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Power-to-fuel energy storage systems comparison for Combined Cycles flexibility

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ABSTRACT

Due to the increasing penetration of renewable energy sources on the grid, the traditional power plants (PP) and the combined cycles, in particular, are increasingly forced to operate in discontinuous mode with continuous load changes. In the present work, two power-to-fuel-to-power processes are investigated as potential solutions to improve the Combined Cycle Power Plant (CCPP) flexibility by adsorbing and storing the electrical energy produced by the PP and not sold to the grid. The analysis was carried out on the Power-to-Hydrogen-to-Power (P2H2P) and Power-to-Ammonia-to-Power (P2A2P) systems investigating and comparing the process in terms of round-trip efficiency, storage energy density, and plant footprint. Despite the P2H system being more competitive from the efficiency point of view, it presents critical issues related to the energy storage density and system footprint as consequence. These problems can be overcome by ammonia which resulted in a much more effective energy storage medium.

Keywords: Power to fuel systems, energy storage, power plant flexibilization, hydrogen, ammonia, decarbonization.

NOMENCLATURE

Abbreviations	
CCPP	Combined Cycle Power Plant
EOH	Equivalent Operating Hours
EU	European Union
LHV	Lower Heating Value
NGCC	Natural Gas Combined Cycle
P2A2P	Power-to-ammonia-to-power
P2H2P	Power-to-hydrogen-to-power
RES	Renewable Energy Sources
Symbols	
n	Year

1. INTRODUCTION

As renewable energy sources (RES) share for electrical energy production is significant (34% in 2019) and is growing to achieve the EU 2030 target (55%) [1][2], conventional power plants are compelled to become more flexible while reducing their carbon footprint – meaning they need to be able to compensate the intermittent RES supply, ensuring a stable and secure supply of energy [4][5][6][7].

In this context, Natural Gas-fired Combined Cycles (NGCC) are currently considered to be the most flexible power plants to operate in the European grid to facilitate the penetration of high shares of RES. Hereby, the NGCCs in the present European electricity market must provide ancillary services and backup capacity following the intermittent generation from RES to yield a stable, secure and reliable energy system [8].

To achieve the EU 2030 and 2050 Climate and Energy goals [2] and besides ensuring a high penetration of RES into the grid, the use of alternative carbon-free fuels in already existing dispatchable centralized power plants is required[3]. The injection of alternative fuels, such as hydrogen (H_2) and ammonia (NH_3)[12], in gas turbines, will help the required fuel switch, drastically reducing CO/CO_2/HC emissions. The P2X2P solutions, which are

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currently widely studied coupled with RES [9]- [14], could help the NGCCs to level their load and reduce their environmental impact. Hence, developing proper technologies and solutions to couple P2X2P systems with gas turbine processes is mandatory. In this context, future NGCCs that want to be established in a future energy system penetrated by high shares of RES are compelled to provide flexibility whilst also reducing their carbon footprint.

An answer to this challenge is given by the FLEXnCONFU project [15] that offers an innovative solution to increase flexibility and decarbonize conventional NGCCs by integrating a P2X2P process based on Hydrogen and Ammonia. The project is based on a Power-to-X (P2X) process which includes power conversion, energy storage, and reconversion by using surplus electricity, typically sourced during periods where intermittent RES generation exceeds the market demand.

The concept is used to convert surplus power from NGCC into H_2 and/or NH_3 to be further stored until the energy carrier will be injected together with natural gas into the conventional gas turbine process of the NGCC to generate electricity when the market requires it. Hence, the concept is converting surplus electricity to hydrogen or ammonia and reconverting this temporarily stored energy into electricity which leads to the term P2X2P.

2. PLANT LAYOUTS AND METHODOLOGY

In the present work, two different P2X2P solutions are evaluated and compared from both the technical-energetic point of view and in terms of area required for their installation, also in comparison with the NGCC unit to which they are connected.

- *Power to Hydrogen to Power*

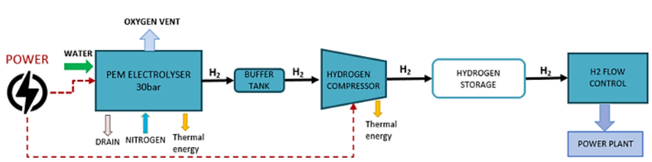

Figure 1: Power-to-Hydrogen-to-Power system layout

Figure 1 reports a simplified layout of a P2H2P system. It is composed of (i) 100MW PEM water electrolyzer operating at 30bar with a specific energy consumption of 4.9kWh/Nm^3[16][17]; (ii) a hydrogen compressor to bring the H_2 pressure at the electrolyzer outlet (30bar) up to the H_2 storage pressure (200bar); (iii)a pressurized gas tube skid in which the gaseous hydrogen is stored at 200bar.

