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Green hydrogen and ammonia synthesis: a techno-economic feasibility analysis for different plant sizes (1 – 60 MW) and scenarios

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Abstract:

As energy and environmental policies for 2030 and 2050 are encouraging several Countries to investigate the viability of alternative green fuels to replace fossil one and help decarbonizing energy sector, hydrogen and ammonia are two promising solutions.

Green hydrogen production is investigated considering both alkaline and PEM electrolysers commercial products, comparing the market solutions from the energetic standpoint considering three different plant sizes, representative of small (1 MW), medium (10 MW) and large (60 MW) scale applications. Hydrogen compression and storage in pressurized tanks is included in the analysis. Considering the drawbacks in hydrogen storage, a second plant lay-out is investigated considering an Air Separation Unit (ASU) and ammonia synthesis plant for the three different sizes. Ammonia is then stored in liquid form. For each solution, a techno-economic analysis is performed to evaluate: (i) CAPEX; (ii) OPEX; (iii) hydrogen and ammonia production costs. Authors evaluate the economic feasibility comparing final costs for green hydrogen and ammonia with market values, considering different scenarios and different green electrical energy prices. Finally, the authors investigate the influence of electrolysers' CAPEX decrease in a next future scenario (2030) on economic feasibility.

Keywords:

Hydrogen production; Energy; techno-economic analysis; green ammonia.

1. Introduction

To mitigate climate change in an effective and timely manner, rapid decarbonization of the global economy is needed. The transformation is already well advanced in the electrical energy sector in several industrialized countries, where competitive renewable energy technologies are increasingly replacing coal and gas-fired power plants [1]. Focusing on EU-27 Countries, total CO_2 emissions reduced from 4000 Mtons in 2005 to 3000 Mtons in 2020, with a strong increase in Renewable Energy Sources (RES) share on gross electrical (from 16.4% in 2005 to 37.4% in 2020), thermal (from 12.4% in 2005 to 23% in 2020) and transport consumptions (from 1.8% in 2005 to 10.3% in 2020) [2]. In the next years, according to the ambitious targets set for 2030, RES contribution is expected to further increase, helping the decarbonisation process.

In this context, the production [3][5] and transport [6][4] of hydrogen, ammonia [7][8][9] and other energy carriers [10][11] are receiving increasing attention, as they have the potential to replace coal, oil, and fossil gases as a global energy feedstock. Both hydrogen and ammonia do not contain carbon atoms, thus they do not impact in terms of CO_2 emissions, and they are considered very interesting alternatives to mitigate GHGs growth if they are produced starting from renewable electricity by the water electrolysis process. In this context, both Power to Hydrogen (P2H) and Power to Ammonia (P2A) are two of the most interesting emerging technologies having great potential as renewable energy storage for long periods, producing a chemical that can be considered as both an effective energy carrier and, in case of ammonia also an effective hydrogen carrier, and as alternative carbon free-fuel [10]. Both P2H and P2A have the potential to play an important role in the transition to a low-carbon economy [7]. They offer a way to store and use renewable energy, which can help to reduce greenhouse gas emissions and improve energy security. Furthermore, both technologies offer a pathway to decarbonize sectors such as transportation and industry, which have traditionally been difficult to decarbonize.

Despite the promising potential, there are still several technical and economic challenges that need to be addressed. For example, both processes are currently energy-intensive, and the production cost is still

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relatively high compared to traditional methods. However, ongoing research and development in this area are expected to reduce costs and improve efficiency, making P2H and P2A increasingly viable options for a low-carbon future.

In this paper, in-depth research and evaluation of the market available technologies are reported. Moreover, the analysis and comparison of energy and economic feasibility for both hydrogen and ammonia production processes are carried out. The study is developed considering different plant sizes to evaluate the impact of the economy of scale. The fuel production cost for both the P2H and P2A is calculated for each plant size and considering different economic scenarios and different energy sources. The results are then compared with the market price of hydrogen and ammonia produced from fossil fuels.

2. Technologies

2.1. Electrolysers (hydrogen production)

Electrolysers are electrochemical devices that are used to split water molecules into hydrogen and oxygen using electricity. As fuel cells, electrolyzers are made by a certain number of electrolytic cells, each cell includes two electrodes and an electrolyte. More cells are connected in series to produce a stack to have the desired hydrogen production. Electrolysers' subsystems include equipment for cooling, hydrogen purification, DC/DC, and a supply system for demineralized water. Electrolysers are classified as Alkaline (AEC), Proton Exchange Membrane (PEMEC), and Solid Oxide Electrolysers (SOEC) [12]. The main features are reported in Table 1.

