Combined Life Cycle Analysis of Wind Energy and Hydrogen Production

João Maria Pais de Vasconcelos de Herédia
joaomheredia@tecnico.ulisboa.pt

Instituto Superior Técnico, Universidade de Lisboa, Portugal

December 2021

Abstract

Green hydrogen is regarded as a promising solution to address the energetic transition, especially in the mobility sector. This work shows a life cycle assessment (LCA) to evaluate the environmental impacts of centralized hydrogen production in Portugal through electricity supply from offshore wind farms (OWF). Two scenarios are considered, with two configurations each. In scenario 1, 5% of small and 16% of heavy vehicles of the Portuguese fleet are considered to be fuel cell electric vehicles (FCEV) by 2050 with a demand of $112.65\,kton\,H_2/year$. Scenario 2 considers 30% of small and heavy vehicles are FCEV with a demand of $435.1\,kton\,H_2/year$ by 2050. Configuration A assumes all generated energy by the OWF serves to produce hydrogen with a plant power ratio (PPR) of 62.5%. In configuration B (PPR=25%), only 38% of the energy is used to produce hydrogen, to take advantage of the curtailment effect. For LCA, the RECIPE method was used and two impact categories were considered: midpoint and endpoint. In the midpoint analysis, OWF has the greatest impact in all categories. In the endpoint analysis, resources are the category with the most impact. Configuration A has 3.65 and 5.21 and configuration B has 6.89 and $9.84\,kg\,CO_2/kg\,H_2$ emissions with and without end-of-life respectively. Compared with steam methane reforming, configuration A and B have a reduction between 55-70% and 15-40% in the CO_2 emissions respectively. Regarding the mobility sector, it was concluded $kg\,CO_2/km$ emissions from the FCEV were 40-80% lower compared to ICE vehicles.

Keywords: Offshore wind energy, Electrolysis, Life cycle assessment, Centralized hydrogen production, Green hydrogen, Fuel cell electric vehicle (FCEV).

1. Introduction

The Paris Agreement, signed by almost every nation in the world aims to keep the global temperature rise this century well below 2 °C above pre industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 °C [1]. To achieve the targets in the Paris agreement, the global energy system must undergo a profound transformation from largely based on fossil fuels to an efficient and renewable low carbon energy system with a reduction of around 3.5% of CO_2 emissions per year from now until 2050 [2].

The motivation to study the life cycle of hydrogen production by offshore wind energy in Portugal is threefold:

1. Portugal pledged to ensure neutrality of it's emissions by the end of 2050 as a contribution to the Paris Agreement by developing the road map for the Carbon Neutrality 2050 (RNC2050) [3].
2. Offshore wind energy production is rapidly growing and technologies are developing.
3. Power-to-Hydrogen on the global energy transition could be the solution to help decarbonise some of the most fossil fuel dependent sectors.

Hydrogen is an **energy carrier and not a source of energy**, being a complementary to the electricity in the energy transition [1]. **Portugal made their policy and intentions very clear**, with the publication of the National Strategy for Hydrogen based on the path and discussion related to the PNEC 2030, RNC2050 and in the a draft of the National Strategy for Hydrogen (EN-H_2) [4], [3] and [5]. This strategy aims to promote the gradual introduction of the hydrogen as a sustainable pillar and a more comprehensive strategy of transition to a decarbonized economy. Based on the current national energy system, a set of strategic configurations for the hydrogen value chain was determined [4]. **In this thesis, the focus will be on the power to mobility (P2M) value chain.**

2. Methodology

Life cycle assessment (LCA) is one of the most established methods for estimating the environmental performance associated to the life cycle of products and services from raw material through to production, use, end-of-life treatment, recycling and final disposal. According to the international organization for standardization (ISO) 14040/44 standards, the LCA comprises four phases [6]: **goal and scope definition** which identify the purpose of the LCA, the expected results of the study and defines the limits and assumptions based on the definition of the objective, **life cycle Inventory** which quantify the inputs and outputs of each unit operation including data collection, **impact assessment** which allows to evaluate the possible environmental impacts associated with the system's inputs and outputs and **interpretation of results** where the findings from the inventory analysis and the impact assessment phases are considered together to present consistent results based on the goal and scope definition phase of the study.

2.1. Goal of the Study

The goal of this project is to analyse the life cycle and to quantify the potential environmental impacts of hydrogen production in Portugal by PEMWE using electricity generated from offshore wind energy in a centralized way.

2.2. Scope of the Study

2.2.1 Functional Unit

The functional unit serves as a base for calculations and all inputs and outputs of the model are related to the functional unit. The chosen functional unit is defined as 1 kg of dried hydrogen produced in Portugal in PEMWE plants with a standard quality of 5.0 and 350 bar pressure at 60 °C operating temperature.

2.2.2 System description and Boundaries

This study is a cradle-to-grave LCA, assessing the energy consumption and emissions associated with the hydrogen production using Siemens Silyzer 300 PEMWE with 17.5 MW each (stage B) with the electricity generated from an OWF comprising of 70 Vestas $V164 - 8.0\,MW$ wind turbines with a total power of 560 MW (stage A). The hydrogen is then compressed by a mechanical reciprocating piston compressor from 30 bar to 350 bar (stage C) and stored in tanks type I (stage D) to be transported by truck to the the refueling station. The OWF includes the WTs, 66 kV inter array cables, an offshore substation, 150 kV transmission cable and an onshore substation. **The lifetime of the system is considered to be 20 years [7].** The number of OWF and the number of PEMWE connected to each wind farm depends on the scenario. There are eight steps for each of the four stages of the system as shown in Figure 1: **raw material extraction**, **material processing**, **manufacturing of the components**, **construction and set-up of each of the stages** , **operation and maintenance of the system**, **dismantling**, **waste management**, after the product has served it 's intended function and is returned to the environment as waste or recycled and **landfill, incineration or recycling.**