- *Power to Ammonia to Power*

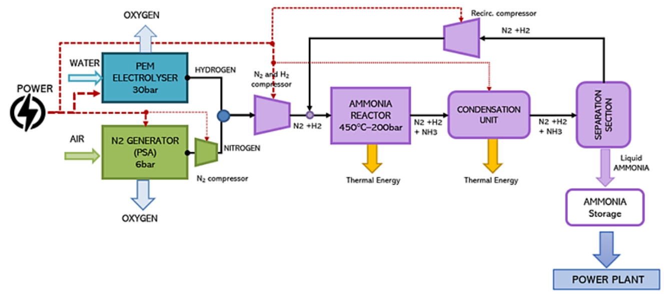

Figure 2: Power-to-Ammonia-to-Power system layout

Figure 2 shows a simplified layout of a P2A2P system on which the following calculations are based. The P2A2P system is composed of (i) 100 PEM water electrolyzers for the hydrogen production as for the P2H2P system; (ii) a Pressure Swing Adsorption (PSA) unit for the nitrogen generation with a specific energy consumption of 1.25kWh/kg$_{N2}$[18][19]. This solution has been selected since the PSA unit is easier to be managed and more flexible compared to the cryogenic distillation; (iii) a nitrogen compressor to bring the N_2 pressure at the PSA outlet (6bar) up to the H_2 outlet pressure (30bar); (iv) an N_2-H_2 mix compressor to bring the syngas pressure from 30bar up to the reactor operating pressure; (v) the ammonia reactor in which the ammonia is synthesized from the N_2 and H_2 in the stoichiometric ration at 200bar and 450°C. The single-pass conversion is assumed at 20% and the overall conversion at 90%[20][21][22]; (vi) a recirculation compressor is required to recirculate the un-reacted gases that have been separated from the liquid ammonia in the separation section back to the reactor inlet. (vi) a condensation unit in which the gaseous stream at the reactor-outlet is cooled down at about 0°C to condensate the ammonia that is then separated and stored; (vii) a pressurized storage tank in which the liquid ammonia is stored.

- *Reference Power plant and baseline scenario*

The study is carried out considering the 400MW Combined Cycle Unit located in EDP's Ribatejo Power Plant, Portugal, as the reference and case study. The unit nominal power is 391MW with a nominal efficiency of 56.7%. The Natural Gas consumption at nominal load is about 16 kg/s (LHV 43MJ/kg). The plant footprint of the 400MW Unit is estimated at 20000 m^2 and used as terms of comparison for the resulting footprint of the P2X processes here evaluated [23][24].

Taking as reference the minimum stable load of 200 MWe of Ribatejo CC Power Plant and considering the land available in the existing plant, as CCGT Power Plants are usually very compact, a 100 MW electrolyzer-based system is then chosen as a good compromise between the CCPP's flexibilization capability and requirements in terms of available space and power input to the electrolyzer.

The storage size is defined in reference to the operating hours of the P2X process: 48-hours storage is considered to cope with weekend power shifts.

Regarding the X2P process, it is assumed that the hydrogen and the ammonia coming from the storage are mixed with the natural gas before entering the gas turbine combustion chamber. Different mix percentage has been evaluated. The power plant's overall efficiency is assumed not affected by the presence of hydrogen/ammonia in the combustion mixture.

The footprint of both the processes is calculated and compared based on the assumptions reported in Table 1.

Table 1Footprint assumption data

	Footprint
PEM Electrolyser	$50m^2/MW_{inst}$ (Based on 5MW plant n. x 40ft container + n. x 20ft utility container [26])
Hydrogen Storage @200bar	50 m^2 /ton H_2 stored in stacked 40ft tube skid [25]
Ammonia Plant *(including the PSA Unit)*	About the 50% of electrolyzer system footprint [27]
Ammonia Storage	About 2.5 m^2 /ton NH_3 Base on commercial tank [28]

3. RESULTS AND DISCUSSION

Table 2 reports the hourly production and the related energy consumption for both the P2X2P systems here investigated.

