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Environmental assessment of an industrial power-to-hydrogen-to-power system - towards decarbonization of existing natural gas fueled CHP plants

Alexandros Macheras[a], Despina Magiri-Skouloudi[b], Sotirios Karellas[c]

[a] Laboratory of Steam Boilers and Thermal Plants, National University of Athens, Heroon Polytechniou 9, 15780 Zografou, Athens, Greece, alexmacheras1996@gmail.com
[b] Laboratory of Steam Boilers and Thermal Plants, National University of Athens, Heroon Polytechniou 9, 15780 Zografou, Athens, Greece, dmskouloudi@mail.ntua.gr, CA
[c] Laboratory of Steam Boilers and Thermal Plants, National University of Athens, Heroon Polytechniou 9, 15780 Zografou, Athens, Greece, sotokar@mail.ntua.gr

Abstract:

Deep decarbonization of the industry sector is a crucial milestone for achieving the EU climate targets towards 2030, as the decarbonization potential of the sector is high, however the transformation required is inherently challenging. In this regard, a preliminary Life Cycle Analysis (LCA) examining the environmental impacts of a green hydrogen-based power-to-H_2-to-power pilot plant is hereby presented focusing on a case study. The studied unit, consisting of hydrogen production, storage and combustion sub-systems, will be integrated into an existing 12MW_{el} natural gas-fueled industrial CHP plant in Saillat-sur-Vienne, France. A number of affecting parameters were identified, e.g. annual operating hours of the electrolyzer, electrolyzer capacity, the allocation of the environmental impacts, electricity source. Their impact on the overall system performance was investigated via sensitivity analysis. An up-scaled case study was also examined, based on a 132.5 MW_{el} natural gas-fueled industrial CHP plant in Viotia, Greece. Based on the studied scenarios, a global warming potential (GWP) decrease in the order of 95% (in kg CO_2-eq. per MJ of produced electricity) is possible for operation with 100% green hydrogen, while the terrestrial acidification impact indicator (in kg SO_2-eq. per MJ of produced electricity) for the same operation is decreased by more than 46%.

Keywords:

Power-to-H_2-to-power; Life cycle analysis (LCA); Decarbonization; Hydrogen energy storage; Sustainability.

1. Introduction

The demand for hydrogen continues to rise globally, with many EU member states acknowledging its critical role in their national energy and climate strategies [1]. The demand for sustainably produced hydrogen in particular has gained significant momentum, both within businesses and regulatory and governance institutions [2], as it is expected to play a major role as an energy carrier in a future climate-neutral economy [1]. Economically and environmentally sustainable hydrogen production is recognized as a vital precondition for the development of a sustainable economy based on H_2. The main current pathway for hydrogen production is from non-renewable energy sources, such as the consumption of natural gas in steam methane reforming (SMR). Apart from that, hydrogen can be produced using a number of technologies: thermochemical (e.g. oil cracking, coal gasification), electrolytic (either alkaline - AE -, proton exchange membrane - PEM - or high temperature electrolysis based on solid oxide electrolyzers - SOEC), biological or more complex processes, e.g. photoelectrochemical processes. Despite technological advances, H_2 production from natural gas is considered unprofitable as it is estimated to be 2 to 3 times more expensive than gasoline production from crude oil. However, SMR leads to lower GHG emissions compared to other H_2 production methods based on fossil fuels [3].

One of the most efficient solutions for hydrogen production is to consume renewable electricity from variable renewable energy sources (VRES), such as wind farms and photovoltaics. This way, two problems can be solved simultaneously; on one hand, the hydrogen generated is renewable, while on the other hand, the electricity curtailment from VRES is avoided through conversion and conservation in a chemical energy storage process. When needed, the produced hydrogen can be converted back to clean electricity. It needs to be noted at this point that a number of gas turbine (GT) designs are already able to run on high hydrogen shares, therefore retrofitting requirements are generally low. The entire hydrogen generation, storage and consumption cycle is what is referred to as a power-to-H_2-to-power application. These systems can greatly enhance the flexibility of existing power grids, allowing higher degrees of VRES penetration, since hydrogen can become a long-term storage option to balance seasonal fluctuations in electricity demand or generation.

To date, to the authors' best knowledge, a very small number of LCA studies were conducted covering entire power-to-X-to-power cycles. The majority of LCA studies focuses on the power-to-X part. The same trend is observed with power-to-H_2-to-power systems. With respect to power-to-H_2 systems, a literature review on recent LCA studies, covering both state-of-the-art installations and future projections, revealed that the majority of them focus on GWP and terrestrial acidification (TA) potential. Main methodological assumptions and results from the literature review are summarized in Table 1.