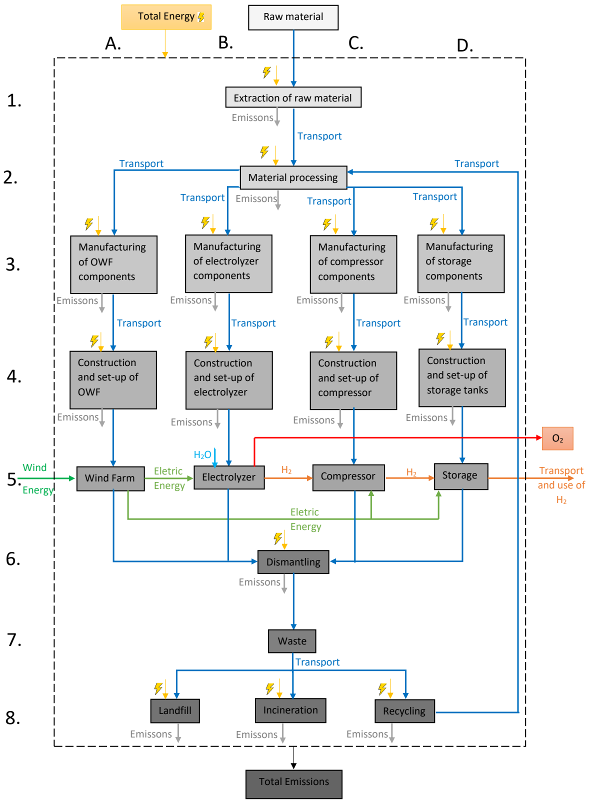

Figure 1: Diagram of system boundaries for LCA.

In figure 1 is presented the system boundaries of the LCA in this study which is considered to be from the wind energy until the distribution of the hydrogen to the refueling stations with four main stages: **OWF, PEMWE, compressor and storage**.

2.3. Definition of scenarios

Two different scenarios are proposed in order to foresee the future of H_2 in the Portuguese fleet by offshore wind energy. Each scenario is divided in two different configurations, according to the plant power ratio (PPR) which is given by equation 1:

$$PPR = \frac{Rated\,PEMWE\,load\,capacity}{OWF\,load\,capacity} \times 100 \quad (1)$$

PPR is the ratio that will define the differences between configurations A and B.

2.3.1 Scenario 1 and 2

The difference between scenario 1 and 2 is the demand for hydrogen in the mobility sector. In scenario 1 only 5% of small vehicles and 16% of heavy vehicles of the Portuguese fleet would be moved by hydrogen in 2050. In scenario 2, the hydrogen needed for a 30% vehicle penetration by 2050 is considered as is going to be seen in the section 2.4. Each scenario is divided in configuration A and B, with different PPR.

Configuration A

Configuration A assumes that almost all the energy generated by the OWF (96.4%) is going to be to produce hydrogen with a PPR of 62.5% because is the maximum PPR, considering the electricity used for H_2 compression and transmission losses as well. The system in this configuration is composed by an OWF which is connected to 20 PEMWE and to 8 compressors each one compressing hydrogen at a rate of 430 kg/h from 30 bar at the outlet of the PEMWE to 350 bar. After the compression stage, the hydrogen is stored in cylindrical type I tanks with capacity to 1000 kg of hydrogen per tank, as already stated in the state of the art chapter, which are then transported by truck to the HRS. The hydrogen produced per day and per system is 77.52 ton/day, so 78 trucks are going to be needed per day and per system as shown in Figure 2.

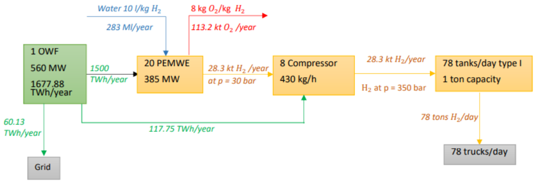

Figure 2: Diagram of system main stages for configuration A.

Configuration B

Configuration B assumes that the PPR is 25% according to [8]. This configuration has the objective of representing the curtailment effect. Only 38% of the energy generated by the OWF is going to to produce hydrogen and 62% are going to be injected directed to the grid. The allocation of these 62% of energy is not considered in this thesis. The system in this configuration is composed by an OWF which is connected to 8 PEMWE and 3 compressors each one compressing hydrogen at a rate of 430 kg/h from 30 bar at the outlet of the PEMWE to 350 bar and then the hydrogen is stored in a cylindrical type I tanks with capacity to 1000 kg of hydrogen per tank which are then transported by truck to the HRS as in configuration A. The hydrogen produced per day and per system in this scenario is 35 ton/day, so 35 trucks are going to be needed per day and per system.

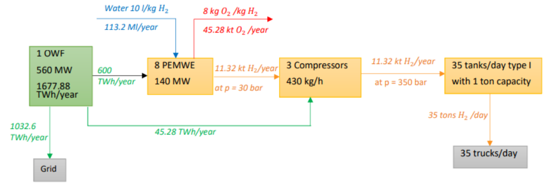

Figure 3: Diagram of System main stages for configuration B.

The four scenarios made are the following: **scenario 1A** with 4 system's of figure 2, **scenario 2A** with 16 system'of figure 2, **scenario 1B** with 10 system's of figure 3 and **scenario 2B** with 39 system's of figure 3.

2.4. Assumptions

In table 1, an estimation of the number of small and heavy vehicles until 2050 assuming that small vehicles have the maximum weight of 3 500 kg is presented [9].

Table 1: Population of Portugal in thousands and number of vehicles by category 2010-2050.

		Small vehicles		Heavy vehicles	
Year	**Population (k)**	**Passenger car**	**Vehicle of goods**	**Trucks**	**Bus**
2010	10 573	4 692 000	1 337 373	65 236	15 425
2015	10 358	4 722 963	1 224 821	49 112	14 717
2020	10 206	4 632 324	1 232 764	50 443	14 676
2025	10 023	4 549 676	1 210 770	49 455	14 414
2030	9 841	4 467 028	1 188 775	48 560	14 152
2035	9 659	4 384 380	1 166 781	47 662	13 891
2040	9 477	4 301 732	1 144 786	46 763	13 629
2045	9 295	4 219 085	1 122 792	45865	13 367
2050	9 113	4 136 437	1 100 798	44 967	13 105

In table 2 is presented the hydrogen consumption for a passenger car, small vehicle of goods and for buses and the annual distance cover per driver and per type of vehicle according to [10], being possible to calculate the annual consumption per vehicle. It was considered that trucks and buses had the same hydrogen consumption of 10 $kg/100km$. For the small vehicles of goods, it was considered that the fuel consumption was 1.5 times higher than a passenger car and the annual distance per driver to be double of a passenger car.

