HYDROGEN FROM DESERT AREAS

Hydrogen production in desert areas for export in comparison to a Dutch domestic hydrogen system

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EES-2018-325

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Research report of Victhalia Zapata

Report: EES-year-number provided by secretary

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ACKNOWLEDGEMENTS

First of all, I would like to give my sincere gratitude to my two supervisors Gideon Laugs and Rene Benders for your support, dedication and guidance throughout the entire period of this project. A warm thank you to both of you. Last but not least, I give thanks to my husband Michael Drossart for been always supportive and encourage me to continue working at my best during the long nights and cloudy days of winter.

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SUMMARY

In the sight of an energy system without significant CO2 emissions, some countries may find that the capacity of a steady and secure supply of their energy demand from domestic renewable energy resources is limited or economically unviable. Solar, wind and wave sources of energy are very variable and dependent on weather conditions. In temperate and polar zones, some countries may find difficulties for keeping up with a higher demand and lower sun irradiance in winter season. Renewable energy import could become a feasible option in a world with a CO2 free energy system and hydrogen as a renewable energy carrier could fill this gap. Hydrogen is seen as an energy carrier that can be extensively used in the transport sector and it can support the penetration of fluctuating renewable energy sources into the electricity market by using hydrogen as storage backup for the electricity system.

In this study the energy and environmental feasibility of producing and exporting hydrogen in Morocco and Australia from solar energy is analyzed and compared to producing hydrogen for domestic consumption in The Netherlands from wind energy. Two systems are defined, a solar to hydrogen system using Morocco and Australia hourly satellite derived solar irradiance, and a wind to hydrogen system in The Netherlands as the reference scenario. For analyzing the energy feasibility, a study of annual hydrogen production and energy return on energy invested (EROI) is performed on both systems. Further, a sensitivity analysis on the annual hydrogen production of the solar to hydrogen system is procured. The environmental feasibility is obtained by performing a life cycle assessment of the expected environmental impact of producing 1 Kg of hydrogen from the two systems. In addition, low and high boundary future hydrogen demand scenarios for The Netherlands were assessed.

The solar to hydrogen system studied from Australia and Morocco attains larger annual production than the Dutch reference scenario even including losses for transportation to The Netherlands. The solar to hydrogen system in Morocco has larger environmental impact, however it has less CO2 emissions than the reference scenario. Both systems got larger energy return on energy invested than biofuels and unconventional oil production.

LIST OF ABBREVIATIONS

CCS: Carbon capture and storage
CED: Cumulative energy demand
EI: Environmental impact
EROI: Energy return on energy invested
GWP: Global warming potential
HHV: High heating value
IGCC: Integrated gasification combined cycle
LC: Life cycle
LCA: Life cycle assessment
LHV: Low heating value
MSD: Mean square deviation
NEV: National energy outlook
NG: Natural gas
PC: Pulverized coal
PEM: Proton exchange membrane electrolysis
SD: Standard deviation error
S2H: Solar to hydrogen
W2H: Wind to hydrogen

1. INTRODUCTION

The current world energy system relies in a large proportion on fossil fuel sources, 81.6% in 2014 (IEA, 2017). Nevertheless, even being a reliable source of energy in the present, its sustainability for future generations remains highly uncertain. And, more importantly, fossil fuel burning and its consequent CO_2 emissions are exerting a large pressure over the environment by raising the Earth global mean temperature. To tackle this problem, 195 countries have come together for the Paris agreement in which it is intended to maintain the global mean temperature below 2°C, for this, short and long-term targets of CO2 emissions reduction must be realized. Accordingly, the EU has set the target, in conformity with the IPCC report, for reducing GHG emissions by at least 40% compared to 1990 levels by 2030 and 80% to 90% by 2050 (European Commission, 2014).

In the sight of an energy system free of CO2 emissions, some countries may find that the capacity of a steady and secure supply of their energy demand from domestic renewable energy resources is limited or economically unviable. Solar, wind and wave sources of energy are very variable and dependent on weather conditions. In temperate and polar zones, some countries may find difficulties for keeping up with a higher demand and lower sun irradiance in winter season. An example of this are the regions of South East Asia and Japan which according to De Vries, et al., 2007; these regions have a renewable supply potential lower than the electricity demand. For all this, renewable energy import may quickly become a feasible option in a world with a CO2 free energy system.

Electricity could be imported, but it has its drawbacks; the electricity produced must be equal to the electricity demanded for every moment and therefore surplus on solar or wind energy might be lost; losses over large distances of high voltage cables could be very high, about 3% for 1000 Km in a HVDC cable (Vaillancourt, 2014). Further, when this cable goes through areas with political instability, vigilance over the cable is going to be needed. In this sense, energy carriers, as hydrogen which can be transported over long distances by means of ship or trucks could be needed to guarantee the security of supply.

Hydrogen is an energy carrier that can be transported over long distances. It has a high energetic content per weight compared to gasoline (33.3 kWh Kg-1 versus 12.4 kWh Kg-1). In addition, it is the most abundant element in the universe and the third most-abundant element on the Earth's surface (Armaroli & Balzani, 2011). Hydrogen production with a low-carbon footprint together with fuel cell technologies have the potential to support the energy transition and energy security goals in sectors that are challenging to decarbonize such as the transport, industry and building sectors (IEA, 2015).

A key target for hydrogen use in a CO2 free economy is the transport sector along with the technology of hydrogen fuel cells. Several important scenarios for a renewable energy system have foreseen hydrogen as an important energy carrier in the transport sector together with biofuels and electricity (Andrews & Shabani, 2014). The sustainability of biofuels for supplying alone the transport sector is questionable because it competes with land needed for crops. The other alternative, electric cars, aside from still currently using a limited resource for their batteries manufacture (lithium), also suffer from long charging cycles (typically six to eight hours), limited range and therefore is still far from representing a convincing solution for long distance transportation ("List of electric cars currently available", 2017); due to all this, hydrogen represents a key piece of the renewable puzzle in the transport sector.

Another potential use of hydrogen is as a backup for variable renewable sources (VRE) of electricity (solar PV and wind); currently, this is already done in remote areas in Australia (SEFCA, 2017).

Intermittent renewable energies have some intrinsic operating challenges in which hydrogen could facilitate its penetration in the energy market (Barton & Infield, 2004). These challenges are:

- Energy production during hours in which the demand is high with low VRE input.
- The contribution of variable renewables to peak demand can be low
- To find enough dispatchable capacity to meet peak demand, including generation capacity, storage and demand response. (IEA, 2012)

Hydrogen is found in the water molecule and therefore in any living thing, while in the atmosphere it is present in small proportion. (Rsc. Org., 2017) Nevertheless, the hydrogen molecule (H_2) is not found freely in our planet and therefore it is not an energy source by itself; it must be produced from other sources of energies through different energy conversion steps (Godula-Jopek, Jehle & Wellnitz, 2012). Currently, the production of hydrogen is well understood by steam reforming natural gas and the costlier method electrolysis of water, this last one could be considered a carbon neutral process if the electricity used comes from a renewable source. In addition, plenty of new methodologies are in studies for improving the efficiency of producing hydrogen from water by combining renewable energy sources. However, due to its low density by volume (2.5Wh L-1), its two main difficulties as an energy carrier are the hydrogen storage and distribution (Armaroli & Balzani, 2011).

A good location for a large-scale hydrogen production could be the Sahara Desert. It receives high quantity of solar energy that can be harvested and exported in the form of hydrogen. In addition, it has plenty of land available that does not compete with other activities as food production, and it is close to Europe. In figure 1 there is a map of the irradiance showing North Africa receiving an annual direct solar irradiance from about 2000 to 2800 kWh/m^2 (Solargis, 2011).

From a global standpoint, a significantly higher direct solar irradiance is manifested in Australia (Figure 1). Further, because of its location in the southern hemisphere, it receives its higher solar irradiance in the winter of the northern hemisphere. Therefore, it could also be an important supplier of renewable hydrogen in the future.

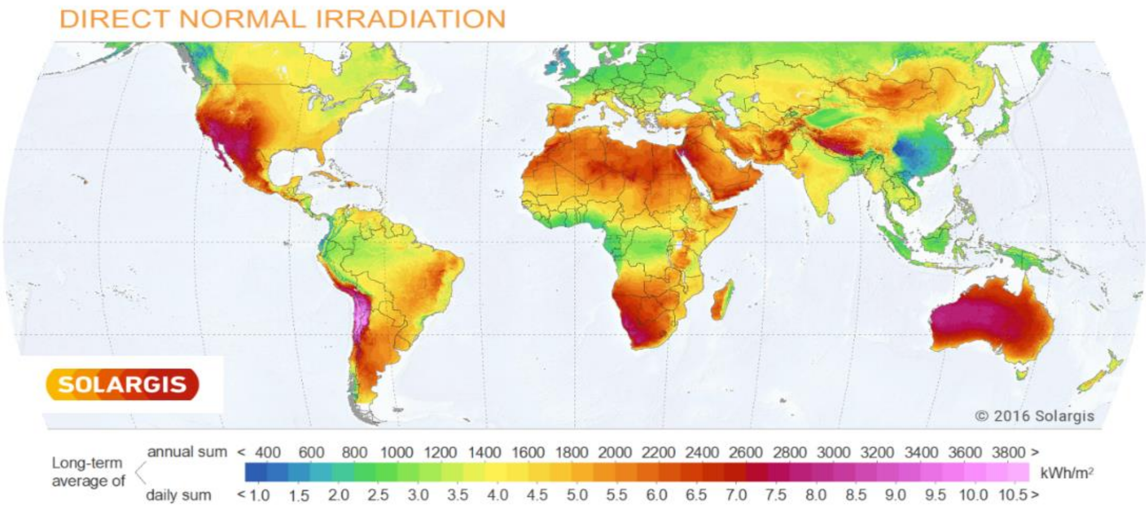

Figure 1: Long term average DNI world map (Solargis, 2016)

1.1 Research aim and questions

Currently there is a high interest on investing in technology development for hydrogen systems produced from renewable energy sources. Hydrogen is seen as an energy carrier that could be extensively used in the transport sector and could support the penetration of fluctuating renewable energy sources into the electricity market by using hydrogen as storage backup for the electricity system. Countries with low renewable energy capacity would be interested in importing renewable energy and an option for this could be hydrogen import. Thereby, this research aims at analyzing technical, energy and environmental feasibility of producing hydrogen from solar energy in deserts for export. To have a reference, this solar-hydrogen will be compared to domestic renewable hydrogen production in a country with limited potential for coupling with the future energy demand in a decarbonized renewable energy system. In this case, the Netherlands is considered because it is a highly industrialized country with limited land available for installing wind or solar parks but with higher potential for offshore windmills.

The main research question that would help to achieve the research aim is:

What is the feasibility of producing hydrogen from solar energy in desert areas for export and how does it compare to domestic production in the Netherlands from wind energy?

The main research question encompasses the following specific questions:

1. What are the current proven technologies available for production, storage and transport of hydrogen and which are the most suitable for a solar-hydrogen system?
2. What is the environmental and energetic feasibility of producing hydrogen for different production scenarios?
3. How does hydrogen from solar energy imported compares to producing hydrogen locally in the Netherlands?
4. What would be the hydrogen energy demand in the Netherlands in a future energy system?

1.2 Boundary settings

This research uses as a starting point that North Africa and Australia would be able to supply its future energy demand with renewable sources and at the same time would be able to export energy to Europe, as it is stated in the Desertec concept for North Africa. Accordingly, it is assumed that there is plenty of land available for building a solar to hydrogen plant that would export all the hydrogen produced.

The analysis made for hydrogen production is based on efficiencies found in literature for each of the subsystems that play a role in converting solar or wind energy to hydrogen energy, and assuming an upscale on production capacity would not affect its efficiency. Energy losses by the interaction between the subsystems were assumed to be of very small proportion and unnecessary to include in the analysis.

1.3 Research methods

For achieving the aim of this research two systems were defined from the production standpoint to cast comparisons among them: 1) The solar to hydrogen system (S2H) and 2) the wind to hydrogen system (W2H). The hydrogen productivity of the first one was analyzed for two scenarios, the Morocco scenario and the Australia scenario; they were compared to the W2H system in the Netherlands which will stand as the reference scenario.

The method for answering the first specific question was based on literature review in which reports from renowned energy research agencies and scientific literature were used for 1) assessing the options available and their maturity status, then 2) defining the technologies to be applied in the solar to hydrogen (S2H) and the wind to hydrogen (W2H) systems.

The feasibility of these systems was mainly analyzed from an environmental and energetic point of view, considering also land use and availability in each of the scenarios compared. The environmental feasibility was done by a life cycle assessment of the S2H system in the Sahara Desert and the results of this study were compared to the W2H system in the Netherlands.

The energetic feasibility was calculated by making use of the energy return on energy invested method for the lifespan of both systems. In addition, the expected electricity production and related hydrogen production throughout the year of both systems were calculated. For analyzing the S2H system productivity, hourly databases of direct normal solar irradiance from Morocco and Australia were used. This database allows to calculate hydrogen production rate differences between summer and winter seasons, hourly variations of electricity production and hours of non-electricity production. The annual electricity production from the W2H system was obtained from literature review and calculating the capacity factor for the North Sea area.

The hydrogen demand in the energy sector was based on literature review about current and expected models on energy consumption and technology developments on hydrogen implementation in the transport and energy sector. From there, information about probable areas of hydrogen introduction to the energy market for 2030 and 2050 were used for replacing fossil energy sources by hydrogen sources.

2. TECHNOLOGY REVIEW AND SYSTEM DEFINITION

2.1 Hydrogen production from solar energy

Several paths can be taken for hydrogen production from solar energy. Figure 2 shows three initial paths considered into this research. The first path is implementing PV cells for photolysis or one step photoelectrochemical water splitting (Turner, 2007).

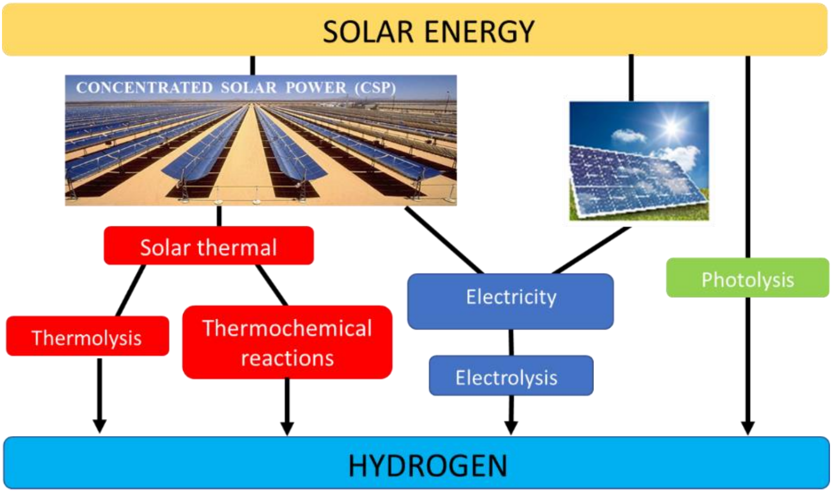

Figure 2: Hydrogen production methods from solar energy

The second path is through electricity coming from CSP or PV panels. Most of commercial water electrolysis system efficiencies are, according to different literature review, ranging from 50% to 75% (IEA, 2007; J. Ivy, 2004) with a large spread of reported theoretical efficiencies. If we multiply these efficiencies with the reported efficiencies for CSP electricity production between 13-17% ("CSP Projects - NREL," n.d.), the overall solar to hydrogen efficiency through electricity would be between 6.5% to 12.8%, without taking in account losses between subsystems. With respect to PV panels, it is well known that they lose efficiency with the increase of temperature. As in Sahara desert temperatures are higher than 25°C, PV panels would have reported efficiencies between 9% to 13% (Skoplaki & Palyvos, 2009).

There are two types of commercially available electrolysis methods, alkaline and proton exchange membrane (PEM) electrolysis. In alkaline electrolysis, iron or nickel steel electrodes immersed in a highly concentrated alkaline aqueous solution are used for separating hydrogen from oxygen. Large capacity alkaline electrolyzer have been successfully implemented, main advantages are the low costs, high reliability and durability but they are not totally suitable for operating with transient power sources; nevertheless, last manufactured alkaline electrolyzer are more capable to pair with the fluctuating solar and wind electricity sources (Godula-Jopek, 2015). PEM cells are more complex, its central component is a set up made of one solid polymer membrane with an electrocatalyst at each side of the membrane (Godula-Jopek, 2015). PEM electrolyzers produce high purity hydrogen for direct use with PEM fuel cells and allows large range of productivity variation. However, one of its main problem is the capital cost required associated with the membranes and noble metal based electrodes, and it is a less mature and reliable technology compared to alkaline electrolyzers (Grigoriev & Fateev, 2017).

Currently, there is a large-scale project, the largest electrolysis plant in Europe (Energiepark Mainz) for coupling a PEM electrolyzer to a local power grid in Germany connected to an 8MW wind farm. It has HHV (high heating value) efficiencies that varies between 59% when running at peak power (6MW) to 64% for 4MW power input until 78% for around 1MW of input power (Kopp et al., 2017).

There are several studies that research different methods for obtaining hydrogen that are more efficient than the mentioned commercial electrolyzers excluding steam reforming from hydrocarbon. Examples are high temperature steam electrolysis (HTSE) and hydrogen from thermal energy. Studies report a reduction of electricity required of about 35% for HTSE with temperatures of 780°C (Godula-jopek & Jehle, 2012). Nevertheless, HTSE have degradation issues that do not allows longer life operations than 3 years (Godula-Jopek, 2015). With respect to thermal methods, there is pure thermolysis and thermochemical multiple cycles. The first one needs temperatures higher than 2000°C (Armaroli & Balzani, 2011; OECD/IEA, 2014) however the maximum temperatures of solar collectors are around 1125 (Perret, 2011).