Table 2 Technical and energetic results for the P2H2P and P2A2P systems

		P2H2P	P2A2P
Hourly production	ton/h	1.8 of H_2	9.2 of NH_3
Energy consumption	MWh	106	116
Electrolyser	MWh	100	100
PSA - N2 generator	MWh	0	8.4
Compression Train	MWh	3.8	4.3
Auxiliaries		2.6	2.8
P2X efficiency	-	56%	42%
P2X2P efficiency	-	32%	24%
48hrs-storage	ton	86	441
	MWh	2.9	2.3

Despite the significant difference between the two P2X processes, the overall energy consumption is almost comparable because most of the energy is absorbed by the electrolyzer plant (95% and 85% for P2H and P2A, respectively). The specific energy consumption in terms of kg of product per MWh consumed resulted in about $17kgH_2/MWh$ and about $80kgNH_3/MWh$.

The resulting P2X efficiencies (based on LHV of the product) are 56% and 42% for the P2H and P2A systems, respectively. This difference is mostly due to the energy losses during the conversion process of the H_2 into NH_3 (about 10% of the hydrogen energy), and the big difference in terms of LHV between hydrogen and ammonia (120MJ/kg for H_2 and 18.8 MJ/kg for NH_3).

However, thanks to the higher density, the ammonia storage solution resulted much more effective, in terms of both occupied volume (722 m^3 of liquid NH_3 against 5400 m^3 of H_2 at 200bar) and specific energy content by volume, as reported in Figure 3. One cubic meter of liquid ammonia contains about 6 times the energy of $1m^3$ of H_2 at 200bar.

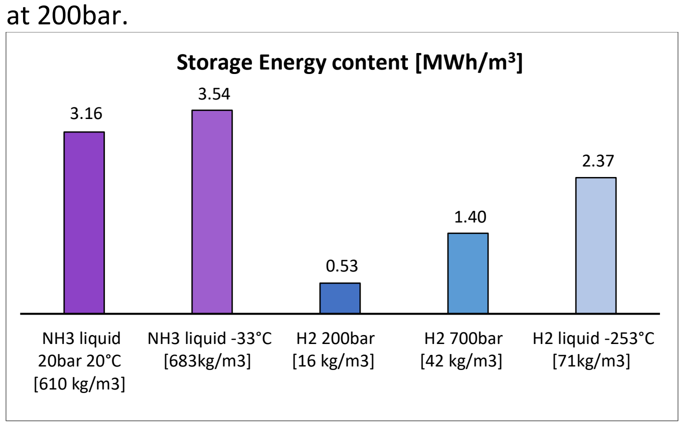

Figure 3 Ammonia and Hydrogen storage comparison in terms of specific energy content in volume

Using the hydrogen and ammonia produced by the P2X system to feed the power plant, the 48hrs-storages can cover a certain number of operating hours depending on the H_2/NH_3 volume content in the fuel mixture.

Figure 4 reports the full-load operating hours of the CC Power plant for both the H_2 and NH_3 storages considering different vol% of these products in blends with the natural gas.

Considering an NG-X mixture at 10% and operating the power plant at full load, the 48hrs storage can last up to 122hrs and 77hrs for the hydrogen and ammonia-based cases, respectively. In terms of CO_2 emission savings, the effect is quite marginal, achieving a percentage reduction of 4.3-3.4%. Aiming at a higher CO_2 emissions reduction, the percentage of H_2/NH_3 in fuel needs to be increased: at 50% vol., the CO_2 emissions are reduced by about 29% and 24% for H_2 and NH_3 respectively. Of course, in this case, the 48hrs storage duration is also reduced to about 17hrs for hydrogen and 12hrs for ammonia with a resulting discharge-charge ratio of about 1:3/1:4. In the end, to achieve the zero-emission target the NG needs to be completely replaced by hydrogen or ammonia. In this case, the charge-discharge ratio resulted in 11:1 and 14:1 for the hydrogen and ammonia 48hrs storage, respectively.

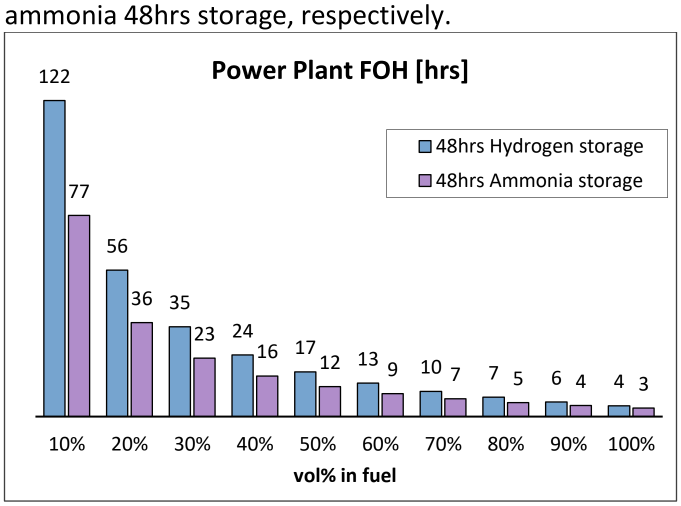

Figure 4 Power Plant Full Operating Hours comparison as a function of the H_2/NH_3 %vol content in fuel.