Table 2: H_2 consumption per driver by type of vehicle from [10].

	Passenger car	Small vehicle of goods	Bus & Truck
H_2 consumption kg/100km	1	1.5	10
Annual distance per driver (km)	15 000	30 000	60 000
Annual H_2 consumption per vehicle (kg)	150	450	6 000

2.4.1 Scenario 1 H_2 consumption

In table 3 is a conservative scenario for the number of small and heavy vehicles fueled by green hydrogen suggested by the Portuguese government in the script and plan for hydrogen in Portugal [4], with only a 5% incidence in the total of small vehicles and 16% in the heavy vehicles in Portugal by 2050 and if the goal of CO_2 neutrality is to be achieved, is necessary a greater effort.

Table 3: Scenario 1 (Conservative scenario) number of H_2 vehicles 2020-2050 according to [4] and the H_2 consumption.

Year	H_2 stations	Small vehicles	Heavy vehicles	H_2 $(kton/year)$
2020	0	0	0	0
2025	10	2 000	500	3.42
2030	30	5 000	2 000	13.05
2035	50	50 000	3 000	28.5
2040	100	100 000	5 000	51
2045	150	175 000	7 000	78.75
2050	210	265 000	9 500	112.65

2.4.2 Scenario 2 H_2 consumption

A more optimistic scenario is presented in table 4 in which by the year 2050, 30% of the small vehicles and heavy vehicles were moved by H_2 with a progressive introduction of the H_2 vehicles in the total Portuguese fleet between 2020 until 2050.

Table 4: Scenario 2 of number of H_2 vehicles 2020-2050 and H_2 consumption.

Year	Small vehicles	Heavy vehicles	H_2 $(kton/year)$
2020	0	0	0
2025	28 857	639	9.89
2030	56 665	1 881	23.19
2035	278 083	4 309	84.25
2040	545 681	7 247	158.08
2045	1 070 395	11 846	295.86
2050	1 574 140	17 422	435.1

2.5. Inventory Analysis

2.5.1 Offshore Wind Farm LCI

The WT considered for this study is the Vestas V164 8 MW wind turbine

Table 5: Inventory OWF components [11], [12], [13], [14], [15], [16], [17].

Component	Formula	Mass $(kton)$	Material
Wind Turbines	$N.m_{WT}$	74.43	—
Floating Foundation	$N.m_{FF}$	482.86	60% Steel 40% Concrete
Inter array cable	$0.03 \times (0.0007P^2 + 0.02P + 6.07)$	7.11	30% Copper, 40% Aluminium, 10% PE, 10% PP, 10% Steel
Offshore Substation [16]	$0.016(h)^{0.19}(\frac{P}{0.133})^{0.48} + \frac{P}{0.133}$	5.99	95% Steel, 2% Copper, 0.5% PE, 1.5% Aluminium, 1% Lubricating oil
Export Cable [18]	$0.075L$	0.75	40% PE, 25% PP , 15% Steel, 10% Copper, 10% Aluminium
Onshore Substation [16]	$16.042(h)^{0.19}(\frac{P}{0.133})^{0.48}$	4.21	95% Steel, 2% Copper, 0.5% PE, 1.5% Aluminium, 1% Lubricating oil
Total Offshore WF	—	575.35	63% Steel, 31% Concrete 0.7% Copper, 0.2% PE, 0.2 % PP, 0.9% Aluminium, 2% Cast Iron, 0.1% Lubricating oil, 0.1 % Electronics, 0.9 % Fiber Glass, 0.5 % Epoxy Resin

In table 5, the inventory for one OWF is shown with all the components. N is the number of wind turbines, m_{WT} and m_{FF} are the mass of each wind turbine and floating foundation respectively, P is the power of the wind farm in MW, h is the depth at which the offshore substation is located in meters and L is the length of the export cable also in meters. The inter array cables mass density is going to be assumed to be $30\,kg/m$ and the weight density of $75\,kg/m$ was considered for the export cables as already stated in the state of the art. The onshore substation was assumed to have the same mass as the topside of the offshore substation.

Wind farm operation and maintenance

Lubricating oil replacement, transport by barge and by helicopter is considered in the operation and maintenance phase while part or platform replacement during the lifetime of the OWF is not considered [16].

In table 6 is summarized all the data about the O&M of the OWF.

Table 6: O&M of the OWF

O&M	Value (year)	Value (lifetime)
Lubricating oil (ton)	236	4720
Transport by barge, diesel (ton)	50	1000
Transport by helicopter, gasoline (ton)	28	560
Total (ton)	314	6.28

Construction and set-up

EPT represents the time required when the energy output equals the energy input at its production, installation, O&M, and EoL stages [17]. The net energy payback time (EPT) is considered to be around 1 year, so 20 times less than the energy produced for the lifetime of 20 years of the OWF [15], [17].

Complete LCI of OWF

In table 7 is presented all the inventory for the OWF including O&M and the energy used for the construction and installation of the OWF.

Table 7: Inventory of one OWF with 70 turbines and 560 MW power.

Material	Total mass $(kton)$	Mass (g/kWh)	Mass (g/kgH_2) Configuration A	Mass (g/kgH_2) Configuration B
Steel	362.64	10.79	372.76	934.53
Concrete	178.7	5.32	183.85	460.94
Cast iron	13.47	0.38	13.87	34.77
Aluminium	5.01	0.14	5.15	12.92
Fiber Glass	4.99	0.14	5.13	12.87
Copper	3.9	0.11	4.01	10.06
Epoxy resin	3.13	0.089	3.22	8.06
PE	1.43	0.041	1.47	3.69
PP	1.27	0.036	1.31	3.28
Electronics	0.74	0.02	0.76	1.9
Lubricating Oil (with O&M)	5.19	0.15	5.34	13.4
Diesel (O&M)	1	0.03	1.03	2.58
Gasoline (O&M)	0.56	0.017	0.58	1.44
	Total energy (TWh)		$(kWh/kg\,H2)$	$(kWh/kg\,H2)$
Energy	1677.88		3.07	7.7

2.5.2 PEMWE LCI

A Siemens Silyzer-300 PEM electrolyzer was chosen. According to Siemens [19], the efficiency of the plant is 62.6% LHV.

