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Life Cycle Analysis of a Hydrogen Valley with multiple end-users

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Abstract. This paper aims to evaluate the environmental impact along the overall life cycle of the various components of a Hydrogen Valley with multiple end-users fed by green hydrogen. As case study, a hydrogen valley including a MW-scale electrolyser powered by different percentages of energy supplied by a wind farm and/or a photovoltaic plant, and an H₂ storage section is considered. The H₂ produced is used to feed a fleet of fuel cell electric vehicles and a stationary fuel cell, while the residue H₂ is injected in a natural gas pipeline considering a maximum safety limit of 5%vol. When the safety limit is reached, the H₂ overproduction can be used to produce biomethane through a biological hydrogen methanation process. With the aim of analysing the actual contribution of these hydrogen-based ecosystems towards more sustainable energy systems, a Life Cycle Analysis of the hydrogen valley is carried out. The results show that the final use of hydrogen for fuel cell electric vehicles produces the most valuable environmental benefits. Moreover, Hydrogen Valley solutions integrated with photovoltaic plants allows to maximize the use of H₂ in fuel cell electric vehicles and therefore are the most valuable choice from an environmental point of view.

1. Introduction

Hydrogen Valleys are integrated ecosystems based on a combination of several hydrogen technologies covering the entire hydrogen value chain: production, storage, distribution, and final use. They represent the first step towards the development of a large-scale hydrogen economy.

As well known, hydrogen is an energy carrier and can be used to favour the replacement of fossil fuels with Renewable Energy Sources (RES) in the industrial, transport, and heating sectors. Moreover, hydrogen production from water electrolysis processes (the so called “Power-to-Hydrogen” technologies, PtH), could play a fundamental role to support the penetration of RES into the electricity supply mix by providing the required long-term storage capacity for non-dispatchable power generation units. Hydrogen can be directly used as a fuel in the power generation, industrial, transport, and heating sectors or can be further converted into other energy carriers (methane, methanol etc.) [1]. For instance, methane can be produced from hydrogen along with carbon dioxide by using biological or thermochemical methanation processes (“Power-to-Methane” technologies, PtM) [2]. Both hydrogen and methane could be also injected into existing natural gas (NG) pipelines.

Hydrogen production from water electrolysis processes allows storing large amounts of energy for long time, thus enhancing the share of intermittent RES plants, such as solar photovoltaics (PV) or wind farms (WF) into the power generation system.

The optimal design of a hydrogen valley depends on the type and the production profile of RES systems, final use of the hydrogen and end-users’ requests, as well as on the chosen objective function

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(minimum hydrogen production cost, maximum RES electricity use, etc.). Different solutions for green H_2 production systems are being studied and discussed in literature [3] and tested in different European countries [4].

These integrated hydrogen-based ecosystems are therefore very interesting solutions to face the environmental problems produced by fossil fuels. As well known, a fair comparison between different energy production chains requires a detailed environmental impact analysis along the overall life cycle of the various components. The latter can be carried out by using a Life Cycle Analysis (LCA) approach. Many recent LCA studies on hydrogen production and use were discussed in literature. The main objective of these studies was to assess the environmental impact related to the different renewable H_2 production technologies, to the different mix of energy supply and to the different H_2 transport and end-use options. Cucurachi et. al [5] developed an ex-ante LCA focused on the comparison between pilot-scale and large-scale electrolyzers. The results showed that large-scale alkaline and Polymer Electrolyte Membrane (PEM) electrolyzers have the same environmental impact of pilot-scale systems. In any case, the origin of electricity supply remains the most important contribution to the environmental performance of the system. Gerloff [6] analysed the potential environmental impact of the three major technologies for green H_2 production, that is alkaline, PEM and Solid Oxide Electrolyzer Cell (SOEC) solutions powered by a mix energy supply composed of electricity from RES and grid. In any case, by increasing the share of electricity produced by wind farms and PV plants, the reduction of the overall CO_2 emissions will be more and more consistent, especially for the SOEC technology. Wulf et al. [7] performed an environmental LCA comparing different hydrogen transport pathways: compressed and transport by means of pipeline or by pressurized gas truck. The results showed that for most of the cases developed, pipeline solution has the lowest environmental impact. Lastly, Wettstein et al. [8] aimed to identify environmental hotspots in the renewable methanation value chain through a life cycle analysis. Electricity source and consumption in hydrogen production are the crucial parameters for environmental emissions, thus with a reduction in the hydrogen production impact, renewable methane is a potential alternative fuel for sustainable mobility sector.