There are hundreds different types of thermochemical multiple cycles under studies with reported theoretical efficiencies of more than 60% coupled with CSP technology (OECD/IEA, 2014). They seem to be very promising technologies, nevertheless, they are in an early phase of development and further research is required for system integration.

2.2 Hydrogen storage and transport

Hydrogen storage is one of the main difficulties for developing further a hydrogen energy economy due to the low density of the hydrogen molecule. Several hydrogen storage options are currently available in literature related to hydrogen carriers such as metal hybrids or ammonia (Singh et al., 2015), but there are only two main options in mature phase of development, and these are pressurized hydrogen storage and liquefied hydrogen storage, they will be explained in the next section. Table 1 shows the different densities of hydrogen and natural gas under normal and pressurized conditions. We can see that hydrogen has higher energy by weight when compared to natural gas but its density under standard condition is extremely low compared to natural gas causing difficulties for storing it.

Table 1: Densities of hydrogen and natural gas under different conditions (Godula-jopek & Jehle, 2012).

Properties @ 293.15 K	Hydrogen	Natural gas
Upper Heating Value (MJ Kg^{-1})	143	55
Density (Kg m^{-3}) STP	0.089	0.717
Density (Kg m^{-3}) @20MPa	14.707	162
Density (Kg m^{-3}) @40Mpa	27	
Liquid Hydrogen (Kg m^{-3})	70.8	430-470

With respect to hydrogen transport, the options are road or rail transport, pipelines or through the sea on ships alike to those used for LNG. At present, most of the hydrogen transportation (≈ 66%) is made by means of local pipelines and distribution over the road (FreedomCAR and Fuel Partnership, 2007).

2.2.1 Pressurized hydrogen storage

For pressurizing hydrogen, several types of compressors can be used ranging from 2MPa to 18 MPa for underground storage, and 35MPa to 70MPa for gaseous transport (OECD/IEA, 2015). At high pressure (>20MPa) the density largely depends on the temperature; the higher the temperature the lower the density. Generally, power demand is between 5.45 MJ Kg^{-1} to 3.03 MJ kg^{-1} for isothermal compression (Godula-jopek & Jehle, 2012). The two most used compressors are piston compressors and diaphragm compressors (FreedomCAR and Fuel Partnership, 2007).

2.2.2 Liquid hydrogen storage (LH_2)

The liquefaction is the process in which the hydrogen is transformed from gas to liquid. The boiling temperature of hydrogen is 20K at ambient pressure, and then it needs to be stored with temperature between 20K and 30K depending on the pressure of the tank. Liquid hydrogen is the current way to store large quantities of hydrogen because of its lower density (FreedomCAR and Fuel Partnership, 2007). Despite this, liquid hydrogen has less density than gasoline and other common fuels. Nowadays, there is a small demand for liquid hydrogen, thus only a small capacity is installed (267.9 Kg d^{-1}) (Godula-jopek & Jehle, 2012). Commercial liquefiers require around 35% of the energy contained in the hydrogen liquefied (FreedomCAR and Fuel Partnership, 2007).

Standards materials for LH_2 tanks are metals as stainless steel or aluminum. Also, for aerial and automotive transport, lighter materials tanks are under investigation. The biggest tank is been developed by NASA, it is an sphere that keeps about 230 tons of LH_2 in a volume of about 3200 m^3 (Godula-jopek & Jehle, 2012).

An important consideration for liquefied hydrogen storage is the boil off rate, the boil off depends largely on the storage capacity of the tank, the smaller the quantity of LH_2 stored, the larger the boil off. The spherical NASA LH_2 tank has a boil-off rate of 0.03% per day. (FreedomCAR and Fuel Partnership, 2007). For large transportation as ships or barges, the boil-off hydrogen can be used as fuel for the ship (Godula-jopek & Jehle, 2012).

Due to the low temperatures, the hydrogen is almost 99.9% pure, all other materials are solidified. To avoid clogging it is important to separate these materials before the cryogenic refrigeration (Godula-jopek & Jehle, 2012), for this the impure hydrogen is precooled and later the impurities are removed. The hydrogen is then cooled further and as final step there is the ortho-para conversion process (Cardella, Decker, Sundberg, & Klein, 2017). Figure 3 illustrates a process diagram of the liquefaction steps.

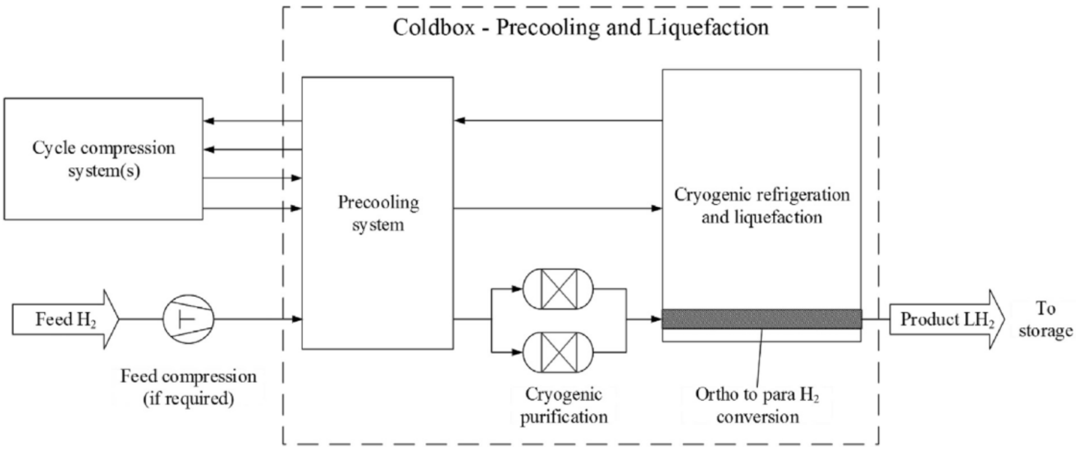

Figure 3: Liquefaction process diagram (Cardella et al., 2017)

2.3 Solar to hydrogen system definition

Given the nature of this study, commercially proven technologies were favored over those that promise better efficiencies but in early phases of development. This led to choose the process of producing hydrogen from electricity. A concentrating solar power plant was chosen as a first subsystem for producing electricity. This because of the high temperatures of the Sahara Desert, previous works made by Desertec in which CSP is favored over PV panels, and the capacity of CSP with thermal storage of delivering electricity in times of zero solar irradiance. With respect to the electrolysis method whether from alkaline or PEM, both could be capable for coupling it with CSP.

Then, the main aspect considered for choosing electrolysis method was the availability of good sources for performing the environmental and energy productivity assessment (LCA and EROEI) which as expected by its larger maturity resulted to be an alkaline electrolyzer.

There are many considerations to take in account for deciding which storage and transportation technology utilize. The transport distance from the production site Tizart in Morocco to the consumer in Rotterdam port; the time that this hydrogen will be stored and the quantity of hydrogen to transport are important factors to take in account. For the first requirement, the transport mode to be used is cargo ships due to the long distance from the production site to the consumer site in the Netherlands (2900 km). For long distance transportation and in ships several authors define liquefaction as the most suitable mode for its transportation (Singh et al., 2015).

Finally, the overall solar to hydrogen system including transport to the port of Rotterdam will be composed by 4 subsystems that are illustrated in

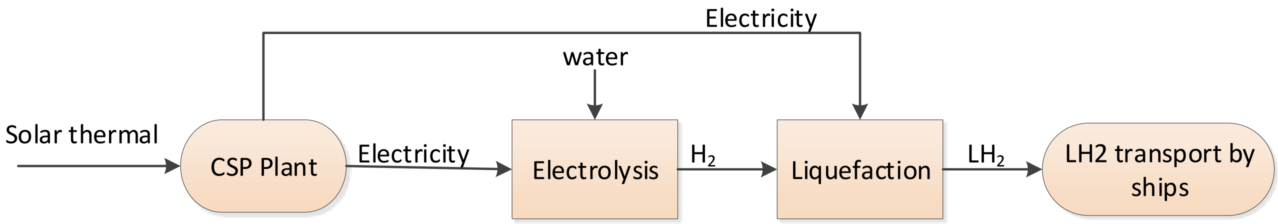

Figure 4. It is assumed that the liquid hydrogen produced will be directly stored in the ships in which it will be transported.

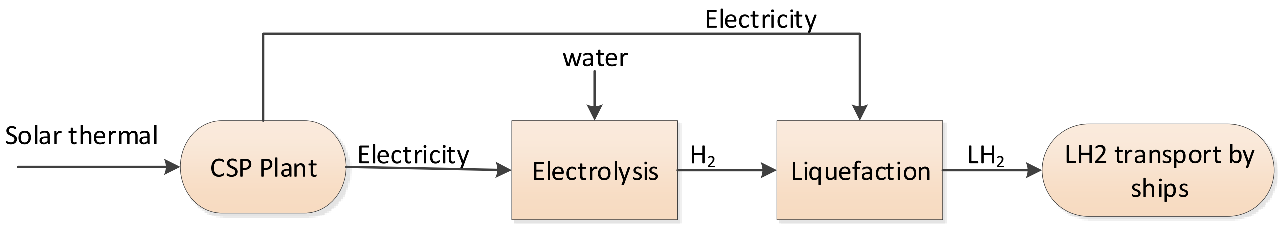

Figure 4: Process diagram for producing hydrogen from solar thermal energy

2.4 Wind to hydrogen system definition

The wind to hydrogen system is studied as a reference for comparing domestic hydrogen production in the Netherlands with importing hydrogen produced in the Sahara Desert and Australia. Therefore, the method for producing hydrogen is going to be the same alkaline electrolysis already defined. The wind energy production is based on the existing Gemini windfarm located offshore Netherlands and the main features of this windfarm are found in the table below.

Table 2: Main features of Gemini wind park ("Gemini - 4C Offshore," n.d.).

Wind farm name:	**Gemini**
Capacity:	600 MW
Area used	70 km^2
Number of windmills turbines	150
Expected life	20 years

Given that this hydrogen will be produce for covering domestic demand the storage subsystem has different requirements. In this case the hydrogen will not be liquefied but it will be pressurized to 400 bars and stored in hydrogen pressurized vessels which is a less energy intensive process. Figure 5 shows the process diagram for the wind to hydrogen system composed by the already mentioned four subsystems.

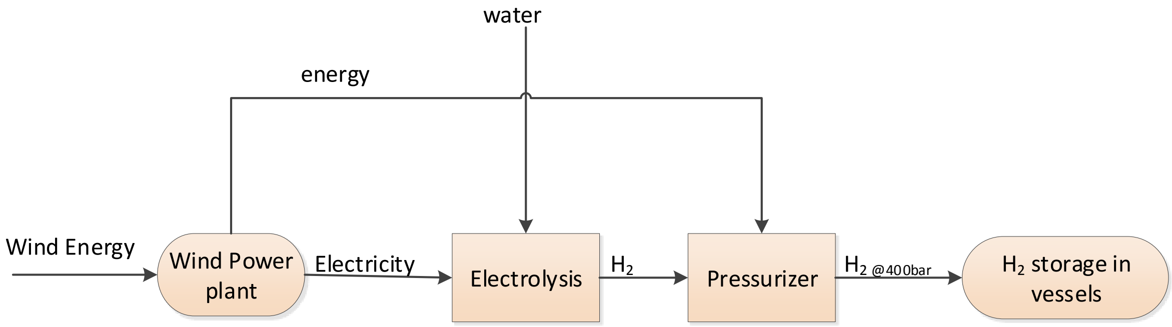

Figure 5: Process diagram for the wind to hydrogen system

3. ELECTRICITY AND HYDROGEN PRODUCTION MODELLING

3.1 Solar to Hydrogen system in Morocco

3.1.1 Model of electricity produced from solar irradiance in Morocco

For capturing all details of hydrogen production rate by implementation of a VRE source, hourly production of electricity demand is needed. It would enable to better asess the capacity factor depending on climate conditions of the location set, the storage capacity and to asess the amount of ships needed. Therefore, an hourly resolution of solar irradiance is needed for calculating the electricity produced. However, hourly resolution irradiance data is scarce. Further, the data available is satellite derived model data, for which it was intended that the Morocco scenario and the Australia scenario would have the same data source with the same irradiance model applied for a better comparison.

The location defined for the hypothetical CSP plant was based on maps of country level solar irradiance and the acces of this land to the sea. The site defined was close to Tizart village in Morocco. Two sources of data were used, one with an hourly frequency but modelled for the area of Casa Blanca and another with a daily frequency in the area of interest close to Tizart taken from a grid model with a resolution of 1º of latitiude by 1º longitude. They were dowloaded from the NREL webpage and NASA webpage respectively ("NASA Surface meteorology and Solar Energy," n.d., "EnergyPlus," n.d.). Both data are satellite derived direct normal irradiance modelled data, they may have an error associated when compared to data measured directly on the surface. For example, comparison of hourly satellite derived irradiance with ground measurements in Saudi Arabia resulted in an hourly MSD error of 36% and annual MSD error of 8% (Geuder, et al., 2003).

The daily solar irradiance, which was measured in the desired area with higher irradiance, represents the daily means taken from 1994 to 2004. It was scaled to hourly irradiance using the Casa Blanca data. This was done to model an hourly electricity production and have insight in the hours in which there is no production of electricity.

The electricity production by unit area (kWh/m^2) was calculated using solar irradiance to electricity efficiency. Several sources were analysed cosidering also current installed CSP plants (IRENA; IEA-ETSAP, 2013; NREL, n.d.), they varies between 13.6% to 17% for CSP without fossil backup. The average of 15.5% of efficiency was used for this analysis. Though the higher efficiency found was for the Ivanpah CSP plant in USA with 28.75% (among the largest CSP plants), it was not considered for this analysis because it has fossil backup.

The area of the solar field used for the calculation was based on the Ivanpah CSP plant, which is among the largest CSP plants. It was defined two CSP towers covering a total land area of 28.4 km^2, meaning covering a 0.0003% of the Sahara desert, and a solar field area used for the calculation of 5.2 km^2.

From there, the hourly electricity production was calculated defining a maximun electricity delivered per hour or capacity. When the irradiance is higher than that capacity the resting energy would be stored for later use in the form of thermal energy with a round trip efficiency of 95% (Izquierdo, Montañs, et al., 2010).The capacity of the power plant was defined by a testing procedure for obtaining a steady electricity production or a large capacity factor while keeping the thermal storage bellow 16 hours of autonomy. Nowadays CSP thermal tanks have storage capacities until 16 hours without receiving solar energy (Izquierdo, et al, 2010).

3.1.2 Hydrogen production and delivery to the Netherlands

The hydrogen production rate by electrolysis of water was calculated with the electricity to hydrogen efficiency. This efficiency is usually calculated from the rate of hydrogen production per unit of electricity consumed. Current electolyzers have an electricity consumption between 4.2 to 7.4 kWh/Nm3 (Godula-Jopek, 2015). For this analysis the Norsk Hydro No 5040 alkaline electrolyser was used as reference for the calculation, with an electricity consumption of 4.8kWh/Nm3 or an efficiency calculated with HHV of 73% (Ivy, 2004).

Electricity consumption for liquefaction processes varies between 10 to 15 kWh per kg of hydrogen liquefied, with reported theroetical electricity consumption for large scale efficient electrolysers in study of 5kWh/kg (Godula-Jopek, 2015). For this study, the electricity consumption used was of 10kWh/kg and from there, using HHV, the LH_2 production capacity per hour in Morocco desert was calculated.

The closest port to the Tizart area is the Agadir port from which the LH_2 will be transported to Rotterdam port in the Netherlands, the transit time is estimated to 7 days ("Port to port distances," n.d.). During this time there will be a boil off lost, this boil off depends on the capacity of the tanks and form (Table 3), larger tanks with spherical forms have less boil off rate. Below there is a table of the boil off rate for LH_2 tanks acording to the storage tank size (FreedomCAR and Fuel Partnership, 2007).It is expected to transport hydrogen every 50000m^3 of hydrogen production, than the boiling rate would be defined to 0.06% of evaporation rate per day.

Table 3: Boil off rate of liquid hydrogen tanks (FreedomCAR and Fuel Partnership, 2007)

Tank Volume (m^3)	Evaporation rate per day
50	0.4%
100	0.2%
20000	<0.06%

3.1.3 Results and analysis

The solar irradiance used for modelling the hourly electricity production of a CSP has a median irradiance of 0.85 kWh/m^{2}h. When analysing the daily sum in Figure 6, the days with higher solar irradiance are found between the 80 to 182 days of the year which belong to the months of April to July, while the days with less irradiance are the last 25 days of the year with a minimun daily irradiance of 6.9kWh/m^{2}day.

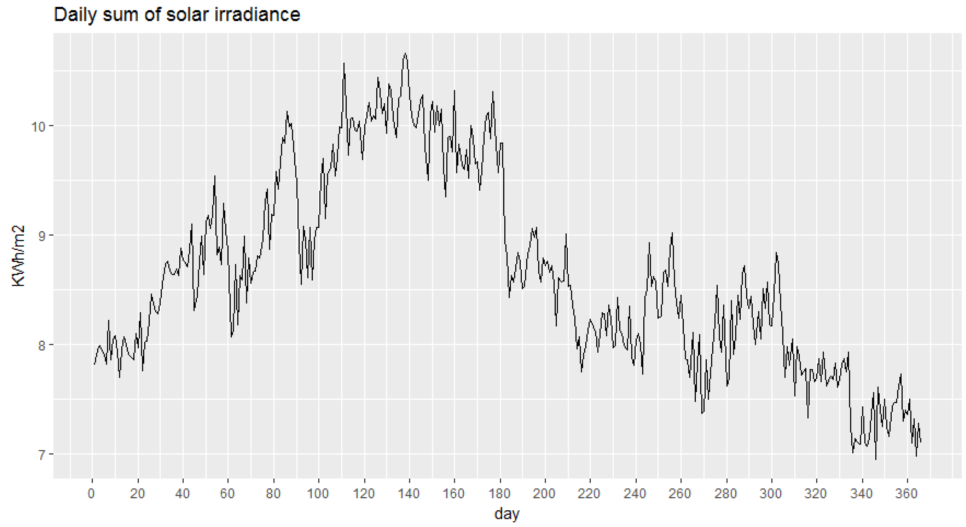

Figure 6: Daily DNI in Tizart area.