PEMWE Operation and Maintenance

For the electrolyzer, lubricating oil replacement is considered for every 2500/3000 h of operation, so 3 times per year. For the lifetime of 20 years, results in 60 replacements which means that for the lifetime of the electrolyzer the lubricating oil is going to be 60 times of the initial one [20].

Complete LCI PEMWE

Table 8 shows the all inventory for each of the Siemens Silyzer 300 PEMWE including the operation and maintenance lubricating oil replacement and the energy for construction of the PEMWE.

Table 8: Siemens Silyzer 300 PEM electrolyzer inventory.

Material	**Mass** (*ton*)	**Mass** ($g/kg\,H_2$)
Steel	178.5	6.3
Concrete	122.5	4.32
Electronics	24.5	0.86
Copper	17.66	0.62
Titanium	18.48	0.66
PE	5.25	0.186
Aluminum	4.45	0.16
Lubricating oil (including O&M)	210	7.42
Ion exchange resins	1.75	0.06
Nafion	0.56	0.02
Activated carbon	0.315	0.012
Iridium	0.026	0.001
Platinum	0.0026	0.0001
Total	584	20.62
Energy ($kWh/kg\,H_2$) **[21]**	-	1.67

2.5.3 Compressor and Storage LCI

Compression Operation and Maintenance

The compressor was designed to run simultaneously to the electrolyzer, so the hydraulic aggregate driving the pistons of the compressor is going to be changed the same times as the electrolyzer [20] which is 60 times during the lifetime of the system.

Complete LCI Compressor

The energy to compress the hydrogen is from the electricity generated by the OWF and is 4 kWh/kg H_2.

Table 9: Compressor material [20], [6].

Material	**%**	**Mass** ($g/kg\,H_2$)
Steel	34	5.9
Concrete	40	7
Cast Iron	5	0.87
Copper	2	0.35
Lubricating Oil (including O&M)	17	2.95
Aluminium	1.5	0.26
PP	0.3	0.05
Electronics	0.2	0.03
Total	100	17.4
Energy ($kWh/kg\,H_2$)	—-	1.4

Storage LCI

In the storage stage, a 350 *bar* pressure and type I tanks with capacity to 1000 *kg* of hydrogen will be considered.

Type I storage tanks have a weight density of $1400\,kg/m^3$ **of hydrogen** according to [22] and at 350 *bar* the density of hydrogen is $23\,kg/m^3$ which means a volume of $43.5\,m^3$ for a $1000\,kg\,H_2$ tank capacity with the tank weighting 60.9 *ton*. A lifetime of 20 years was considered for the tanks according to [23], which means 7300 cycles if each tank is used once a day, so the mass of steel is $8.3\,g/kg\,H_2$.

2.5.4 Material Processing and Manufacturing of System Components

The material processing of the materials used for all the system were the ones assumed by the simaPro software.

All the components of the system are assumed to be produced in their own factory. it's considered that the production is within Europe, therefore **Europe grid mix was assumed to be the electricity used for the manufacturing process.**

2.5.5 Transportation

The major diesel consumption comes from the truck transportation, with the total values for configuration A and B being 17.33 and $43.32\,g/kg\,H_2$ respectively.

2.5.6 End of Life

The end of life corresponds to the phase of landfill, recycle and incineration.

In the overall of the system materials, 59% is recycled, 3% incinerated and 38% land filled. The percentage of recycled materials is high because 90% of the steel is recycled which is the material most used in the system with 60%, so the environmental impacts is expected to decrease when the EoL is considered.

2.5.7 Final LCI of the System

In table 10 are presented all the LCI for the configuration A and B. The values in this table are the values introduced as inputs in the simaPro software for configuration A and B.

Table 10: LCI of configuration A and B.

Materials ($g/kg\,H_2$)	**OWF A (PPR = 62%)**	**OWF B (PPR = 25%)**	**PEMWE** ($g/kg\,H_2$)	**Compression**	**Storage**	**Transportation A**	**Transportation B**	**Total A**	**Total B**
Steel	372.76	934.53	6.3	5.9	10	0	0	394.96	956.73
Cast iron	13.87	34.77	0	0.87	0	0	0	14.74	35.64
Aluminium	5.15	12.92	0.16	0.26	0	0	0	5.57	13.34
Copper	4.01	10.06	0.62	0.35	0	0	0	4.98	11.03
Fiber Glass	5.13	12.87	0	0	0	0	0	5.13	12.87
Epoxy resin	3.22	8.06	0	0	0	0	0	3.22	8.06
PE	1.47	3.69	0.186	0	0	0	0	1.656	3.876
PP	1.31	3.28	0	0.05	0	0	0	1.36	3.33
Electronics	0.76	1.9	0.86	0.03	0	0	0	1.65	2.79
Concrete	183.86	460.94	4.32	7	0	0	0	195.18	472.26
Lubricating oil	4.87	12.22	7.42	2.95	0	0	0	15.24	22.59
Ion exchange resins	0	0	0.06	0	0	0	0	0.06	0.06
Nafion	0	0	0.02	0	0	0	0	0.02	0.02
Activated carbon	0	0	0.012	0	0	0	0	0.012	0.012
Iridium	0	0	0.001	0	0	0	0	0.001	0.001
Titanium	0	0	0.66	0	0	0	0	0.66	0.66
Platinum	0	0	0.0001	0	0	0	0	0.0001	0.0001
Diesel	1.03	2.57	0	0	0	17.33	43.32	18.36	45.89
Gasoline	0.58	1.46	0	0	0	0	0	0.58	1.46
Total	598.02	1499.27	20.62	17.41	10	17.33	43.32	663.38	1590.62
Energy ($kWh/kg\,H_2$)	3.07	7.7	1.67	1.4	0.8	0	0	6.94	11.57

2.5.8 Impact Assessment Methodology

SimaPro software is a professional tool to evaluate the environmental impacts of products, processes and services through their life cycle. It allows to model and analyse the life cycle of a product or service in a systematic and transparent way, following the recommendations of the ISO 14040 series (ISO14040, 2006). The midpoints impacts are considered a point in the chain of cause and effect, focusing on unique environmental problems such as climate change and the endpoint method analyses the environmental impact at the end of this chain of cause and effect. In the ReCiPe methodology, eighteen midpoint indicators and three endpoint indicators are calculated.