It is clear, that the environmental impact of the overall technology chain integrated in a Hydrogen valley is not deeply discussed in literature. Therefore, with the aim to fill this gap and to analyse the actual contribution of these integrated hydrogen-based ecosystems towards more sustainable energy systems, a Life Cycle Analysis of a hydrogen valley is carried out in this study. As case study, a hydrogen valley including a MW-scale electrolyser and different end-users is considered. The electrolyser is fed by the electrical energy produced by a wind farm and/or a photovoltaic plant and, in case, green energy supplied by the grid. Specifically, four different configurations in terms of electrolyser sizes, H_2 storage capacity and RES-based power system are considered and analysed

2. Hydrogen Valley

The Hydrogen Valley analysed in this work is based on a MW-scale PEMEL unit fed by a mix of energy supplied by a wind farm (WF) and a photovoltaic (PV) plant.

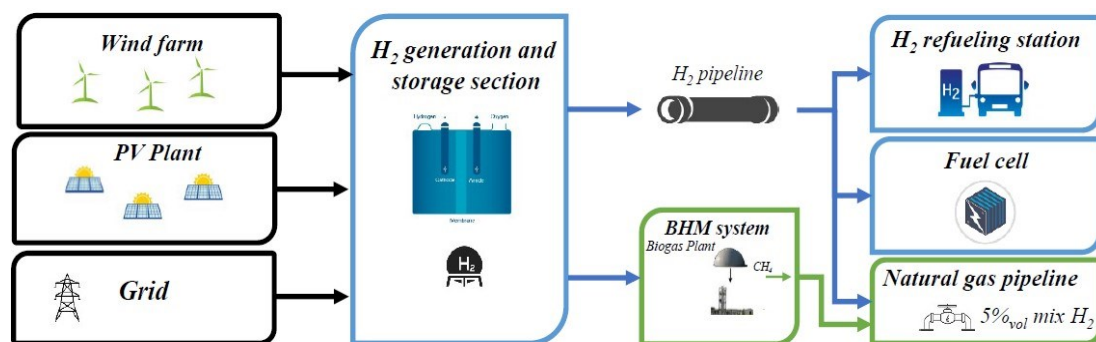


Figure 1. Conceptual scheme of the hydrogen valley [9].

Specifically, the wind farm consists of 30 wind turbines with a total rated power of 45 MW and an expected annual energy production of about 116 GWh/year. A PV system with a rated power output equal to the wind farm (45 MW) and based on 142000 PV modules (360 W power output and 22.1% efficiency at standard conditions) is also considered, with an expected annual energy production of about 80 GWh/year. Therefore, the capacity factor of the PV plant is significantly lower than the WF one, but its daily production profile is more regular and generally leads to a better matching between hydrogen production and end-user demand. In case wind or solar power is not available, the electrolyser can be fed by electricity from the grid. A proton-exchange membrane electrolyser (PEMEL) was selected for the H₂ production section. The hydrogen mass flow rate has been calculated in function of the electrical power input and the PEMEL efficiency, and by considering the AC/DC conversion efficiency and the consumption of pumps and auxiliaries. The nominal conversion efficiency is about 58% but increases with the reduction of the stack power due to the lower ohmic losses (the efficiency is about 80% at 10% of the nominal stack power).

To overcome the mismatch between hydrogen supply and demand, the hydrogen valley is also equipped with an H₂ storage section with an operating pressure range of 2-30 bar. The produced H₂ is used to feed a fleet of fuel cell electric vehicles (FCEV) and a stationary fuel cell, which provides electricity to a train and bus station. In addition, the refueling station is equipped with a compression system to increase the hydrogen pressure up to 500 bar. The residual H₂ is injected in a district natural gas pipeline considering a maximum safety limit of 5%vol. When the safety limit is reached, the eventual H₂ overproduction can be used to produce biomethane through a biological hydrogen methanation process. A more detailed description of the system configuration and the corresponding results of a techno-economic analysis aimed to evaluate the energy performance and the hydrogen production cost can be found in [9]. In the latter paper, the optimal configuration of the hydrogen valley in terms of RES energy supply mix, PEMEL size and H₂ storage capacity was evaluated by determining the expected levelized cost of hydrogen (LCOH).

According to the results of the aforementioned techno-economic analysis, in this paper the environmental impact of the four most interesting solutions have been analysed by means of an LCA approach. Table 1 shows the most important energy data for these four case studies.

Table 1. Main performance of the case studies for the hydrogen valley.

