Power-to-ammonia-to-X: cost assessment of an integrated renewable ammonia-based system providing heat and power for residential use

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Abstract:
Ammonia is increasingly recognized as a potential emission-lean and sustainable energy carrier. Producing fossil-free ammonia from variable renewable energy sources (VRES) through water electrolysis may soon become economically viable. Ammonia is a comparatively cheap and safe medium for hydrogen transport and storage, allowing to cope with the variability of the renewable energy supply in time and space and facilitating the penetration of VRES in the energy systems. Moreover, ammonia features promising properties as a fuel, allowing retrieving stored energy by means of direct combustion or fuel cell use to satisfy heat and power demand during VRES production lows. In particular, its high octane rating makes it suitable for use in spark-ignition (SI) engines, which may be a low-cost, low-complexity, high-reliability solution for local heat and power generation. Power-toAmmonia-to-Power and Heat (P2A2P+H) could thus be an interesting bridging concept in new energy systems. However, such technologies present a low maturity level and their economic performance is highly uncertain and hard to quantify, thus slowing down their implementation. Therefore, the present work proposes a cost assessment of a grid-assisted P2A2P+H system based on a wind farm, an ammonia production and storage plant and a SI engine generator providing power and heat to a residential district. The optimal system designs are investigated by means of a multi-objective optimization method based on a genetic algorithm. Results show that such systems may be commercially competitive if the grid prices increase, and allow a local energy system to be highly self-sufficient, thus preventing risks of shutdowns associated with increasing shares of VRES. Seasonal storage appears particularly relevant and the ammonia system provides non-negligible amounts of heat to the consumers.

Keywords:
Ammonia, Sustainable fuel, Renewable energy storage, Power-to-fuel, Cost analysis.

1. Introduction

Alongside its traditional use as a fertilizer and chemical feedstock, ammonia (NH_3) is increasingly recognized as a potential emission-lean and sustainable energy carrier, as attested by its consideration in several recent global reports and studies, including the International Energy Agency's The Future of Hydrogen report [1]. As a non-carbon molecule carrying 17.8% hydrogen by weight and being a liquid under very mild conditions of less than 9 bar at 20°C (similar to propane) granting it an energy density of 11.4 MJ/L, it appears suited for hydrogen and energy storage and transport in energy systems dominated by variable renewable energy sources (VRES). The current energy-related climate crisis granted ammonia a renewed research interest [2 4] for various applications, including mobility [5 8], small- and large-scale power and heat production [9,10], hydrogen storage [11] and chemical feedstock production [12 14]. Most of ammonia-related research addresses the challenges of minimizing the climate, environmental and health impacts of ammonia production and use, at economically viable costs.

Current estimates of the world annual production are about 180 Mt of ammonia, mainly produced for the fertilizer industry through the carbon-intensive Steam Methane Reforming (SMR) process for hydrogen (H_2) production and energy-intensive Haber-Bosch process for NH_3 synthesis from H_2 and N_2. Therefore, efforts are needed to reduce the carbon footprint of ammonia production, especially if the produced quantities increase due to its use as an energy carrier. Several routes are being investigated for "green" ammonia production. Ammonia from biomass provides significant CO_2 savings at costs that could soon be competitive depending on carbon prices and ammonia market prices [15 19]. Innovative concepts reusing syngas by-products to provide heat and power to the process are under evaluation [20]. Alternatively, solar thermochemical production of ammonia appears feasible in regions with excellent solar resources [21]. However, the large-scale deployment of VRES to cover an increasing share of the global power demand makes Power-to-Ammonia (P2A) concepts particularly interesting for mid- and long term energy storage between periods of VRES production highs and lows. Thus, Life Cycle Assessments (LCA) of several Power-to-Ammonia routes are reported in the literature [22,23] to evaluate and compare their climate, environmental and health impact. They show a CO_2 reduction up to a factor six between ammonia produced from windpowered electrolytic hydrogen instead of SMR, and benefits of wind over PV solar regarding fossil resources depletion and the eutrophication and acidification potentials. Furthermore, several studies [24 34] investigated the design, thermodynamic performance and economic viability of P2A systems. Zhang et al. [35] additionally compared P2A with the biomass routes and found that P2A could achieve the highest system efficiency up to 74%, but at currently non-profitable costs (544-666 USD/t NH_3) due to the high costs of the electrolyzers stacks.