Table 1. Electrolysers' comparison

	AEC	PEMEC	SOEC
Electrolyte	Liquid (solution 20-30% KOH)	Solid (Polymeric membrane)	Solid (Ceramic)
Operating temp. [° C]	60 – 80	60 - 80	800 - 900
Efficiency [%]	70 - 75	70 - 75	85 - 90
Lifetime [hours]	100,000	80,000	< 20,000
Start-up time	Fast (minutes)	Very fast (seconds)	Slow (hours)
Current density [mA -cm^2]	0.2 – 0.4	1 – 2	0.5 – 1
Maturity	High (TRL9, Market solutions)	High (TRL9, Market solutions)	Medium (TRL7, Demonstration, early market)

While SOEC are still in development, AEC and PEMEC are experimenting a significant market diffusion in the last years, and commercial solutions are available from many producers also for significant sizes (multi-MW solutions). AEC are the most mature technology (developed in the last 50 years), they have lower costs than PEMEC and higher lifetime. However, compared to PEMEC, they have some drawbacks, as they have longer start-up time and dynamic response, which can represent a drawback in case of coupling with intermittent RES, such as wind and solar. Furthermore, PEMEC have higher compactness and allow for very high H_2 purity (99.99% vs 99.5% for AEC). Table 2 reports the main electrolysers' products, for sizes higher or equal to 1 MW, available on the market and their features in terms of technology, efficiency, and volume. It is worth observing that PEMEC performance are very similar to AEC and that both the technologies offer high power solutions in a wide range.

Table 2. Main AEC and PEM electrolysers' commercial products [13-18]

Type	Producer and model	Delivery pressure	Power	H_2 production	Energy Cons.	Efficiency	Off design
AEC	Mc Phy Mc Layzer 400-30	30 bar	1.8MW	400 Nm^3/h	4.5 kWh/Nm^3	78%	N/D
AEC	Mc Phy Mc Layzer 800-30	30 bar	3.6MW	800 Nm^3/h	4.5 kWh/Nm^3	78%	N/D
AEC	Nel Hydrogen A485	200 bar	1.6MW	390 Nm^3/h	4 kWh/Nm^3	88%	15-100%
AEC	Nel Hydrogen A1000	200 bar	3.1MW	785 Nm^3/h	4 kWh/Nm^3	88%	15-100%
AEC	Nel Hydrogen A3880	200 bar	12.4MW	3100 Nm^3/h	4 kWh/Nm^3	88%	15-100%
AEC	Sunfire Hylink	30 bar	10.5MW	2230 Nm^3/h	4.7 kWh/Nm^3	75%	25-100%
PEMEC	Nel Hydrogen MC500	30 bar	2.2MW	492 Nm^3/h	4.5 kWh/Nm^3	79%	10-100%
PEMEC	Nel Hydrogen M3000	30 bar	13.3MW	2952 Nm^3/h	4.5 kWh/Nm^3	79%	10-100%

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PEMEC	Nel Hydrogen M5000	30 bar	22 MW	4920 Nm^3/h	4.5 kWh/Nm^3	79%	10-100%
PEMEC	Cummins Hy Lizer 1000	30 bar	4.6 MW	1000 Nm^3/h	4.6 kWh/Nm^3	77%	N/D
PEMEC	Cummins Hy Lizer 4000-30	30 bar	20MW	4300 Nm^3/h	4.6 kWh/Nm^3	77%	N/D
PEMEC	ITM POWER 3MEPCUBE	30 bar	2 MW	400 Nm^3/h	5 kWh/Nm^3	70%	N/D
PEMEC	ITM Power 2GEP Skid	30 bar	5MW	1002 Nm^3/h	5 kWh/Nm^3	70%	N/D
PEMEC	H-TEC Systems HCS	30 bar	10 MW	2100 Nm^3/h	4.8 kWh/Nm^3	74%	20-100%
PEMEC	Plug Power EX-4250D	40 bar	10 MW	2000 Nm^3/h	5 kWh/Nm^3	70%	N/D
PEMEC	H-TEC Systems ME450	30 bar	1 MW	210 Nm^3/h	4.8 kWh/Nm^3	74%	20-100%

Considering that PEMEC and AEC products available products on the market are similar from the efficiency, size, outlet pressure standpoints, PEMEC are chosen for the present study, considering that they guarantee higher purity and the have an advantage in terms of response, which make them more feasible for coupling with RES (i.e. wind energy) [5].

2.2. Air Separation Unit (ASU)

The required Nitrogen for the synthesis of Ammonia is usually obtained from the air (i.e. a mixture of N_2, O_2, and other gases) utilising an Air Separation Unit (ASU). The commercially available technologies for the nitrogen production are three: (i) Cryogenic Fractional Distillation; (ii) Pressure Swing Adsorption (PSA); (iii) membrane separation. All of them differs in operating principle, capacity, and energy consumption. The ASU is based on the Cryogenic Fractional Distillation approach starting from the liquefaction of the air and then the distillation and separation in its main components (O_2, N_2, Ar, etc). This process is usually employed for medium to large capacity plant (200 – 400,000 Nm^3/h of N_2), allows to obtain a very high purity level (up to 99.999%), the energy consumption ranges between 0.25 and 0.4 kWh/Nm^3 of N_2 and, considering the complexity of the process, the load range is quite limited (60%-100%). The PSA system is a discontinuous mechanical process based on the adsorption principle by means of vessels packed with Carbon Molecular Sieves that retains a specific molecule. The adsorption process depends on the operating pressure and the higher the pressure, the higher the N_2 purity at the outlet and the higher the energy consumption. Commercially, the PSA units operate at 6-8 bar, the N_2 purity can reach the 99.999% and the related energy consumption is up to 1.25 kWh/Nm^3 for very high purity nitrogen. Such a system is usually employed for medium-small applications (5-5000 Nm^3/h of N_2). As for the PSA, also the Membrane Separation is a pressure-driven process. The working principle is based on a selective gas permeation through a membrane substance that allows specific molecules to flow. The driving force is the difference in partial pressure between the two sides of the membrane. In the case of nitrogen production, when compressed air pass through the membrane's fibres, oxygen, water vapour, and carbon dioxide are selectively removed, creating a nitrogen-rich product stream. However, the purity grade that is achievable with membrane separation is usually in the range of 95%-99.5% resulting not suitable for ammonia synthesis via Haber-Bosch process. In the present work, considering the size and the purity required, the PSA technology is considered for the production of the nitrogen needed for the ammonia synthesis.