Case study	% WT-PV	% RES to EL	PEMEL [MW]	E.E from the grid [GWh/year]	H ₂ storage [m ³]	H ₂ production [t/year]	SOFC H ₂ demand [t/year]	FCEV H ₂ demand [t/year]	NG grid H ₂ demand [t/year]	BHM H ₂ demand [t/year]
A	100% WT	15%	6.8	0,528	1200	269,6	90	65,7	113,9	0
B	100% PV	15%	6.8	0,392	150	211,3	90	65,7	55,6	0
C	50% WT - 50% PV	15%	6.8	0,287	600	256,1	90	65,7	100,4	0
D	50% WT - 50% PV	25%	11.16	0,072	750	468,4	90	65,7	128,4	184,3

3. LCA methodology

The energy and environmental performance analysis of the four scenarios for the hydrogen valley was carried out using the life cycle analysis (LCA) methodology. The LCA methodology is based on the ISO 14040 guidelines and allows to assess the environmental impact (use of energy and materials, as well as the polluting emissions) of a product throughout its overall life cycle, from raw material extraction to production, use and final disposal [10,11]. The definition of the goal and scope, the system boundaries and the assumptions of the study are described below.

3.1. Goal and scope definition

The analysis aims to compare the impact on human health, resource consumption and the environment of the Hydrogen Valley previously described with that of a reference scenario, in which, as shown in Figure 2, the end users' demands are satisfied in a conventional manner.

In particular, the goal is to evaluate if the environmental impact resulting from the various life-cycle stages of the Hydrogen Valley components could nullify the benefits of replacing conventional energy sources. Various system configurations were developed in order to identify the most environmental solution. The system is designed to produce the hydrogen needed to meet the demand of utilities. Therefore, the functional unit chosen for this LCA study is 1 kg of hydrogen produced by the electrolysis section. The attributional life cycle analysis was carried out on SimaPro 9 software. Data from literature and the Ecoinvent 3.7 database were used to develop the analysis.

3.2. System description

Figure 2 shows the system boundaries for all the four cases developed. In particular, the FCEV fueling station includes the PEM fuel cells and the type IV storage tanks installed onboard the vehicles, as well as the hydrogen compressor. From an environmental perspective, these are the main components that differentiate the FCEVs from traditional buses. The biological methanation process is integrated in the analysis only in scenario D. The hydrogen consumption related to the SOFC and the FCEV fueling station remains constant, meanwhile, depending on the scenario, there will be a different amount of hydrogen injected into the natural gas grid.

As already mentioned, in the reference scenario the end users' demands are satisfied in a conventional manner. Specifically, the electricity for the railway station hub is supplied by the grid, the buses are powered by diesel fuel and fossil natural gas is extracted and burned to generate thermal energy. In order to make a comparison with the case studies, a system expansion approach (which is described in the ISO 14044) has been used to include the reference scenario in the system boundaries. The environmental impact associated with this scenario is actually an avoided impact and therefore has a negative sign.

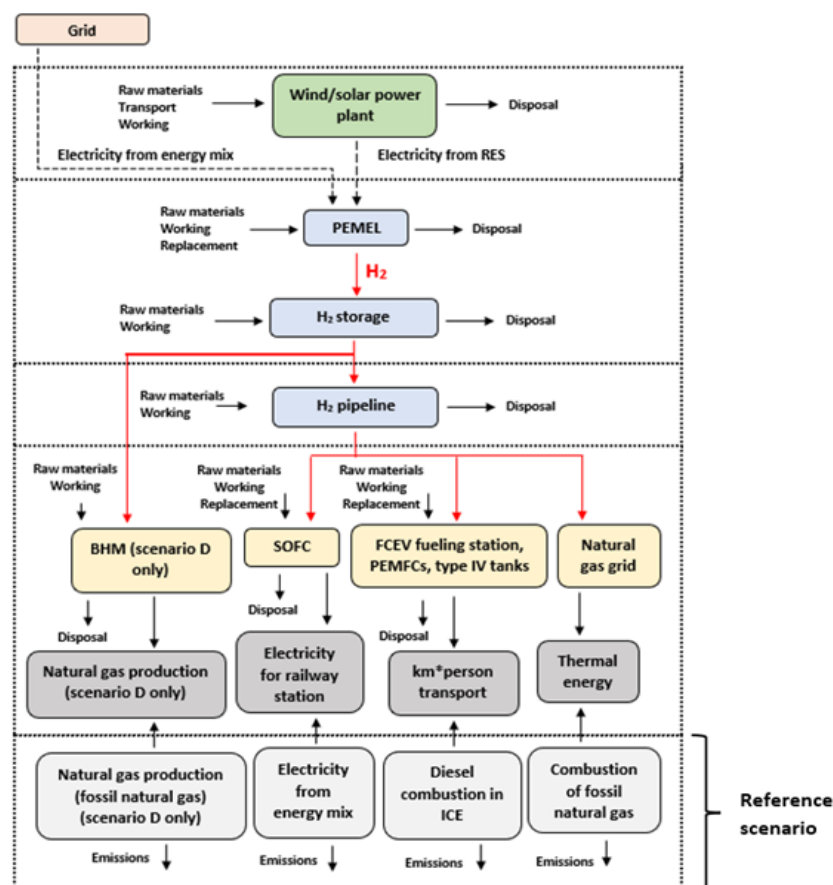


Figure 2. Boundaries of the Hydrogen Valley.