It has been highlighted that ammonia can be considered as both an energy storage medium and a direct fuel for heat and power applications, and it was shown in [36] to have the best power-to-fuelto-power ratio among other artificial fuels. A LCA by Bicer and Dincer [37] showed that ammonia has a considerable CO_2 mitigation potential when produced from wind-powered electrolysis and used as a fuel for city transportation and power generation (gas power plant). Ikäheimo et al. [10] studied a global case where ammonia storage would enable a 100% renewable power and heat system for northern Europe, with final conversion happening through combined cycle gas turbines. Their Powerto-Ammonia-to-Power (P2A2P) system would compete with natural gas at gas prices above 70€/MWh. Rouwenhorst et al. [38] conducted a review of possible Power-to-Ammonia-to-Power (P2A2P) systems for islanded locations and showed potential for high storage efficiency and estimated costs about 300350 €/MWh. They suggest fuel cells or gas turbines as the conversion technologies. Other studies [39 50] suggested fueling Solid Oxide Fuel Cells (SOFC) with ammonia for various applications, including heat and power combined cycles with gas turbines. However, the low maturity level and complexity of that technology appear as temporary barriers. Morgan et al. [51] studied the case of wind-powered islanded ammonia production as a substitute to diesel fuel and showed a potential for significant diesel savings if the price of diesel exceeded 10 USD/gallon. They assumed a round-trip efficiency of the ammonia production process of 50%. Palys et al. [13] proposed an integrated system based on wind turbines to provide ammonia and energy to a rural community, by means of combustion based gensets for the Ammonia-to-Power conversion.

While those investigations highlight the interest and the research progress in P2A2P systems that may improve the long-term reliability and efficiency of future VRES-dominated energy systems, the deployment of such solutions will require further efforts due to the low maturity and complexity of the associated technologies, inducing non-competitive costs. Therefore, it appears reasonable to consider the use of other mature technologies in the P2A2P context, such as the Internal Combustion Engine (ICE) for Ammonia-to-Power conversion. Previous work [52 54] showed that it is a very suitable technology for ammonia conversion, with efficiencies comparable with conventional fuels operation and no or little need for design modification. Moreover, ICE units for Combined Heat and Power (CHP) plants are a very mature technology, being able to ensure high reliability, modularity and fast ramp-ups at low to moderate capital and maintenance costs.

Thus, the present work aims at gaining more insights into the feasibility and relevance of Power-toAmmonia-to-Power and Heat (P2A2P+H) systems in the specific case of ICE use for heat and power generation. To that end, simple realistic techno-economic assumptions are used to conduct a cost assessment of such a system allowing to match the energy supply of a wind farm with the demand of a grid-connected local community. Optimal system sizing is investigated thanks to a multi-objective optimization based on a genetic algorithm, and the resulting designs are presented and analyzed.

2. Methodology

2.1. System description

The proposed system matches the annual energy demand of a typical Belgian community with the energy production of an onshore wind farm installed in Belgium on an hourly basis, with possible assistance of the electrical grid. The demand data originates from the OpenEI database [55] of the US Department of Energy for one typical American dwelling in Olympia, a city with a 99% weather similarity with Brussels. The hourly electricity and heat demands were considered and scaled to a typical Belgian dwelling as suggested in [56]. The resulting demand is shown in Fig. 1 for power and Fig. 2 for heat. The different energy consumption items of the database were sorted between electricity and heat (originally gas) following a high electrification scenario: the heat demand actually only corresponds to space and water heating. The size of the community was adapted by multiplying the individual demand vector by the number of dwellings, that was taken as 1000 to be relevant to a megawatt-scale wind farm.