The area defined for the solar field, 5.2 km^2, is equal to two times the area of one of the largest CSP installed (Ivanpkha CSP). The electricity production would come from two CSP plants with an optimized capacity of 175MW each. Figure 7-a shows the hourly solar thermal energy received by the two towers considering the efficiency defined for the CSP plants and the area of the solar fields.

In a solar to hydrogen system, a CSP towers can be favored over parabolic through types. CSP towers can deliver a more constant power supply because the heliostats can collect the maximum possible solar energy by being oriented to the sun throughout the day. (Izquierdo et al., 2010). A CSP tower with thermal energy storage would also be important for maintaining the power supply during night hours, a common medium for storing high temperatures thermal energy is molten salt (NREL, n.d.).

Figure 7-b represents the hourly thermal energy storage in the molten salt tanks, the maximum hourly stored solar energy would be enough to deliver electricity for 15.9 hours without receiving solar energy, which is in the realistic range. According to the same study about the influence on electricity costs of different arranges of CSP, a good solar multiple for a storage tank capacity of 16 hours of autonomy that reduces costs would be around 4. It is defined as the thermal power collected in the solar field divided by the thermal input to the power block (Izquierdo, et al, 2010). The CSP subsystem suggested have the features shown in Table 4. Figure 7-c illustrates the hourly solar electricity production pattern throughout the year.

Table 4: Features of the solar to electricity subsystem.

CSP	2 CSP Towers with molten salt storage tanks
Capacity	175MW x 2
Solar field area	2.6 km^2 x 2
Total land area	14.2 km^2 x 2
Thermal storage capacity	16 hours
Solar Multiple	2.5 x 2
Lifespan	30 years

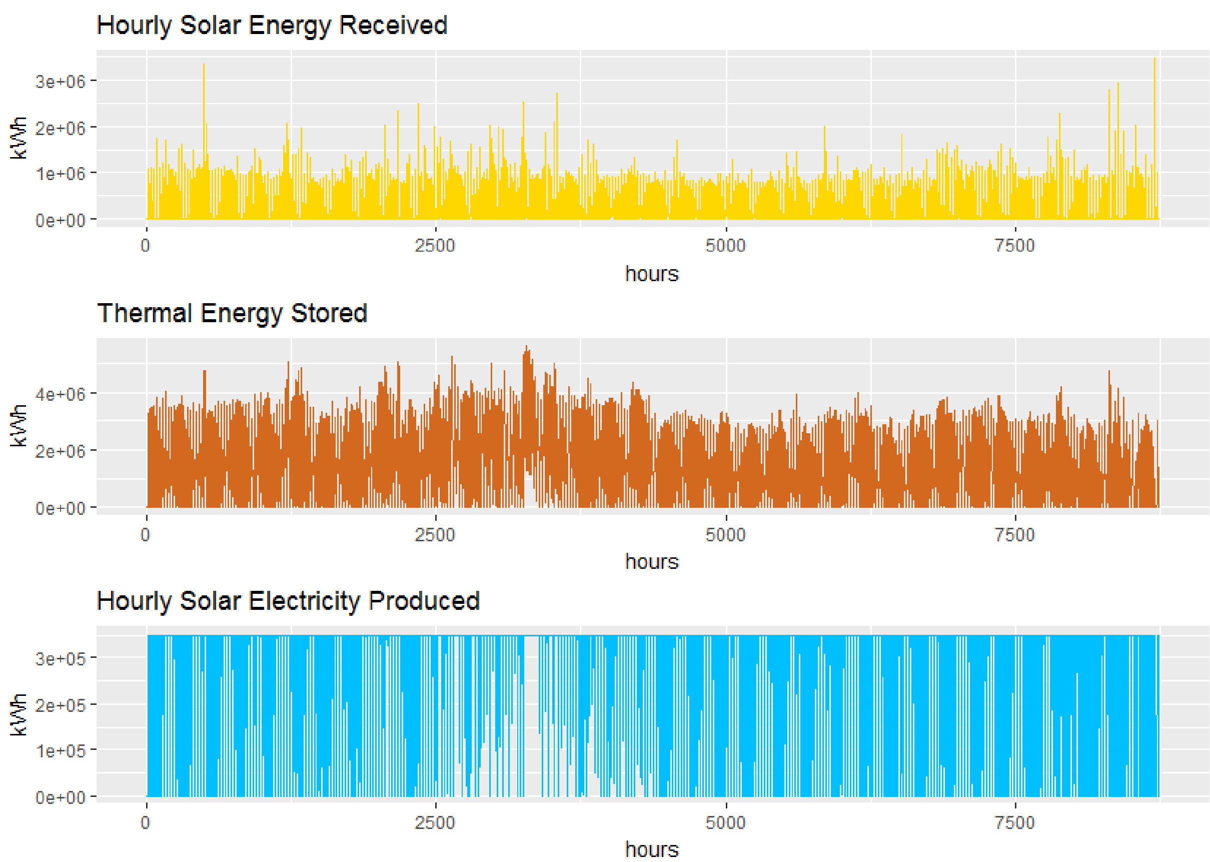

Figure 7: Morocco result, from top to bottom: a. Hourly thermal energy received; b. Hourly thermal energy stored; c. Hourly solar electricity produced.

The expected rate of daily liquid hydrogen production is illustrated in Figure 8, the highest rates of hydrogen production correlates to electricity production with a maximum production of 116 tons per day. The minimum hydrogen production during winter times is 41 tons, with a median production rate of 92 tons.

For this study it was defined a LH_2 boat capacity of 3540 tons or 50000m^3. Hydrogen would be transported in average every 37 days with 10 shipments to the Netherlands every year. Current LNG ships have capacities between 120000 to 140000 m^3, if these ships were to be used for this study, it would take around 88 days of LH_2 production for filling this boat, this would incur in on site storage capacities and larger hydrogen losses by boil off.

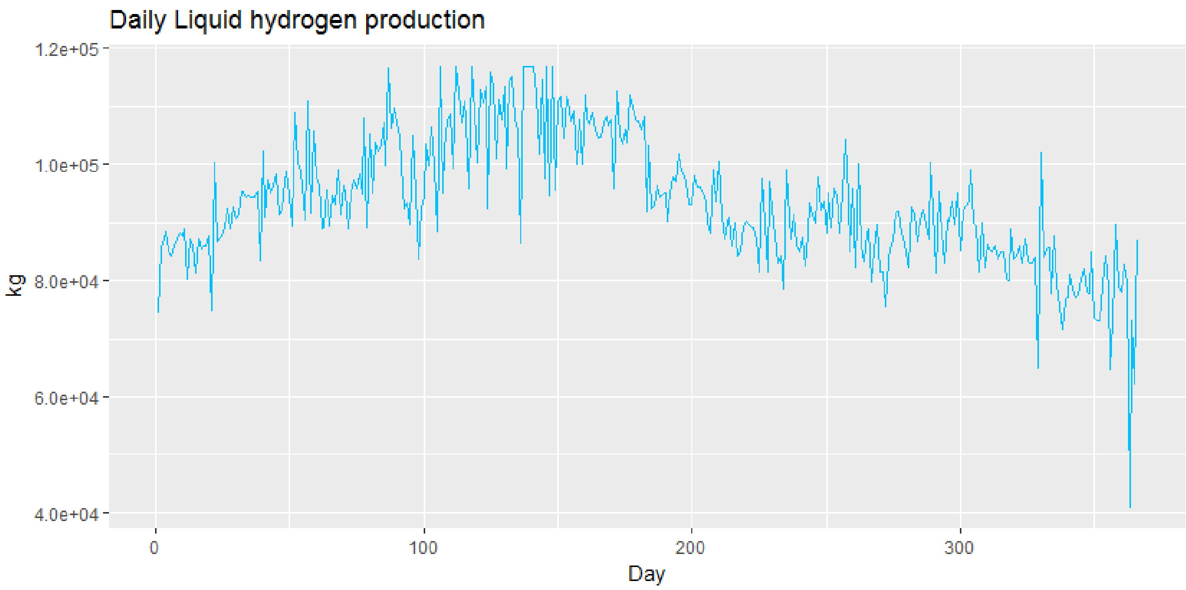

Figure 8: Liquid hydrogen production per day from solar thermal energy

Finally, Figure 9 shows the annual yield for each subsystem including the amount of hydrogen arriving to the Netherlands every year, we can see that there is no much losses of LH_2 during transportation by using information from Table 3 and not considering the energy used by the ship.

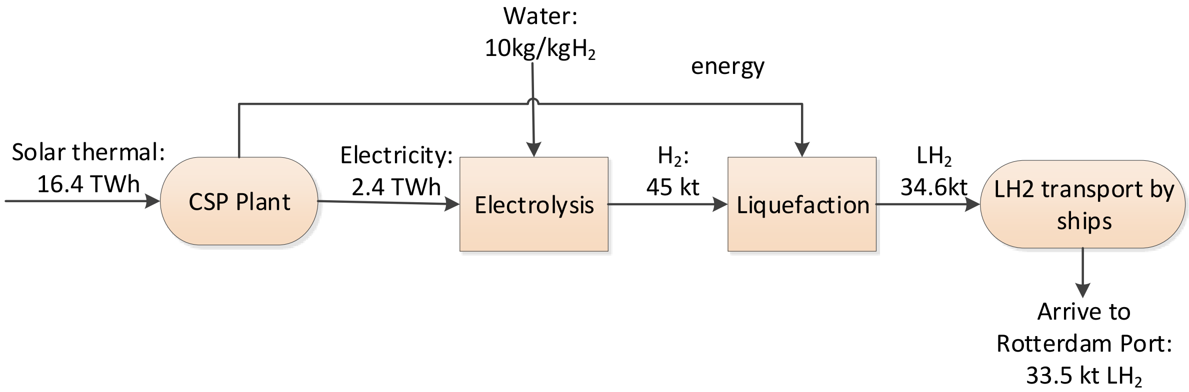

Figure 9: Annual yield for each subsystem of the solar to hydrogen system from Morocco.

3.2 Solar to hydrogen system in Australia

As explained in the introduction, a region in the world with very high DNI and with plenty of unpopulated land is Australia. The analysis of hydrogen production and the amount that arrives to the port of Rotterdam was made following the same methodology as explained for the Morocco site, with the same system applied, same script, and same efficiencies for calculating the electricity and hydrogen produced. The DNI data used is also coming from the same sources as from the Morocco data, but the data is available from the 1983 to 2005. The site chosen has -23° of latitude and 119° of longitude, located to the East of Karijini national park. The daily irradiance pattern is illustrated in Figure 10, the site used has a maximum irradiance of 11kWh/day, 1.4 times higher than the lowest irradiance.

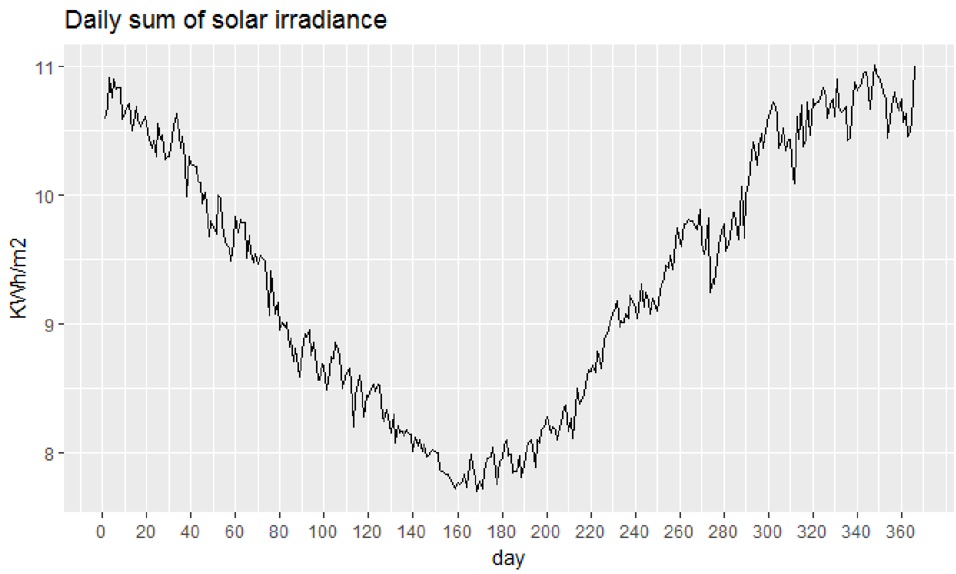

Figure 10: Daily DNI in area set for Australia

Figure 11-a shows the hourly solar energy received by the CSP subsystem considering its efficiency, if we compare it to the pattern in Morocco (Figure 7-a), Australia has a more steady hourly pattern, with less spikes, which it can be seen also for the hourly thermal energy in storage (Figure 11-b).

The optimum capacity was set to 350MW, as can be seen in Figure 11-c, with a larger capacity factor of 87.4% and a maximum stored energy sufficient for 15.4 hours of production at its capacity. As expected the electricity pattern differs largely from Morocco to Australia because of the change in seasonality by being in the South hemisphere. For obtaining a capacity factor larger than 90% which allows to have a steadier electricity supply to the electrolyzer, a power capacity of 300MW would make it possible but then the storage would be unrealistically high requiring a capacity of 264.3 hours of CSP autonomy.

The annual electricity production and consequently hydrogen production is higher than the Morocco scenario. Figure 12 shows this annual yield. Over the year there is 12.5% more electricity production than in Morocco. However, the transport distance from the Fremantle port, closed to the site chosen, to Rotterdam port is 17777.92 km and one month by cargo ship. ("Port to port distances," n.d.).

During the year 10.5 ships would arrive to the port of Rotterdam with the same capacity of 50000m^3 summing to 37.2kt of cryogenic hydrogen arriving to this port, meaning 11.1% more hydrogen production than from Morocco per year. Nevertheless, the travelled distance from Australia is 6 times larger. If it is assumed that the ship fuel consumption is directly dependent on the travelled distance, the efficiency of the shipping would be reduced in 5%. Therefore, the increment in hydrogen delivered would surpass the increment on fuel consumed during the shipping by 6%.

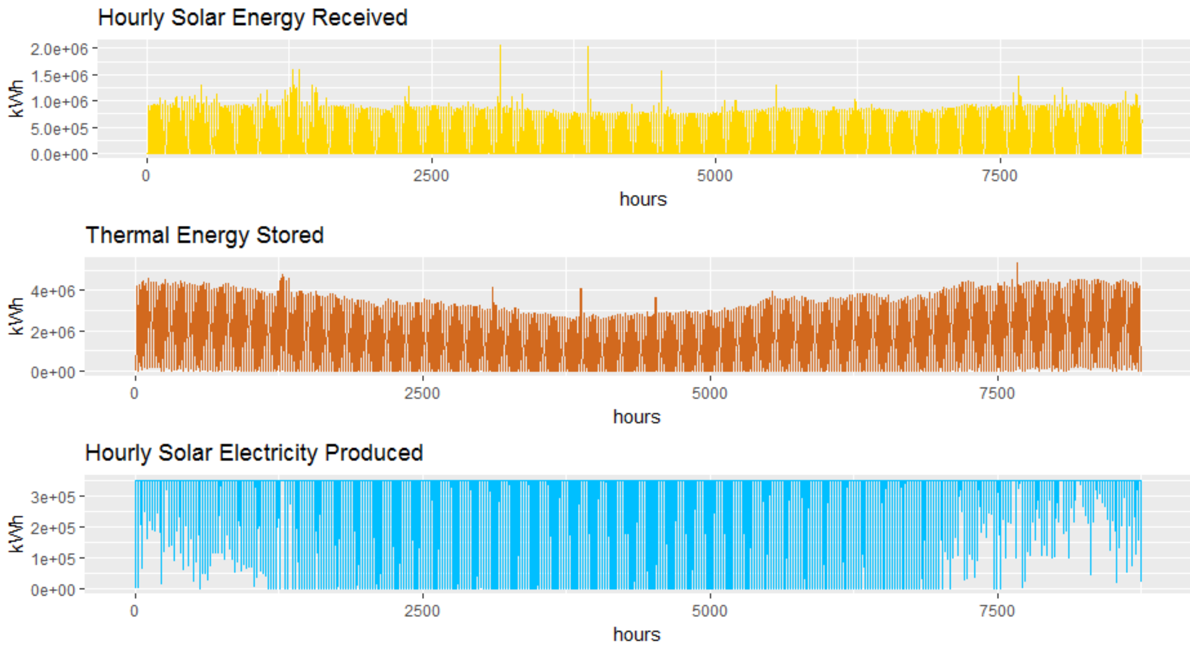

Figure 11: Australia result, from top to bottom: a. Hourly thermal energy received; b. Hourly thermal energy stored for later used; c. Hourly solar electricity produced.