3.3. Life Cycle Inventory Analysis (LCI)

In order to evaluate the environmental impact of the system, the material and energy flows related to the entire life cycle of all the components were defined. The life cycle starts from the extraction of raw materials and ends with the disposal of the components. Materials recycling was assumed for the most common metals, such as steel, aluminum, and copper. In addition, the impact of the transport phase was taken into account only for the heavier components (wind farm and PV solar plant), while it was assumed as negligible for the others. Since this is a greenfield application, no impact related to the decommissioning of pre-existing components or infrastructure has been considered.

The wind farm is modeled according to the data published by Vestas [12,13] and by A. Schreiber et al. [14]. The inventory also takes into account direct land occupation as reported by P. Denholm et al. [15]. The PV plant is based on the 2020 IEA-PVPS Task 12 report [16], with additions from the same 2011 report [17]. The PEM electrolyser model is based on the study carried out by N. Gerloff et al. [6]. The data for the hydrogen transport pipeline and charging station for FCEVs are taken from the study of C. Wulf et al. [7] PEMFCs for vehicular applications, along with type IV tanks installed in vehicles, are based on the study by L. Usai et al. [18]. The SOFC model is developed by adapting the study of G. Di Florio et al. [19], and the anaerobic digestion and upgrading processes were modeled with an Ecoinvent dataset (biogas purification to methane). The reactor for biomethanation was developed according to S. Wettstein et al. [8]. Recycling of metallic materials was modeled according to the "avoided impact" approach, that is, one kilogram of recycled material allows for replacing a defined amount of an equivalent new material. The steel waste replaces a similar amount of cast iron, the aluminum waste is melted to produce a similar amount of secondary aluminum. The Copper waste is refined ("fire refining" and "electrolytic refining") to remove impurities according to C. Jingjing et al. [20]. Due to the lack of information, no recycling scenario related to noble metals used as catalysts in PEMEL was defined. However, as it will be seen in the following, this assumption has a major impact on the results of the study. In addition, no dataset related to iridium is available on Ecoinvent. Therefore, it is assumed to replace this metal with rhodium, which also belongs to the platinum group and is quite similar in rarity and production process.

The impact of the RES plant is allocated according to the amount of electricity absorbed by the electrolysis process. For example, if PEMEL absorbs 15 percent of the annual energy produced, 15 percent of the total impact of the plant will be considered, and so on.

3.4. Life Cycle Impact Assessment (LCIA)

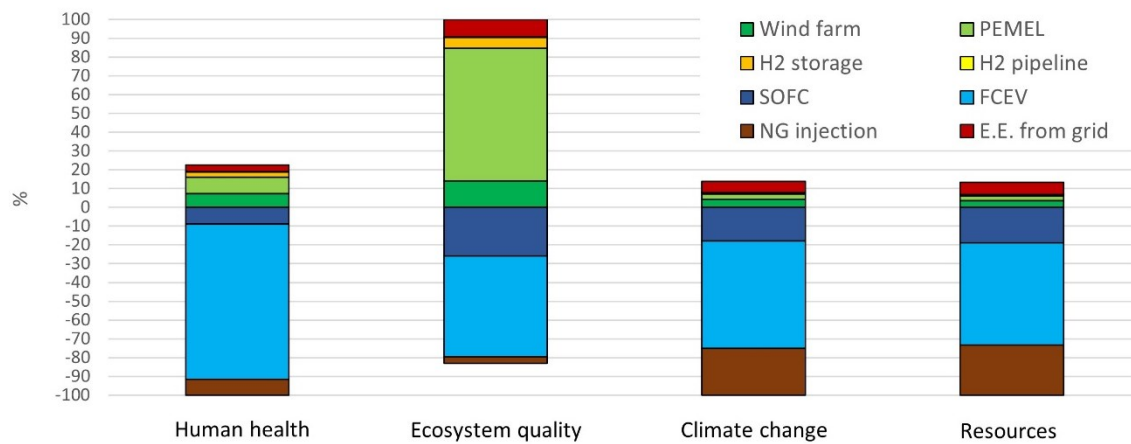
The impact evaluation was carried out using the Impact 2002+ method [21] with an intermediate subdivision (midpoint) in 15 impact categories, which are summarized in 4 damage indicators: Human health (carcinogens, non-carcinogens, respiratory organics, respiratory inorganics, ionizing radiation, ozone layer depletion), Ecosystem quality (aquatic ecotoxicity, terrestrial ecotoxicity, terrestrial acidification/eutrophication, aquatic acidification, aquatic eutrophication, land occupation), Climate change (global warming), Resources (non-renewable energy, mineral extraction).