2.3. Haber-Bosch reactor

The SoA process for the synthesis of ammonia is known as Haber-Bosch process developed in the early 20th century. It is a thermochemical Fe-based catalytic process in which H_2 and N_2 (almost in stoichiometric ratio, 3:1) react at high pressure (140-250 bar) and temperature (300-500°C) according to the following reaction:

$$N_2 + 3H_2 \rightarrow 2NH_3 \qquad \Delta H_0 = -92\ kJ/mol$$

The ammonia synthesis reaction is exothermic and the number of moles decreases, thus it is favoured by low temperature and high pressure. Traditional process reach single-pass conversion around 15%-30% at typical working conditions (i.e 200 bar and 400-500°C, respectively). The overall conversion reach up to 95% with a recirculation factor around 7 to 10. The most used catalyst is Fe-based and therefore it is very susceptible to poisoning in presence of oxygen and water, and, for this reason, the required reacts purity is very high. In order to overcome the drawbacks of Fe-based catalysts and to reduce the operating conditions, new catalyst mostly based on ruthenium has been developed.

2.4. Hydrogen storage

Hydrogen storage represents one of the most critical aspects for the development of the hydrogen economy on global scale. In fact, despite its high energy content in mass terms (LHV 120 MJ/kg), hydrogen has a very

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low density (0.09 kg/m^3 at ambient conditions), thus its energy content in volume terms is low (3.0 kWh/m^3). Today, there are three commercial solutions for hydrogen storage: (a) compressed gas; (b) liquid; (c) metal hydrides. Solution (a) is the most employed, as it presents high maturity for different scales [19]. Depending on the employed materials and to the final pressure storage, it is possible to identify four different tanks typologies for the storage. Type I consists in iron tanks (max pressure 200 bar), type II in aluminium tanks (max pressure 300 bar), type III in composite pressure vessel made of a metallic liner fully-wrapped with a fiber-resin composite (max pressure 700 bar) and Type IV in pressure vessel made of polymeric liner fully-wrapped with a fiber-resin composite (max pressure 700 bar). Type III and IV guarantee the best performance in terms of energy content (about 1300 kWh/m^3), thus they are considered in this study. In case of compressed gas storage, compression has to be considered. Since hydrogen is produced by electrolysers at 30 bar, the energy to bring it to 700 bar is estimated in 2.2 kWh/kg [20].

2.5. Ammonia storage

The ammonia presents physical characteristics very similar to the LPG and therefore they can share both the storage solutions and the infrastructure.

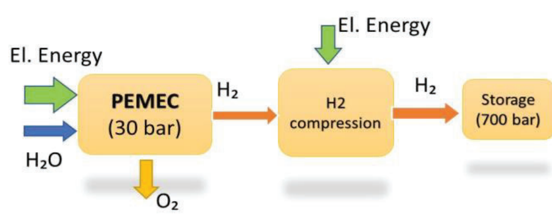
The ammonia can be stored in three main solutions: (i) fully-refrigerated tank; (ii) semi-refrigerated tank; (iii) pressurised tank. The first one is usually adopted in case of very high-capacity storage (10-50 ktons). In this case, the ammonia is stored at ambient pressure and saturation temperature (-33°C). The tank is equipped with a refrigeration circuit to maintain the design temperature and manage the blow-off. Such a solution is usually used as local storage at the production site or for the transportation into tanker ship, as well for the semi-refrigerated system. In this case, the ammonia is stored in liquid form at around -5°C - 0°C and saturation pressure (3-5 bar). The pressurised ammonia tank stores the ammonia as a liquified compressed gas at ambient pressure and related saturation pressure till a maximum of around 20bar. Inside this type of storage, both the liquid and vapour phase co-exist in equilibrium as function of the ambient temperature. This solution is mostly used for small-medium capacity, and for truck and rail transportation.

3. Case studies

In the present section, different case studies are analysed, considering:

- Small size case (1 MW electrolysers)
- Medium size case (10 MW electrolysers)
- Large size case (60 MW electrolysers)

For the three sizes, both green H_2 and NH_3 plant layouts are investigated. An energy and volume analysis is carried out, trying to minimize electrical energy consumption and occupied space for each configuration, considering the available products on the market. Figure 1 presents a simplified plant layout for green hydrogen production in a Power-to-Hydrogen (P2H) process. RES electrical energy gives power to electrolyser, splitting water in hydrogen and oxygen at a certain pressure (assumed 30 bar in this case). At the outlet, a compression system brings the hydrogen to the desired pressure level for the storage (from 200 to 700 bar, according to the scenario). The so produced H_2 has a very high purity and can be used in fuel cell electric vehicles, or for industrial/chemical applications. In P2A configuration, green hydrogen is compressed up to 200 bar and mixed with N_2, sequestered by ASU and then compressed; the reactants are sent to a Haber-Bosch synthesis loop and the so produced ammonia is stored in liquid form [21].