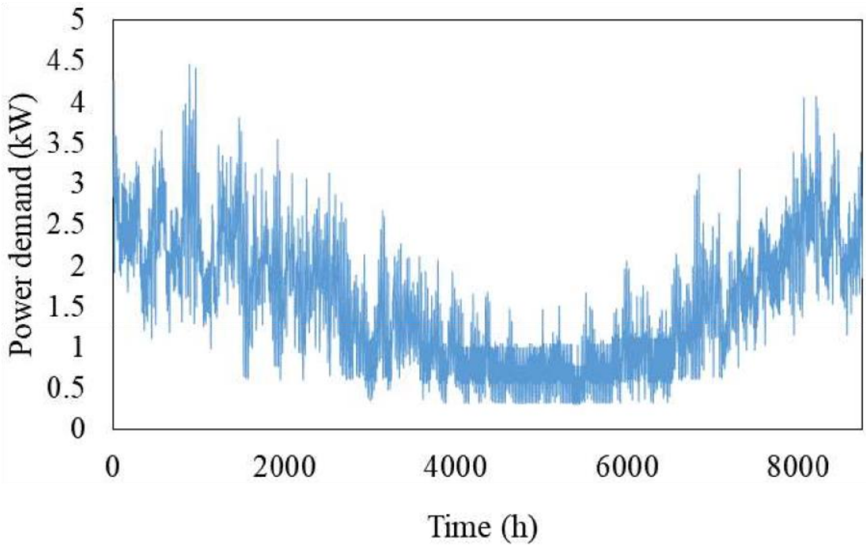

Fig. 1. Yearly power demand of a typical Belgian dwelling.

The data for wind energy is taken from the EMHIRES dataset for West Flanders [57], and an average annual capacity factor vector is obtained with hourly resolution for the period 1986-2015, that is shown in Fig. 3. The vector is multiplied by the nominal capacity of the wind farm to obtain the wind power profile.

The matching between the demand and the supply happens thanks to the Power-to-Ammonia-toPower and Heat system shown in Fig. 4 and follows different scenarios:

- If the demand exceeds the wind power supply: all the wind power is allocated to fulfil the demand, the ICE plant furnishes the maximum or required power from the stored NH_3 and electricity is bought from the grid to fill any remaining design-dependent gap. The NH_3 production plant is operated under minimal power to avoid a costly shutdown.
- If the wind power supply exceeds the demand: all the demand is directly covered by the wind power. The NH_3 production plant is operated with the remaining renewable power to produce and store NH_3. The engine runs at minimal power to utilize the purge flow of the Haber-Bosch loop.

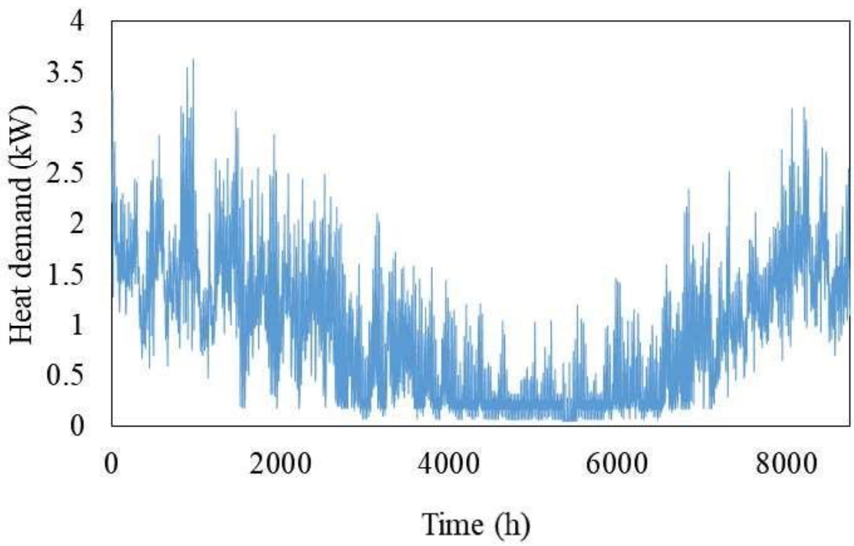

Fig. 2. Yearly heat demand of a typical Belgian dwelling.

If the heat provided by the CHP plant does not satisfy the demand, the additional heat is provided by individual heat pumps fed by either renewable or grid power. The heat pumps are taken into account in the costs calculations for the whole system, though being commissioned individually in the dwellings.

