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A Comparative Techno-Economic Assessment of Green Ammonia Production in Selected European Locations

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Abstract. Green ammonia is emerging as a promising carbon-free energy carrier and chemical feedstock for the decarbonization of the industrial, maritime, and power sectors. However, its economic competitiveness remains strongly constrained by the intermittent nature of renewable energy sources and the optimal design and operation of integrated production plants. This work presents a comprehensive techno-economic optimization of a stand-alone photovoltaic-powered green ammonia production system comprising a Proton Exchange Membrane electrolyzer, battery energy storage system, hydrogen storage, cryogenic air separation unit, Haber–Bosch synthesis loop, and ammonia storage. The model allowed to identify optimal plant configurations that minimize the Levelized Cost of Ammonia for seven representative European locations characterized by different solar resources. The results demonstrate that solar resource availability has a strong impact on Levelized Cost of Ammonia, with Southern European locations achieving production costs as low as 4.60 €/kgNH_3, while Northern regions exceed 6.00 €/kgNH_3. The analysis further highlights the importance of photovoltaic plant and the electrolyzer as main cost drivers, whereas improvements in Haber–Bosch operational flexibility can substantially increase plant availability, reduce photovoltaic curtailment, and improve the overall economic competitiveness of renewable ammonia production.

1. Introduction

Ammonia (NH_3) is one of the most extensively produced and utilized chemicals worldwide, with a current global production exceeding 190 Mt yr^{-1} [1]. Approximately 70% of the ammonia produced globally is used for fertilizer manufacturing [2], and its demand is projected to increase over the coming decades as a consequence of population growth and increasing food demand [3]. Beyond its traditional role in the fertilizer industry, ammonia has recently attracted considerable attention as a promising carbon-free energy carrier and fuel. Its relatively high volumetric energy density and ease of storage and transportation in liquid form under relatively mild conditions make ammonia an attractive candidate for decarbonizing hard-to-abate sectors, including maritime transportation, power generation, and high-temperature industrial processes [4].

Despite these advantages, nearly all commercial ammonia is currently produced through the conventional Haber–Bosch (HB) process, where nitrogen obtained from air separation reacts with

hydrogen produced primarily via natural gas steam methane reforming. The reliance on fossil-derived hydrogen results in significant greenhouse gas emissions, making ammonia production responsible for more than 1% of global CO_2 emissions [5] and one of the most carbon-intensive industrial chemical processes worldwide.

The rapid decline in renewable electricity costs, particularly from photovoltaic (PV) systems, together with the increasing penetration of renewable energy sources into modern power systems, has stimulated growing interest in the production of green ammonia, in which hydrogen is generated through water electrolysis powered by renewable electricity. Numerous demonstration projects and research initiatives have recently been launched worldwide to validate the technical feasibility of the concept [6–9]. While technological viability has been largely demonstrated, its economic competitiveness remains one of the principal barriers to large-scale deployment.

The economic performance of green ammonia production is generally evaluated through the Levelized Cost of Ammonia (LCOA), which is influenced by several factors, including renewable electricity prices, resource availability, plant location, financing conditions, infrastructure accessibility, and system operational flexibility. In contrast, the LCOA of conventional fossil-based ammonia is currently ranging between approximately 0.10 and 0.30 €/kgNH_3, establishing a particularly challenging benchmark for renewable alternatives.

Several techno-economic studies have attempted to quantify the current and future cost of renewable ammonia production. Nayak-Luke et al. [10] reported minimum LCOA values of approximately 0.41 €/kgNH_3 for off-grid renewable energy systems located in favorable regions, projecting further reductions to around 0.30€/kgNH_3 by 2030. Armijo and Philibert [11] estimated production costs of approximately 0.84€/kgNH_3 for autonomous renewable ammonia systems. Pawar et al. [12] investigated the spatial variability of green ammonia production costs across India, reporting LCOA values between 0.73 and 1.15 €/kgNH_3, depending on local renewable resource availability. More recent studies reported LCOA values of approximately 1.04 €/kgNH_3 for PV-powered systems, decreasing to 0.99 €/kgNH_3 when revenues from surplus electricity exports were considered [13]. Other reviews indicate instead that renewable ammonia production costs could achieve slightly higher range, between 1.00 and 2.44 €/kgNH_3, depending on plant size, technology configuration, renewable resource quality, and geographical location [14]. Given the extreme variability of results in the literature, this work aims to propose a grounded analysis on the cost of standalone green ammonia production based on Haber-Bosch process. A comprehensive optimization framework is developed for an off-grid photovoltaic-powered green ammonia plant, considering the sizes of the several sub-systems such as the installed capacities of the photovoltaic array, battery energy storage system (BESS), electrolyzer, hydrogen storage, and Proton Exchange Membrane (PEM) Electrolyzer. The optimization is performed for several European locations characterized by markedly different solar resource availability, enabling a systematic assessment of the impact of local climatic conditions on system sizing, operational strategies, renewable energy utilization, and overall economic performance. Furthermore, the effect of HB operational flexibility on plant design and cost competitiveness is investigated, providing new insights into the role of flexible ammonia synthesis in reducing renewable energy curtailment and storage requirements.