4. Results and discussion

The results of the analysis for the four scenarios shown in Table 1 are reported in this section. Every result is normalized to the functional unit.

4.1. Scenario A

As shown in Table 1, Scenario A refers to a Hydrogen Valley using 15% of the power produced by a wind farm to produce the hydrogen used by a stationary fuel cell, a hydrogen refuelling station and for the injection into the NG pipeline.



Damage category	H ₂ Valley Scenario A	Wind power plant	PEMEL	H ₂ storage	H ₂ pipeline	SOFC	FCEV	NG Injection	Electricity from grid
Human health (DALY/kgH ₂)	-1.902E-04	1.825E-05	2.133E-05	6.306E-06	5.898E-07	-2.192E-05	-2.029E-04	-2.044E-05	8.605E-06
Ecosystem quality (PDF*m ² *yr/kgH ₂)	1.846E+01	1.532E+01	7.752E+01	6.120E+00	3.598E-01	-2.823E+01	-5.898E+01	-3.783E+00	1.013E+01
Climate change (kg CO ₂ eq/kgH ₂)	-2.354E+02	1.165E+01	7.344E+00	2.181E+00	3.479E-01	-4.896E+01	-1.562E+02	-6.825E+01	1.647E+01
Resources (MJ primary/kgH ₂)	-3.893E+03	1.573E+02	1.165E+02	3.212E+01	5.045E+00	-8.457E+02	-2.444E+03	-1.198E+03	2.841E+02

Figure 3. Results for the four damage categories – Scenario A.

Figure 3 shows the contribution of the different sections to the environmental impact for the aforementioned categories as percentage of the overall impact of the system. Overall, the “Human health”, “Climate change” and “Resources” categories have a negative impact, which indicates an advantage of the case study compared to the reference scenario based on the use of fossil fuels. The largest beneficial contribution comes from the use of hydrogen for feeding the FCEVs for public transport, thanks to the substitution of diesel fuel. Both the SOFC and the hydrogen injection into the NG grid show a relevant contribution, mainly related to the reduction in GHG emissions and non-renewable resources consumption.

On the contrary, the “Ecosystem quality” category shows a higher impact in comparison to the reference scenario. In fact, in this case, the lower environmental impact related to the substitution of fossil fuels in the three final uses is not able to compensate the environmental impact caused by the production processes of the main components of the hydrogen valley, and in particular of the PEMEL.

The critical point of the PEMEL is clearly represented by the iridium used as anodic catalyst in the electrolytic cells. Iridium (as well as rhodium) is indeed one of the rarest known materials, with a concentration of 3×10^{-6} ppm in Earth’s crust and a yearly production lower than 10 t; it is obtained as a subproduct in the production process of more common noble metals (silver, gold, platinum). The catalyst loading, normalized to the PEMEL nominal power, is currently close to 0.67 g/kW (although an older value, 0.8 g/kW, has been used in the LCI phase). Thanks to the expected technological progress, this value could reach 0.33 g/kW in a few years and 0.05 g/kW by 2035 (in the latter case the impact associated to the catalyst could be reduced by 16 times) [22].

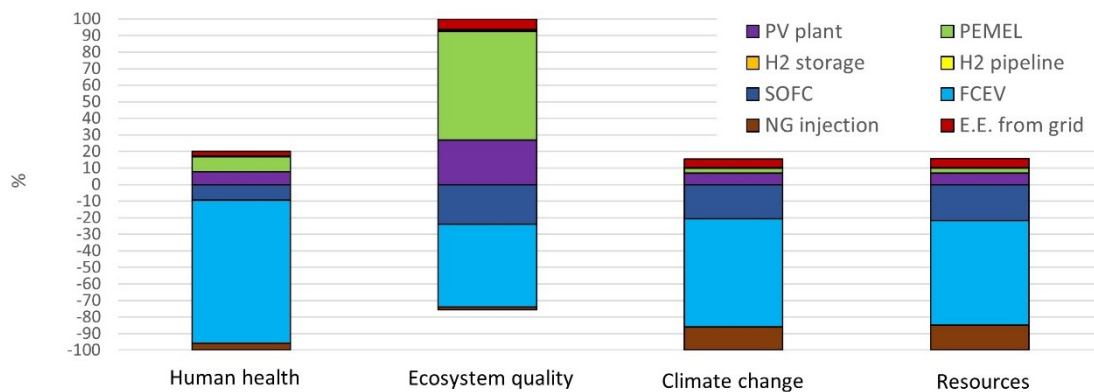
The aforementioned technological progress, along with the development of efficient processes for disposal and catalysts recycling, could potentially lead to a significant reduction in the PEMEL’s impact, thus extending the environmental benefits of the hydrogen valley to the “Ecosystem quality” category too.