The resulting environmental impacts vary greatly in both selected categories, as can be seen in Table 1. This can be explained given the complex nature of such systems. This complexity includes differences in equipment selection, scale, design and configuration, as well as different options of external power supply, depending on the local energy production mix and the RES current or future potential of the targeted location in each study. Therefore, these results are not directly comparable with those of the present study, since special attention must first be given to all underlying methodological and technical differences. It is observed that most LCA studies report their findings on a mass basis (per kg H_2); however, the energy content of the produced hydrogen, commonly expressed through its high heating value (HHV), is also a widely accepted selection. Findings from an evaluation of H_2 production through combining a solid oxide (SOEC) electrolysis plant with a nuclear power plant [4], as well as an SMR-H_2 [5] production case study are also included in the table for comparison purposes.

Table 1. Summary of literature overview

Reference year	LCA tools	Functional unit	System boundaries	Technology, nominal capacity	GWP (kg CO_2-eq)	TA (kg SO_2-eq)
2050 [6]	ReCiPe 2016	1 kWh_e	Power-to-H_2-to-power	881 MW	0.07	0.4×10^{-3}
2021 [7]	Sima Pro, ReCiPe 2016	1 kg H_2	Power-to-H_2	PEM, 10 MW	0.26	-
2015 [4]	Sima Pro, ecoinvent	1 kg H_2	Power-to-H_2	SOEC	0.42	-
2050 [8]	OpenLCA, ecoinvent 3.4	1 kg H_2	Power-to-H_2	PEM, 100 MW - 1 GW	0.77	5.2×10^{-3}
2050 [8]	OpenLCA, ecoinvent 3.4	1 kg H_2	Power-to-H_2	AE, 100 MW - 1 GW	0.7 - 0.8	5.3 - 5.7×10^{-3}
2017 [9]	Sima Pro, ecoinvent 3.3	1 kg H_2	Power-to-H_2	PEM, 1 MW	29.5	4.7
2050 [9]	Sima Pro, ecoinvent 3.3	1 kg H_2	Power-to-H_2	PEM, 1 MW	3	2.1
2017 [10]	Umberto NXT, GaBi, CML	1 MJ H_2	Power-to-H_2	AE, 5 MW	0.02	0.3×10^{-4}
2016 [11]	Sima Pro, ecoinvent 3.1	1 MJ H_2	Power-to-H_2	PEM, 100 kW	5×10^{-3}	-
2015 [12]	GaBi 5	1 MJ H_2	Power-to-H_2	PEM, 1 MW	5×10^{-3}	-
2018 [5]	GREET 2017	1 kg H_2	Power-to-H_2	PEM, N/A	2.21	11.8×10^{-3}
2018 [5]	GREET 2017	1 kg H_2	Power-to-H_2	SOEC, N/A	5.1	7.8×10^{-3}
2018 [5]	GREET 2017	1 kg H_2	SMR-to-H_2	N/A	12.13	8.7×10^{-3}

The present study, investigating the HYFLEXPOWER pilot installation to be coupled with the 12 MW_{el} NG-fueled CHP plant of a paper mill located in Saillat-sur-Vienne, France, focuses on assessing the system's environmental performance and providing insights on potential future improvements of large scale industrial power-to-H_2-to-power systems, to be integrated in both fossil-based or retrofitted industries or power plants.

An up-scaled scenario is also evaluated in this direction, using the 132,5 MW_{el} CHP plant of an aluminum plant located in Viotia, Greece as a basis.

2. System description

Following the ISO 14040:2006 and 14044:2006 standards, the study consists of four stages: goal and scope definition, inventory analysis, impact assessment and interpretation of results. The LCA study was performed using Sima Pro v.9.1.1 software, while the life cycle inventory (LCI) for the system was compiled using the attributional approach of the Ecoinvent v.3.7 database, cut-off model. Impact assessment was performed using the midpoint and endpoint versions of the ReCiPe 2016 method, hierarchist (H) perspective. The main product of the studied system is electricity; however, heat is also generated from the CHP plant, while oxygen is also generated in the electrolysis unit. Therefore, the studied processes are multifunctional. Sub-division is selected as the preferred strategy to resolve multifunctionality. Where sub-division was not possible, mass, economic or energy allocation of the impacts among the input and output flows was implemented. For the distribution of impacts between the heat and electricity produced by the CHP unit, exergy allocation is followed, according to EU legislation [13]. Within the sensitivity analysis, the allocation methods were altered in order to provide more support to technology developers during decision making.

The equipment being installed for the HYFLEXPOWER pilot plant installation consists of: a PEM electrolyzer of 1.25 MW nominal power, a hydrogen compressor and three hydrogen storage tanks with a total volume of 69 m^3, along with the necessary piping and process control instrumentation. Minor GT modifications are required, mainly regarding the burners, fuel provision and control systems.