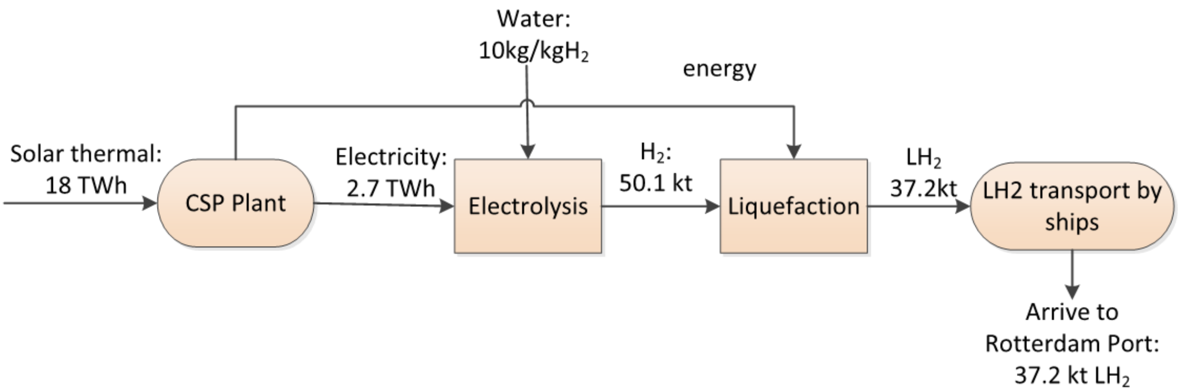

Figure 12: Annual yield for each subsystem of the solar to hydrogen system from Australia.

3.3 Wind to Hydrogen system

The electricity production from the 600MW Gemini wind park was based on a previous study (Schroeder, 2017). It was calculated by considering losses for transmission to the coast, conversion and degradation losses. This calculation was based on a capacity factor of 45% assumed for areas with very high and constant wind speed (Schroeder, 2017). Then, the wind park Gemini has a calculated electricity production of 2.1 TWh per year with a lifespan of 20 years (Schroeder, 2017). The electrolyzer has the same HHV efficiency of 73% and the compressor used has an electricity consumption of 8 kWh by kg of hydrogen compressed (Koj, et al., 2017). Below the annual hydrogen production, we can see that compared to liquefaction, there is less losses for pressurizing the hydrogen.

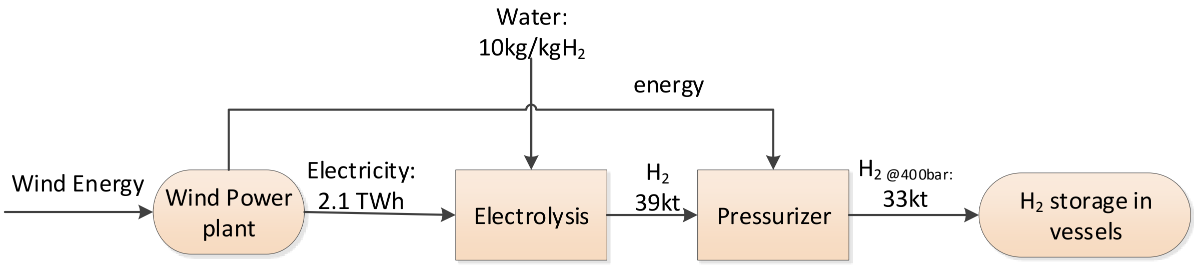

Figure 13: Annual yield for each subsystem of the wind to hydrogen system.

It is important to highlight that wind power plants have larger dependence on weather condition because they do not have any storage system. Consequently, the power supply will be more variable for the electrolysis causing changes in the energy efficiency of this process. Figure 14 retrieved from the already mentioned Energiepark Mainz project shows the dependence of the electrolysis efficiency on the power supplied, we can see it varies between 58% to 80% of efficiency for a difference in power of 4000kW (Kopp et al., 2017).

Using hourly data of Dutch North Sea wind electricity production from 2010 to 2014 for an installed capacity of 1000MW retrieved from NOAA webpage, a median capacity factor of 42% was calculated with a SD error of 2.5%. Translating this capacity factor to productivity, the annual electricity production in this area could varies between 1.8TWh to 2.1TWh.

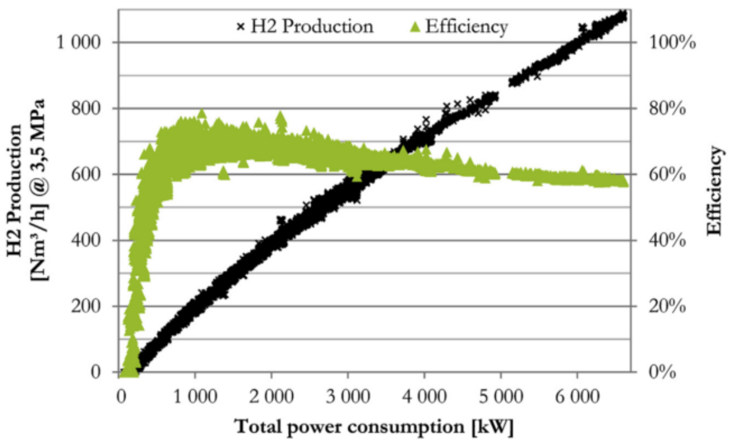

Figure 14: Hydrogen production and efficiency as a function of the total power supplied (Kopp et al., 2017).

4. ENVIRONMENTAL IMPACT: LIFE CYCLE ASSESSMENT

4.1 Methodology

There are many methods for assessing the environmental impact of projects within the energy sector with different degrees of quantification, LCA has a high degree of quantification because it assess the environmental impact used by a product's life considering the quantities of resources and materials used for obtaining a unit of this product (Finnveden et al., 2002). The ISO 14044 standard, applied to this study, has been created for detailing the requirements for conducting a LCA (ISO, 2006) then having more uniformity for been able to compare different LCA product analysis under the same category. It involves four phases illustrated in Figure 15, the scope explains the system boundary to be analyzed; within this first step it is also defined the functional unit of the study, it can vary for a same product. The second phase or inventory phase involves the collection of the data, the input/output of all the materials used in all the product's LC phases. The third step is the LC impact assessment; there are several methods for assessing it which focuses in different impact categories. The last step would be the analysis and interpretation of the LC inventory and/or impact assessment made (ISO, 2006).

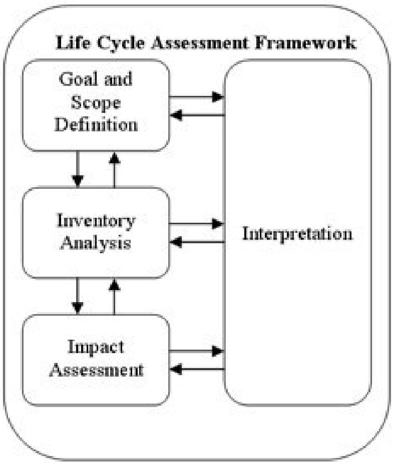

Figure 15: Life cycle assessment phases (ISO, 2006)

The LCA applied in this study was performed by making use of Simapro software. The aim of this LCA is to make a comparison of the environmental impact of the two systems defined for this study. The analysis was made for each system separately with the aim of investigating the processes and materials that cause the larger impacts for each system.

The functional unit defined is 1kg of H_2 produced, for the S2H system would be 1kg of hydrogen that arrives to the Netherlands, while for the wind to hydrogen system there is no transport of hydrogen after is produced and stored. The scope defined for both system is cradle to grave than including the construction of materials for building the installation of each subsystem, the materials used during operational phase and the resources used for disposing and treating the waste at the end of life of each subsystem.

The LCA approached applied was attributional, it describes the pollution and resource flows within the systems attributed to the delivery of the functional unit defined (Rebitzer et al., 2004). The inventory was performed by literature review of previous LCAs made for each subsystem. All the subsystems' inventories, excluding the Gemini wind park, are based on smaller versions with less capacity of productivity than the required for this study. Then, the quantities for the materials used were linearly scaled up according to the productivity needed for these conceptual systems. Details on the references used, the multipliers for scaling up the materials and the inventory tables are shown in appendices section.

In Simapro, each process or material is provided in two versions, unit and system; the unit version was used because it allows to trace the contribution of all individual processes involved in each of the materials selected in the inventory (Goedkoop, el at., 2016). The output for each subsystem was the amount of product needed from that subsystem to deliver the functional unit of 1kg of hydrogen. I mean, that for the material used in the CSP subsystem, the output was 72.15 kWh which is the needed electricity for obtaining 1kg of hydrogen in the port of Rotterdam. Figure 16 and Figure 17 illustrates the output needed in each subsystem for producing the functional unit.

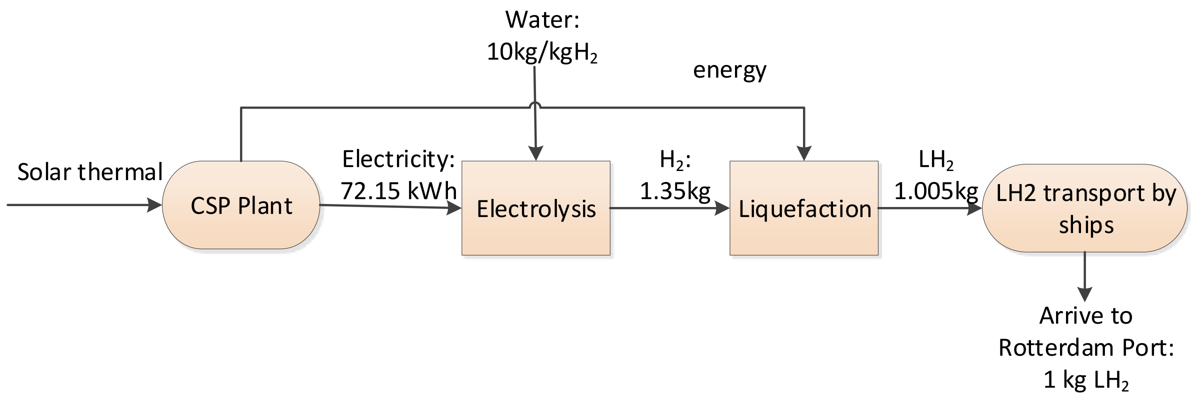

Figure 16: Energy required for each subsystem for producin 1kg of hydrogen from solar energy

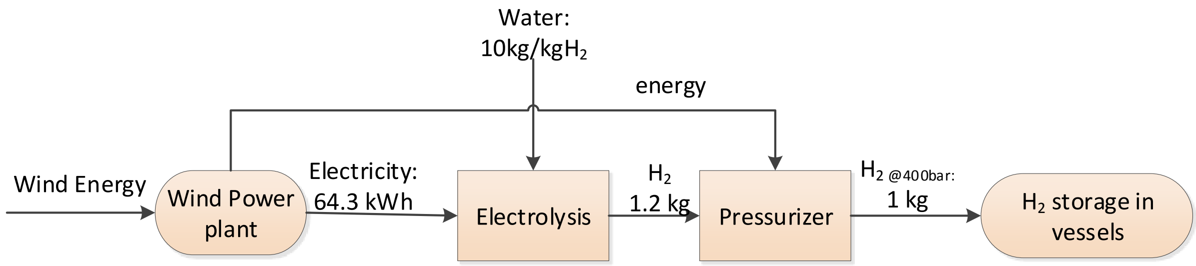

Figure 17: Energy required for each subsystem for producin 1kg of hydrogen from wind energy

The lifespan for both system studied was set to 30 years which is the lifespan of nowadays CSP plants (Whitaker, et al., 2013). Nevertheless, wind power plants and electrolyzers have a lifespan of 20 years while the liquefier and compressor used have a lifespan of 15 years; for theses subsystems a multiplier of 1.5 and 2 respectively was applied to their inventory. With respect to the disposal phase, a list with rates of recycling and their references is found in appendices section, the materials not included in that list were processed according to the Netherlands scenario for waste treatment.

The method applied for the environmental impact was the EDIP 2003 within Simapro, it calculates the global warming category with a time horizon of 100 years as defined by the IPCC 2007 (Pré, 2016). The different categories studied are listed below.

- Global warming
- Ozone depletion
- Acidification
- Terrestrial eutrophication
- Aquatic eutrophication N-eq and P-eq
- Ozone formation
- Human toxicity
- Ecotoxicity water and soils

- Resource depletion

4.2 Results and Analysis

4.2.1 Solar to hydrogen system in Morocco

Figure 18 shows the single score result of this system excluding the grave phase, easy to notice that the construction phase of the CSP subsystem is the main responsible of the overall system's environmental impact with aquatic eutrophication by phosphorus the main category impacted followed by human toxicity by water contamination. The steel is the material with larger contribution to the EI with 91% and 89.4% respectively for both categories. The solar energy collecting subsystem is the one that contributes most to the EI. This is due to the large quantity of heliostats (173500 x2) required for such a large solar field ("CSP Projects - NREL," n.d.).

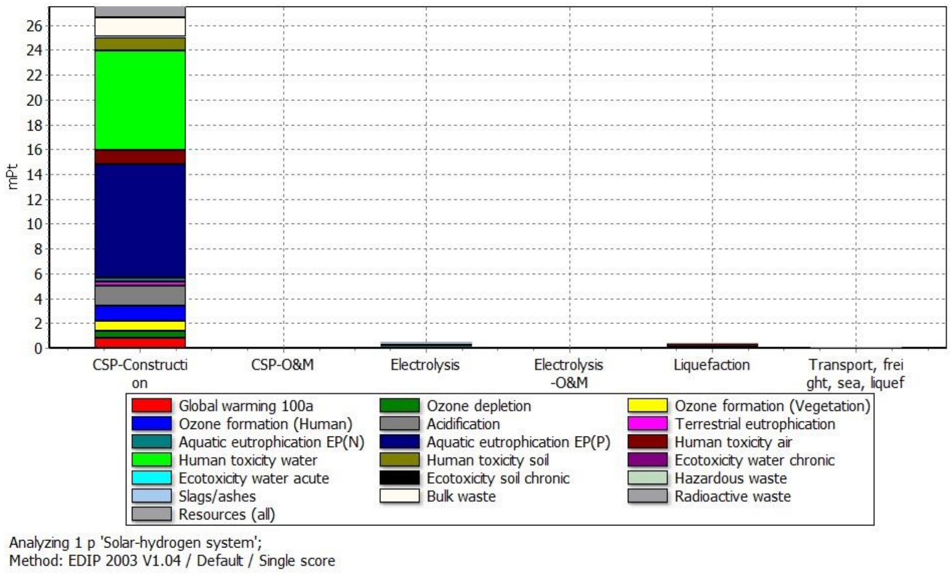

Figure 18: EI single score analysis of the solar to hydrogen system

In Figure 19 we can see that when including the grave phase, human toxicity by water contamination passes to be the largest impacted category by this system with 35% of the impact caused by the grave phase; while for aquatic eutrophication by phosphorus a 24% of the impact made during the life of this system can be reduced by the grave phase. In overall, the disposal phase has a negative impact reducing the total EI of the S2H system. The values of each of the impact categories are shown in appendices.

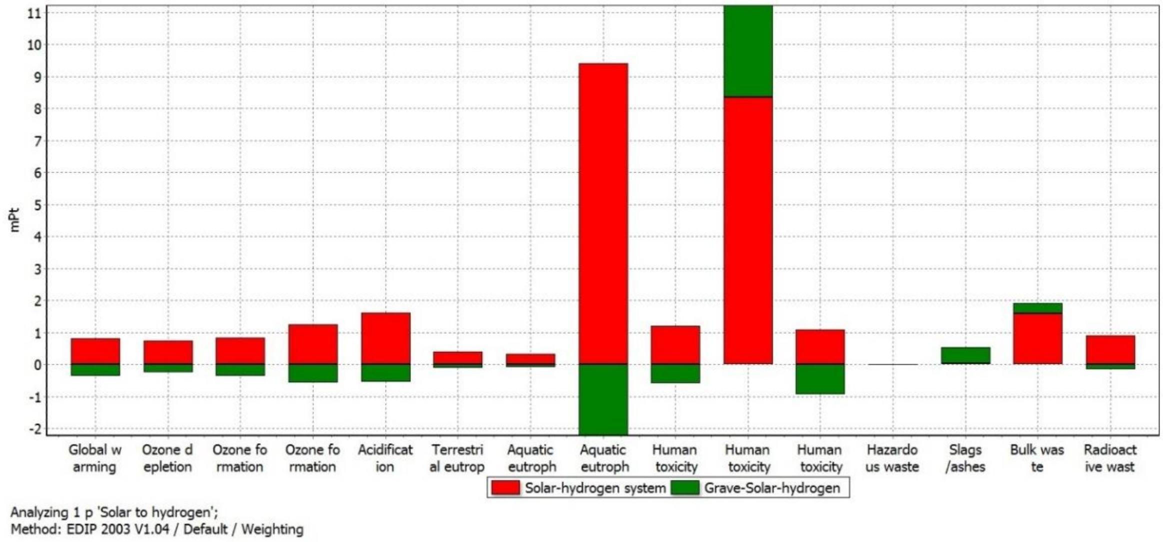

Figure 19: EI weighting analysis of the solar to hydrogen system from cradle to grave.

4.2.2 Wind to hydrogen system

In Figure 20 we can see that also for this system the electricity production process is the main contributor of the environmental impact with human toxicity by water contamination and water eutrophication by phosphorus the main categories impacted. The windmills nacelles are the components that contribute most to the environmental impact with cooper the material that contributes most with 81.1% for human toxicity and 77.9% for the aquatic eutrophication.