2. Methods

2.1 Modelling framework and system configuration

The reference green ammonia production plant considered in this study is illustrated in Figure 1, which presents the overall configuration of the off-grid renewable ammonia system and its main subsystems. The plant is directly coupled to a PV array that supplies renewable electricity to a PEM electrolyzer for hydrogen production via water electrolysis. A BESS is integrated into the system to mitigate the intermittency of photovoltaic generation and ensure a stable power supply to the downstream processes.

The PEM electrolyzer consumes demineralized water and produces high-purity hydrogen and oxygen. While oxygen is assumed to be vented to the atmosphere, the hydrogen is stored in a low-pressure storage tank operating at 30 bar. The storage of hydrogen at lower pressure levels even if leads to higher footprints, allows to reduce the capital and operational expenditures related to its construction, maintenance as well as safety equipment and procedures. The stored hydrogen is subsequently compressed to the operating pressure required by the HB synthesis loop, typically ranging from 180 to 250 bar, through a dedicated hydrogen compressor.

Nitrogen required for ammonia synthesis is supplied by a cryogenic Air Separation Unit (ASU). The electrical demand of both the hydrogen compressor and the ASU is met by the PV system and the BESS, depending on the instantaneous availability of renewable electricity. Ammonia synthesis is carried out in a conventional Haber–Bosch reactor, whose operational flexibility is represented by two key parameters: the minimum stable operating load and the minimum restart (or setup) time required to resume operation following a shutdown. These parameters strongly influence the plant ability to accommodate the variability of renewable electricity generation and therefore play a crucial role in determining the overall system design and economics.

The produced ammonia is stored in a dedicated storage facility before being dispatched. Since the storage is assumed to operate only as a short-term buffer and the stored ammonia is withdrawn within 72 hours, the ammonia storage capacity is considered effectively unconstrained.

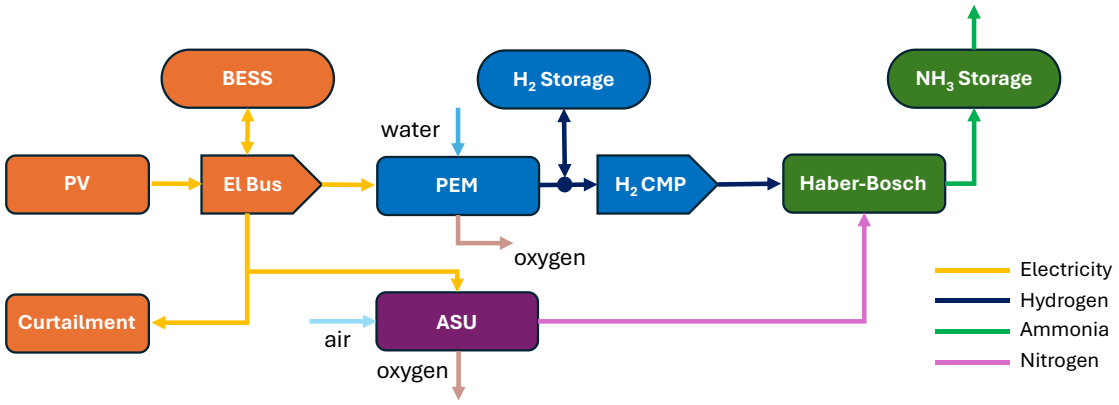


Figure 1. Simplified layout of the standalone green ammonia production system.