2.1. Goal and scope definition

The present analysis focuses on the electricity generated by the system, with the heat regarded as a co-product. Selected system boundaries include four main stages, namely supply of resources and raw materials, equipment construction, operation, as well as end-of-life waste management scenarios. Equipment construction and assembly for all components of the pilot unit is considered to take place in France. Any available information on significant transport activities (e.g. those modelled in global market datasets of the ecoinvent database) are also included in the LCI. In this sense, the study is considered a «Cradle-to-grave» analysis. System components are assumed to be constructed in the EU, while their assembly takes place in France. Whenever available, country-level data were used for background processes, while global market datasets were considered in other cases. The existing installation is considered to be operating at a yearly capacity factor of 95%. The *operational lifetime* of the system is estimated (based on manufacturers' inputs) at 20 years. The *functional unit* was selected as 1 MJ of electricity generated by the system. System boundaries are schematically depicted in Figure 1 within the green dashed line, while background processes are colored blue.

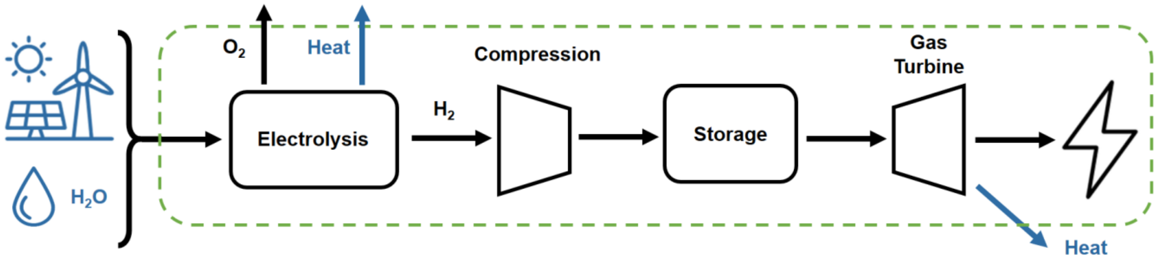

Figure 1: System boundaries, main components and processes

In a later step, in the form of a sensitivity analysis, other alternative scenarios were examined, apart from the reference scenario developed to illustrate the annual operation of the facility. The annual operating hours of the electrolyzer, its efficiency and its installed capacity, the impact allocation method regarding the environmental impacts at different stages of the process, as well as the source of electricity were selected as major impacting parameters.

Availability and quality of data – limitations of the study: since the studied installation is still at the construction stage, information on component design and operational parameters are not yet disclosed in detail for all parts of the system. In this context, existing gaps in data are filled by assumptions based on relevant literature and design/sizing calculations or estimations based on international standards and norms. Main assumptions were reviewed by the HYFLEXPOWER project coordinating team and the CHP plant operators. The availability of curtailed electricity for hydrogen generation is assessed based on year-long (2020) data from the French grid from the ENTSO-E platform [14]. Power pricing data were also taken from recent reports [14, 15]. Instrumentation, sensors, safety equipment and other auxiliary systems are not included in the present LCI. Additional processing and energy consumption for end-of-life decommissioning of the installation was not included in the LCA models. Heat integration utilizing the waste heat dissipated during electrolyzer operation is not considered within the scope of the present study. Oxygen storage and transport / use scenarios are also not included in the LCI.

3. Inventory Analysis - General assumptions

LCI information on the design, construction and operation of system components is retrieved from component manufacturers whenever possible. The detailed LCI of the hydrogen compressor was not currently available at the time of data collection, therefore only the power consumption during operation is taken into account for hydrogen compression. Other general assumptions are listed below:

- Regarding equipment transportation, all long distance transportation (>200 km) is considered to take place via 16 – 32-ton trucks.
- Manufacturing of prototype components takes place in Germany, thus an average transport of 1000 km is considered. Non-prototype components, e.g. piping, are considered to be manufactured in France and transported for 500 km.
- O&M inventory is modelled according to available input from equipment manufacturers. All materials required for equipment maintenance and replacement are considered to be locally manufactured and transported via a 3.5-ton truck for 200 km.
- The distance to the end-of-life waste treatment facility is taken as 100 km and waste is transported from the plant via a 21-ton truck.
- With respect to the end-of-life phase, all metallic and plastic components are considered to be 100% recycled. Any materials for which recycling datasets are not available through the ecoinvent database are assumed to be landfilled following appropriate waste treatment practices.

3.1. Scenario development

A number of scenarios were developed to form the basis of the present case study. A brief description of each scenario follows.