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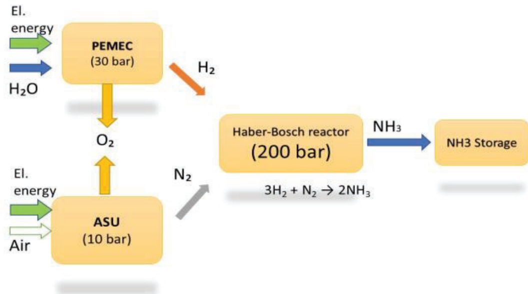

Figure. 1. Simplified plant layouts for P2H and P2A configurations

3.1. Small size (1 MW)

The 1 MW size is well-established in today's electrolyser market for both AEC and PEMEC technologies, as reported in Table 2. Considering PEMEC, the H-TEC PEM ME450 model is investigated as possible solution. Assuming the P2H plant operating for 4000 equivalent hours per year (considering average capacity factor for wind energy production, according to IRENA data), consumptions are nearly 700 ton/year of H_2O and 4165 MWh of electrical energy (4000 MWh for PEMEC, 165 MWh for H_2 compression up to 700 bar) for hydrogen production equal to 75 ton/year. The required space is about 87 m^2, including PEMEC (53 m^2) and storage (34 m^2).

In case of P2A configuration, operating for the same equivalent hours per year, water consumptions are the same, while electrical energy are slightly increased up to 4360 MWh (4000 MWh for PEMEC, 130 MWh for ASU, 230 MWh for nitrogen and hydrogen compression up to 200 bar for Haber-Bosch process), for ammonia synthesis equal to 425 ton/year. In this configuration, the required area results 87 m^2, including PEMEC (53 m^2), Haber-Bosch plant (26.5 m^2), ASU (1.4 m^2) and storage (6.1m^2).

3.2. Medium size (10 MW)

The medium size analysed in the present study is 10 MW, which is a capacity that is available for the single products for both PEMEC and AEC technologies (Table 2). However, considering that the minimum load is usually around 10-20%, this would imply a minimum available electrical energy from RES equal to 1-2 MW, which can decrease the operation time during the year. Thus, the combination of more commercial units in parallel is considered to guarantee higher plant flexibility. Considering PEMEC, two Cummins HyLYZER® 1000-30 (4.5 MW each) and one H-TEC PEM ME450 (1MW) models. Assuming the P2H plant operating for 4000 equivalent hours per year, consumptions are nearly 7000 ton/year of H_2O and 42470 MWh of electrical energy (40720 MWh for PEMEC, 1750 MWh for H_2 compression up to 700 bar) for hydrogen production equal to 795 ton/year. The required space is about 373 m^2, including PEMEC (113 m^2) and storage (260 m^2). It is worth noting that, in this case, the storage is the most influent voice in terms of area.

In case of P2A configuration, operating for the same equivalent hours per year, water consumptions are the same calculated for P2H 10 MW configuration. Electrical energy consumption slightly increases to 4360 MWh (40720 MWh for PEMEC, 1300 MWh for ASU, 2300 MWh for nitrogen and hydrogen compression up to 200 bar for Haber-Bosch process), for ammonia synthesis equal to 4250 ton/year. In this configuration, the required area results 242 m^2, including PEMEC (113 m^2), Haber-Bosch plant (56.6 m^2), ASU (11.4 m^2) and storage (61 m^2).

3.3. Large size (60 MW)

The large size analysed in the present study is 60 MW, corresponding to the size in the Tees Green Hydrogen project in UK for the production of green hydrogen using electrical energy generated by the Teesside offshore wind farm provided to local corporate customers to support decarbonisation [22]. Two options are investigated for the present case study: (a) 3 PEMEC units Cummins HyLYZER® 4000-30, 20 MW each; (b) 28 PEMEC units Cummins MC500, 2.2 MW each.

Assuming the P2H plant operating for 4000 equivalent hours per year, consumptions are nearly 38500 ton/year of H_2O and 247 GWh of electrical energy (237 GWh for PEMEC, 10 GWh for H_2 compression up to 700 bar) for hydrogen production equal to 4640 ton/year. In case of option (a), the required space is about 1842 m^2, including PEMEC (450 m^2) and storage (1392 m^2). Adopting solution (b), the required space results considerably higher (2232 m^2) due to the higher modules number.

In case of P2A configuration, operating for the same equivalent hours per year, water consumptions are the same calculated for P2H 60 MW configuration, while electrical energy consumption slightly increases to 4360 MWh (237 GWh for PEMEC, 5.2 GWh for ASU, 13.9 GWh for nitrogen and hydrogen compression up

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to 200 bar for Haber-Bosch process), for ammonia synthesis equal to 25500 ton/year. In this configuration, the required area results 1060 m^2, including PEMEC (450 m^2), Haber-Bosch plant (225 m^2), ASU (10 m^2) and storage (375m^2).

4. Economic analysis

An economic analysis is then carried out to calculate the cost of green hydrogen and ammonia. The discussion continues by comparing the cost of producing hydrogen and ammonia obtained from green sources and the price on the market in the years 2021/2022. In addition, an analysis is performed on the possible incentives to be provided and the LCOE break-even in order to bridge the gap between the cost of fuels from fossil fuels and renewable energy sources.