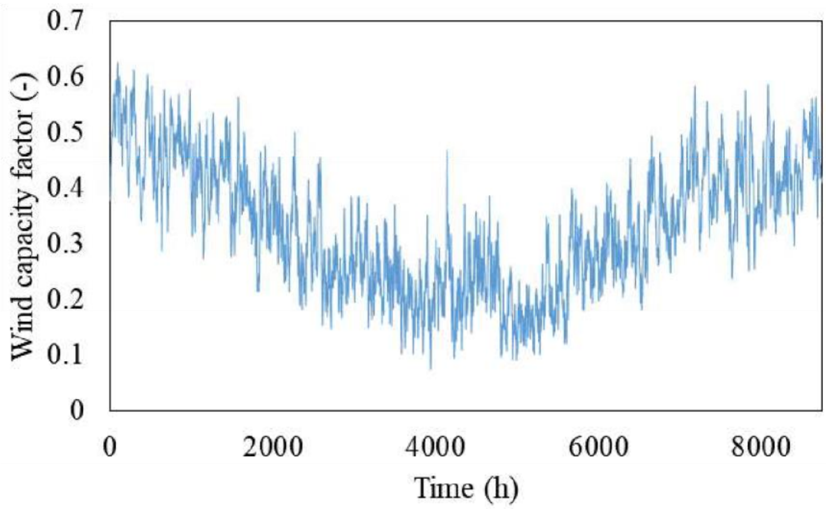

Fig. 3. Yearly wind capacity factor for a typical Belgian location.

Black box models were chosen for the system components and no physical models were included. The NH_3 production virtually consists in an electrolyzer, an air separation unit, a hydrogen buffer storage, and a Haber-Bosch system comprising one or several compressors or reactors, as well as all the necessary heat exchangers and expanders, but none of those components is modelled here. For the sake of simplification, a single efficiency coefficient was applied between the input power (wind farm) and the output mass of ammonia (LHV basis) in accordance with data from the literature. The purge flow of the Haber-Bosch process is used in the ICE CHP plant as a fuel. The ICE CHP plant may consist of several units in order to provide a good ramp-up behavior, flexibility and operate at the highest efficiency. No losses are assumed from the NH_3 storage tanks. The assumptions on the system components are summarized in Table 1.

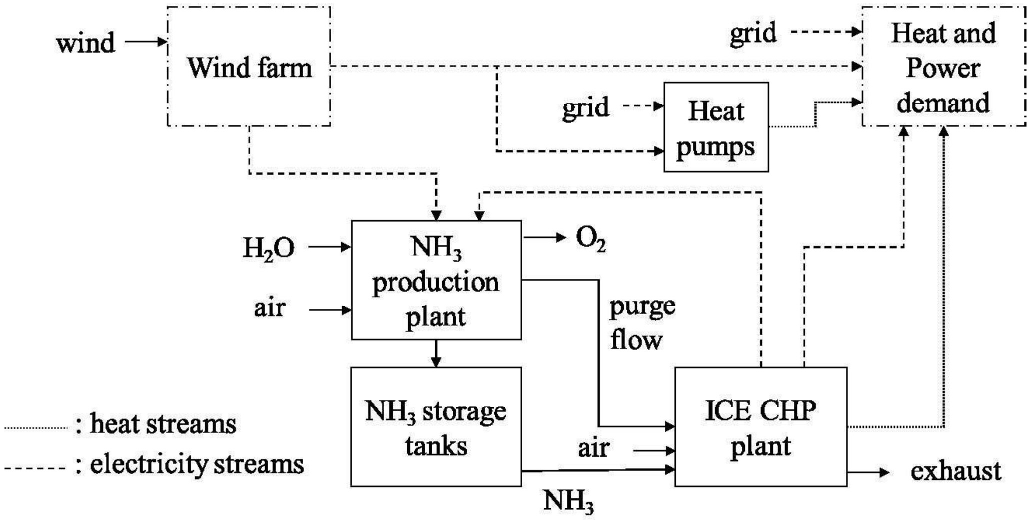

Fig. 4. Schematic of the system streams.