3.1.1. Scenario 1.1: Pilot scale existing installation - paper mill CHP plant, Saillat-sur-Vienne, France

The existing CHP plant consists of a Siemens 12 MW_{el} gas turbine covering the annual heat demand of a neighboring paper mill. The GT can currently be supplied with a maximum hydrogen percentage of 5 % vol. Annual operational data for the existing NG-fueled CHP plant were provided by Siemens Energy, Engie and CENTRAX [16, 17]. The electrical efficiency of the GT is set as 34.2%. An annual operation of 8322 hours is considered.

3.1.2. Scenario 1.2: HYFLEXPOWER pilot installation - reference scenario, Saillat-sur-Vienne, France

For the HYFLEXPOWER power-to-H_2-to-power system, the LCI for electrolyzer construction, as well as the required balance-of-plant (BOP) components, was modelled by upscaling the LCI of a 1 MW PEM electrolyzer from a recent study [9], while operational data was provided by Siemens Energy. Regarding the maintenance phase, which is scheduled every 5300 hours, an existing dataset from ecoinvent regarding a 2 kW PEM electrolyzer was up-scaled to 1.25 MW capacity. The 1.25 MW electrolyzer is modelled using an average efficiency of 70%, consuming 400 L/h of deionized water and 1200 kW of electricity for the production of 16.9 kg/h high purity hydrogen (99.5%-99.9%) and 381.9 kg/h high purity oxygen [18]. The reference scenario for the HYFLEXPOWER installation considers electrolyzer operation during the hours that correspond to an electricity price lower than 20 €/MWh. For 2020, these amount to 2530 hours and the average price during these hours is equal to 9,91 €/MWh [14]. For the reference scenario, the electricity is considered to be sourced from large onshore wind farms (>3 MW unit capacity, modelled using the French dataset from ecoinvent).

Since curtailed electricity is supplied to the studied system, the methodological approaches for burden allocation vary. An option would be to consider this curtailed electricity as a waste, given that it would be otherwise lost, thus allocate zero environmental impacts to it according to the relevant ISO standards. However, since stored electricity by the system is not lost, this assumption is not accurate; furthermore, the electricity supply was found to be perhaps the most important contributor affecting the environmental performance of electrolysis-based systems [19, 20]. The selected approach in the present study was thus to allocate a fraction of the environmental burdens of the electricity supply chain by applying economic allocation on the supplied electricity, using the average price for electrolyzer operation [14] and the average electricity price for French industrial consumers of 102.4 €/MWh [15] for 2020 as reference values. Impact distribution between hydrogen and oxygen generated by the electrolyzer also follows economic allocation, with reference prices of 10 €/kg and 1 €/kg respectively [21].

Hydrogen is considered to be generated at 35 bar and consequently compressed at 200 bar (gas storage) prior to storage, while it is decompressed at 21 bar before injecting in the gas turbine for combustion. It is thus estimated that 59 hours of continuous electrolyzer operation are required to completely fill the storage tanks. However, emptying of the storage tanks happens at a much quicker pace (approx. 1 hour for operation fueled with 100% H_2). Therefore, it is assumed that there is no simultaneous generation and consumption of hydrogen throughout the unit's annual operation. Based on these assumptions, the annual electricity production from H_2 is calculated at 490.6 MW_e/a. The annual consumption of hydrogen then amounts to 0.49% on fuel thermal input basis. Post-combustion of hydrogen in the existing HRSG unit is considered uneconomical, since its efficiency is lower than the CHP unit and heat selling price is not high enough to justify the use of hydrogen solely for heat generation; therefore, hydrogen post-combustion is not investigated in the present study.

Information on the operational parameters and required GT modifications was provided by Siemens Energy, Engie and CENTRAX. Turbine modifications were modelled based on the existing LCI for the construction of a 10MW gas turbine in Europe from the ecoinvent database (Gas turbine, 10MW electrical (RER) construction). In particular, 640 kg of reinforcing carbon steel (RER) and the required "average metal working, GLO" activity from ecoinvent were added as an estimation for modelling the GT modifications. The annual loads are expected to remain constant regardless of the consumed fuel mix. The LCI of the hydrogen storage tanks was compiled based on construction information from DoE [22], while the LCI covering the construction of hydrogen piping and fittings was estimated according to ASME/ANSI B36.10/19 standard [23], selecting Schedule 80 piping wall thickness.

3.1.3. Scenario 1.3: Large scale industrial installation - existing aluminum facility CHP plant, Viotia, Greece

The evaluation of the performance of a larger installation was afterwards performed, using a 132.5 MWe GT unit as the basis of a hypothetical future scenario. This GT is part of the CHP plant providing heat to the neighboring aluminum industry. The annual operational data of the existing plant were provided by Aluminium of Greece. A total of 8000 hours of annual operation are considered in this case.