All the results were considered in the characterisation process, which facilitates the

comparison between impact scores of different impact categories.

3. Results and discussion

3.1. Impact assessment analysis and interpretation

LCA results for each evaluated impact category associated with the scenario considered are reported in this section. A positive impact potential indicates a burden to the environment (negative environmental effect), while a negative potential indicates environmental emissions savings (positive environmental effect).

In this section the values are all in order of the functional unit of $1\,kg$ of H_2.

Midpoint analysis

In Figures 4 and 5 the midpoint analysis with eighteen different categories are presented. The units in the graphics vary between categories and are in order of scale of units. CC, MD and HT are in kg, FD in hg, TE, FEco, MEco and ME in dg, TA, FE, PDF and PMF in g and OD in $0.1\,mg$. It's possible to see that for configuration A the OWF has the biggest impact in almost all categories only losing to the OD category where the PEMWE has a slightly higher influence with 48.24% compared to the 37.65% from the OWF. In the land occupation, ALO has the higher values when compared to ULO and NLT. These values were the expected because in the LCI phase, it's possible to see that the OWF has the major mass contribution by far and is the part of the system that needs more energy. In the WD category, the values are very similar between the OWF and the PEMWE which can be explained by the $10\,kg$ of water needed to produce $1\,kg$ of H_2. The storage of H_2 and transport of material have the lowest impact in every category, because the hydrogen storage tanks are going to be used 7300 times in their lifetime and in the transportation stage is only considered the diesel consumption of the trucks transporting the material necessary.

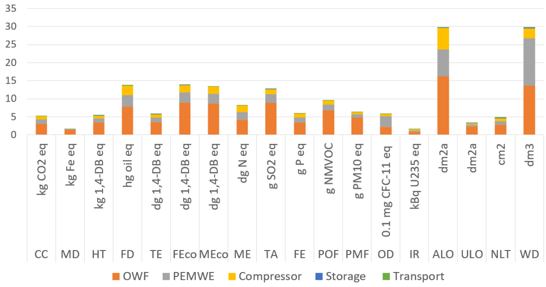

Figure 4: Midpoint analysis of the scenario A.

In configuration B, OWF has the highest influence in all categories because the PPR is going to be 25% for configuration B compared to 62.5% from configuration A, which means that the OWF will have even more impact in all the system because for each OWF there is less hydrogen being produced. Storage of H_2 and transport of material has the lowest impact as in configuration A and as shown in Figure 5.

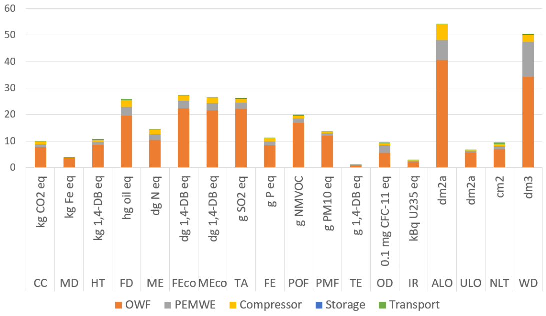

Figure 5: Midpoint analysis of the scenario B.

Endpoint analysis

Figures 6 and 7 show the endpoint analysis of configuration A and B.

For configuration A presented in figure 6, resources is the category with the biggest environmental impacts with 58.3% of the contribution, followed by human health and ecosystems which account for 38.9% and 2.8% respectively.

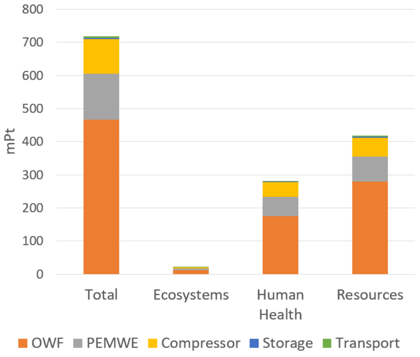

Figure 6: Endpoint analysis of the scenario A.

For configuration B presented in figure 7, resources is also the biggest environmental impact with 59.3%. The contribution from human health and ecosystems is 38% and 2.7% respectively. From the analysis of the figure is possible to understand that the main contribution comes from the OWF with a contribution of 64.9% for configuration A and 81.8% for configuration B. In configuration B the contribution of the OWF is higher than in configuration A because in configuration B, there is part of the energy that is not used to produce hydrogen, while in configuration A almost all the energy from the OWF is used to produce H_2. The contribution from the other stages for configuration A and B are 19.3% and 9.7 % from PEMWE, 14.5% and 7.3% from the compressor, 0.6% and 0.3 % from storage and 0.7% and 0.9% from transport respectively.

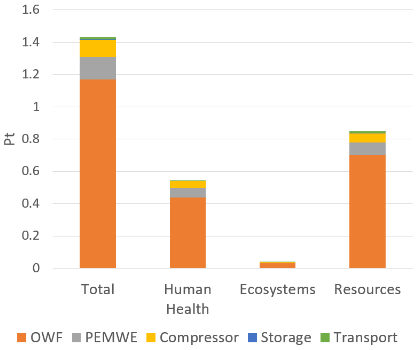

Figure 7: Endpoint analysis of the scenario B.

3.2. Comparison of Scenarios

3.2.1 Configuration A and B

Figure 8 shows the difference between the scenarios A and B for the midpoint parameters in order to the functional unit. There is only necessity to do this comparison for configuration A and B because scenario 1 and 2 have the same values in order to the functional unit, being only different in the demand for hydrogen. Configuration B has higher impacts in every parameter compared to configuration A which is the expected because of the PPR as already explained before and because the allocation of the energy that is injected into the grid in configuration B is not considered. If the functional unit was kWh and all the energy was considered in both configurations, there would be no difference between configurations.

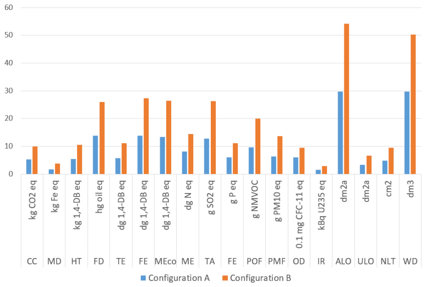

Figure 8: Comparison between scenario A and B using a midpoint analysis.