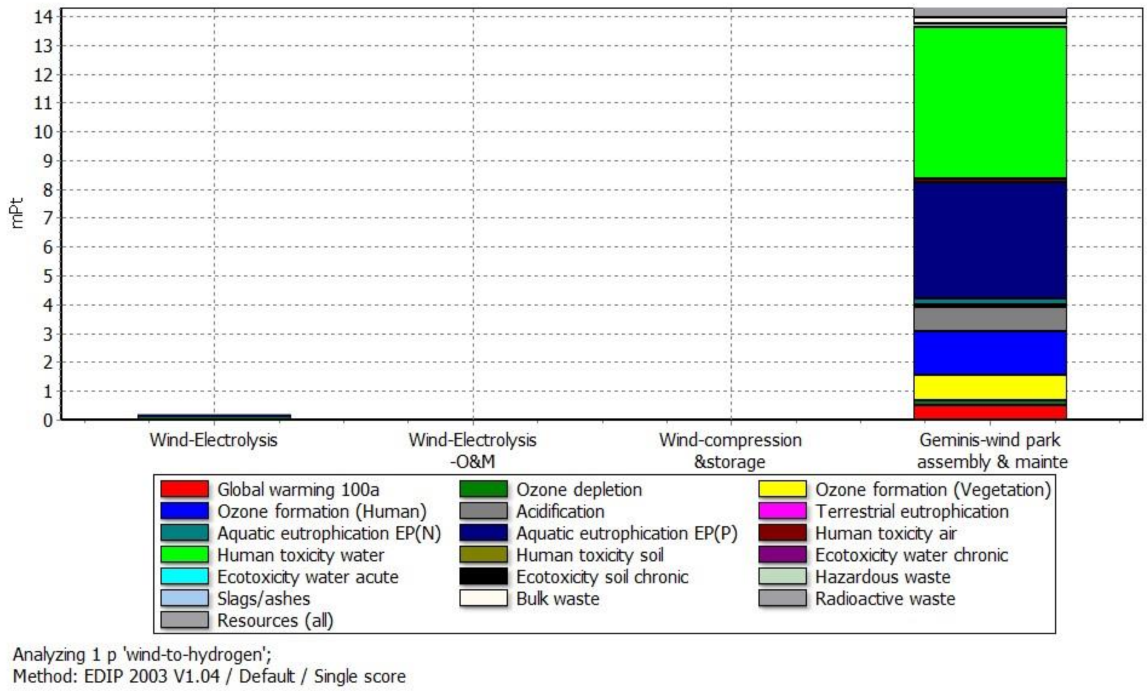

Figure 20: EI single score analysis of the wind to hydrogen system

Figure 21 shows the weighting results from cradle to grave. In overall the total impact of the grave phase is positive meaning that with the scenario used for waste treatment (explained in appendix) the disposals phase increases the total system EI, human toxicity by water contamination is the largest impacted category by the disposal phase.

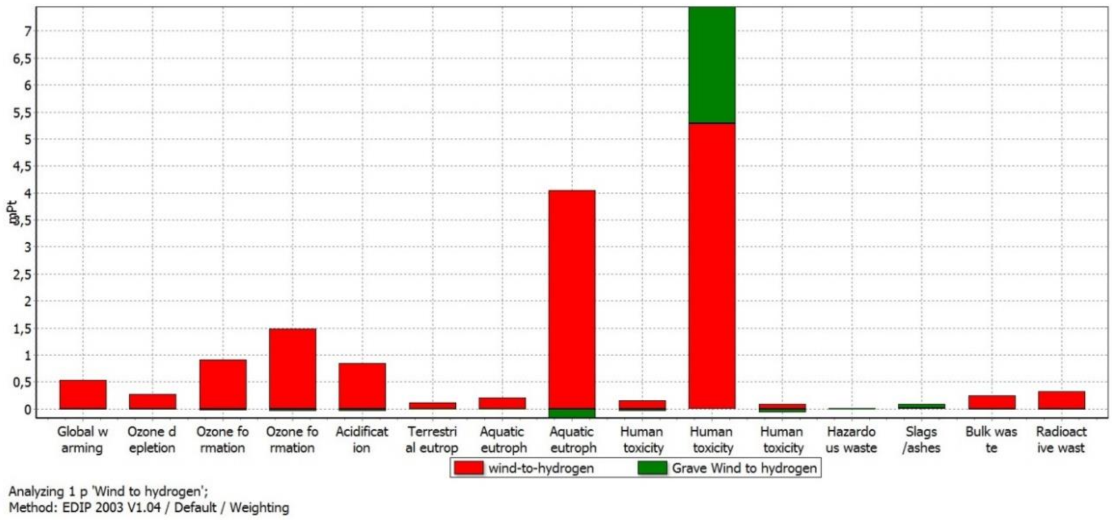

Figure 21: EI weighting analysis of the wind to hydrogen system from cradle to grave.

4.2.3 LCA systems comparison

According to the ISO standards for LCA, it is not recommended to compare products applying the weighting step. Because of this, the comparison must be made for each of the impact categories until the characterization result (as shown in Figure 23). There are 13 categories in which the solar to hydrogen system has a larger impact, from 13% more for aquatic eutrophication (P) to 88% more impact for bulk waste; while the categories in which the wind to hydrogen system has a larger impact are six with differences from 9.5% more for global warming potential to 35% more for hazardous waste. Table 16 in appendices section show the values obtained for each impact categories for both systems.

The main aim of developing such a complex system would be for maintaining the security of supply in the energy sector and reducing the greenhouse gas emissions. Therefore, an important impact category to compare between these systems and other energy related systems would be global warming potential. Results from LCA global warming potential in this sector are generally given by unit of electricity produced, whereby a conversion of hydrogen to electricity would be needed. According to the IEA fuel cells road map report, fuel cells have HHV efficiency from 32% to 70% for producing electricity. Then, the GWP for producing electricity from the solar to hydrogen system would be 118gCO_2 eq/kWh and from the wind to hydrogen system would be 130gCO_2 eq/kWh for a 70% HHV efficiency. Using the 32% HHV efficiency, the emissions would be 258 gCO_2 eq/kWh for the solar to hydrogen system and 285 gCO_2 eq/kWh for the wind to hydrogen system.

Figure 22 shows the median, maximum and minimum CO_2 life cycle emissions equivalent of different electricity sources retrieved from the IPCC 2014 report, and the emissions calculated for the two studied systems with its average. The first sources shown until coal are flexible sources that can be seasonally stored or used when is needed and then comparable to electricity from hydrogen fuel cells. We can see that the two hydrogen systems have lower CO_2 emissions then the current commercial available fossil sources, omitting nuclear energy which has a very low CO_2 emission. Nuclear energy seems to be so far the best option for mitigating climate change in this graph; nevertheless, its well-known drawbacks of public acceptance and high risks of catastrophic accidents make necessary the development of alternative flexible electricity sources. With respect to biomass, a source that can be used when needed, the two hydrogen systems studied have less CO_2 emissions.

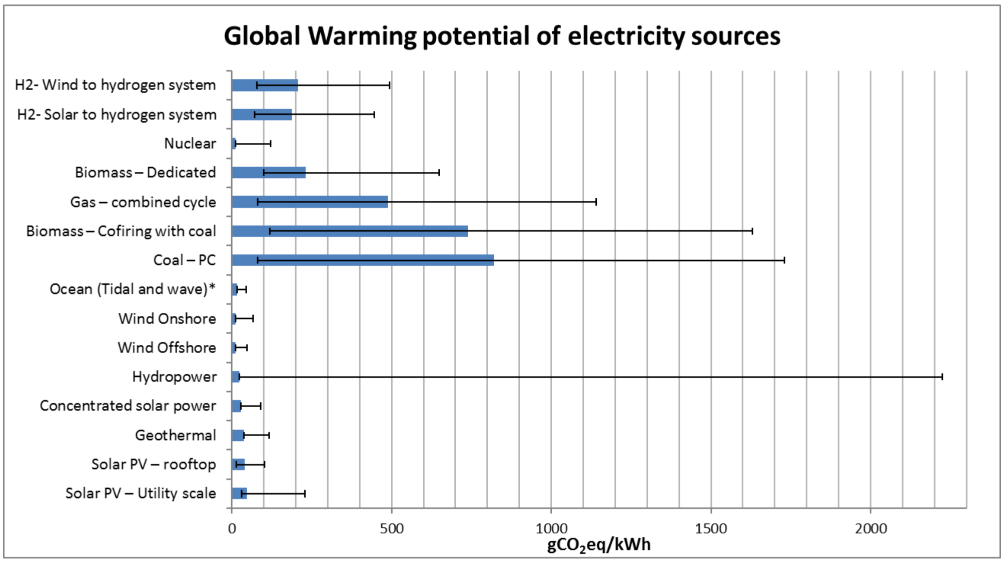

Figure 22: GWP of varied electricity sources including the results in this study (Bruckner et al., 2014).

4.2.3.1 Water consumption

Water footprint was not studied in this environmental impact; however, it could be potentially high for both systems given the large consumption of water during electrolysis. The study used for doing the inventory of the electrolysis subsystem indicated a water usage of 10 kg of water by kg of hydrogen produced (Koj, et al., 2017) and the CSP subsystem for the S2H system has an annual water consumption of 127934 m^3 for the heliostats cleaning and the steam cycle part (Whitaker et al., 2013), while for the maintenance of the wind park subsystem does not require direct use of water. Using this information, the water consumption of the solar to hydrogen system is larger with 17.3kg of water per kg of hydrogen delivered to the Netherlands, while the wind to hydrogen system would consume 11.81 kg of water per kg of hydrogen delivered.

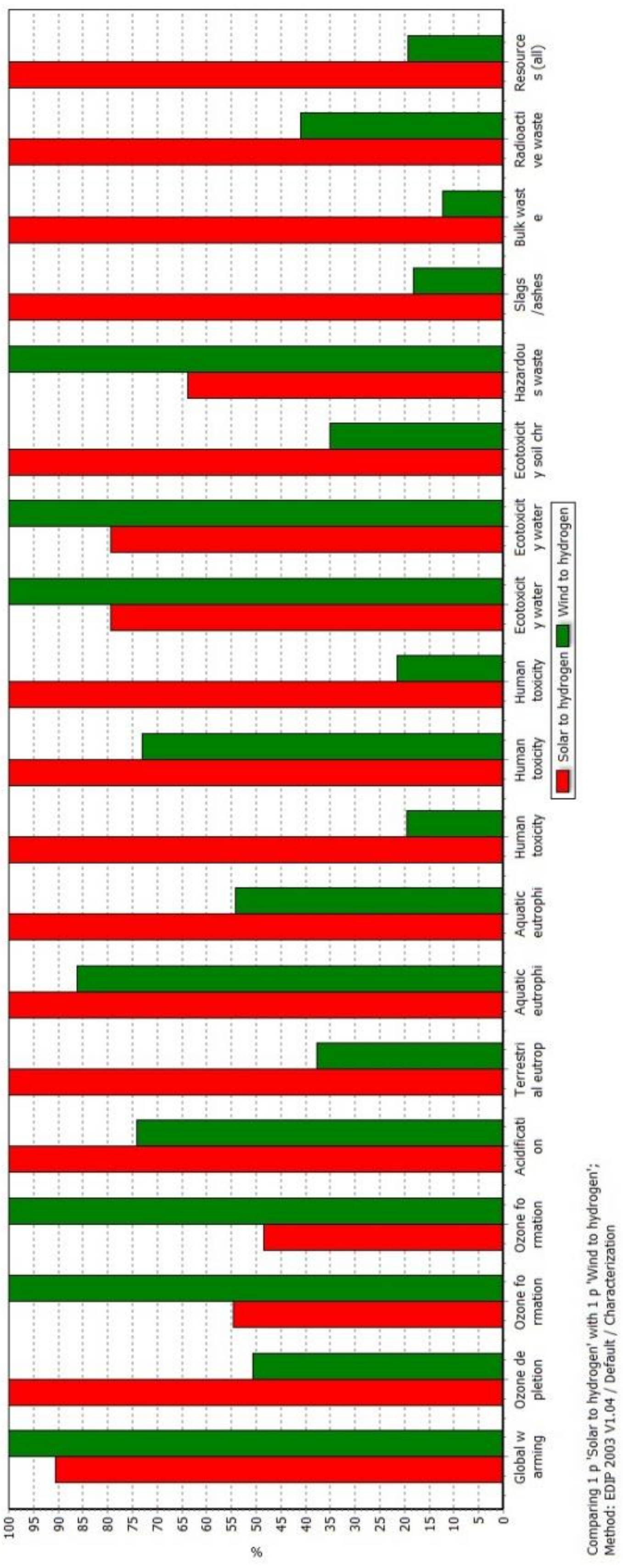

Figure 23: Systems comparison of the environmental impact from cradle to grave

5. ENERGY RETURN ON ENERGY INVESTED

5.1 Methodology

Energy return on energy invested has been a useful tool for comparing different energy sources, a straightforward indicator for analyzing the relevance of developing forward a certain alternative energy source. The larger the EROI the better this technology is from an energy perspective. Nevertheless, there are different approaches used for calculating it and a lack of standardization in the methodologies applied, which make it difficult to compare with other studies (Murphy, Hall, Dale, & Cleveland, 2011). There are four types of EROI studies according to the boundaries used for performing the study, mainly for calculating the energy invested. Standard EROI considers the direct and indirect energy used to generate that output, applied to fuels would be at the point until is extracted or produced and does not include the energy associated to labor and financial services. Point of use EROI includes everything defined for the standard EROI but the boundary of the analysis is expanded to the energy cost for getting the fuel to the place where it will be consumed; other types are extended and societal EROI (Hall, Lambert, & Balogh, 2014).

According to the boundaries set for both hydrogen systems in study, the EROI performed was a point of use EROI and then a comparison with others fuels EROI studies would have to consider that an extra energy cost for transportation or storage of the hydrogen is embedded in the result of this study. Also, as for the standard and the point of use EROIs, the disposal phase is excluded for the cumulative energy demand analysis.

The energy demand used for calculating the EROI was performed by making use of Simapro software. The method applied was the cumulative energy demand by Ecoinvent. It aims at searching the energy use thought the life cycle of the product in study including the direct and indirect energy consumption (Pré, 2016). The cumulative energy demand is given in terms of five impact categories which are different types of energy sources.

Regarding the inventory, in the solar to hydrogen system is included the energy consumed for the assembly of the CSP as for the maintenance of the heliostats and general maintenance; the energy consumption for the construction of the liquefaction subsystem was assumed to be the same as the construction of the electrolyzer, while the energy used for the transport is given from Simapro. The energy used for the electrolyzer construction and maintenance is the same for both systems. With respect to the wind electricity subsystem, fuels used during construction phase of the separate components were included, and for the compression and storage subsystem energy for assembling their components was also included in the inventory.

5.2 Results and analysis

Figure 24 shows the percentages of cumulative energy demand by subsystem as a fraction of the overall energy demanded for producing hydrogen from solar energy. We can see that the most demanding process is the construction of the CSP plant followed by the energy demand during the operational phase of the CSP plant with an important 11% added for the transport of hydrogen from Morocco to the port of Rotterdam.

Figure 25 shows the subsystems that consume more energy for the wind to hydrogen system; we can see that most of the energy demanded is related to the wind park assembly and maintenance with 95.9% of the total energy demanded. Diesel accounted for the maintenance of the Gemini wind park is the major contributor to the energy demand.

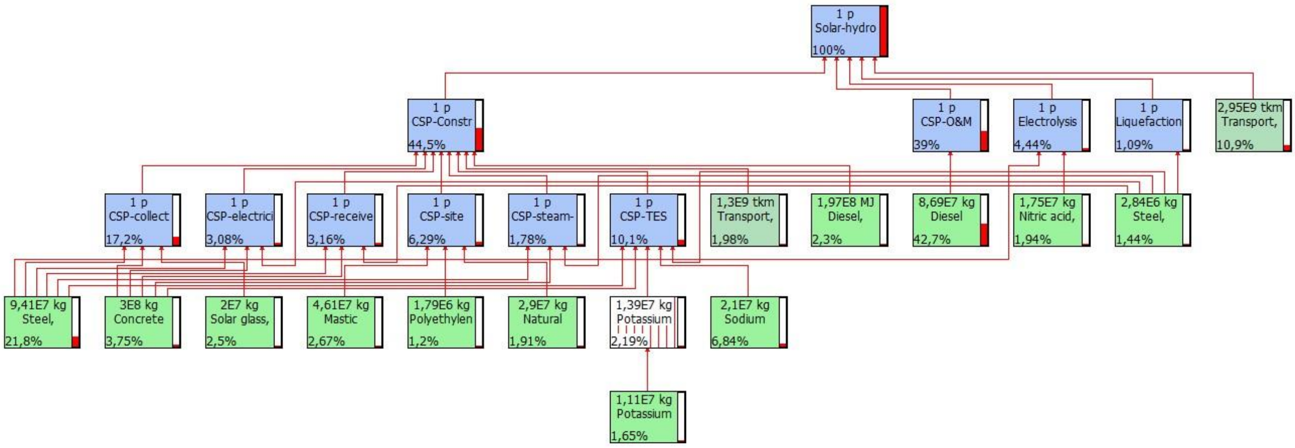

Figure 24: Cumulative energy demand proportions for the solar to hydrogen system.