3.1.4. Scenario 1.4: Large scale power-to-H2-to-power scenario – aluminum CHP plant, Viotia, Greece

The hypothetical future scenario was developed by extrapolating equipment design and operation to large scale. An advanced electrolyzer model by Siemens Energy, with a nominal capacity of 17.5 MW, maximum H_2 generation of 340 kg/h and deionized water consumption of 10 L/kg H_2. The hydrogen storage department consists of 11 hydrogen storage tanks with a capacity of 1 ton each. Filling time is estimated at 32.4 hours. Data on RES curtailment for the Greek grid is not yet available; therefore, ENTSO-E data for the French grid is again used to estimate annual amounts of curtailed electricity. Again for the reference scenario, the hours corresponding to prices lower than 20 €/MWh are 2530, however taking into account the assumption of nonsimultaneous hydrogen generation and consumption, the annual operating hours of the electrolyzer drop to 2466.5, resulting in a 0.9% annual consumption of hydrogen on fuel thermal input basis.

4. Impact Assessment Results

As already mentioned, the analysis was conducted in Sima Pro software, using the ReCiPe 2016 method. The conducted contribution analysis verified the prevalence of electrolyzer construction in all impact categories for the reference scenario in both the pilot unit (as shown in Figure 2) and the future large scale scenario (as shown in Figure 3). The most apparent difference between the two installations is the significantly lower proportion of electrolyzer manufacturing on the overall GWP of the life cycle of the large scale unit, when compared to the pilot scale. More specifically, while it dominates the GWP impacts of the smaller unit, at Fig. 3 the dominant life cycle stage is that of electrolyzer operation. The same trend is observed between the two systems in all impact indicators.

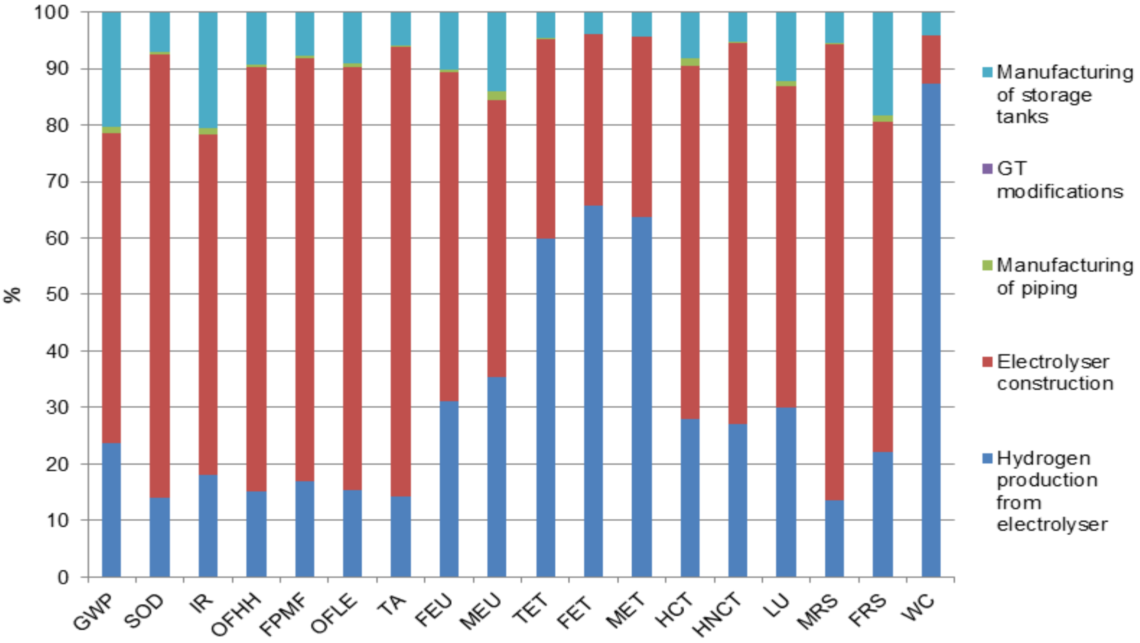

Figure 2: Impact assessment of 1MJ of electricity produced by the pilot scale HYFLEXPOWER installation (Sc.1.2) – fuel mix: 100% hydrogen

The absolute values for the two main examined indicators are presented in Table 2. For both studied systems, the average impact per MJ of electricity produced during the entire year is not substantially lower than that of the NG-fueled operation. This happens because there are at present not as high amounts of curtailed electricity throughout the year, in order to maintain a steady supply of green hydrogen, capable of substituting large amounts of natural gas. As the penetration of VRES steadily increases, however, this is expected to change.