Finally, the footprint of the two P2X processes has been evaluated: the P2H plant footprint, considered the stacked tube skid, resulted in about 9320m^2 against the 8610 m^2 of the P2A systems. These correspond to 47% and 43% of the 400MW CC-Unit footprint (20000m^2), respectively. In Figure 5, the main components' footprint distribution is reported for the P2H and P2A systems. In both cases, most of the area is occupied by the 100MW electrolyzer plant (54% and 58% for the P2H and P2A, respectively). The footprint of the 48hrs-200bar hydrogen stacked tube skid storage is about 86% of the electrolyzer plant and occupies about 46% of the total required surface. Considering installing the hydrogen tube skid in raw, the required area would increase up to about 8000m2, accounting for 60% of the total P2H footprint and corresponding to about 1.6 times the electrolyzer plant. In the P2A system, the sum of the area required by the Ammonia synthesis unit and the 48hrs-ammonia storage resulted in 72% of the electrolyzer footprint and 42% of the total required surface so even lower than required by the sole hydrogen storage system.

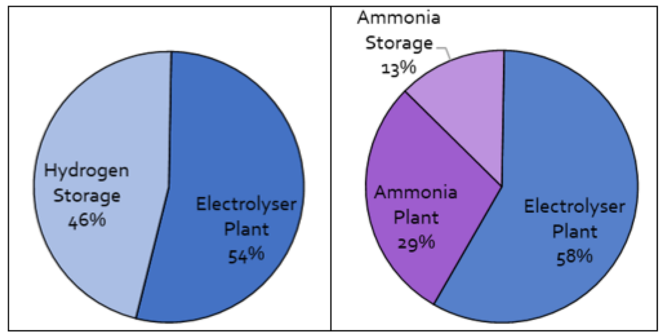

Figure 5 P2H2P and P2A2P footprint distribution

4. CONCLUSION

In the present work, two power-to-fuel-to-power processes were investigated as a potential solution to improve the Combined Cycle Power Plant flexibility by adsorbing and storing the electrical energy produced by the PP and not sold to the grid. The analysis was carried out on the P2H2P and P2A2P systems investigating and comparing the process in terms of round-trip efficiency, storage energy density, and plant footprint.

The main conclusions are summarized as follow:

- The P2H and the P2A systems overall energy consumption resulted almost comparable, however, the P2H2P system turned out to be the best solution in terms of round-trip efficiency.
- In terms of storage energy content per volume, ammonia storage is much more effective than compressed hydrogen storage. Only the liquid hydrogen storage could be almost comparable with the ammonia storage, but the issues and the costs related to the liquefaction process must be considered.

- Considering a 48hrs-storage, the energy content of both the H_2 and NH_3 storage resulted in 2.9 and 2.3 MWh, respectively. Using the H_2 and NH_3 in blend with the NG to feed the power plant and reduce the CO2 emissions, the storage duration depends on the amount of H_2/NH_3 in the blend. To keep the charge-discharge ratio around 1:1, the vol percentage of H_2/NH_3 in fuel should be around 20% with quite limited advantages from the environmental viewpoint.
- In terms of footprint, the P2A plant, despite the presence of the synthesis unit, was found to be much more effective than the P2H plant. This is because of the 200bar hydrogen storage that required an area even higher than the electrolyzer power plant. In this sense, an alternative solution for hydrogen storage needs to be evaluated.

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https://flexnconfu.eu/

REFERENCE

[1] "Renewable energy statistics - Statistics Explained." [Online]. Available: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Renewable_energy_statistics [Accessed: 05-Aug-2021]

[2] "Clean energy for all Europeans package | Energy." [Online - Accessed: 05-Aug-2021]. Available: https://ec.europa.eu/energy/topics/energy-strategy/clean-energy-all-europeans_en

[3] M. Minutillo, A. Perna, A. Sorce, 2020, Green hydrogen production plants via biogas steam and autothermal reforming processes: energy and exergy analyses, Applied Energy, Vol.277, pp.115452_1-15.

[4] O. Alsayegh, S. Alhajraf, H. Albusairi, Grid-connected renewable energy source systems: challenges and proposed management schemes, Energy Conversion and Management, 51 (2010), 1690-1693 10.1016/j.enconman.2009.11.042.