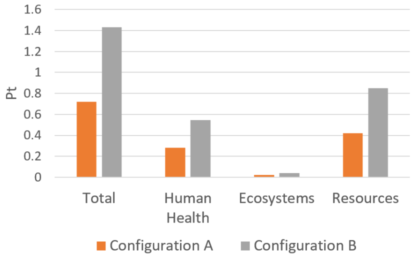

Figure 9: Comparison between scenario A and B using a endpoint analysis.

Figure 9 shows the difference between the scenarios A and B for the endpoint parameters. Configuration B has again higher impacts in every parameter compared to configuration A.

3.3. Discussion of results

3.3.1 Comparison with different energy sources

SMR process has average emissions of $11.5\,kg\,CO_2\,eq./kg\,H_2$ according to [7]. The $CO_2\,eq./kg\,H_2$ for configuration A and B are presented in table 11. **For configuration A** the value of $5.21\,kg\,CO_2\,eq./kg\,H_2$ was found with the major contribution from the OWF with 58.77%, followed by the PEMWE, Compressor, storage and transport with a 22.58%, 18.13%, 0.34% and 0.19% contribution respectively. **For configuration B** the value increases to $9.84\,kg\,CO_2\,eq./kg\,H_2$ with a even bigger contribution of the OWF with 78.02%. This values does not include the EoF and most of the materials can be recycled, reducing the environmental impact by 25-35% according to [17] and [6]. It's going to be considered a reduction of 30% in the CC value of CO_2 emissions considering the EoL process. So, the total emissions are 3.65 and $6.89\,CO_2\,eq./kg\,H_2$ with the EoL for configuration A and B respectively. Comparing with SMR process, the emissions reductions from configuration A are 55% and almost 70% without and with EoL respectively and for configuration B are 15% and 40% without and with EoL respectively. In configuration B the emissions reduction is not the ideal result with low CO_2 emissions reduction compared to the SMR process, but can not be forgotten that this values are in function of kg of H_2 and in configuration B great part of the electricity is going to be injected on the grid which is not take into consideration.

Table 11: GHG emissions ($CO_2\,eq.$), whole system with and without EoL.

Configuration A	CC (kg $CO_2\,eq.$/kg H_2)	%	configuration B	CC (kg $CO_2\,eq.$/ kg H_2)	%
Total without EoL	5.21	100	**Total without EoL**	9.84	100
OWF	3.06	58.77	**OWF**	7.68	78.02
PEMWE	1.18	22.58	**PEMWE**	1.18	11.95
Compressor	0.94	18.13	**Compressor**	0.94	9.6
Storage	0.018	0.34	**Storage**	0.018	0.18
Transport	0.01	0.19	**Transport**	0.025	0.25
EoL	-1.56	-30%	**EoL**	-2.95	-30%
Total with EoL	3.65	-	**Total with EoL**	6.89	-

The values found on the literature for a similar process of this thesis are around $2\,kg\,CO_2\,eq./kg\,H_2$ including EoL and only producing hydrogen. When comparing the results of this thesis with the literature, the value of the configuration A with EoL should be the one to be used. The value is $3.65\,kg\,CO_2\,eq./kg\,H_2$ which is 80% higher when compared to the value of $2\,kg\,CO_2\,eq./kg\,H_2$. This can be explained by the fact that in that study from [20], is only considered a WT and the cable connection to the electrolyzer for the wind farm part and is not even considered the foundation of the WT. In this thesis is considered all the components of the OWF with the FF having the biggest material impact in the inventory of the OWF with 84% of the mass of all the OWF as already stated in the chapter 2 of this thesis.

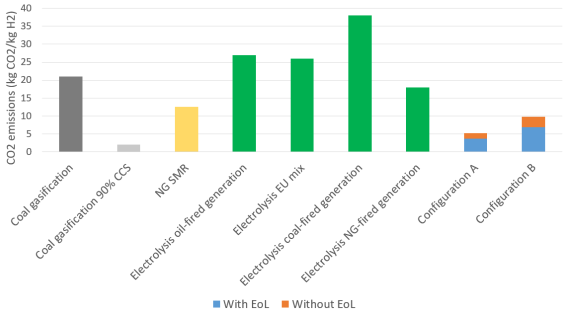

Figure 10: CO_2 emissions during hydrogen production from different energy sources [24].

In Figure 10 is possible to see the $kg\,CO_2/kg\,H_2$ emissions by different energy sources. Electrolysis from coal-fired generation causes $38\,kg\,CO_2/kg\,H_2$, followed by oil fired generation with $27\,kg\,CO_2/kg\,H_2$ and $18\,kg\,CO_2/kg\,H_2$ for natural gas (NG) according to [24]. When compared to the process of electrolysis by coal-fired generation, hydrogen production by the offshore wind energy according to the results of this thesis has 90.4%, 86.3%, 82% and 74.2% less $CO_2/kg\,H_2$ emissions produced for configuration A and B with and without EoL respectively. Compared with electrolysis from oil-fired generation, configuration A has 86.5% and 80.7% with and without EoL $CO_2/kg\,H_2$ emissions reduction and configuration B has 75% and 64% less $CO_2/kg\,H_2$ emissions with and without EoL respectively. Compared with electrolysis from NG, configuration A has 80% and 71% and configuration B has 62% and 45.4% $CO_2/kg\,H_2$ emissions reduction with and without EoL respectively. Electrolysis from EU electricity mix causes $26\,kg\,CO_2/kg\,H_2$ which means a 86.5%, 80%, 73.5% and 62.2% reduction for configuration A and B with and without EoL. Coal gasification has $21\,kg\,CO_2/kg\,H_2$ emissions and SMR from NG has $11.5\,kg\,CO_2/kg\,H_2$. The $CO_2/kg\,H_2$ emissions reduction for configuration A and B with and without EoL respectively are 82.6%, 75.2%, 67.2% and 53.2% compared with coal gasification. For the SMR process from NG the comparison has already been made. Coal gasification with 90% CCS has emissions of only $2.1\,kg\,CO_2/kg\,H_2$ which is 42.5% less than configuration A with EoL. This can be explained by the fact that the emissions in that process are only from the combustion and from the CCS process, without counting with the infrastructure necessary. In Figure 11 it's possible to see the emissions in $g\,CO_2/MJ$ of the respective fuel. It's considered the emissions regarding the production and combustion of the fuel. There are only emissions regarding the combustion in the petrol, diesel and CNG cases which have the major contributions when compared to the production for the same cases. configuration A with and without EoL has lower emissions per MJ of fuel when compared with all the others fuels. Configuration B counting with the EoL stage has only greater emissions when compared to Hydrogen from coal gasification with CCS. If the EoL is not considered, configuration B has almost the same value of the diesel and petrol cases.