2.2 Energy, process, and economic modelling

PV generation is calculated using weather data retrieved by the NASA POWER Data Viewer API, which are used to compute the electric power generated by the PV following the methodology detailed in [15]. The BESS is modelled through the following energy balance:

$$E_{BESS,t+1} = E_{BESS,t} + \eta_{ch} P_{ch,t} \Delta t - \frac{P_{dis,t} \Delta t}{\eta_{dis}} \quad (1)$$

where the charge and discharge efficiency are assumed equal and result in an overall round-trip efficiency:

$$\eta_{RT} = \eta_{ch} \cdot \eta_{dis} \quad (2)$$

Process units (PEM electrolyzer, compressor, ASU, and Haber–Bosch synthesis) are modelled using specific energy consumption (SEC) values. All components' main technical specifications and assumptions are reported in Table 1.
The off-grid green ammonia production system economic performance is evaluated using the Levelized Cost of Ammonia, expressed as:

$$LCOA = \frac{\sum_{i=1}^{N} CAPEX_i CRF_i + OPEX_i}{\mathrm{m}_{NH_3}} \quad (3)$$

where $CAPEX_i$ is the capital investment required for each i-th component of the plant, CRF_i is the Capital Recovery Factor which is used to actualized the initial capital investment into an equivalent annual cost over the lifetime of the project, N is the lifetime of each component expressed in years, $OPEX_i$ are the operational expenditures for each component i-th and m_{NH_3} is the total amount of ammonia produced in a year. Component costs, O&M fractions, and lifetimes are reported in Table 2, including replacement and residual value accounting, the discount rate assumed is 8%.

Table 1. Main technical specifications and assumptions.

Component	Capacity range	Op Parameters	Efficiency/SEC	Source
PV	100 MW	Off-grid	450 W/m²	[OEM]
BESS	5 MWh – 25 MWh	Min SOC: 20%/0.25C-rate	92%	[22]
PEM electrolyzer	10%-100% PV power	H_2 outlet pressure 30 bar	53 kWh/kgH_2	[16], [17]
H_2 compressor	Annual Peak H_2 flow rate	3-stage Intercooled	3.5 kWh/kgH_2	[16]
H_2 storage (pressurized)	1 t -10 t	Storage pressure 30 bar	1 t -10 t	[18]
Cryogenic ASU	Annual Peak N_2 flow rate	N_2 pressure 200 bar	140 kWh/tN_2	[19]
HB	1000 kgNH_3/h	Minimum setup period range: 12h-48 h; Min load 40%	0.75 MWh/kgNH_3	[20] ,[21], [22]

Table 2. Economic parameters.

Component	CAPEX	OPEX (% of CAPEX)	Lifetime [years]	Source
PV	800 €/kW	2.0%	20	[23], [24], [25]
BESS	300 €/kWh	1.5%	12	[26]
PEM Stack	700 €/kW	2.5%	7	[16], [27]
PEM BoP	1100 €/kW	2.5%	25	[16], [27]
H_2 compressor	8,000 €/(kgH_2/h)	3.0%	25	[28], [16]

H_2 storage	800 €/kgH_2	2.0%	25	[29], [30]
Cryogenic ASU	1.5 m€/(tN_2h)	2.3%	25	[20], [19]
HB	2,750 €/(kgNH_3/h)	2.3%	25	[31], [20]
NH_3 storage	0.80 €/kgNH_3	3.0%	25	[32]

2.3 Optimization problem and solution approach

To evaluate the techno-economic performance of the proposed green ammonia plant under different design configurations, a simulation model was developed in MATLAB in fully off-grid configuration, with no electricity import from or export to the external grid.

Figure 2 presents the flowchart of the algorithm governing the plant energy management strategy. The simulation is performed with an hourly resolution over an entire year using the meteorological data associated with each geographical location. At every time step, the available photovoltaic electricity is first allocated to satisfy the instantaneous electrical demand of the plant.