Table 1. System components characteristics.

Item	Characteristic	Unit	Value
NH_3 production plant	Energy efficiency	%	50 [51] or 74 [35]
	Minimal required power	% of nominal capacity	20 [34]
	Purge flow	% of NH_3 output	5
ICE power plant	Power efficiency	% of fuel energy	40
	Heat efficiency	% of fuel energy	40
Heat pumps	Coefficient of performance	-	4

2.2. Cost and self-sufficiency analysis methods

The proposed cost assessment follows the essential steps of the method proposed in [58] with some simplifications and aims at estimating the Levelized Cost of Energy (LCOEn) over the entire lifetime of the studied energy system. The assumptions for the cost estimates and calculations are summarized in Table 2. For each system design, total capital costs are calculated as a sum of the capital expenditures (CAPEX) for each system components (wind farm, NH_3 plant, NH_3 tanks, CHP plant, heat pumps). They are then annualized by multiplying by the capital recovery factor, given in Eq. (1):

$$Capital\ Recovery\ Factor = \frac{i(1+i)^T}{(1+i)^T-1}, \qquad (1)$$

where i is the interest rate and T the lifetime of the system. The annual Operational Expenditures (OPEX) are then added, with no distinction between fixed and variable operation and maintenance costs. No replacement costs were considered, even though electrolyzer stacks may have a shorter lifetime than the rest of the system, and should thus be replaced in a more detailed analysis. The total annualized costs are eventually obtained by adding the annual electricity expenses, when electricity is bought from the grid. The result is finally divided by the total annual energy demand, yielding the LCOEn.

Since the proposed system is connected to the power grid and the costs of current P2A2P systems is not yet competitive with the market price of electricity, another target parameter has been introduced in the present study, namely the Self-Sufficiency Ratio (SSR). It quantifies the ability of the energy supply system to satisfy the demand without assistance of the power grid. It gives an indication on the resilience of the local energy system against blackouts, what should become increasingly relevant in VRES-dominated power grids. The SSR is calculated in Eq. (2):

$$SSR = 1 - \frac{E^a_{grid}}{E^a_{dem}} \quad , \qquad (2)$$

where E^a_{grid} is the annual total energy consumption from the grid and E^a_{dem} is the annual total energy demand.

Table 2. Economic assumptions for this study.

Cost item	Unit	Value
Onshore wind farm (CAPEX)	€/kW	850 [10]
Onshore wind farm (annual OPEX)	€/kW	55 [10]
NH3 production plant: Electrolyser + H2 buffer + ASU + Haber-Bosch (CAPEX)	€/kW	1740 [10]
NH3 production plant: Electrolyser + H2 buffer + ASU + Haber-Bosch (annual OPEX)	€/kW	29 [10]
NH3 storage (CAPEX)	€/kg NH3	2.7528 [38]
Engine power plant (CAPEX)	€/kW	1000 [59]
Engine power plant (annual OPEX)	€/kWh	0.02 [59]
Heat pump (CAPEX)	€/unit	3000
Grid electricity price	€/MWh	200-400
Interest rate (constant)	%	10
System Lifetime	years	20

2.3. Optimization method

Based on the former system model and economic assumptions, a search for optimal designs is conducted, aiming at minimizing the LCOEn, while maximizing the SSR. The Nondominated Sorting Genetic Algorithm (NSGA-II) [60,61] is a multi-objective optimization method which effectively handles complex, non-linear models. The NSGA-II algorithm starts from an initial population of design samples, out of which it creates an offspring based on crossover probability (90%) and mutation probability (10%) [32]. The population and offspring samples are sorted based on their dominance in the objectives. The top half samples compose the next generation, where more isolated samples in the design space are favored to ensure an optimal diversification of the set of solutions. This process is repeated until the maximum number of generations is reached. In this work, a population count of 120 samples is evaluated over 300 generations. The design parameters are the nominal capacities of the NH_3 production plant and the ICE CHP plant.

3. Results and discussion

Figure 5 presents the results of the optimization for a wind farm nominal capacity of 6 MW, and different cases corresponding to different assumptions with respect to the efficiency of the Power-toAmmonia system and grid electricity price. All other characteristics or assumptions but the design parameters remain unchanged. The different cases are summarized in Table 3.