[5] A. Bouakkaz, A.J.G. Mena, S. Haddad, M.L. Ferrari, 2021, Efficient energy scheduling considering cost reduction and energy saving in hybrid energy system with energy storage, Journal of Energy Storage, Vol.33, pp.101887_1-13.

[6] M. Rivarolo, A. Freda, A. Traverso, 2020, Test campaign and application of a small-scale ducted wind turbine with analysis of yaw angle influence, Applied Energy, 279 (2020), 115850.

[7] J. Beiron, R.M. Montañés, F. Normann, F. Johnsson, Flexible operation of a combined cycle cogeneration plant – A techno-economic assessment, Applied Energy, 278 (2020), 115630.

[8] R.M. Montañés , M. Korpas, L.O. Nord, S. Jaehnert, Identifying Operational Requirements for Flexible CCS Power Plant in Future Energy Systems, Energy Procedia, 86 (2016), 22-31.

[9] M. Rivarolo, L. Magistri, A.F. Massardo, Hydrogen and methane generation from large hydraulic plant: Thermo-economic multi-level time-dependent optimization, Applied Energy, 113 (2014), 1737-1745.

[10] C. Chen, A. Yang, Power-to-methanol: The role of process flexibility in the integration of variable renewable energy into chemical production, Energy Conversion and Management, 228 (2021), 113673.

[11] D. Bellotti, A. Sorce, M. Rivarolo, and L. Magistri, "Techno-economic analysis for the integration of a power to fuel system with a CCS coal power plant," J. CO2 Util., vol. 33, 2019, doi: 10.1016/j.jcou.2019.05.019.

[12] M. Ozturk, I. Dincer, An integrated system for ammonia production from renewable hydrogen: A case study, Int. Journal of Hydrogen Energy, 46 (2021), 5918-5925.

[13] M.G. Bozo, M.O. Vigueras-Zuniga, M. Buffi, T. Seljak, A. Valera-Medina, Fuel rich ammonia-hydrogen injection for humidified gas turbines, Applied Energy, 251 (2019), 113334.

[14] Ferrari M., Rivarolo M., Massardo A.F. "Hydrogen production system from photovoltaic panels: experimental characterization and size optimization", Energy Conversion and Management, 116 (2016), 194-202.

[15] https://flexnconfu.eu/ , last access on 28/07/2021.

[16] H. Van 't Noordende and P. Ripson, "Gigawatt green hydrogen plant: State-of-the-art design and total installed capital costs," Institute for Sustainable Process Technology (ISPT), 2020

[17] R. M. Navarro, R. Guil, and J. L. G. Fierro, "Introduction to hydrogen production," Compend. Hydrog. Energy, pp. 21–61, Jan. 2015, doi: 10.1016/B978-1-78242-361-4.00002-9.

[18] "The Energy Costs Associated with Nitrogen Specifications - O'Neill Industrial." [Online]. Available: https://oneillcompressedair.com/2020/04/21/the-energy-costs-associated-with-nitrogen-specifications/. [Accessed: 05-Aug-2021].

[19] Atlas-Copco, "On-site Industrial Gases", 2019 https://www.atlascopco.com

[20] Appl M. Ammonia, 2. Production Processes. In: Ullmann's Encyclopedia of Industrial Chemistry, Weinheim: Wiley-VCH; 2012, p. 139-226. https://doi.org/10.1002/14356007.o02_o11

[21] Morgan E.R., Techno-economic feasibility study of ammonia plants powered by off-shore wind, 2013, Open Access Dissertations, 697.
[22] Bellotti D., Rivarolo M., Magistri L., Clean fuels synthesis from green hydrogen: a techno-economic comparative analysis, E3S Web of Conferences 238, 03001 (2021), doi.org/10.1051/e3sconf/202123803001
[23] https://portugal.edp.com/pt-pt/central-termoeletrica-do-ribatejo
[24] Central Termoelétrica do Ribatejo, Descrição da Instalação Geral, Agosto de 2001
[25] “China Hygrogen tube skid factory and manufacturers | Enric.” [Online]. Available: https://www.cimc-enric.com/hygrogen-tube-skid-product/. [Accessed: 06-Aug-2021].
[26] Denis T., Power to hydrogen to power solution, Cummins – Hydrogenics, FLEXnCONFU Webinar, 2020
[27] Private communication by PROTON Venture
[28] “Ammonia storage tanks.” [Online]. Available: https://www.ntotank.com/ammonia-storage-tanks. [Accessed: 05-Aug-2021].