To evaluate the economic viability [10], the Fuel Production Cost (FPC) is considered for both green hydrogen and ammonia, calculated as follows and expressed in €/kg:

$$FPC = (Annual\ Fixed\ Costs + Annual\ Variable\ Costs)/(Total\ Annual\ Production) \quad (1)$$

Where Annual Fixed Costs (AFC) are determined starting from the Total Capital Investment (TCI), considering the plant lifetime in years (n) and the WACC as rate (r):

$$AFC = TCI \cdot (r * (1+r)^n)/((1+r)^n - 1) \quad (2)$$

Annual Variable Costs (AVC) include electrical energy cost and the OPEX of each plant component

$$AVC = \sum_i OPEX_i + El.Energy\ cost \quad (3)$$

Economic analysis is performed considering the main assumptions reported below:

- Equivalent Operating Hours (EOH) for all the plant configurations are estimated in 4,000 h/year, considering that the renewable energy is produced by wind farms [23].
- Levelized Cost Of Electricity (LCOE) depends on the application scenario, assumed for the present analysis from IRENA 2021 report [23]. More in detail, for onshore wind farms LCOE is assumed 42 €/MWh for Europe, 31 €/MWh for USA, 28 €/MWh for China scenarios; for offshore wind farms LCOE is assumed 65 €/MWh for Europe, 78 €/MWh for USA, 79 €/MWh for China scenarios.
- Plant lifetime 20 years, corresponding to 80,000 equivalent operating hours, which is the guaranteed lifetime for electrolysers according to literature and producers [12][24].
- WACC 5%.

Capital Expenditure (CAPEX) for both alkaline and PEM electrolysers represents one of the most important voices for the economic feasibility, as electrolysers have a significant investment cost, as reported also in recent studies. Thus, a cost function is determined for both technologies based on recent data collected by IRENA in 2020 report as function of the installed power *P*, expressed in MW. The obtained cost functions are reported in Table 3. For the considered sizes, alkaline technology has a CAPEX of 1002 €/kW, 600 €/kW and 400 €/kW for 1 MW, 10 MW and 60 MW respectively, while PEMEC technology has higher CAPEX of 1155 €/kW, 742 €/kW and 526 €/kW for the same sizes [24].

The main assumptions for CAPEX and OPEX calculations are reported in Table 3.

Table 3. Main CAPEX and OPEC estimations for economic analysis [10][12][24]

Component	CAPEX	OPEX
PEMEC	$1155 \cdot 10^3 \cdot P^{0.808}$ [€]	4.5% CAPEX
AEC	$1002 \cdot 10^3 \cdot P^{0.778}$ [€]	4.5% CAPEX
H_2 compressors	16000 M_{H2} [€]	2% CAPEX
H_2 storage tanks	480 M_{H2} [€]	-
ASU	1450 M_{N2} [€]	2% CAPEX
Ammonia synthesis loop	50890 $M_{NH3}^{0.65}$ [€]	2% CAPEX

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Ammonia storage	0.9 M_{NH3} [€]	-

4.1. Main techno-economic results

4.1.1. Annual costs breakdown

The first analysis is performed in order to evaluate the main costs distribution for both P2H and P2A configurations for 1 MW, 10 MW and 60 MW PEMEC sizes, respectively. For this first analysis, an average LCOE for electrical energy equal to 50 €/MWh is considered.

Figure 2 shows the cost breakdowns for green hydrogen production. Annual costs, including both CAPEX and OPEX contributions are about 0.48 M€/year for small size (1 MW), 4.00 M€ for medium size (10 MW) and 20.81 M€ for large size (60 MW). It is worth noting that the most relevant component is the cost of electrical energy for all the investigated sizes, followed by electrolysers' CAPEX and OPEX: these voices impact for 85-90% of total annual costs. Observing the three case studies, it is evident that, as the size increases, due to the decrease in the electrolysers CAPEX (sizing up), their incidence on the total percentage tends to diminish; in percentage terms, electrical energy cost influence increases more and more.

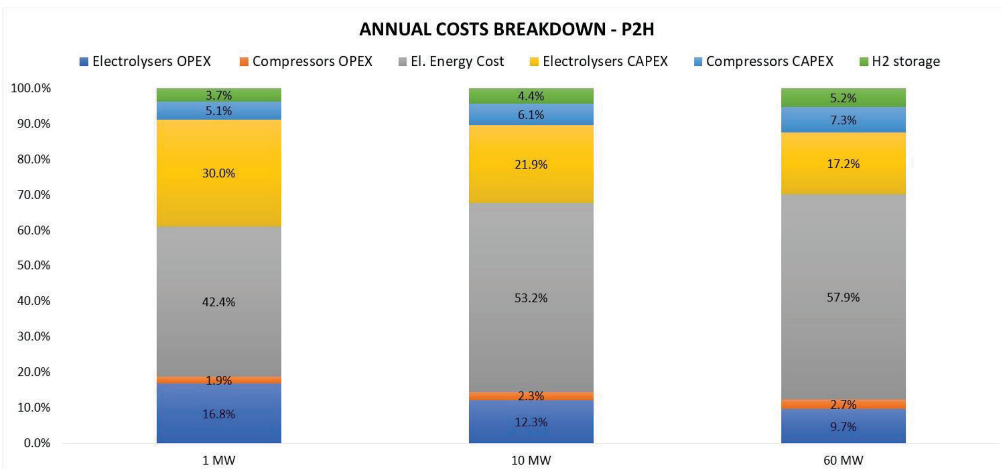

Figure. 2. Costs breakdown for P2H solutions

Figure 3 shows the main results for P2A configuration. Costs are slightly higher than in the P2H case: 0.56 M€/year for 1 MW size, 4.31 M€/year for 10 MW size and 21.12 M€/year for 60 MW size.