Table 2. Indicator values for 1 MJe produced by the examined systems

Impact category	Unit	Sc. 1.1 (BAU, 100% NG)	Sc. 1.2 (pilot, avg. annual fuel mix)	Sc. 1.2 (pilot, 100% H_2)	Sc. 1.3 (large scale BAU, 100% NG)	Sc. 1.4 (large scale pilot, avg. annual fuel mix)	Sc. 1.4 (large scale pilot, 100% H_2)
GWP	kg CO_2-eq	7,56E-02	7,53E-02	2,66E-03	1,70E-01	1,68E-01	1,30E-03
TA	kg SO_2-eq	7,47E-05	7,45E-05	3,95E-05	1,70E-04	1,68E-04	9,29E-06

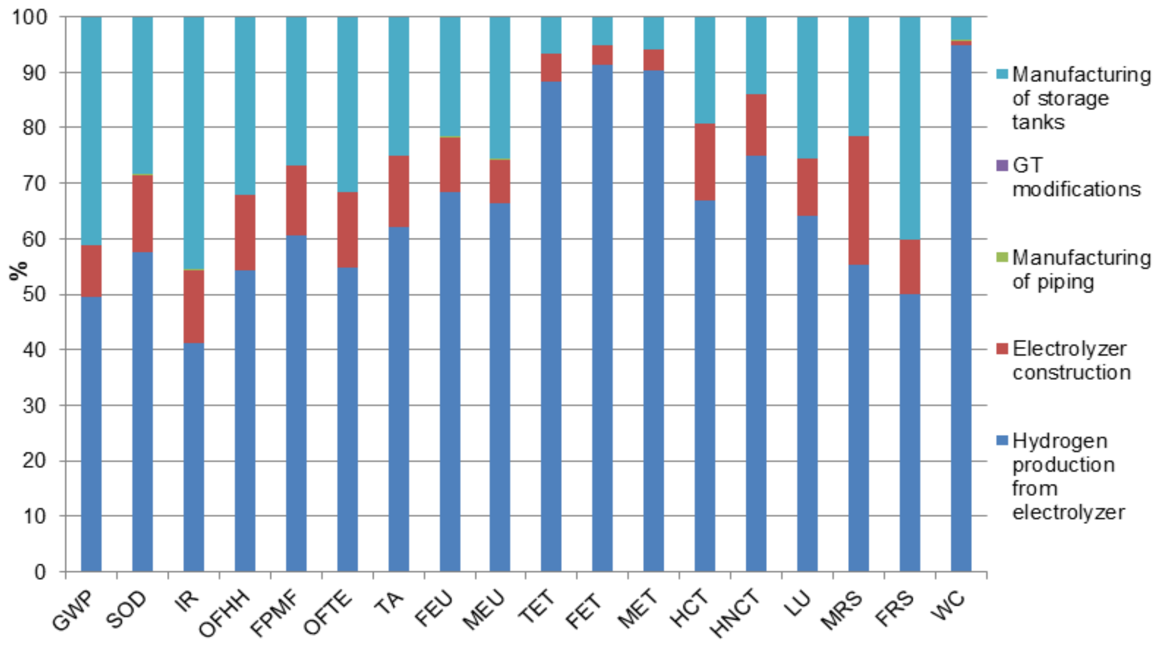

Figure 3: Impact assessment of 1MJ of electricity produced by the large scale scenario (Sc.1.4) – fuel mix: 100% hydrogen

An *uncertainty analysis* was performed for the GWP impact of electricity production from 100% H_2 for both installations using the Monte Carlo-based tool embedded in Sima Pro. The analysis revealed that, for a 95% confidence interval, the CO_2-equivalent emissions of green hydrogen-sourced electricity vary between 2.41 and 2.93 g CO_2-eq/MJ for the pilot installation. For the large scale scenario, again for a 95% confidence interval, the CO_2-equivalent emissions of green hydrogen-sourced electricity vary between 1.16 and 1.46 g CO_2-eq/MJ.

A preliminary *sensitivity analysis* was subsequently conducted for both studied systems (pilot and large scale) by varying the main identified affecting parameters as shown in Table 3. The results are shown in Figure 4. In general, the large scale unit appears to be less sensitive to single factor variations than the pilot installation. However, as the electricity consumption stage affects the large scale more intensely than the pilot scale, the aluminum scenario appears to be more sensitive regarding the selected impact allocation percentage for the electricity supplied to the unit.