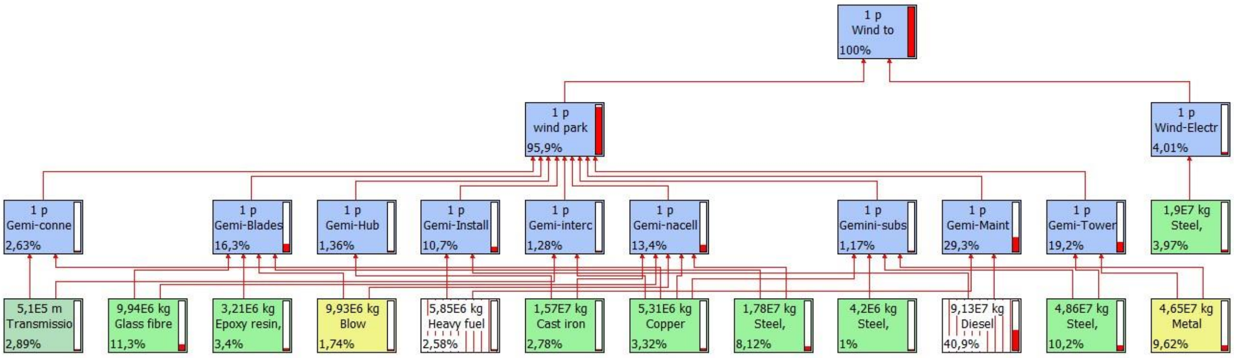

Figure 25: Cumulative energy demand proportions for the wind to hydrogen system

In Figure 26 is observed that for the five different energy sources considered, the wind to hydrogen system consumes more energy, particularly renewable energy sources in which 498TJ more VRE sources is consumed by this system compared to the solar to hydrogen system. This is because the materials from the W2H system are accounted to come from Europe, with larger share of renewable energy, while for the S2H system the materials are accounted to come from the rest of the world given that Morocco is not available in the database. The classification of energy demand by source is based on the available Simapro databases of the energy demand for producing raw materials. Therefore, it largely depends on the energy mix of the country where the raw materials are produced.

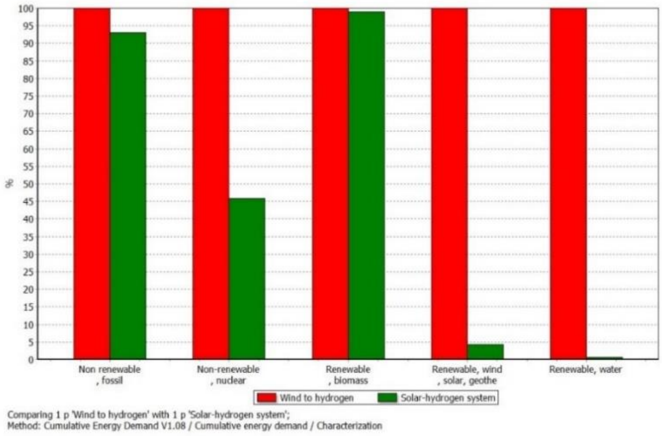

Figure 26: Comparison of cumulative energy demand by energy source.

Summing up the cumulative energy demand of all the energy sources, the wind to hydrogen system has a CED of 12.6PJ, almost 10% more energy demand than the 11.4PJ consumed by the solar to hydrogen system as shown in Figure 27. In the cumulative energy demand result is not included the energy efficiency of both systems, this would be embedded in the EROI's result.

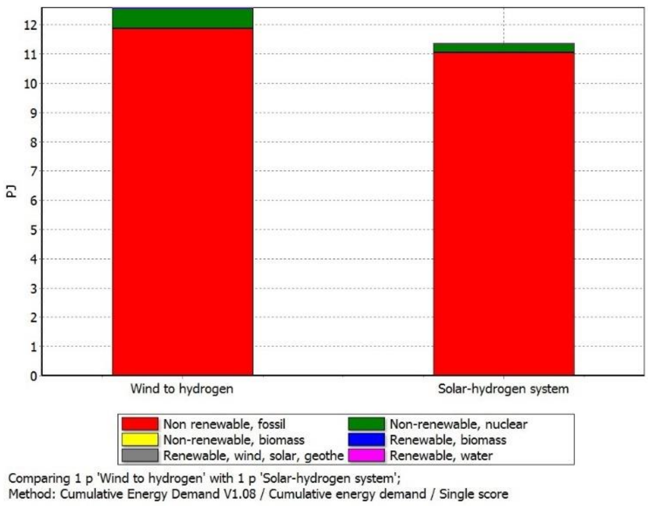

Figure 27: Cumulative energy demand single score result for both systems.

The total energy return during the 30 years lifespan of the solar to hydrogen system is 145.7 PJ and for the wind to hydrogen system is 140.4 PJ. Then, the energy return on energy invested is 12.8 for the S2H system and 11.1 for the W2H system. If we compare these two systems EROI with the EROI from fuels shown in Figure 28 we can tell that the two systems under study attain larger EROI than the unconventional hydrocarbon production tar sands (mean of 5) and oil shales (mean of 1.4) (Hall, et al., 2014). This implies that the hydrogen system as it was studied has a higher EROI, better result, without having the hassles of depleting fossil reserves and emitting larger quantities of CO_2 to the atmosphere. Nevertheless, it should be noted that these are conceptual systems for which it was assumed linear scalation of each of the subsystems (excluding the wind park) for calculating the materials needed. The sources of the inventory for each of the subsystem, excluding the Geminis wind park, were based on smaller versions with less productivity capacity and then the values were linearly scaled up according to the productivity needed for this study. Also, the energy production for both system is based on modeled data with uncertainties already explained in the electricity and hydrogen production section.

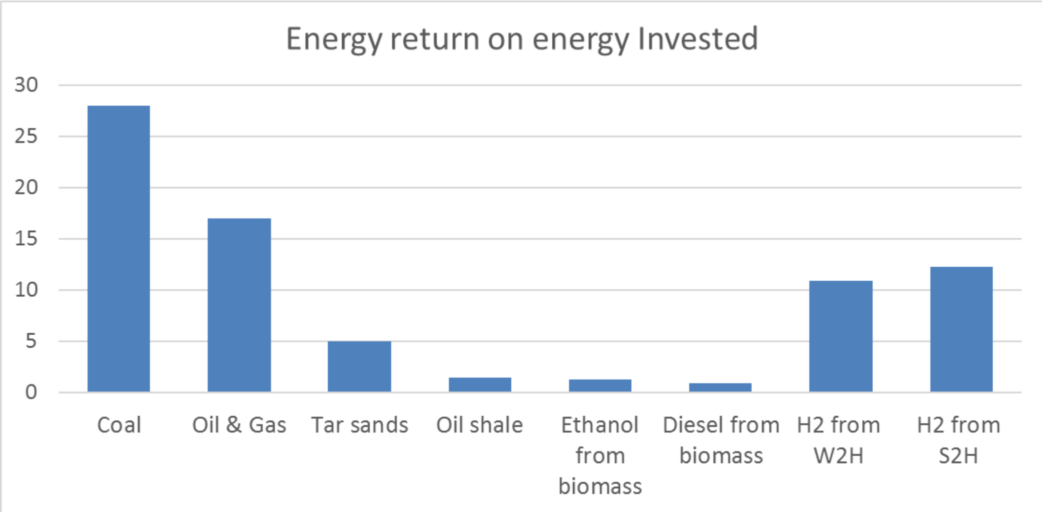

Figure 28: Mean EROI with standard deviation bars for thermal fuels (Hall et al., 2014)

6. SENSITIVITY ANALYSIS

A sensitivity analysis was performed on the satellite modelled data. In this case, a satellite derived data (HelioClim-3) extracted from the SODA-pro webpage for the year 2005 was used. The analysis was performed for the S2H system in Morocco for the same location (Latitude 29.6, Longitude -8.7), however it is not available for the area of Australia. Then, it can be analyzed the sensitivity of the irradiance modelled data on hydrogen production and consequent EROI for the S2H system in Morocco and how does it compare to the W2H system.

Figure 29 shows the daily sum pattern of this data, we can see that day by day the pattern looks different from the original data used (Figure 6). However, the annual sum of solar irradiance is only 2% less than the previous result for Morocco. These differences could be associated to differences in the radiative models and atmospheric correction applied. In addition, the data used is the mean between 10 years while the compared soda data is representative only for the year 2005.

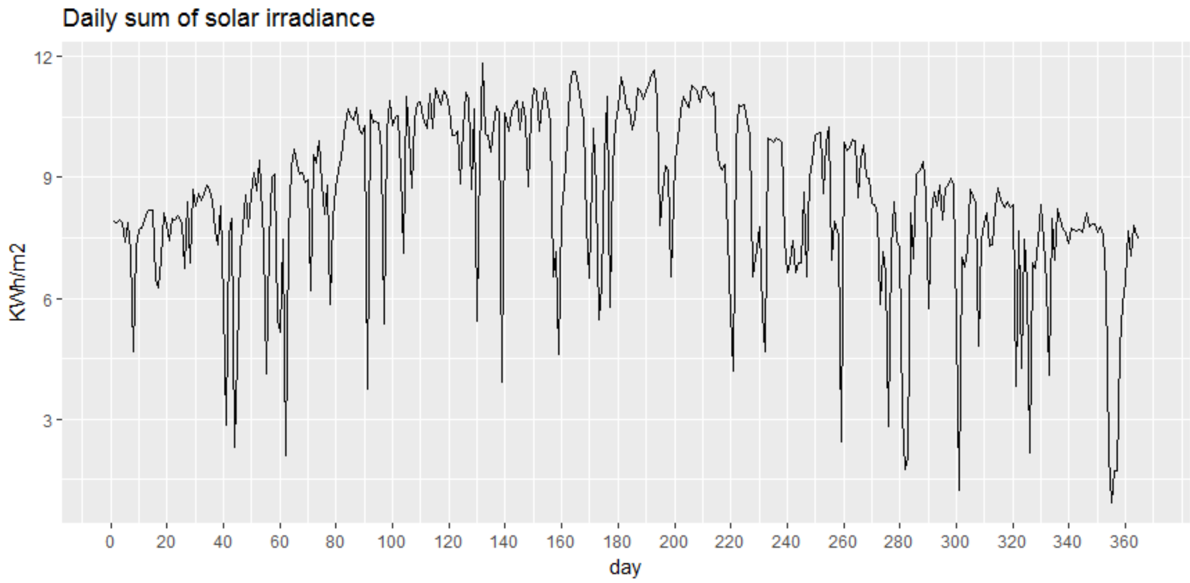

Figure 29 Morocco's daily sum of DNI for the sensitivity analysis.

The CSP receives 16.4TWh of solar energy annually, enabling to produce 2.4 TWh of electricity with a capacity factor of 78.5%. The capacity of the CSP stayed the same 350MW for a better comparison. This optimal capacity would lead to a thermal storage of 15.9 hours of autonomy.

As for the initial data, 33.5kt of LH_2 per year to the Netherlands would be delivered. This would result in a similar EROI of 12.5. The time in filling each ship would be in average 37.3 days, a few hours of difference compared to the original data.

In the end, both satellite derived data have similar annual production but different patterns of hourly production rates which creates differences on the calculated capacity factors. When compared the patterns of Figure 30-b and c from the original patterns in Figure 7 we can see that this pattern of electricity production looks more as expected with less times of no electricity production during half of the year.

Figure 30 Sensitivity analysis of Morocco electricity production. From top to bottom: a. Hourly thermal energy received; b. Hourly thermal energy stored; c. Hourly solar electricity produced

7. HYDROGEN ENERGY DEMAND SCENARIOS FOR THE NETHERLANDS

Currently, in the Netherlands there is a large interest on hydrogen technologies, there is a coalition "DutchHy" formed by industry, research agencies and local governments with the aim of promoting research demonstration and political inclusion in the agenda of hydrogen projects, according to their report 69 actors are active in hydrogen and fuel cells areas(Denys & Barten, 2016) including the so called "Power to gas" studies. Nevertheless, when analyzing the National Energy outlook (NEV) for the energy sector until 2030 based on current and intended policies (Schoots & Hammingh, 2015), hydrogen seems to play a non to incidental roll in the energy mix of 2030 in the Netherlands. Despite this, because of its completeness, it was the baseline for analyzing possible hydrogen demand in the future. The scenario used was the outlook based on "existing polices" including current official measures and international binding policies as the Emission Trading System agreed in The Kyoto Protocol, then providing a starting point for building a more sustainable with less fossil fuel energy sources scenario for the Netherlands that gives a more relevant roll to hydrogen.

A Sankey diagram was made with the values of final energy consumption (Figure 31) for visualizing the expected energy consumption by sector and its energy sources given by the ECN outlook 2015. Thus, the values of heat, electricity and motor fuels sectors are given as secondary energy that fulfills the energy demand of each consuming sector. From there, hydrogen was introduced in consuming sectors in which it is expected that hydrogen will replace other sources; it was assumed that differences in efficiencies, for example from petrol combustion to fuel cells, are irrelevant for this analysis, then enabling to have an insight in the magnitudes of future hydrogen demand.

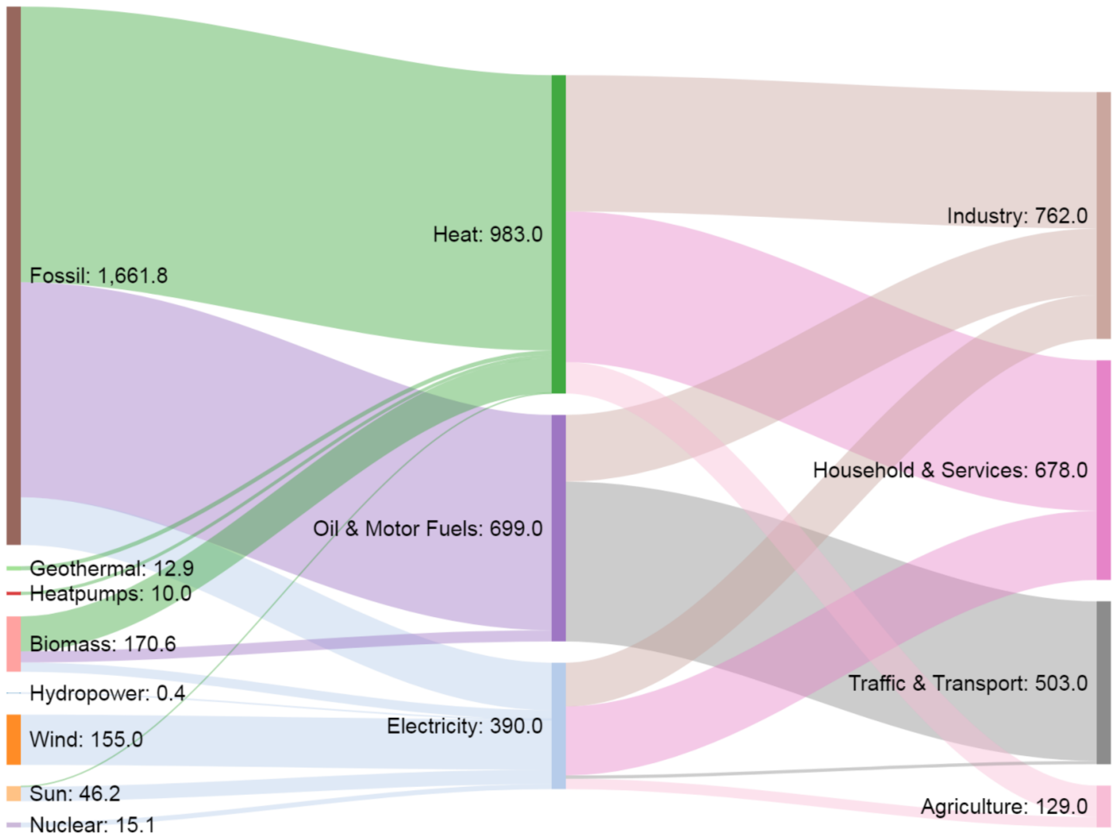

Figure 31: Primary Energy consumption by sector, numbers are given in peta joules (PJ) (PBL Outlook, 2015).

Future hydrogen demand will depend in several variables that are difficult to measures, such as further development of hydrogen related technologies, market driving forces, price, development of competing technologies, policies, willingness and public acceptance. Therefore, giving one number for future hydrogen consumption would be a bold statement. In this sense, for estimating the possible hydrogen consumption in 2030 two extreme scenarios were made (low and high estimation).

7.1 Low boundary of hydrogen deployment scenario in the energy mix:

It was intended to use the PBL outlook of existing policies for the low hydrogen use scenario. Though, as explained before, it does not directly consider hydrogen as part of the energy mix in 2030. It is mentioned that pilots and market introduction studies on hydrogen implementation for the transport sector are included in stablished and intended policies (Ministry of Infrastructure and the Environment, 2014).

Hydrogen also represented a 3% of the total investments made from 2004 to 2013 in the field of energy innovation, while the largest shares went to renewable energies and energy efficiency techs. There is the action plan for the introduction of fuel cell vehicles to the market between 2020 and 2030. According to the same source, buses are one of the first markets for hydrogen implementation; adding to this, The Netherlands has its own bus manufacturing industry (Ministry of Infrastructure and the Environment, 2014).

Based on the prior information, hydrogen implementation for the bus transport sector would be the only field in which hydrogen plays a role in the energy mix of 2030 for the low boundary scenario. In 2014, 1% of travel time in the Netherlands was made by bus(Statistics Netherlands, 2016). Assuming this is proportional to the energy consumption and the same share of buses is kept until 2030, the total hydrogen demand would be of 5PJ for this scenario.

7.2 High boundary of hydrogen deployment scenario:

For estimating the high hydrogen deployment scenario in 2030 each of the sectors in which hydrogen could play a role were analyzed. A very high deployment would be unrealistic given the current state of maturity of hydrogen related technologies and, in several literatures is mentioned that if hydrogen will play a large role in the energy mix would be around or after 2050. Then, for the transport sector, in which it is expected that hydrogen will play an important role, an analysis of existing scenarios in literature was made and the highest scenario with 30PJ of hydrogen usage for this sector was applied (Cuelenaere et al., 2014). In this scenario it is expected a high development of new and all renewable energy sources for the transport sector.

For electricity supply, the role of hydrogen is very uncertain. In the scenario of 100% renewables for 2030 made by Delft in 2014, the hydrogen could play a role for residual energy storage (electricity to gas) and for supporting in times of low solar wind production with 73PJ for electricity supply. Nevertheless, it is very uncertain or unprovable that for 2030 the energy mix will be 100% renewable and then this figure was not included, but it should be noted that for 2050 this could be a realistic scenario for achieving the Paris agreement targets.