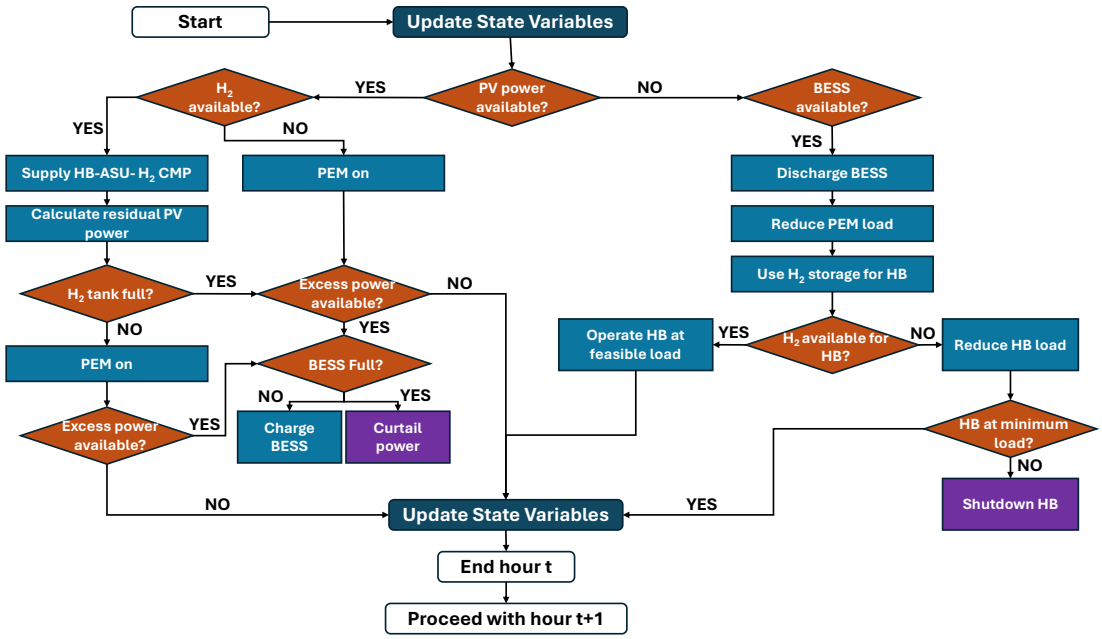


Figure 2. Energy management strategy for the off-grid green ammonia production system. The illustrated control loop is applied to a single hour of operation and is repeated sequentially for each hour of the year to simulate the annual system performance.

The PV power is primarily supplied to the PEM electrolyzer and to the balance-of-plant auxiliaries, including the ASU and the hydrogen compressor. Whenever the PV generation exceeds the instantaneous demand, the surplus electricity is used to charge the BESS. Any remaining excess electricity that cannot be stored is considered curtailed. Conversely, when the available PV generation is insufficient, the BESS supplies the remaining electrical demand until its minimum state of charge is reached.

The PEM electrolyzer is operated whenever sufficient electrical power is available to meet its minimum operating load. The hydrogen produced is stored in a low-pressure storage tank, which

acts as an energy buffer to decouple the intermittent renewable electricity generation from the continuous hydrogen demand of the Haber–Bosch synthesis process.

The operation of the Haber–Bosch reactor is governed by both hydrogen availability and its operational flexibility constraints. The reactor is allowed to operate only when sufficient hydrogen is available to sustain at least its minimum stable operating load and adequate electrical power is simultaneously available to supply the associated auxiliaries. If the hydrogen stored in the tank is insufficient, the algorithm verifies whether the combined power available from the PV array and the BESS can produce the additional hydrogen required to maintain reactor operation through the electrolyzer. If this condition is not satisfied, the Haber–Bosch reactor is shut down and can only be restarted after the prescribed minimum restart (setup) time, which represents one of the key flexibility parameters investigated in this study. Such a restart time is representative of the time required to restart the reactor following a medium-term outage, which is primarily dictated by the need to reheat the catalyst to restore its activity and to purge the excess nitrogen used to prevent air leaks into the reactor.
The optimization targets the different capacities of the PEM, BESS and H2 storage system to minimize the LCOA and respecting hourly operational constraints such as reactor flexibility, PV capacity, geographical location and annual ammonia production. The optimization is performed through a grid parametric search methodology.