Table 3. Different cases studied.

Case	Power-to-Ammonia efficiency	Grid electricity price
Case 1	50 % [51]	200 €/MWh
Case 2	74 % [35]	200 €/MWh
Case 3	50 % [51]	400 €/MWh
Case 4	74 % [35]	400 €/MWh

Preliminary investigations showed that under current assumptions, the size of the wind farm mostly determines the SSR of the system, due to the remaining significant cost barrier of the P2A2P+H system. For each case, the lower left design with smallest SSR has a negligible P2A2P+H system. However, optimal designs with P2A2P+H cover the SSR range 0.92-0.94 at LCOEn of 67-74€/MWh, slightly higher than the production price of electricity for 200€/MWh market price, as shown in Fig. 5. A better efficiency of the P2A process allows reaching a better SSR at the same LCOEn, as expected. From a cost perspective, the system appears not to be competitive at present, but the advantages of a high SSR may prove to justify the high cost of energy. Moreover, the cases with a higher market price of electricity (Cases 3 and 4) show a higher optimized LCOEn of the system between 83 and 87 €/MWh, but it would be competitive with the grid price before taxes (about 120 €/MWh). However, the SSR range described by the Pareto front of the optimized trade-offs is narrowed at higher electricity prices. Thus, it is likely that P2A2P systems could become competitive in scenarios with increasing grid electricity prices caused by an increasing share of VRES. In such a scenario, the advantages of a high SSR, such as blackout resilience appear more decisive.

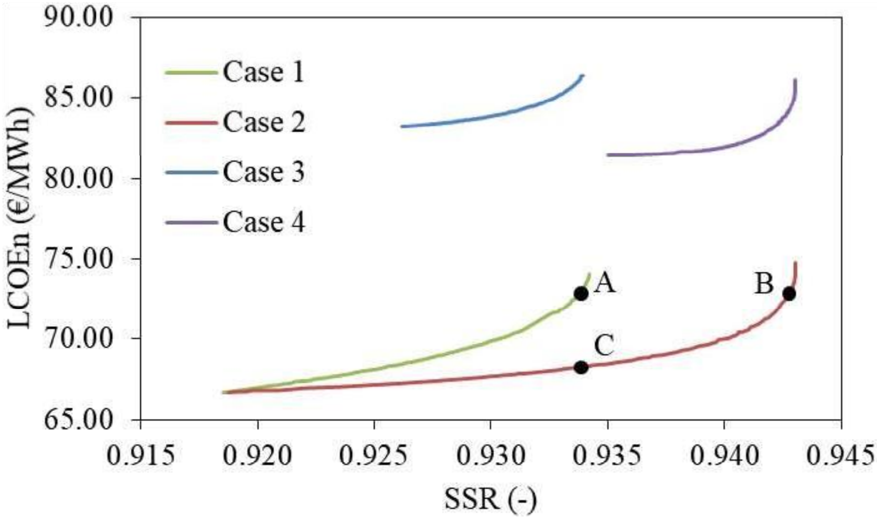

Fig. 5. Trade-offs between the optimal LCOEn and SSR.

Among the optimal designs in Fig. 5, three designs (A,B,C) are given in Table 4 and compared in the following. At equivalent LCOEn, design B presents one point SSR benefit over design A, thanks to the better P2A efficiency in Case 2. The size of the engine plant increases in consequence to take advantage of the additional quantities of NH_3 produced. Design C presents the same SSR as Design A, but this is only thanks to the better efficiency of the P2A system, since both the size of the P2A system, as well as the engine plant are reduced.

Table 4. Optimization results for chosen designs.