Table 3. Variation of selected impacting parameters

Parameter	Unit	Examined range (pilot installation)	Examined range (large scale installation)
Electrolyzer lifetime	hrs	60.000 - 100.000	146.000 - 186.000
Storage capacity	tonnes	0,5 - 1,5	9 - 13
Electrolyzer efficiency	%	60 - 80	65 - 85
Electrolyzer BOP & maintenance	%	± 20	± 20
Electricity impact allocation	%	± 20	± 20

The sensitivity of the studied system regarding the choice of electricity supply was investigated by altering the supply to the reference scenario for the pilot HYFLEXPOWER installation. This was performed using the respective ecoinvent datasets for the French energy production system. Results are presented in Figure 6. The local grid supply mix resulted in the highest GWP, followed by the PV, while wind and hydropower were the most beneficial in terms of GWP. Hydropower however resulted in significant terrestrial acidification (TA) impact, as well as mineral resource scarcity (MRS). On the other hand, wind dominated the categories of freshwater (FET) and marine ecotoxicity (MET), as well as human non-carcinogenic toxicity (HNCT). PV demonstrated the lowest ranking performance of all studied RES, with the highest impacts in ozone formation

(OFHH, OFTE), PM formation (FPMF), TA, freshwater eutrophication (FEU), terrestrial ecotoxicity (TET), human carcinogenic toxicity (HCT) and land use (LU). The impacts on ionizing radiation (IR) are minor in all RES scenarios as compared to the local grid, which is easily explained given the significant proportion of nuclear power in the French grid. The variation of annual *electrolyzer operating hours* was performed for the HYFLEXPOWER pilot installation following the price profiles from the ENTSO-E platform. According to the data, for prices lower than zero, the electrolyzer would operate for 184 hours. For prices lower than 10 €/MWh,

Figure 4: Results of the preliminary sensitivity analysis regarding the GWP impacts of green hydrogen-sourced electricity from pilot (a) and large scale (b) installations, all values in kg CO$_2$-eq/MJe

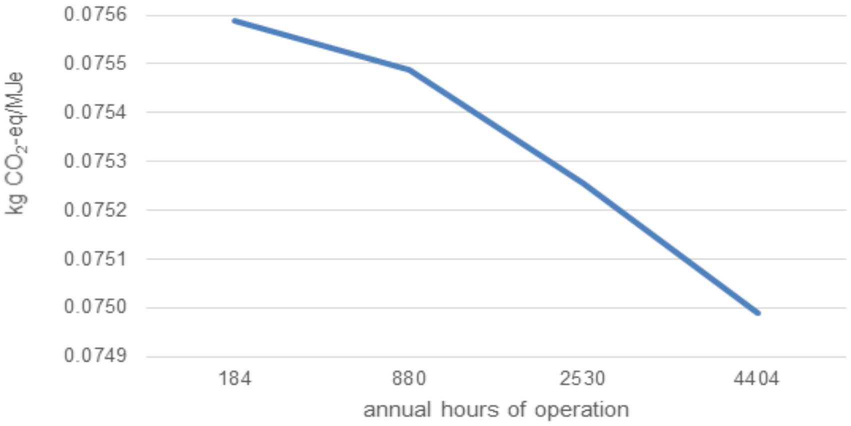

Figure 5: Variance of the GHG emissions of the year-long operation of the HYFLEXPOWER pilot installation, depending on the hours of electrolyzer operation (kg CO$_2$-eq/MJ electricity)

the electrolyzer would operate for 880.5 hours, while for maximum operation, the electrolyzer would operate whenever curtailment would occur, regardless of electricity price, i.e. for 4404 hours. Again, no continuous operation for more than 59 hours was observed for 2020, therefore the produced hydrogen is assumed to be stored for subsequent combustion throughout the year-long operation of the plant. The results are presented in Figure 5.