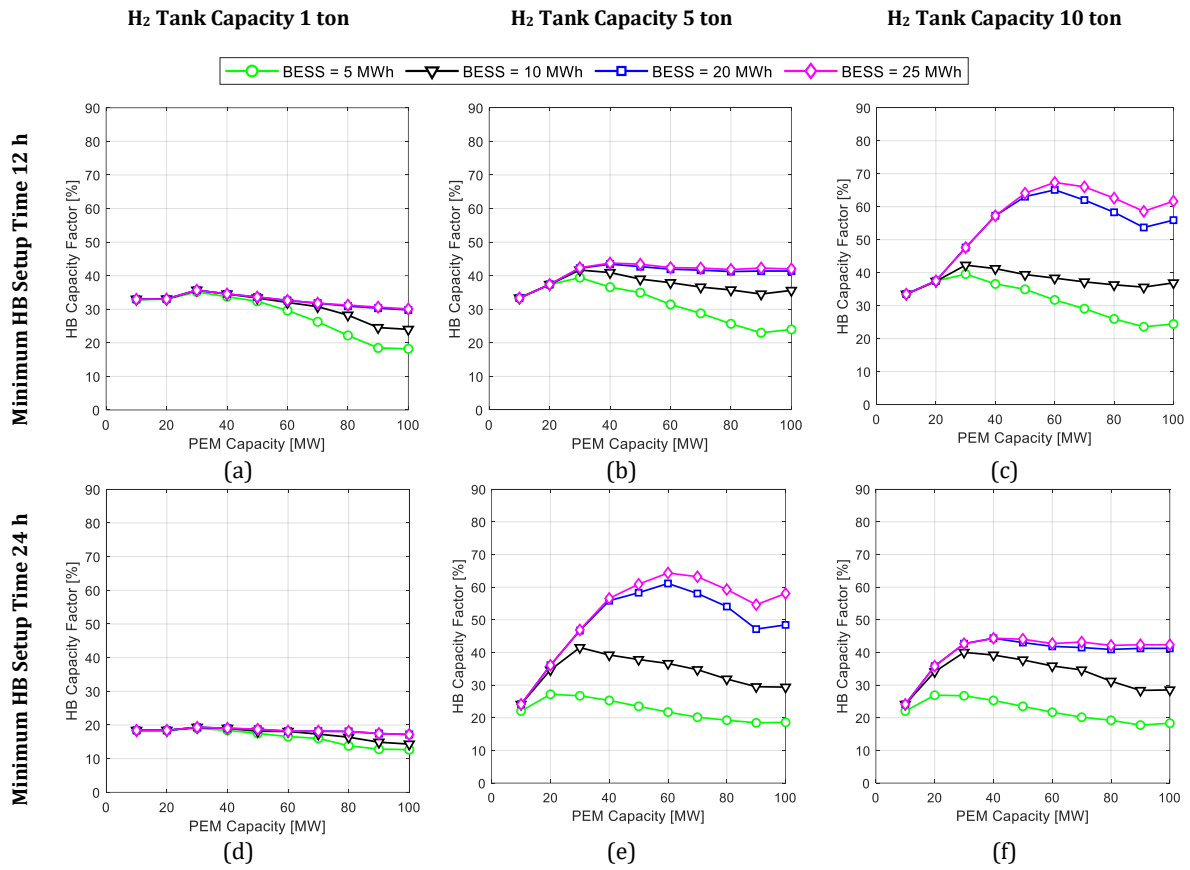
3. Results and discussion

Before performing the optimization, the developed model was employed to conduct a sensitivity analysis of the main design and operational parameters influencing the economic performance of the proposed ammonia production system. The analysis was carried out considering Sardinia (Cagliari) as the reference location, owing to its high solar resource availability and its suitability for renewable ammonia production. The results of the analysis were used to refine the search space for the grid-search optimization and to validate the obtained results. The capacities of the PEM electrolyzer, BESS, and hydrogen storage tank were systematically varied to evaluate their influence on both plant operation and annual ammonia production. Particular attention was devoted to the HB reactor capacity factor, which represents one of the key indicators governing the annual ammonia output and, consequently, the LCOA.