In this scenario, a case in which the Netherlands does not import natural gas for own use was studied and included. According to the NEV outlook 2015, natural gas produced in 2030 will represent the 88% of the demand. The remaining 12% for this analysis will be covered by methanation of
Carbon captured from the natural gas burnt for producing electricity (73.6PJ of NG for electricity). If all the carbon captured would be methanized, 160 PJ of methane could be produced, nevertheless, in this case the production would be for covering only the remaining 12% which is 111PJ of methane.

The quantity of hydrogen demand for carbon methanation was calculated with the chemical formula for this reaction here below, and the rate of CO2 captured by electricity produced from natural gas burnt in a combined cycle power plant of 387Kg/MWh (Rubin, Chen, & Rao, 2007). Finally, for producing 111PJ of CH_4, it is needed 152.9 PJ of hydrogen.

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2\,O$$

7.3 Scenarios result analysis

The results of high and low scenarios for hydrogen consumption are illustrated in Figure 32 .As mentioned before the low scenario for 2030 would require 5PJ of H_2 in the energy mix, this would represent a still low percentage (0.2%) of the total expected energy consumption for 2030, but it is very probable if the current trend interests of R&D on hydrogen would continue. A quadratic extrapolation of this low scenario to 2050 results in a hydrogen demand of 15PJ. It would represent a 0.72% of the energy mix if the total demand of energy in 2050 is the same as in 2030.

The high hydrogen deployment scenario would demand 183PJ of hydrogen for 2030, this represents a 9% of the energy consumption. It seems a low share but this demand would require a fast development of hydrogen storage technologies, update of the security norms for hydrogen systems, a change of high duty and/or public transport sector, and the development of methanation plants. If this scenario is extrapolated to 2050, 549PJ of hydrogen would be needed, representing a share of 26.5% of the expected energy demand in 2030.

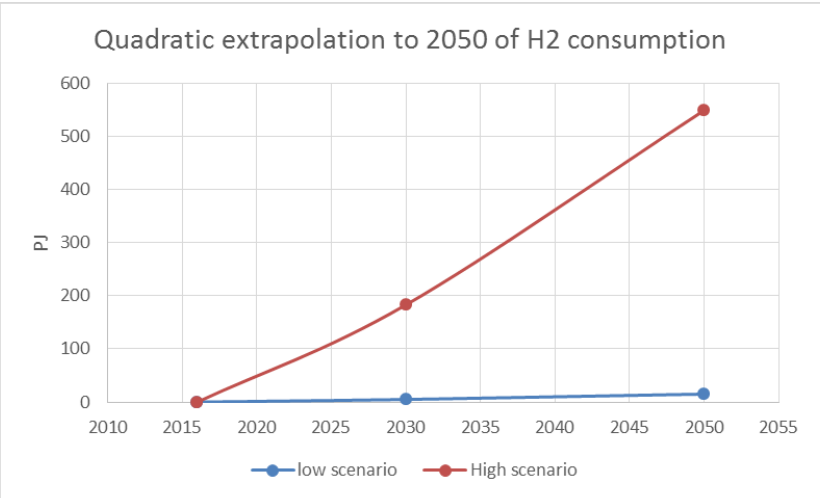

Figure 32: Low and high scenario for hydrogen energy consumption in 2030 and 2050

A monthly hydrogen demand for methanation was calculated assuming that the current pattern of monthly gas consumption can be applied to the share of hydrogen used for methanation in the upper boundary in 2030 (Figure 33). It would result in a hydrogen demand for methanation of 21.6PJ/month during winter times and 12.5 PJ/month during summer times plus a constant demand in the transport sector of 2.5PJ/month for 2030.

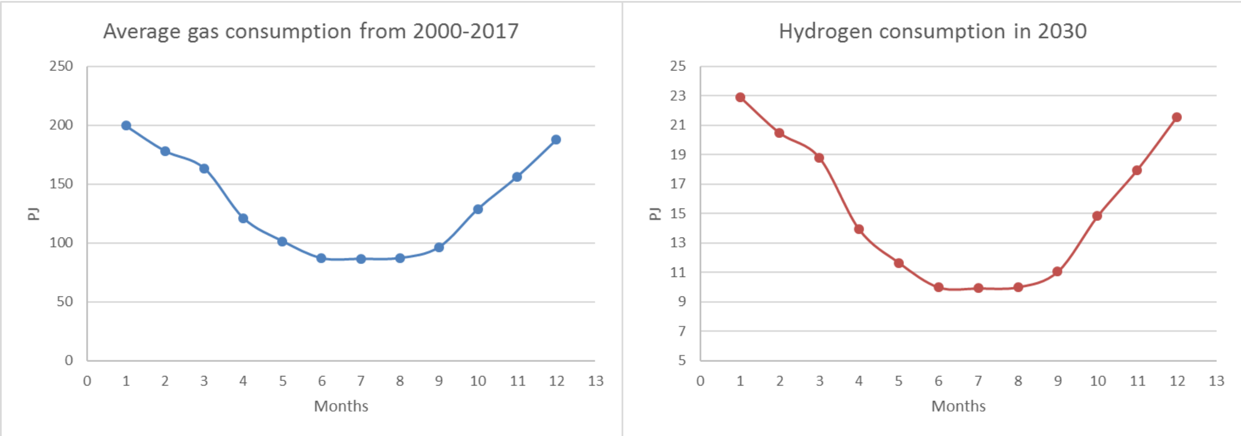

Figure 33: Left: monthly energy consumption pattern for gas and electricity (CBS, n.d.); right: monthly hydrogen demand for methanation using the upper boundary scenario for 2030.

8. DISCUSSION

8.1 About possible technology evolutions

The systems defined for converting solar and wind energy into hydrogen implement technologies that are in mature phases of development. This to make a reliable analysis that does not depend on uncertain technology developments. Nevertheless, currently there is a large quantity of research focus on developing systems more efficient for producing hydrogen from solar or wind energy that in the future could enable to increase the overall efficiency of this processes. However, with respect to the hydrogen transport method chosen, currently there is no commercially available LH_2 transoceanic tankers and difficulties related to the low cryogenic temperature of hydrogen and low energy content by volume could make hydrogen carriers as ammonia, which its transport is well known and commercially practiced nowadays, a better option in a near future when the process of filtering back hydrogen from ammonia is well established.

8.2 Productivity and efficiency aspects

The capacity of the CSP power plants was defined in order to maximize the capacity factors while at the same time having a thermal storage not larger than 16 hours of autonomy as current used CSP storage capacities (“CSP Projects - NREL,” n.d.). The capacity factors are 80.3% for the Morocco system and 87.4% for Australia. They may look suspiciously high when compared to CSPs installed, around 55% (IRENA; IEA-ETSAP, 2013) but it was set in this way as a special case for coupling it with electrolyzers for hydrogen production.

A comparison of the annual production of the three scenarios resulted that the S2H system in Australia has the largest production with a CSP power capacity of 350 MW and annual electricity production of 2.7TWh; followed by the S2H system in Morocco with the same power capacity but a lower annual production of 2.4TWh. The Morocco scenario in turn produces 1.5% more hydrogen than the reference hydrogen scenario in the Netherlands. This last one, the W2H system, has a power capacity of 600 MW with a capacity factor of 45%.

In the hydrogen production calculus for the S2H system, the boil off rate is included but not the energy required for transporting the hydrogen from the deserts to Rotterdam port. The Australia scenario delivers 11.1% more hydrogen than the Morocco scenario; however, it would potentially be 5% less efficient during transportation under the assumption that it is directly dependent on the distance travelled. Thus, 6.1% more energy would arrive to Rotterdam port. Altogether the Australia scenario is more feasible in energy terms than the Morocco scenario for exporting hydrogen to the Netherlands.

The energy return on energy invested for the S2H in Morocco is higher than the W2H system in the Netherlands, with an EROI of 12.8 and 11.1 each. It is not a large difference but it is a very important outcome for analyzing the energy feasibility of producing hydrogen in desert areas for export purposes. Furthermore, both systems had better EROI outcome than current unconventional fossil fuels production, ethanol and diesel from biomass.

It is important to highlight that both S2H productivity including the capacity factors of the CSP plants were calculated using irradiance synthetic data based on two sources, this with the aim of having the same data sources and same settings for Morocco and Australia scenario. At the same time, a sensitivity analysis was performed on the satellite modelled data for Morocco which excluded the oddity of using synthetic data from two sources. It resulted on an annual total irradiance received of 2% less than the initial data used and a capacity factor difference of 1.8% less with respect to the initial result. It is a small difference, for which it was considered best to keep the initial synthetic database to maintain the uniformity between the Morocco and Australia scenario for better comparison. Furthermore, the EROI obtained in the sensitivity analysis is still higher than the W2H system, with a very small difference of 0.3 of EROI with respect to the initial value. In the end, if the sensitivity results were applied on the Australia scenario, the conclusion would not change. The Australia scenario would deliver more hydrogen over Morocco scenario, which in turn would have a larger EROI than the W2H system scenario in The Netherlands.

8.3 The land issue

The area occupied by the wind electricity subsystem is 70 km^2 offshore the Netherlands ("Gemini - 4C Offshore," n.d.). For 2030 it is expected that the Netherlands will demand 2070 PJ of energy (Schoots & Hammingh, 2015), if we assume that this value would be the same for the total energy demand in 2050 and the Paris targets would be accomplished, this country would need to cover an important portion of this expected demand by offshore wind energy and then, disposing this area for producing only 4.68 PJ/year with hydrogen will be unlikely. On the other hand, the area occupied by the CSP subsystem is 28 km^2 allowing to deliver 4.8 PJ/year of hydrogen to the Netherlands from an area that represents a very small percent of the Sahara Desert.

Deserts are very low to non-arable lands with low population density. Therefore, producing hydrogen there would potentially have a low land use environmental impact compared to biomass. Biomass requires large areas of arable land that may compete with lands for agricultural purposes.

8.4 Environmental aspects

The environmental impact of both systems, S2H in Morocco and W2H in the Netherlands, is mostly related to the electricity production subsystems by more than 90%. The wind nacelles for the wind electricity subsystem and the steel for the solar electricity subsystem are the most important contributors of the environmental impact. The S2H system is the one having the largest impact by difference for most of the environmental categories (68% of the categories). However, the life cycle CO_2 emissions of the wind to hydrogen system is larger by 9.5% which is the main category to be considered given that an important goal for building such a system would be reducing GHG emissions from the energy sector while making use of renewable resources.

Both systems have larger life cycle CO_2 emissions when compared to intermittent renewable energy sources and hydropower for producing electricity but when compared to biomass, which is not intermittent, the hydrogen systems studied have less CO_2 emissions; and as expected, when compared to fossil sources, these systems emit less than half the emissions of common fossil power plants.

On the other hand, hydrogen systems could potentially have a larger water footprint, especially in desert areas where fresh water availability is limited. Furthermore, the S2H system requires 11% more water for the operational phase. However, it is important to highlight that electrolysis of seawater is in research (Fukuzumi, et al., 2017) and also, there are options for reducing fresh water consumption as implementing a water desalination plant or minimizing the water consumed for the CSP subsystem with dry cleaning and dry cooling technologies in the S2H system (A. Poullikkas, et al, 2013).

8.5 Rightsizing production with future demand

Two hydrogen demand scenarios for 2030 and extrapolated to 2050 were made for having an insight on the need of the Netherlands for importing hydrogen and the capacity of desert areas to cover this demand. They were built using the HHV calorific content of hydrogen for replacing other sources of energy in the transport and heating consuming sector. However, as explained in chapter 6, the values given should only be be taken as a reference of the order of magnitude.

The Morocco S2H scenario would deliver 96% (4.8PJ) of the low boundary expected Dutch hydrogen consumption for 2030, which in turn represents only a 0.2% of the expected total Dutch energy consumption for that year. This low boundary covers the energy consumption of the public bus transportation.

The high boundary for 2030 demands 183PJ of hydrogen, 9% of the total energy mix, which would imply fast changes in the transport sector and implementation of methanation for heating purposes. For covering this demand 39 S2H systems in Morocco would have to be built with 187 PJ of LH_2 annual delivery. Due to the heating demand changes from season to season, in winter 64% more hydrogen is required than in summer which would have to be tackled by adding seasonal storage vessels to the systems. This would imply a boil off rate of around 11% of the stored LH_2 for six months.

In 2050 the high boundary scenario would demand 549PJ, this would imply 115 S2H systems covering still less than 1% of the Sahara Desert. However, 118 W2H systems would be needed which would require a 14.5% of the Dutch North Sea.

8.6 Recommendations for future research

- Acquire ground DNI data, for at least one year, to calibrate the satellite derived data used. It would allow to minimize uncertainty related to weather conditions changes and the inherent uncertainty of the modelled data. At the same time, the satellite derived data continues to be useful because it allows to predict better the hourly solar irradiance by having larger hourly sample data.
- Analyze the hydrogen production considering the dependence of the electrolyzer efficiency with the power input, especially for the wind to hydrogen system. This for obtaining a more accurate hydrogen production rate from wind energy.
- Study the water footprint that these systems would exert over the environment and a study of water availability in the two desert scenarios before carrying out the S2H system.
- Make an economical assessment that includes life cycle cost analysis of both systems. It would enable to have a larger view on the feasibility of carrying out these systems.

9. CONCLUSION

This research aims at investigating the environmental and energy feasibility of producing hydrogen in desert areas for export to the Netherlands and compare it to producing hydrogen from wind energy for domestic purposes in the Netherlands. Two systems were defined, a solar to hydrogen (S2H) system studied under two geographic scenarios, Morocco and Australia, and the wind to hydrogen (W2H) system in the Netherlands as reference scenario. The Australia scenario was studied from its annual capacity of producing hydrogen while for the two others, a study of their life cycle environmental impact and cumulative energy demand were also assessed. In addition, two scenarios, low and high boundaries of expected hydrogen demand in The Netherlands for 2030 were performed.

The S2H system in Australia has an optimal defined CSP capacity of 350MW with a resulting annual electricity production of 2.7 TWh and with the capacity to deliver 37.2 kt H_2/year to the Netherlands. The Morocco scenario with the same capacity resulted on 2.4TWh of annual electricity production and an annual hydrogen delivery to the Netherlands of 33.5 kt. Considering differences in transported distances, the Australia scenario will potentially deliver 6.1% more energy than the Morocco one. At the same time, both scenarios have the capacity of delivering more hydrogen than the domestic scenario, which has a wind park installed capacity of 700MW and an annual hydrogen production of 33kt. An important result for assessing the energy feasibility would be the energy return on energy invested. The EROI of the S2H system in Morocco is larger than the EROI of the W2H system with 12.8 and 10.9 each. Both attain larger EROI than unconventional hydrocarbons, bioethanol and biofuels (Hall, et al., 2014).

The S2H system in Morocco has larger environmental impact for most of the categories studied, more water consumption and then potentially more water footprint. However, it has a lower life cycle CO2 emission by little difference than the W2H system, 3.22 and 3.56 kg CO2 eq/kgH_2 respectively. Both, after considering their efficiency for producing electricity with fuel cells, have larger CO_2 emissions than intermittent renewable energy sources, but lower emissions than fossil fuel sources and the not intermittent renewable biomass source for electricity production.

An important aspect to consider is the availability of land. The W2H system uses 70km^2 for the electricity subsystem covering an area that will potentially be needed for producing electricity in a renewable Dutch energy system. In addition, it is 2.5 times larger than the S2H electricity subsystem which it would cover a smaller percentage of the Sahara Desert.

Both systems deliver almost the expected low boundary hydrogen demand for 2030 (>90%), which in turn is only a 0.2% of the expected total Dutch energy consumption for that year. The high boundary for 2030 demands 183PJ of hydrogen. For covering this demand 39 S2H systems in Morocco would be needed producing annually 187 PJ of LH_2; or a minimum of 39 W2H systems with annual production of 183.3PJ of H_2. Due to the heating demand changes from season to season, in winter 64% more hydrogen is required than in summer which would have to be tackled by adding seasonal storage vessels to the systems. This would imply a boil off rate of about 11% of the stored LH_2 for six months.

To conclude, S2H systems in desert areas for export are a promising and feasible option in net energy terms compared to the reference W2H system. In addition, it covers less geographic area and have less CO_2 emissions; hence contributing to the energy transition. However, S2H systems in deserts require especial monitoring on water footprint.

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11. APPENDICES

11.1Inventory tables and data explanation for the LCA and EROI analysis.

11.1.1 Solar to hydrogen system

11.1.1.1 Concentrating solar power

The inventory of this subsystem was taken from the tower CSP LCA study made by Michael Whitaker. The CSP tower analyzed had a capacity of 115MW with 6682 heliostats and a solar field area of 964,712 m^2. It was assumed that a 150MW tower CSP plant would have similar materials requirements, and then the multiplier used for most of the components of the CSP was 2 given that in this study 2 CSP towers of 150MW are needed. Nevertheless, in the system analyzed there are 173,500 heliostats per CSP arrange. Consequently, the multiplier used for the collector system was 52, the energy for cleaning the heliostats was also scaled up with the 52 multipliers. Table 4 to 8 shows the materials and energy consumption during construction and operation phase of the reference CSP tower.

The transport required during construction phase was assumed to be the same as the transport needed during Gemasolar CSP construction in Spain, it was not used the transport given by Michael Whitaker because it was based on a project made in USA.