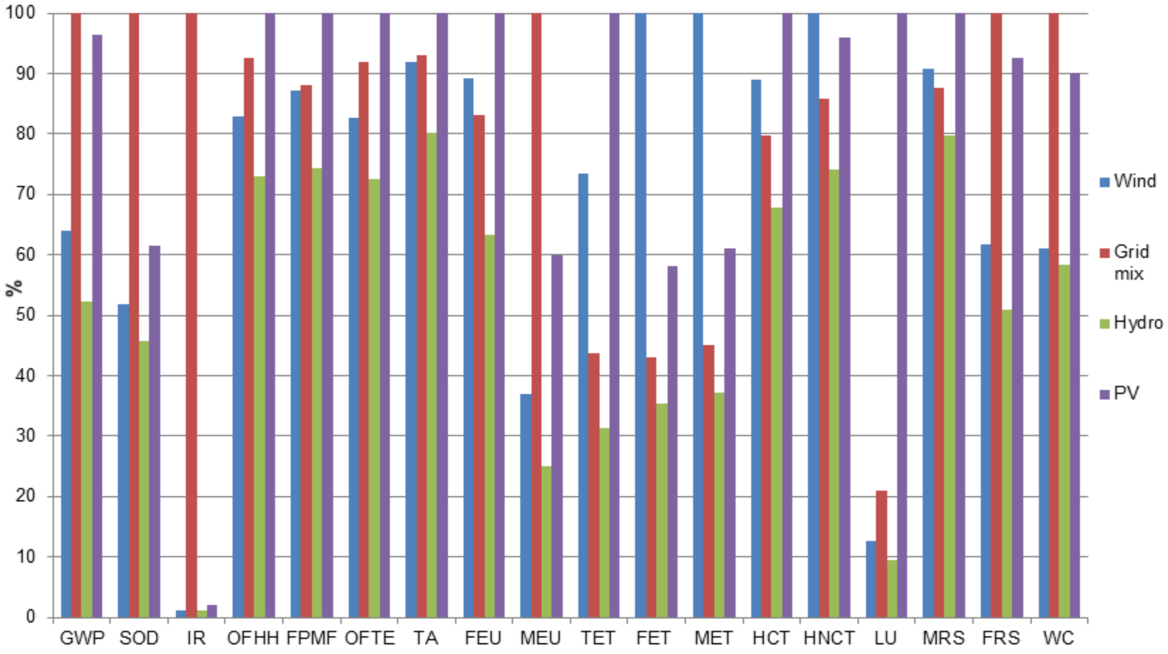

Figure 6: Comparative impact assessment of 1MJ of electricity from hydrogen, generated by the HYFLEXPOWER pilot scale system, connected to different electricity sources

5. Interpretation and Conclusions

In this study, the environmental performance of the HYFLEXPOWER pilot installation was discussed. The results were compared to the performance of the existing conventional CHP GT plant supplied with natural gas from the European grid. Using the ReCiPe 2016 method, the impact of the HYFLEXPOWER system was found to be lower than that of the conventional gas fuelled GT with respect to global warming, ozone depletion and terrestrial acidification among other indicators, mainly due to reduced fossil resource consumption. On the contrary, the performance of the system is worse in terms of ecotoxicity, non-carcinogenic human toxicity and mineral resources, mainly due to the selected energy supply. The differences observed when comparing the pilot scale unit with a large scale hypothetical scenario, based on the Aluminium of Greece NG-fuelled CHP plant, are in line with findings from relevant literature on up-scaling of emerging technologies.

The resulting GHG and SO_2-eq emission savings are low, with 128.4 tons CO_2-eq (0.5 %) and 61.8 tons SO_2-eq (0.2%) saved annually in the HYFLEXPOWER pilot plant reference scenario. However, these values correspond to 2020 curtailment data. If combined with future projections on RES domination in the EU grid, the environmental impacts of the studied installations will drop significantly, demonstrating the potential for industrial decarbonisation through renewable energy storage using power-to-H_2-to-power cycles with green hydrogen as a carrier. Optimization of the design, size, heat integration and other operational parameters of each installation must be performed in site-specific studies, to ensure optimal efficiency and offer maximum NG replacement ratios. The further development of electrolysis technologies will lower the environmental impacts of the studied systems even further, as on the one hand their efficiency and operational lifetime will further increase, and on the other hand less quantities of critical raw materials will be used in manufacturing these components.

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Nomenclature

AE	Alkaline electrolysis	LCA	Life Cycle Assessment
BOP	Balance of plant	LCI	Life Cycle Inventory
CCU	Carbon Capture and Utilisation	LU	Land use
CHP	Cogeneration of Heat and Power	MET	Marine ecotoxicity
CH_4	Methane	MEU	Marine eutrophication
CO	Carbon Monoxide	MRS	Mineral resource scarcity
CO_2	Carbon Dioxide	NG	Natural gas
ETS	Emissions Trading Scheme	OFHH	Ozone formation, Human health
EU	European Union	OFTE	Ozone formation, Terrestrial ecosystems
FET	Freshwater ecotoxicity	PEM	Proton exchange membrane
FEU	Freshwater eutrophication	PM	Particulate matter
FPMF	Fine particulate matter formation	PVC	Polyvinyl Chloride
FRS	Fossil resource scarcity	RED	Renewable Energy Directive (EU)
GHG	Greenhouse Gas	RES	Renewable Energy Source(s)
GT	Gas Turbine	SMR	Steam methane reforming
GWP	Global warming potential	SOD	Stratospheric ozone depletion
HCT	Human carcinogenic toxicity	SOEC	Solid oxide electrolysis cell
HHV	High heating value	SS	Stainless Steel
HNCT	Human non-carcinogenic toxicity	TA	Terrestrial acidification
HRSG	Heat recovery steam generator	TET	Terrestrial ecotoxicity
H_2	Hydrogen	TRL	Technology Readiness Level
H_2O	Water	WC	Water consumption
IR	Ionizing radiation		

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