4.2. Scenario B

Scenario B is very similar to Scenario A, but the Hydrogen Valley uses 15% of the power produced by a PV plant. The substitution of the wind farm with the PV plant obviously leads to a disadvantage in terms of capacity factor (about 1780 equivalent hours/year against 2580 hours/year of the wind farm), but its daily production profile is more regular and predictable.

This allows the use of a smaller H₂ storage tank (150 m³, against the previous 1200 m³) and a reduction in the amount of electricity supplied by the grid (392 MWh/year against 528 MWh/year). Overall, the hydrogen production is reduced by 58.3 t/years, with a corresponding reduction of the hydrogen available for injection into the NG grid. As already mentioned, the contribution of this final use to the overall results is not negligible, but it is still lower than that of the FCEVs, as confirmed by Figure 4.

When the results are referred to the functional unit, the environmental benefits for Scenario B related to the “Human health”, “Climate change” and “Resources” categories are better than those of scenario A. On the other hand, the impact on “Ecosystem quality” is noticeably worse. This is caused by the solar power plant, which has a higher environmental impact in this category (almost 2.5 times higher than the wind farm), mostly due to the direct land occupation.

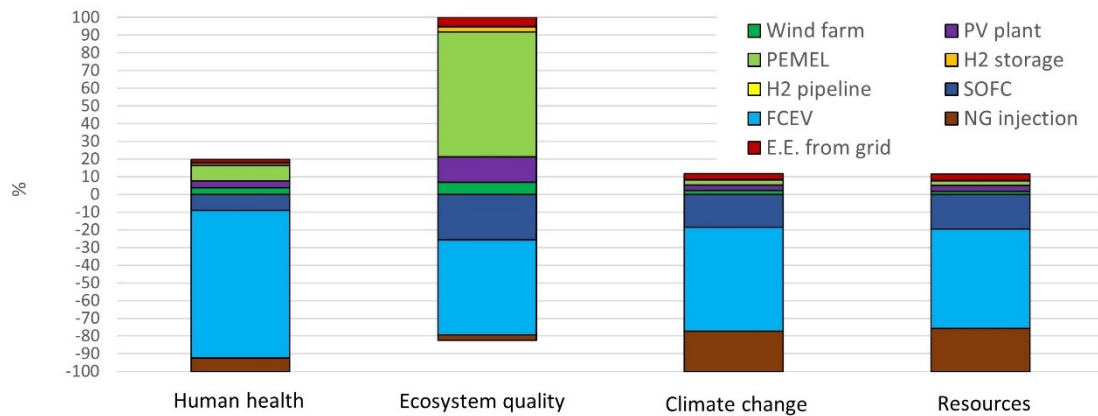


Damage category	H ₂ Valley Scenario B	PV power plant	PEMEL	H ₂ storage	H ₂ pipeline	SOFC	FCEV	NG Injection	Electricity from grid
Human health (DALY/kgH ₂)	-2.390E-04	2.347E-05	2.721E-05	1.003E-06	7.525E-07	-2.797E-05	-2.589E-04	-1.273E-05	8.140E-06
Ecosystem quality (PDF*m ² *yr/kgH ₂)	3.675E+01	4.042E+01	9.891E+01	9.749E-01	4.591E-01	-3.602E+01	-7.525E+01	-2.357E+00	9.607E+00
Climate change (kg CO ₂ eq/kgH ₂)	-2.573E+02	2.101E+01	9.371E+00	3.478E-01	4.439E-01	-6.247E+01	-1.992E+02	-4.240E+01	1.562E+01
Resources (MJ primary/kgH ₂)	-4.165E+03	3.507E+02	1.486E+02	5.111E+00	6.436E+00	-1.079E+03	-3.119E+03	-7.478E+02	2.693E+02

Figure 4. Results for the four damage categories – Scenario B.

4.3. Scenario C

In Scenario C the RES electrical energy is supplied by both a wind farm and a PV plant (50/50). The integration of the two different power sources allows to minimize the mismatch between hydrogen supply and demand, thus reducing the optimal size of the storage tank (600 m³) and the amount of electricity supplied by the grid (287 MWh/year). Figure 5 also shows a direct comparison between the solar plant and the wind farm. The latter shows a lower impact in all four damage categories and, in the “Ecosystem quality” category.