In the 1 MW case, most of the total annual cost (80%) is related to the electrolysers and the electrical energy costs. In the 10MW case, due to the sizing up of the electrolysers, the electricity cost, in percentage terms, becomes increasingly preponderant, around 53.5%. For the 60 MW size, as electrolysers and ammonia synthesis unit installed powers increase, their cost incidence decreases more and more, while electrical energy cost gains even more importance (61.7%).

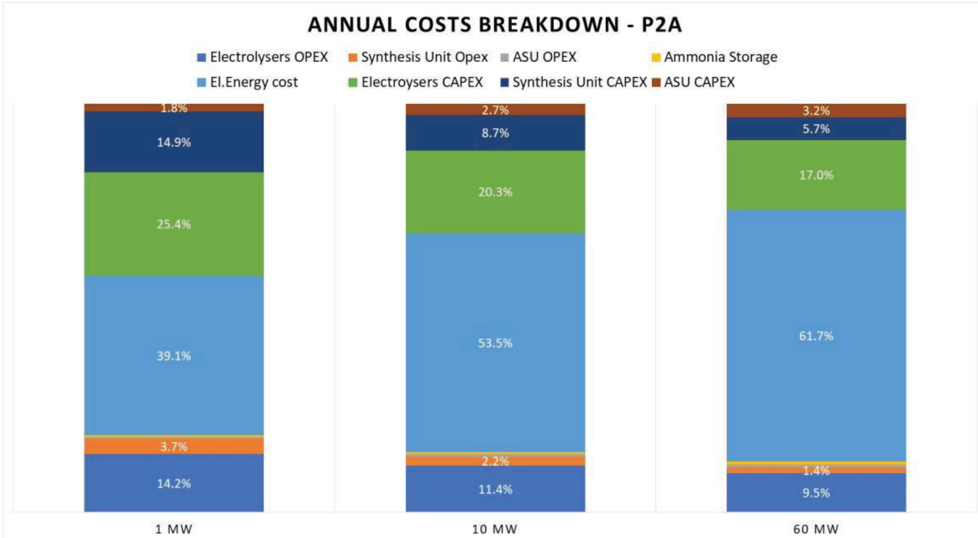

Figure. 3. Costs breakdown for P2A solutions

4.1.2. Results for different scenarios

In the previous analysis for costs breakdown, an average LCOE value of 50 €/MWh was assumed. In the present research the electrolysers are powered by renewable electricity generated by on shore/offshore wind turbine; thus, different LCOE values are investigated, according to the operating scenario. In this way, it is possible to investigate the influence of electrical energy cost. In this study, three geographic scenarios are considered: Europe, China and USA. LCOE values are obtained by 2021 data published by IRENA, reported in Table 4 [23]. Offshore wind plants are characterized by higher costs: in EU Countries the technology is well developed, thus costs are slightly lower for this kind of technology.

Table 4. LCOE estimations for economic analysis in different scenarios

	LCOE Wind on shore [€/MWh]	LCOE Wind offshore [€/MWh]
Europe	42	65
China	28	79
USA	31	78

For each scenario, the FPC for Hydrogen and ammonia are calculated. Figure 4 and Figure 5 show the main results. Production costs are positively affected by LCOE decrease and size increase (which lead to lower specific CAPEX for installed MW). As far as Hydrogen production is concerned, the lowest value is 3.1 €/kg (China, wind on shore, 60 MW) and the highest is 7.9 €/kg (USA, wind offshore, 1 MW). For P2A configuration, the FPC ranges between 0.6-1.2 €/kg for large size (60 MW) and 1.2-1.6 €/kg for small size (1 MW), depending on the cost of electricity.