Figure 3 illustrates the results of the simulation referred to the Haber–Bosch capacity factor, defined as the ratio between the number of hours during which the reactor is operational and the total number of hours in a year (8,760 h). The minimum restart time has the strongest impact on reactor availability. For a hydrogen storage capacity of only 1 t (Figures 3a, d, and g), increasing the minimum restart time from 12 h to 48 h drastically reduces the achievable HB capacity factor, from approximately 35% to less than 10% for almost all the PEM installed capacities considered. This reduction is primarily due to the inability of the Haber–Bosch reactor to resume operation promptly after shutdowns caused by hydrogen shortages. A longer restart time prevents the plant from taking advantage of subsequent periods of high solar irradiance, during which hydrogen production could otherwise recover. With a 12 h restart time, a reactor that shuts down in the evening can typically be restarted by late morning of the following day, allowing operation during the remaining daylight hours. In contrast, if the minimum restart time is 48 h, a shutdown occurring overnight generally prevents the reactor from restarting for two consecutive days, even if sufficient hydrogen becomes available in the meantime. This substantially reduces the annual operating hours of the ammonia synthesis loop and, consequently, its capacity factor.

Increasing the hydrogen storage capacity substantially mitigates this limitation. As shown in Figures 3(c), 3(f), and 3(i), enlarging the storage capacity from 1 t to 10 t allows excess hydrogen produced during periods of high solar generation to be accumulated and subsequently supplied to the Haber–Bosch reactor during periods of low or zero photovoltaic production. This additional buffering capability significantly reduces the frequency of reactor shutdowns and increases the overall plant availability. For the most flexible reactor configuration (12 h restart time), the maximum HB capacity factor increases from approximately 35–40% with a 1 t storage tank to values exceeding 65% when the hydrogen storage capacity reaches 10 t and PEM and BESS capacities overcome 50 MW and 20 MWh respectively (Figure 3.c).

The installed capacity of the PEM electrolyzer also plays a crucial role in determining reactor utilization. For all hydrogen storage capacities, increasing the electrolyzer size initially leads to a marked improvement in the HB capacity factor. A larger electrolyzer enables a greater fraction of the available photovoltaic electricity to be converted into hydrogen during periods of high solar irradiance, thereby increasing the hydrogen inventory available for continuous ammonia synthesis. However, this benefit gradually diminishes as the electrolyzer capacity approaches the installed PV capacity.



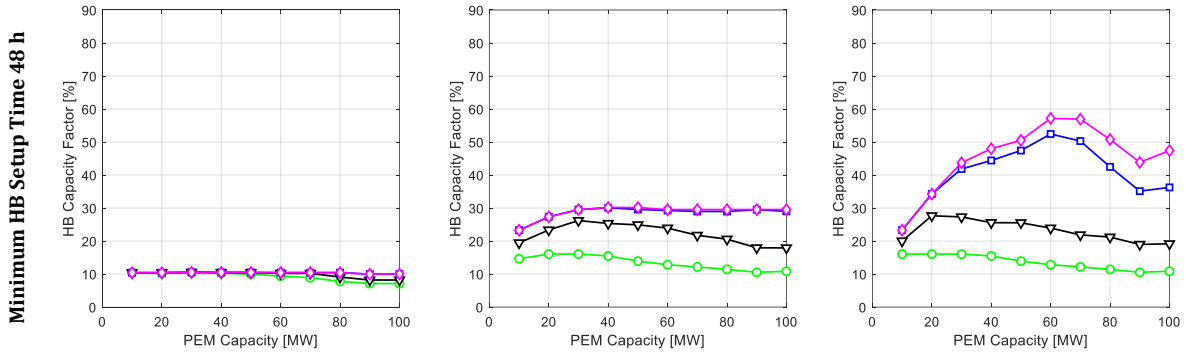
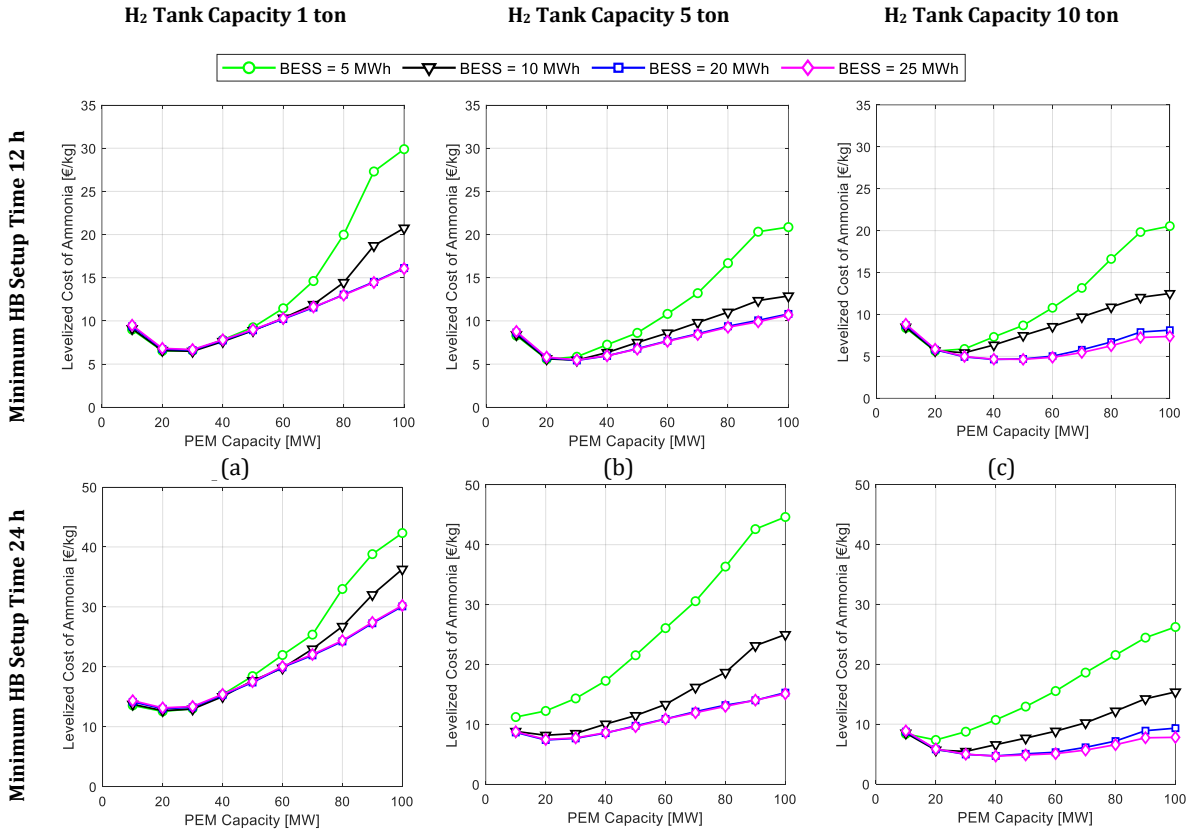