Damage category	H ₂ Valley Scenario C	Wind power plant	PV power plant	PEMEL	H ₂ storage	H ₂ pipeline	SOFC	FCEV	NG Injection	Electricity from grid
Human health (DALY/kg ₀₂)	-2.050E-04	9.606E-06	9.684E-06	2.245E-05	3.315E-06	6.209E-07	-2.308E-05	-2.136E-04	-1.898E-05	4.920E-06
Ecosystem quality (PDF·m ² ·yr/kg ₀₂)	2.043E+01	8.083E+00	1.667E+01	8.161E+01	3.225E+00	3.788E-01	-2.971E+01	-6.209E+01	-3.514E+00	5.779E+00
Climate change (kg CO ₂ eq/kg ₀₂)	-2.457E+02	6.130E+00	8.668E+00	7.731E+00	1.148E+00	3.663E-01	-5.154E+01	-1.644E+02	-6.326E+01	9.410E+00
Resources (MJ primary/kg ₀₂)	-4.042E+03	8.278E+01	1.445E+02	1.226E+02	1.691E+01	5.310E+00	-8.903E+02	-2.573E+03	-1.113E+03	1.624E+02

Figure 5. Results for the four damage categories – Scenario C.

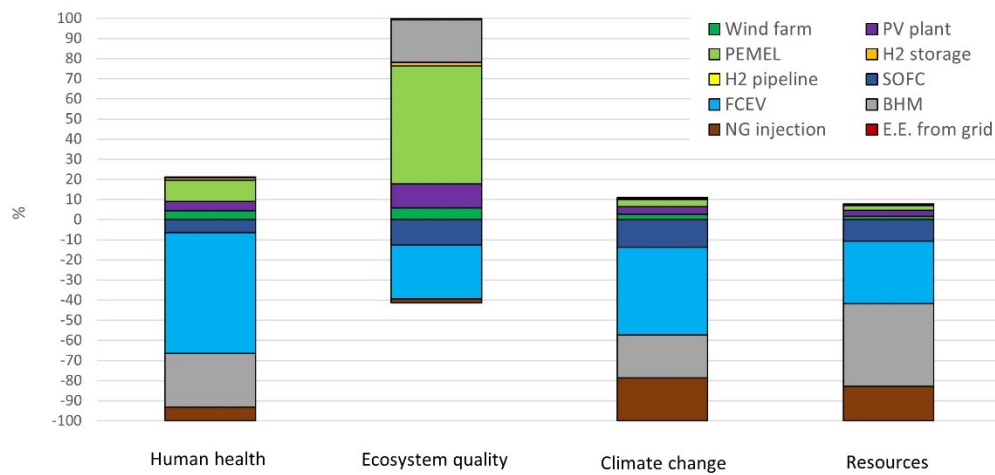
The overall benefits on “Human health”, “Climate change” and “Resources” stand halfway between the two previous scenarios: slightly higher than A and slightly lower than B. The impact on Ecosystem quality” is slightly higher than A, but much lower than B, with the size of the solar farm being obviously the key factor.

4.4. Scenario D

As reported in Table 1, Scenario D refers to a Hydrogen Valley using 25% of the power produced by a wind farm and a PV plant. In this case, the introduction of a BHM process allows to take full advantage of the hydrogen surplus, thus avoiding production curtailment.

The introductions of a BHM process leads to a strong reduction in the “Resources” category impact, while in terms of “Human health” and “Climate change”, the impact reduction of the BHM process compared to that of the FCEVs is roughly 50%. It is worth noting that, in order to obtain these results, the BHM process requires almost 3 times more hydrogen than the refueling station (184.3 t/year versus 65.7 3 t/year). Unlike the other final uses, the BHM process has a harmful impact on the “Ecosystem quality” category, mainly related to the land occupation caused by biogas production.

The overall results show that this scenario is the worst in terms of “Human health”, “Ecosystem quality” and “Climate change”, while the benefits on the “Resources” category are higher than the other scenarios.



Damage category	H ₂ Valley Scenario D	Wind power plant	PV power plant	PEMEL	H ₂ storage	H ₂ pipeline	SOFC	FCEV	BHM	NG Injection	Electricity from grid
Human health (DALY/kg _{H2})	-1.530E-04	8.753E-06	8.817E-06	2.045E-05	2.263E-06	3.395E-07	-1.262E-05	-1.168E-04	-5.167E-05	-1.326E-05	6.768E-07
Ecosystem quality (PDF*m ² *yr/kg _{H2})	7.451E+01	7.344E+00	1.520E+01	7.451E+01	2.199E+00	2.071E-01	-1.625E+01	-3.395E+01	2.690E+01	-2.455E+00	7.942E-01
Climate change (kg CO ₂ eq/kg _{H2})	-1.834E+02	5.572E+00	7.899E+00	7.045E+00	7.835E-01	2.003E-01	-2.818E+01	-8.988E+01	-4.398E+01	-4.419E+01	1.294E+00
Resources (MJ primary/kg _{H2})	-4.168E+03	7.536E+01	1.317E+02	1.119E+02	1.155E+01	2.904E+00	-4.868E+02	-1.407E+03	-1.851E+03	-7.792E+02	2.220E+01

Figure 6. Results for the four damage categories – Scenario D.