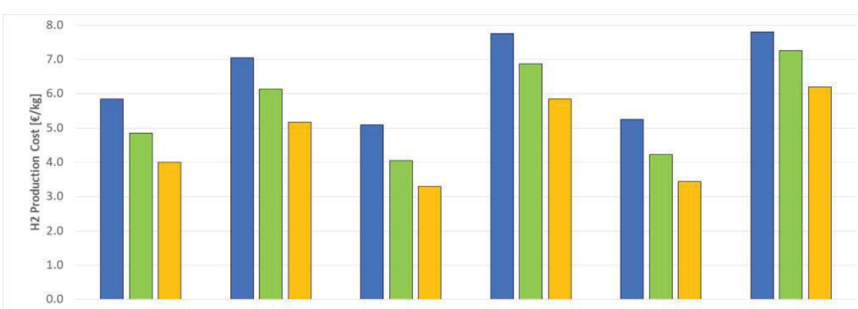

Figure. 4. Hydrogen production costs for different sizes in China, Europe, USA

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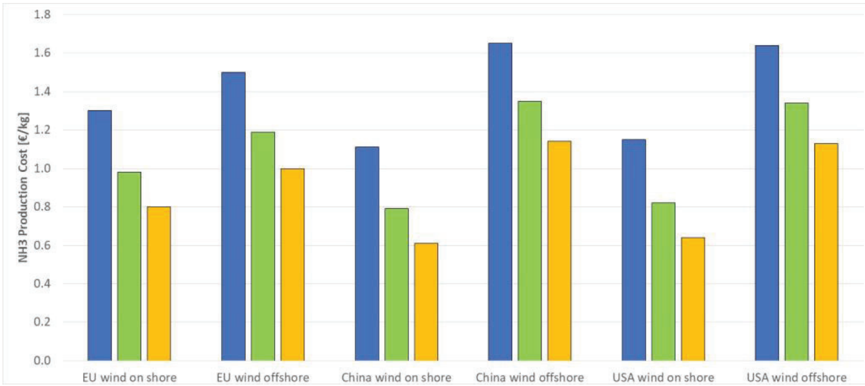

Figure. 5. Ammonia production costs for different sizes in China, Europe, USA

4.1.3. Comparison with actual H_2 and NH_3 market costs

In order to evaluate the economic feasibility of the proposed solutions, it is interesting to provide a comparison between the cost of green hydrogen/ammonia and their market prices in the last two years. Concerning Hydrogen, the most of it is produced by steam reforming of natural gas (grey hydrogen), thus its market price strongly depends on natural gas price [25]. Figure 6 compares the different H_2 production costs in the EU scenario with grey H_2 market price. While in a scenario with low-medium NG prices (until September 2021) green H_2 solutions are not economically feasible, the situation is different in a scenario characterised by high fossil fuels cost (2022). In this case, most of the green H_2 solutions, in particular the medium and large size ones become competitive from the economic standpoint.

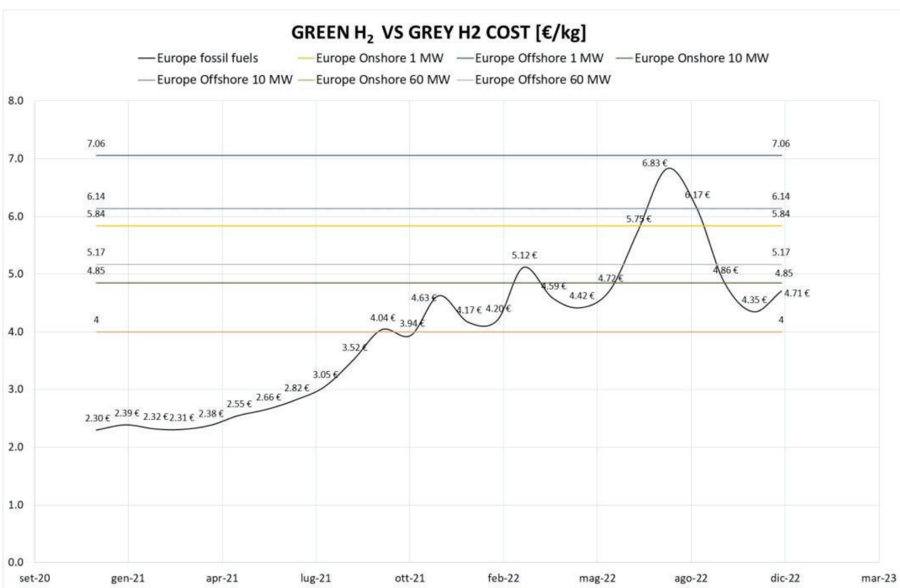

Figure. 6. Comparison with market (grey) Hydrogen prices (2021-2022) in Europe

Figure 7 shows a similar trend for ammonia solutions, also in this case for EU scenario [26]. It is worth noting that green solutions are not affected by the fossil fuel market price variations.