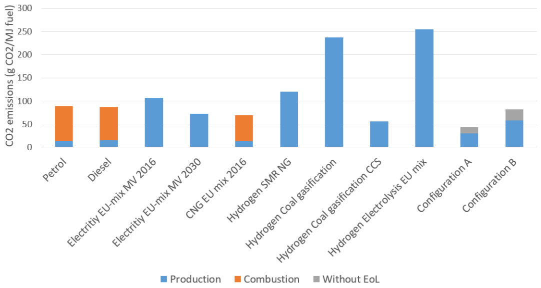

Figure 11: CO_2 emissions per MJ of Final Fuel.

3.3.2 Comparison to mobility from conventional fuels

To obtain a comparison in the mobility sector from conventional fuels, results are compared based on specific GHG emissions ($kg\,CO_2\,eq./km$. Data for conventional fuels are taken from [20] and [25] including upstream processes such as exploration of mineral oil and refinery processes. The GWP of petrol is around $84\,g\,CO_2\,eq./MJ$ [7] and the energy density of petrol is $35\,MJ/L$, which leads to a $2940\,g\,CO_2\,eq./L$ of petrol. Considering a fuel consumption of $6.2\,L/100\,km$ for small vehicles from [20], means a $182.28\,g\,CO_2\,eq./km$ for petrol vehicles.

For diesel vehicles it's around $88\,g\,CO_2\,eq./MJ$ [7] and the energy density of diesel is $45.5\,MJ/L$, which leads to a $4004\,g\,CO_2\,eq./L$ of diesel. Considering a fuel consumption of $4.6\,L/100km$ for small vehicles according to [20] and $40\,L/100km$ for heavy vehicles, this means a $184.18\,g\,CO_2\,eq./km$ and $1601.6\,g\,CO_2\,eq./km$ for small and heavy vehicles respectively.

The values for the small vehicles found for configuration A and B are 52.1 and $98.4\,g\,CO_2\,eq./km$ respectively without the EoL. Considering the EoL stage, the emissions will reduce to $36.5\,g\,CO_2\,eq./km$ for configuration A and $68.6\,g\,CO_2 eq./km$ for configuration B.

For the heavy vehicles, the values for the CO_2 emissions are 521 and $984\,g\,CO_2\,eq./km$ for configuration A and B respectively without the EoL and counting the EoL the values reduce to 365 and $689\,g\,CO_2\,eq./km$ repectively for configuration A and B.

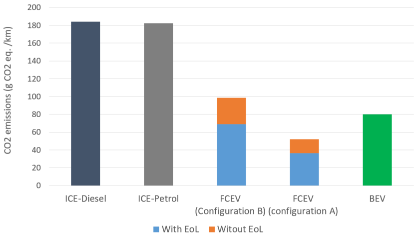

Figure 12: Specific g CO_2 eq./km emissions of different power trains for small vehicles.

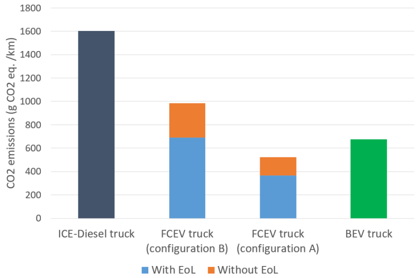

Figure 13: Specific g CO_2 eq./km emissions of different power trains for heavy vehicles.

In Figures 12 and 13 it's possible to see that the FCEV has always lower $g\,CO_2\,eq./km$ emissions when compared to the diesel and petrol vehicles in small and heavy vehicles.

For small vehicles shown in Figure 12, there is a reduction of almost 80% and 60% for configuration A and B with EoL and 70% and 50% for configuration A and B respectively without EoL in the $g\,CO_2\,eq./km$ emissions comparing with ICE vehicles. When compared to a small battery electric vehicle (BEV), only the configuration B without EoL has higher emissions, with around 20% more $g\,CO_2\,eq./km$ emissions than a BEV vehicle. Configuration A with and without EoL have 55% and 35% respectively lower $g\,CO_2\,eq./km$ emissions and configuration B with EoL has 14% $g\,CO_2\,eq./km$ emissions reduction when compared to BEV.

For heavy vehicles presented in Figure 13 there is a reduction of 77.2% and 67.5% in the $g\,CO_2\,eq./km$ emissions for configuration A with and without EoL respectively and of 57% and 38.5 for configuration B with and without EoL, comparing with an ICE diesel truck. Comparing with an heavy BEV which has 674 $g\,CO_2\,eq./km$ emissions, only configuration A has lower emissions with a 46% and 23% $g\,CO_2\,eq./km$ emissions reduction with and without EoL. Configuration B has 2.2% and 46% higher emissions with and without EoL comparing with an heavy BEV.