Design	Installed capacity of the P2A system (kW)	Installed capacity of the CHP plant (kW)	LCOEn (€/MWh)	SSR
A	537	465	72.5	0.933
B	527	703	72.5	0.943
C	213	300	68	0.933

Figure 6 presents the quantities of NH_3 produced and stored in the different designs as a function of time. The maximum tank capacity approaches 120 metric tons for Design B, with the best P2A efficiency. Due to the scaling of the wind power plant, the period of the year in which the energy production exceeds the demand is between the end of summer and the beginning of winter. Thus, the period of ammonia storage in the P2A system corresponds to that period, with short-term variations to balance the system. It should be highlighted that the period of ammonia storage stretches over several months, which is one of the main interests of using gaseous or liquid fuels as energy storage media. The different system designs affect the magnitude of ammonia storage, but its temporal shape does not vary with the present design parameters. The most ammonia needs to be stored for the design proving the highest SSR in the case of high P2A efficiency (B). However, for a constant SSR, Design C requires less storage than Design A.

Another interest of the proposed system is to take advantage of ammonia combustion to provide heat to the community thanks to the enthalpy of the hot exhaust gases. Design B corresponds to the configuration with the maximal heat provided by the P2A2P system, with 10.2% of the annual heat demand satisfied by the engine plant. In the design with a less efficient P2A system (A), the amount of heat furnished by the engine is about 7% of the total demand. It falls down to 4.7% for Design C, as expected due to the smaller size of the P2A2P components. Those values are relatively modest because they compete with very efficient and relatively affordable heat pumps in the present model. Still, it appears that a non-negligible amount of the required heat can be provided to the community thanks to the system. Moreover, as heat pumps are individual pieces of equipment, there might be cases where a collective heat network remains the preferred solution.

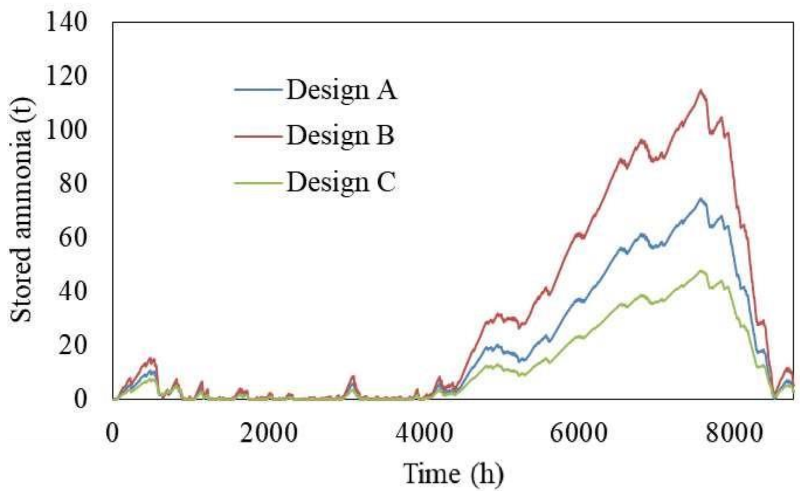

Fig. 6. Yearly evolution of ammonia storage in selected system designs.

4. Conclusions

This paper present the methodology and the first results of a techno-economic assessment on the use of ammonia as an energy storage medium for stationary heat and power applications. A modelled Power-to-Ammonia-to-Power and Heat system was used to match the energy demand of a local community with the power production of a wind power plant, based on simple techno-economic assumptions from the literature. It includes a combined heat and power plant based on internal combustion engines, that benefit from a high technological maturity level, a high flexibility and reliability, and a fast dynamic behavior. A multi-objectives optimization was attempted to look for optimal designs by means of a genetic algorithm.

First results demonstrate a high self-sufficiency potential of such an energy system at costs that slightly exceed the current electricity grid prices. Increased grid prices result in optimal designs becoming competitive. The system allows for seasonal energy storage during periods of high production and low consumption, that is allowed by the great stability of the ammonia fuel. That makes it an asset for future energy systems dominated by Variable Renewable Energy Sources.

Future work should refine the models assumptions and their uncertainties, by looking into the physical processes of the system components, particularly the Haber-Bosch loop and its dynamic behavior, as well as the engine performances based on previous experimental data. A real distinction between the heat and power supply may also be of interest, in the form of an assessment on the system's exergy.

Acknowledgments

The research leading to these results has received funding from the French Government's "Investissement d'Avenir" program: "Laboratoire d'Excellence CAPRYSSES" (Grant No ANR-11-LABX-0006-01).

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