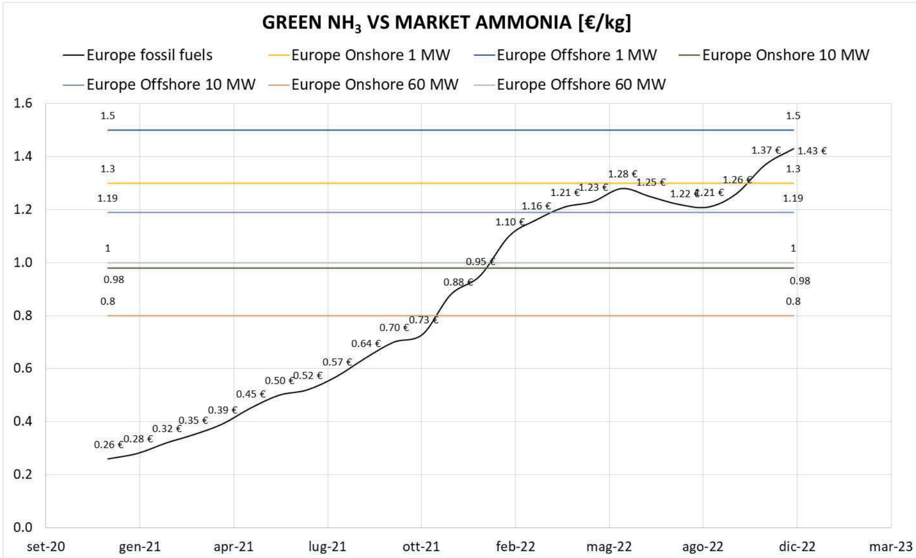

Figure. 7. Comparison with market ammonia prices (2021-2022) in Europe

4.1.4. Next future scenario (2030)

In this section, the feasibility economic analysis is performed considering a next future European scenario (2030). To carry out the analysis, CAPEX reduction for PEM electrolysers is considered, starting from the study recently published by Gorre et al. [27]. In particular, according to new assumptions, specific CAPEX is 665 €/kW for 1 MW size, 470 €/kW for 10 MW size and 415 €/kW for 60 MW. LCOE from wind energy is assumed the same, considering that wind energy power plants are today a fully mature and developed technology, at least in the EU scenario. As Figure 8 shows, for on shore wind plants hydrogen costs range from 3.7 to 4.4 €/kg, with a significant reduction compared to actual costs shown in Figure 4 (from 4 to 5.8 €/kg); for offshore wind farms, H_2 costs range from 4.9 to 5.7 €/kg: also in this case, a significant reduction can be noted. The same trend is found for P2A configurations, with a minimum cost for 60 MW onshore (0.73 €/kg vs 0.8 €/kg in today scenario) and a maximum cost for 1 MW offshore (1.47 €/kg vs 1.50 €/kg in today scenario).

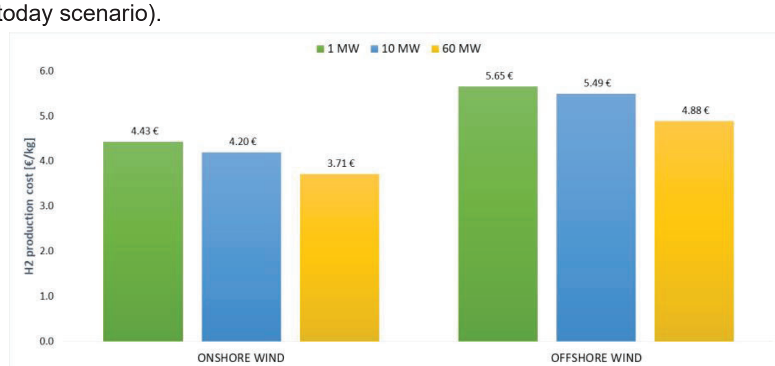

Figure. 8. Hydrogen production costs in Europe from RES (2030)

5. Conclusions

Green hydrogen and ammonia are considered among potential candidates to replace fossil fuels in the next future. However, hydrogen is still facing challenges for storage and transport. Green ammonia is another promising alternative.

The present study focused on different types of feasibility analyses:

- *Energy analysis*: for both green fuels, three different plant sizes are investigated, representative of small (1MW), medium (10 MW) and large (60 MW) electrical energy input. For the same size, electricity consumption varies within very limited ranges. The most impacting term is due to the PEM

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electrolysers, which is common to both the configurations, while the impact of hydrogen compression (for P2H) and ASU/ammonia synthesis for (P2A) have a limited influence.

- *Volume analysis*: in the analysis of the overall dimensions, different results are obtained depending on the sizes. For 1 MW size, similar results are obtained for P2H and P2A configurations. In the case of medium and large sizes (10 and 60 MW), the impact of storage for P2H configuration becomes dramatic, thus this kind of solution seems not to be the best option. For large size, it is important to consider to couple different PEMEC modules, in order to guarantee also higher plant flexibility, in particular in presence of not constant/programmable RES electrical energy input.
- *Economic analysis*: the first analysis is performed to evaluate annual costs breakdown for all the sizes and the configurations investigated. The most relevant voices are electrical energy and PEMEC costs (together 75-85% of the total, depending on the configuration). Then, a scenario analysis is performed to investigate the influence of LCOE, considering both on shore and offshore wind farms, in EU, China and USA scenarios. Finally, production costs for hydrogen and ammonia are compared with market prices (2021-2022), finding out that small scale plants (1MW) are not economically feasible, if not encouraged by proper incentives. On the other hand, medium and large scale configurations (10MW and 60MW) are worthy solutions, in particular in a scenario (2022) characterized by higher natural gas cost and consequent larger production costs for grey hydrogen and ammonia.
- *Future scenarios*: in next future scenario (2030), it is realistic to assume a decrease in PEMEC market costs, which should lower green H_2 and NH_3 production costs. Furthermore, their lifetime may be extended, LCOE from offshore wind farms may be lower too and fees related to grey fuels production (or incentives to green fuels) may be included by some Countries: these latter factors may increase the economic feasibility of the solutions investigated in the present paper.

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Nomenclature

AEC	Alkaline Electrolysers
AFC	Annual Fixed Costs
ASU	Air Separation Unit
FPC	Fuel Product Cost (€/kg)
IRENA	International Renewable Energy Agency
LCOE	Levelized Cost of Electricity (€/MWh)
LHV	Lower Heating Value (MJ/kg)
n	Plant lifetime (years)
PEMEC	Proton Exchange Membrane Electrolysers
P2A	Power to Ammonia
P2H	Power to Hydrogen
PSA	Pressure Swing Adsorption
RES	Renewable Energy Sources
SOEC	Solid Oxide Electrolysers
TCI	Total Capital Investment (M€)
WACC	Weighted Average Cost of Capital

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