering components	25 000
Structural fasteners	7 000
Rotor	190 000
Blades (3)	130 000
Hub casting	15 000
Blade bearings	20 000
Pitch system	10 000
Spinner	2 000
Rotor auxiliary systems	4 000
Fabricated steel components	8 000
Structural fasteners	7 000
Tower	70 000
Steel	60 000
Tower internals	7 000

Table 23: The Estimated cost of the main turbine structure

Phase 3. Installation and grid installation.

During this phase heavy machinery such as cranes, excavation work is also done during this phase, after laying foundations there is a waiting period of 2 weeks to allow curing of the foundation or the base to take place. Installation to be carefully conducted in order for the structure to bear the weight of the turbine.

Items	Estimated cost in (£/MW)
Assembly, installations and commissioning, profit and warranty	340 000
Cables	170 000
Export cables	130 000
Array cable	35 000
Cable protection	2 000
Turbine foundation	280 000
Transition piece	100 000
Corrosion protection	20 000
Scour protection	10 000
Offshore substation	120 000
Electrical system	45 000
Facilities	20 000
Structure	60 000
Onshore substation	30 000
Building (offices, toilets, kitchen), security and access	8 000
Electrical systems and equipment	22 000
Operation base	3 000

Table 24: Estimated costs of assembly, installation and commissioning, profits and warranty

Commissioning usually involves tests such as electrical tests electrical infrastructure, inspection routine of civil engineering quality tests and records. At this stage careful testing is essential for a good quality wind farm which will be handed over and maintained by the service department.

Items	**Estimated cost in (£/MW)**
Installation and commissioning	650 000
Foundation installation	100 000
Offshore substation installation	35 000
Onshore substation construction	25 000
Onshore export cable installation	5 000
Offshore cable installation	220 000
Cable burial	20 000
Cable pull-in	7 500
Electrical testing and termination	6 500
Cable laying vessel, route clearance, survey works and cable protection systems	186 000

Table 25: The Estimated costs of phase 3 Installation and commissioning

Phase 4. Operation and maintenance

After the commissioning phase the wind farm will be handed over to the operations and maintenance department, in the case of a small scale wind farm arrangements are usually made for regular maintenance visits.

Items	**Estimated cost in (£/MW)**
Maintenance and service	50 000
Turbine maintenance and service	33 000
Balance of plant maintenance and service	18 000

Table 26: The Estimated cost of Operation and Maintenance

Phase 5. Decommissioning

This is the last phase of a project's lifecycle which is the opposite of an installation phase, after all the work has been done the site must be left in the same condition as it was before any construction activities took place. A process of rehabilitation must be conducted and supervised by an Environmental team ensuring that the land is rehabilitated and returns to its natural state.

Items	Estimated cost in (£/MW)
Decommissioning	330 000
Turbine decommissioning	45 000
Foundation decommissioning	75 000
Cable decommissioning	140 000
Substation decommissioning	65 000

Table 27: The Estimated costs of Decommissioning phase