4. Conclusions

Throughout the course of this study, taking into account the initial objectives, several achievements were attained: Currently, there are three main technologies of electrolyzers: AWE, PEM and SOE. A PEMWE Siemens Silyzer 300 was chosen for the calculations due to it's better operational flexibility to the intermittent wind production. There are many ways to store hydrogen, with either the necessity to compress the hydrogen or to lower the temperature to very low levels because of the high volume density. In this thesis the hydrogen is compressed and stored in tanks type I, because although these tanks are the heaviest, they are the best economical option without expensive materials. In the LCI phase, it was concluded that the major material contribution came from the OWF with around 90% of the weight of the system. In the OWF, the major contribution is from the FF with 84% of the total weight of the OWF. Reducing the FF quantity of material would decrease significantly the environmental impacts, although would not be simple because the FF needs to have a proper mass distribution in order to maintain stability on the WT. The storage stage has a very low contribution for the $CO_2\,eq./kg\,H_2$ emissions with only 0.34% and 0.18% contribution from configuration A and B respectively, because the storage tanks are used every day for 20 years. This means that during their lifetime they complete a total of 7300 cycles of filling up the tanks with hydrogen and empty the hydrogen in the HRS, resulting in a high utilization of these tanks. For the impact assessment, midpoint and endpoint analysis were considered for a better evaluation of the environmental impacts. In the midpoint, OWF had the greatest environmental impact in every category, except on the ozone depletion (OD) category in configuration A where PEMWE has greater impact. In the end point analysis, it became clear that resources are the category with the most impact for both configurations. In the CC category the values obtained were 3.65 and 5.21 $kg\,CO_2\,eq./kg\,H_2$ for configuration A with and without EoL and 6.89 and 9.84 $kg\,CO_2$ eq./kg of H_2 for configuration B with and without EoL respectively. Compared to the SMR process, there is between 55-70% reduction in emissions for configuration A and 15-40% for configuration B respectively. Comparing the CO_2 emissions with coal gasification and electrolysis from non renewable energy sources, it was possible to conclude that the reduction on $kg\,CO_2/kg\,H_2$ emissions were between 40-90%. Comparing with coal gasification with 90% CCS, the $kg\,CO_2/kg\,H_2$ emissions are between 40-80% higher. According to the values obtained in this thesis, hydrogen is a better option than fossil fuels in a LCA perspective for the mobility sector, with a range of approximately 40-80% reduction of the $CO_2\,eq./km$ emissions compared to ICE vehicles. Compared to BEV, configuration A has between 20-55% less $CO_2\,eq./km$ emissions, so green hydrogen is an alternative which should be exploited according to this study and from a LCA perspective.

References

[1] Emanuele Taibi, Raul Miranda, and Thomas Winkel. Hydrogen from renewable power: Technology outlook for the energy transition. *International Renewable Energy Agency*, 2018.

[2] Dolf Gielen and Ricardo Gorini. Future of wind: Deployment, investment, technology, grid integration and socio-economic aspects (a global energy transformation paper). *International Renewable Energy Agency*, 2019.

[3] Direção-Geral de Energia e Geologia. Road map for carbon neutrality 2050: Long term strategy for carbon neutrality of the portuguese economy by 2050. 2019.

[4] Direçao-Geral de Energia e Geologia. Roteiro e plano de ação para o hidrogénio em portugal.

[5] Paulo Partidário, Ricardo Aguiar, Paulo Martins, Carmen Rangel, and Isabel Cabrita. The hydrogen roadmap in the Portuguese energy system – Developing the P2G case. *International Journal of Hydrogen Energy*, 45, 2019.

[6] Samane Ghandehariun and Amit Kumar. Life cycle assessment of wind-based hydrogen production in western canada. *International Journal of Hydrogen Energy*, 41(22):9696–9704, 2016.

[7] Kay Bareiß, Cristina de la Rua, Maximilian Möckl, and Thomas Hamacher. Life cycle assessment of hydrogen from proton exchange membrane water electrolysis in future energy systems. *Applied Energy*, 237:862 – 872, 2019.

[8] Tiago José Rosário Lucas. Feasibility of wind energy for hydrogen production: the windfloat atlantic case-study, 2020.

[9] Veículos rodoviários motorizados em circulação: total e por tipo de veículos.

[10] Thomas D., Mertens D. (Colruyt), M. (Sustesco), Van der Laak W., and Francois I. Power-to-gas roadmap for flanders. *WaterstofNet vzw*, 2016.

[11] B.M. (Bas) Roelofs. *Material Recovery from Dutch Wind Energy*. PhD thesis, TU Delft, 2020.

[12] Juhua Yang, Yuan Chang, Lixiao Zhang, Yan Hao, Qin Yan, and Changbo Wang. The lifecycle energy and environmental emissions of a typical offshore wind farm in china. *Journal of Cleaner Production*, 180:316–324, 2018.

[13] Shifeng Wang, Sicong Wang, and Jinxiang Liu. Life-cycle green-house gas emissions of onshore and offshore wind turbines. *Journal of Cleaner Production*, 210:804–810, 2019.

[14] L. Fingersh, M. Hand, and A. Laxson. Wind turbine design cost and scaling model. 2006.

[15] Priyanka Razdan and Peter Garrett. Life Cycle Assessment of Electricity Production from an onshore V110-2.0 MW Wind Plant. *Vestas Wind Systems A/S*, 12 2015.

[16] Nilay Elginoz and Bilge Bas. Life cycle assessment of a multi-use offshore platform: Combining wind and wave energy production. *Ocean Engineering*, 145:430–443, 2017.

[17] Yu-Fong Huang, Xing-Jia Gan, and Pei-Te Chiueh. Life cycle assessment and net energy analysis of offshore wind power systems. *Renewable Energy*, 102:98–106, 2017.

[18] M.J. Kaiser and B. Snyder. Offshore Wind Energy Installation and Decommissioning Cost Estimation in the U.S. Outer Continental Shelf. U.S. Dept. of the Interior. 2011.

[19] Large scale pem electrolysis for industrial applications.

[20] Jörg Burkhardt, Andreas Patyk, Philippe Tanguy, and Carsten Retzke. Hydrogen mobility from wind energy – a life cycle assessment focusing on the fuel supply. *Applied Energy*, 181: 54–64, 2016.

[21] Mathieu Delpierre. Assessing the environmental impacts of wind-based hydrogen production in the Netherlands using ex-ante LCA and scenarios analysis. *Journal of Cleaner Production*, 299, 2021.

[22] Ramin Moradi and Katrina M. Groth. Hydrogen storage and delivery: Review of the state of the art technologies and risk and reliability analysis. *International Journal of Hydrogen Energy*, 44(23):12254–12269, 2019.

[23] O. Comond and D. Perreux. Methodology to improve the lifetime of type III HP tank with a steel liner. *International Journal of Hydrogen Energy*, 34(7):3077–3090, 2009.

[24] IEA. The future of hydrogen. 2019.

[25] Eckard Helmers, Joana Leitão, Uwe Tietge, and Tim Butler. CO2-equivalent emissions from European passenger vehicles in the years 1995–2015 based on real-world use: Assessing the climate benefit of the European “diesel boom”. *Atmospheric Environment*, 198:122–132, 2019.