Table 5: Mass of Embodied Materials in the Reference CSP Tower Plant for the Manufacturing and Constructions Phases (Whitaker et al., 2013)

Material	Site Improvement (metric tons)	Receiver System (metric tons)	Collector System (metric tons)	TES System (metric tons)	SG System (metric tons)	EPG System (metric tons)	Total (metric tons)
Aggregate	7.47E+04	-	-	-	-	4.48E+02	7.51E+04
Aluminum	2.39E-02	6.12E+00	-	1.66E+01	7.30E+00	2.57E+02	2.87E+02
Asphalt	9.22E+03	-	-	-	-	-	9.22E+03
Brick	-	-	-	7.38E+02	-	-	7.38E+02
Calcium Silicate	-	5.93E+01	-	-	2.58E+01	4.67E+01	1.32E+02
Carbon Steel	9.91E+01	3.28E+03	2.78E+04	5.25E+02	2.90E+03	5.18E+03	3.98E+04
Concrete	6.24E+02	5.30E+04	7.16E+04	2.88E+03	1.01E+04	1.22E+04	1.50E+05
Copper	1.13E+00	4.18E+01	-	9.99E+00	6.83E+01	1.84E+02	3.05E+02
Epoxy Resin	-	6.99E-01	-	1.00E-01	6.72E-01	4.67E+00	6.14E+00
Fiber Board	-	-	-	3.33E+01	-	-	3.33E+01
Fiber Glass	-	2.08E-02	-	-	1.60E-02	3.84E+01	3.84E+01
Foam Glass	-	-	-	1.51E+02	-	-	1.51E+02
HDPE	3.50E+02	1.05E+00	-	4.94E-01	8.83E-01	5.02E+01	4.03E+02
Lubricating Oil	-	-	-	-	-	2.66E+01	2.66E+01

Mineral Wool	-	6.68E+01	-	1.47E+02	-	1.29E+00	2.15E+02
Nickel Alloys	-	3.86E+00	-	5.81E-01	1.28E+00	1.31E-02	5.73E+00
Polypropylene	4.90E+01	2.85E-02	-	-	2.20E-02	2.58E-01	4.93E+01
Potassium Nitrate	-	-	-	6.97E+03	-	-	6.97E+03
Propylene Glycol	-	-	-	-	-	1.17E+01	1.17E+01
PVC	-	1.25E+01	-	2.09E+00	9.78E+00	2.23E+01	4.66E+01
Rip rap	5.80E+03	-	-	-	-	-	5.80E+03
Rubber	-	7.12E-01	-	-	4.23E+00	3.41E+00	8.35E+00
Sodium Nitrate	-	-	-	1.05E+04	-	-	1.05E+04
Solar Glass	-	-	1.00E+04	-	-	-	1.00E+04
Stainless Steel	-	2.11E+02	-	4.52E+02	1.43E+02	3.41E+01	8.40E+02
Transformer Oil	-	-	-	-	-	5.53E+01	5.53E+01
Zinc	8.52E+00	1.20E+01	-	3.50E-01	1.03E+01	8.42E+00	3.97E+01
Total	9.08E+04	5.67E+04	1.09E+05	2.24E+04	1.33E+04	1.86E+04	3.11E+05

Table 6: Mass of Embodied Materials replacement components used during the O&M phase of the reference plant (Whitaker et al., 2013)

Materials	**Site improvement (metric tons)**	**Receiver System (metric tons)**	**TES System (metric tons)**	**SG System (metric tons)**	**EPG System (metric tons)**	**Total (metric tons)**
Carbon Steel	5.96E-01	5.69E+01	3.07E+00	4.50E+01	4.71E+01	1.53E+02
Copper	1.17E+00	1.53E+01	3.21E-01	1.09E+01	1.32E+01	4.09E+01
Fiber Glass	-	-	-	-	1.54E+01	1.54E+01
Graphite	1.32E-02	1.80E+01	7.12E-02	4.08E+00	-	2.22E+01
Iron	-	-	-	-	1.25E+00	1.25E+00
Lubricating Oil	-	-	-	-	1.38E+02	1.38E+02
Nickel Alloys	-	5.26E-02	1.18E+00	2.23E-01	-	1.45E+00
Potassium Nitrate	-	-	2.02E+02	-	-	2.02E+02
Sodium Nitrate	-	-	3.03E+02	-	-	3.03E+02
Stainless Steel	9.89E-02	1.62E+00	5.64E-01	4.61E+00	4.14E+00	1.10E+01
Total	1.88E+00	9.19E+01	5.10E+02	6.48E+01	2.19E+02	8.88E+02

Table 7: CSP Tower Reference Plant Construction Energy (Whitaker et al., 2013)

Phase	**Diesel (MJ)**
Construction	8.87E+07

Table 8: CSP Tower Reference Plant Operational Water Consumption (Whitaker et al., 2013)

Item Description	Annual Water Consumption (cubic meters/year)
Heliostat Water Wash	56,000
Steam Cycle and Balance of Plant	71,934
Total	**127,934**

Table 9: CSP Tower Reference Plant Specialized Equipment Fuel Consumption in the Operation Phase (Whitaker et al., 2013)

Item Description	Quantity	Fuel Type	Annual Fuel Consumption (liters/yr)
Heliostat Water Wash Truck	14	Diesel	118,000
General Maintenance: 3/4 ton truck	4	Gasoline	810

Table 10: Transport required during construction phase (Kuenlin, et al., 2013)

Transport	**tkm**
rail transport	1.4E+07
lorry>16t, fleet average	3.46E06
Transoceanic freight ship	2.38E07

11.1.1.2 Water electrolysis subsystem

The inventory of this subsystem was taken from work made by Jan Christian Koj for alkaline electrolyzers. The reference electrolyzer has a lifespan of 20 years and a maximum annual hydrogen yield of 1036512kg. Given the difference with the annual yield needed and the lifespan for the studied system a multiplier of 65.5 was used. Table 10 shows the materials and energy considered in the LCA analysis.

Table 11: Main materials and energy usage during construction and operational phase of the reference electrolyzer (Koj et al., 2017)

Cell stack construction per alkaline electrolyzer		
Framework		
Material	Unit	Value
Copper	t	2.0
Unalloyed steel	t	200
Cells		
Nickel	t	19
Aluminum	kg	450
Calendered rigid plastic	kg	780
Polytetrafluoroethylene	kg	78
Acrylonitrile butadiene styrene	kg	160
Polyphenylene sulfide	kg	340
Polysulfones	kg	260
N-Methyl-2-pyrrolidone	t	1.3
Aniline	kg	49

Acetic anhydride	kg	54
Terephthalic acid	kg	88
Nitric acid	kg	33
Hydrochloric acid	kg	130
Graphite	kg	430
Lubricating oil	kg	0.48
Zirconium oxide	t	1.1
Carbon monoxide	kg	150
Decarbonized water	t	11
Deionized water	t	86
Electricity	GJ	36
Heat	GJ	88
Steam	MJ	700
Industrial machine production	kg	0.16
Plaster mixing	kg	780
Ventilation system, central, 1 x 720 m3/h, polyethylene ducts, with earth tube heat exchanger {GLO}| market for | Alloc Def, U		1
Air separation facility {RoW}| construction | Alloc Def, U		1
Water tank	l	31200
Operation—per kg of hydrogen produced		
Electricity	MJ/kg H2	180
Deionized water	kg/kg H2	10
Nitrogen	g/kg H2	0.29
Potassium hydroxide	g/kg H2	1.9
Steam	kg/kg H2	0.11

11.1.1.3 Hydrogen Liquefaction

The inventory for this subsystem was taken from the study made by Cristina Wulf on system variation for hydrogen transport. It is based on an advanced concept for liquefiers with a production rate of 50l/day. It was also linearly upscale to the capacity needed for this study with a multiplier for each material of 1.84. Table 11 shows the input materials used for this analysis.

Table 12: Main materials for the construction of the liquefaction plant (Walf & Zapp, 2017).

	Unit	Value
Construction material		
Chromium steel	t	595
Reinforced steel	t	380
Concrete	m^3	20 300
Copper	t	150
Aluminium alloy	t	140

11.1.2 Wind to hydrogen system

11.1.2.1 Gemini Windpark inventory

The inventory used was taken from the study made by the peer student Stephan Schroeder. This wind park has a lifespan of 20 years so a multiplier of 1.5 was used to increase the lifespan to 30 years, grid connection cables and the transport of the electricity to onshore was included in the inventory as materials for building the offshore substations. Main features of this wind park are shown in table 12.

Table 13: Gemini wind park main features

Location of wind farm	**NL (North Sea)**
Average depth of sea bottom	32m
Distance from shore	70.2km
Capacity of windfarm	600MW
Capacity of wind turbine	4 MW
Lifespan	20 years
Total length of HV cable	181 km
Total length of MV cable	140 km
Transportation distance for non-recycled materials	100 km
Transportation distance for recycled materials	400 km

11.1.2.2 Water electrolysis subsystem

The inventory used for performing the LCA and EROI analysis was the same used for the electrolyzer of the solar to hydrogen system. The difference was in the multiplier applied to the inventory data and the subsystem output produced as the total hydrogen produced for this system is different than the solar to hydrogen system. In this case the multiplier applied was 56.89.

11.1.2.3 Hydrogen Compressor

The hydrogen compressor was retrieved from a study confounded by the European commission (NEEDS, 2008). The compressor is based on a diaphragm type compressor used on a hydrogen fueled station in Reykjavík with an annual compressing capacity of 47250kg of hydrogen. The compressor capacity needed would have a capacity of compressing 32.6kt of hydrogen, then a liner scale up was applied to the inventory given. Table 13 shows the materials included in the analysis.

Table 14: Hydrogen compressor materials (NEEDS, 2008)

Compressor	Unit	Value
chromium steel 18/8	kg	1899.45
cast iron	kg	599.6025
ethylene glycol	kg	7.00245
lubricating oil	kg	18.00225
aluminium production mix	kg	59.96025
tube insulation, elastomere	kg	15.0255
copper	kg	44.93475

heat, natural gas	MJ	3600.45
transport, lorry 32t	tKm	513.135
Storage Module	Unit	**Value**
chromium steel 18/8	kg	84057.75
diesel, burned in building machine	Mj	856.17
transport, lorry 32t	tkm	8405.775

11.1.3 Disposal Scenario Used for both system

The recycling rates, but cooper and plastic rates, were retrieved from a LCA study performed to the Gemasolar power plant in Spain (Whitaker, et al., 2013). It was assumed that similar rates could be applied to Morocco and the Netherlands. The cooper recycling rate was retrieved from the global calculated recycling rate given from Statista webpage; in Simapro the recycling process was not found whereby it was assumed that the recycling process for steel was similar to the recycling process for cooper. Plastic recycling rates were retrieved from The Facts report 2016, an energy recovery process of the resting 39.5% could not be included within Simapro (PlasticsEurope, 2016). Materials and percentage of materials that are not included in this list were treated under the Netherlands scenario for waste treatment available in Simapro.

Table 15: Disposal and recycling rates

Material	Treatment	Rate
Steel (reinforced and chromium steel)	Reinforced steel to recycling {CH}	90%
	Reinforced steel to final disposal {CH}	10%
Concrete	Concrete, not reinforced to recycling {CH}	95%
	Concrete, collection for final disposal {CH}	5%
Glass	Glass sheet, collection for final disposal{CH}	100%
Plastics	Waste polyethylene/polypropylene product/ collection for final disposal {CH}	30.8%
	Mixed plastics {GLO}/ recycling of mixed plastic	29.7%
Cooper	Steel and Iron/ recycling of steel and Iron {GLO}	30%

11.1.4 Environmental impact results table for both system

Table 16: Environmental impact of both system per impact category.

Impact category	Unit	Solar to hydrogen	Wind to hydrogen
Global warming 100a	kg CO2 eq	3.225598956	3.56247846
Ozone depletion	kg CFC11 eq	1.60812E-07	8.15912E-08
Ozone formation (Vegetation)	m2.ppm.h	23.82962833	43.6324705

Ozone formation (Human)	person.ppm.h	0.001647793	0.003407
Acidification	m2	0.326078434	0.241403859
Terrestrial eutrophication	m2	0.309021171	0.116482702
Aquatic eutrophication EP(N)	kg N	0.001413227	0.0012176
Aquatic eutrophication EP(P)	kg P	0.002021503	0.001092834
Human toxicity air	person	262888.8919	51082.88257
Human toxicity water	m3	407.3986383	297.2376948
Human toxicity soil	m3	1.038934799	0.222649194
Ecotoxicity water chronic	m3	57221.59664	72102.30115
Ecotoxicity water acute	m3	6288.075773	7929.855846
Ecotoxicity soil chronic	m3	7.281010016	2.551581664
Hazardous waste	kg	5.86105E-05	9.19718E-05
Slags/ashes	kg	0.172240652	0.031509884
Bulk waste	kg	2.356976224	0.29033034
Radioactive waste	kg	0.000108109	4.43617E-05
Resources (all)	PR2004	0.014915878	0.002876352

11.2Units conversion table

The unit conversions used during this study are found in table 16. For calculating energy content of hydrogen it was always used the HHV because at 25 C and 1 atm, the energy released when water is formed is 39 kWh/kg of hydrogen (HHV) and for the reverse process or electrolysis the same energy in reverse would be needed (Ivy, 2004).

Table 17: Units conversion table

Hydrogen conversion units	Value
HHV	39 kWh/kg
HHV	141.8MJ/kg
Energy density (hydrogen gas @ STP)	12770Kj/m^3
Density (hydrogen gas @ STP)	0.089kg/Nm^3
Cryogenic hydrogen energy density	10086.2MJ/m^3
Cryogenic hydrogen density	70.8kg/m^3

11.3 Script for the hourly electricity and hydrogen production calculus

The script below was written in R language and was used for calculating the annual electricity and hydrogen production of the solar to hydrogen system from hourly direct normal irradiance.

```
options(stringsAsFactors = FALSE)
#Data entry
```

```
Q <- dnih$se      #Hourly solar energy harvested with 15.5% efficiency
maxse <- 300000           # Capacity of CSP subsystem
HHV.kWh.kg= 39            #HHV
electrolysisn=0.73        #electrolysis efficiency
liq.kWh.by.kgh2 =10       #rate of electricity consumption for liquefaction
ship.cap.kg = 50000*70.8          #Capacity of LH2 ship in kg
boil_off = 0.06/100        #boil off rate per day in ship
time.ship=7       #time travel in days from Tizart port to Rotterdam port
```

#Hourly solar energy to be stored for later use

```
Excess_se <- (dnih$se-maxse)
for (i in 1:length(Excess_se)){
  if (Excess_se[i]<0){Excess_se[i]=0}
}

Excess_se<- Excess_se*0.95
```

#Calculating the hourly electricity produced by making use of Q and excess_se

```
se.to.h <- vector("numeric", length(Excess_se))
Cumu_store <- vector("numeric", length(Excess_se))
Cumu_store[1] <-0
for (j in 2:8784){Cumu_store[j] = Cumu_store[j-1]+Excess_se[j]
 for(t in 1:length(se.to.h)) {
   if (Q[t]> maxse){se.to.h[t]=maxse
   } else if((Q[t]<maxse)&(Cumu_store[t]==0)){se.to.h[t] = Q[t]
   } else if((Q[t]<maxse)&(Cumu_store[t]>=maxse)){(se.to.h[t] = maxse) & (Cumu_store[t+1]= Cumu_store[t]-(maxse-Q[t])+Excess_se[t])
   } else if((Q[t]<maxse)&(Cumu_store[t]<maxse) & (Cumu_store[t]>0)) {(se.to.h[t] =Cumu_store[t])&(Cumu_store[t+1]=Excess_se[t+1])      #{(se.to.h[t] = Q[t]+(Cumu_store[t]*0.4)) & (Cumu_store[t+1]=(Cumu_store[t]*0.6)+Excess_se[t+1])
   }
  }
}


se.to.h[8784] = Cumu_store[8783]-se.to.h[8783]
Cumu_store[8784] = 0

Cumu_store <- Cumu_store[-8785]
solarh <- cbind(se= Q,hstore= Excess_se,Cumu_store , se.to.h )
solarh <- as.data.frame.matrix(solarh)
solarh$hour <- c(1:8784)

capacity.factor.csp. <- sum(se.to.h)/(maxse*8748)


#Calculating hydrogen produced from electrolysis
solarh$se.convertedh = solarh$se.to.h*electrolysisn
solarh$se.loss.electro = solarh$se.to.h - solarh$se.convertedh
```

```
#Calculating liquefation
solarh$h.liquefied = solarh$se.convertedh*(1-(liq.kWh.by.kgh2/HHV.kWh.kg))
solarh$se.loss.liq = solarh$se.convertedh - solarh$h.liquefied

solarh$h2kg_0 = solarh$se.convertedh/HHV.kWh.kg
solarh$hl2kg_1 = solarh$h.liquefied/HHV.kWh.kg

solarh$day <- dnih$day
transport<- aggregate(list(lh2=solarh$hl2kg_1, h2_kg=solarh$h2kg_0), by= list(day=solarh$day), sum)
colnames(transport)[2] <- 'lh2'
transport$cumsum.lh2 <- cumsum(transport$lh2)

#modelling time in filling each tank
current.sum <- 0
for (c in 1:nrow(transport)) {
  current.sum <- current.sum + transport[c, "lh2"]
  transport[c, "cumsum.lh2"] <- current.sum
  if (current.sum >= ship.cap.kg) {
    transport[c, "index"] <- 1
    transport[c, "cumsum.lh2"] <- ship.cap.kg
    current.sum <- current.sum - ship.cap.kg

  }
}

a <- which(transport$index == 1)
b = vector("numeric", length(a))
for (t in 1:length(a))
  b[t] <- a[t+1]-a[t]
time.fill.tank.lh2 <- mean(b[1:length(b)-1])

#Calculating how many ships arrive to Rotterdam per year
ship_per_year = length(which(transport$index==1))
lh2.arrive.nl=          (ship.cap.kg*(1-(boil_off*time.ship))*ship_per_year)          +
(transport$cumsum.lh2[366]*(1-(boil_off*time.ship)))
lh2.arrive.nl
lh2.arrive.nl*39 #hhV in kWh/kg
```