Table 2 summarizes the main results for the four considered scenarios.

Table 2. Comparison of the overall results.

Damage category	Unit	Scenario A	Scenario B	Scenario C	Scenario D
Human health	DALY/kg _{H2}	-1.902E-04	-2.390E-04	-2.050E-04	-1.530E-04
Ecosystem quality	PDF*m ² *yr/kg _{H2}	1.846E+01	3.675E+01	2.043E+01	7.451E+01
Climate change	kg CO _{2,eq} /kg _{H2}	-2.354E+02	-2.573E+02	-2.457E+02	-1.834E+02
Resources	MJ primary/kg _{H2}	-3.893E+03	-4.165E+03	-4.042E+03	-4.168E+03

All scenarios lead to benefits in the “Human Health”, “Climate Change” and “Resources” damage categories but worsen the environmental impact in the “Ecosystems Quality” damage category. Therefore, if the latter is assumed as key damage category, the best scenario for the studied Hydrogen valley is A, otherwise the best scenario is B. However, in order to determine the best scenario, a single score calculation approach can also be used. The latter comprises three phases: 1) the results for the four damage categories are normalized using normalization factors; 2) the normalized values are weighted according to their importance; 3) the weighted values are added together in order to obtain a single score. In particular, Table 3 reports the overall environmental impact of the four scenarios evaluated by assuming the Impact 2002+ approach, in which all the damage categories have the same weight (and therefore the same importance) and the normalization factors are calculated from statistical data referred to Western Europe (141 person*year/DALY for “Human health”, 7.3E-5 person*year/PDF*m²*year for

”Ecosystem quality”, $1.01\text{E-}4$ person*year/kg_{eq} CO₂ for ”Climate change” and $6.8\text{E-}6$ person*year/MJ for ”Resources”).

Table 3. Results of the single score calculation in comparison with the fraction of hydrogen consumed by the fuelling station.

Damage category	Unit	Scenario A	Scenario B	Scenario C	Scenario D
Human health	mPt/kg _{H2}	-26.8	-33.7	-28.9	-21.6
Ecosystem quality	mPt/kg _{H2}	1.36	2.70	1.51	5.45
Climate change	mPt/kg _{H2}	-23.8	-26	-24.8	-18.5
Resources	mPt/kg _{H2}	-25.6	-27.4	-26.6	-27.4
Total	mPt/kg _{H2}	-74.8	-84.4	-78.8	-62.1
H ₂ to FCEV	-	24%	31%	26%	14%

Table 3 also shows the percentage of hydrogen used for fueling the FCEVs and demonstrates that the environmental benefits are strictly related to this hydrogen end-use, which appears to be the most impactful. In fact, the best scenario according to the Impact 2002+ approach is B, where roughly 31% of the overall hydrogen production serves the FCEVs. Scenario B is followed by C (26%), A (24%) and D (14%).

5. Conclusions

A Life Cycle Analysis of a Hydrogen Valley with multiple end-users was carried out in this study. The hydrogen-based ecosystem includes a MW-scale PEM electrolyser fed by a mix of energy supplied by a WF and a PV plant, an H₂ storage section and a pipeline for distribution. The green H₂ is used to feed a fleet of fuel cell electric vehicles and a stationary fuel cell, for injection in the NG grid and, in case of overproduction, to produce biomethane. Four different system configurations have been compared with a reference scenario based on the use of fossil fuels, in order to evaluate if the environmental impact resulting from the various life-cycle stages of the Hydrogen Valley components could nullify the benefits of replacing conventional energy sources. The analysis was carried out following the ISO 14040 and 14044 guidelines and using SimaPro 9 software.

According to the results, all four scenarios lead to benefits in the “Human Health”, “Climate Change” and “Resources” damage categories but worsen the environmental impact in the “Ecosystems Quality” damage category. The use of hydrogen for refueling the FCEVs produces the most valuable environmental benefits and therefore the fraction of hydrogen consumed by the fueling station is the most important parameter in determining the best configuration for the Hydrogen Valley. Specifically, the configuration where the electrical energy is produced by a PV plant (scenario B) allows to maximize this parameter and is therefore the most favorable choice. However, two critical issues are observed. Firstly, this scenario has a very high impact on the “Ecosystem quality” category, mainly due to the direct land occupation of the PV modules, which is a clear disadvantage in comparison to the wind farm. Lastly, according to the techno-economic analysis carried out in a previous paper [18], scenario B is also the least profitable in terms of levelized cost of hydrogen production.

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