Figure 3 – Haber-Bosch Capacity Factor as a function of PEM and BESS capacity and varying Hydrogen Tank storage capacity (1 ton, 5 ton and 10 ton), as well as for different Haber-Bosch reactor flexibility, considered as the minimum setup time required for restarting the plant (12h, 24h and 48h).

Beyond this point, hydrogen production becomes constrained by the limited availability of renewable electricity rather than by the electrolyzer itself, resulting in only marginal improvements in reactor utilization despite further increases in installed electrolyzer capacity (Figure 3). The influence of the BESS is more limited and becomes significant only when sufficiently large PEM electrolyzers and hydrogen storage tanks are installed. Under these conditions, the electrolyzer can exploit the electricity stored in the battery during transient periods of reduced solar generation, extending hydrogen production beyond daylight hours and partially smoothing the inherent intermittency of photovoltaic generation.



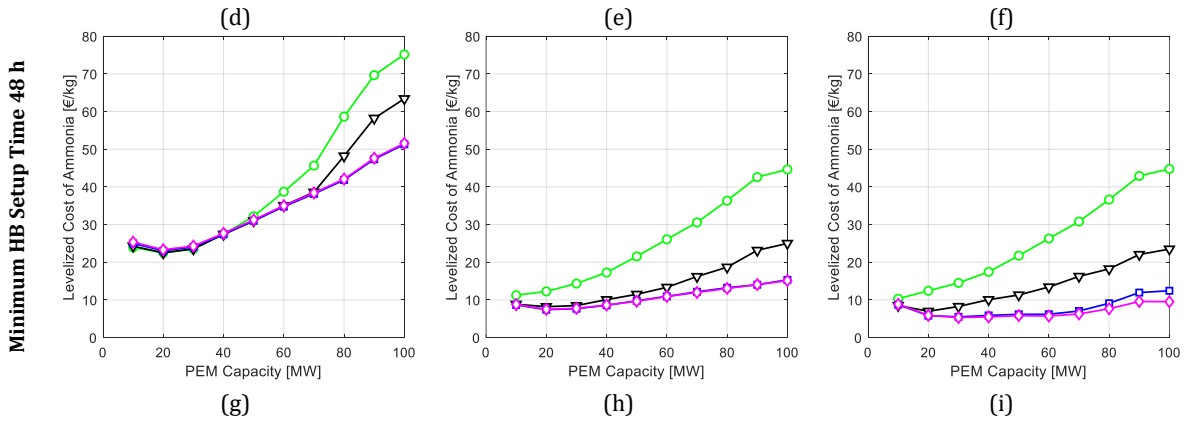


Figure 4 – Average Hydrogen Tank Level as a function of PEM and BESS capacity and varying Hydrogen Tank storage capacity (1 ton, 5 ton and 10 ton), as well as for different Haber-Bosch reactor flexibility, considered as the minimum setup time required for restarting the plant (12h, 24h and 48h).

Consequently, increasing the BESS capacity from 5 MWh to 25 MWh results in noticeable improvements in HB capacity factor only for the larger hydrogen storage configurations (5–10 t) and electrolyzer capacities above approximately 30–40 MW. Conversely, for small hydrogen storage capacities, the battery provides only limited benefits because hydrogen buffering, rather than short-term electrical storage, becomes the dominant constraint limiting continuous reactor operation. A maximum HB capacity factor does not always however concide with the minimization of the LCOA as also the capital costs required to increase the capacity of the several system components have an impact on the economics of the plant, as showed in Figure 4.

For the location considered in fact, assuming the maximum reactor flexibility associated with a minimum setup time of 12 hours, a minimum LCOA of approximately 5€/kg can be achieved for a PEM capacity of roughly 40 MW, a hydrogen tank with a capacity of 10 tons and a BESS capacity of 25 MWh (Figure 4.c)

The PEM electrolyzer has a substantial impact on the overall cost because it is one of the most capital-intensive components of the plant, particularly when the limited lifetime of the PEM stack and the associated replacement costs are taken into account. At higher PEM capacities, the Levelized Cost of Ammonia (LCOA) can increase up to 30 €/kgNH_3, especially when the hydrogen storage capacity is insufficient. In this case, the limited ability to store excess hydrogen reduces the number of hours during which the Haber–Bosch reactor can operate, thereby decreasing annual ammonia production, as shown in Figure 4a.

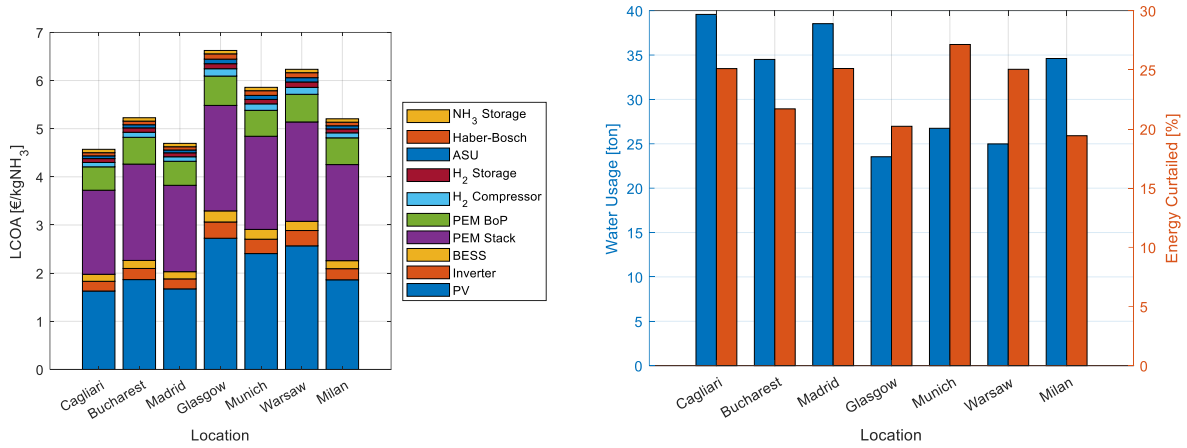
Lower reactor flexibility leads to an even greater increase in the LCOA. When the Haber–Bosch unit cannot operate effectively at partial load, its annual capacity factor decreases significantly, resulting in very low yearly ammonia production and a poorer utilization of the installed plant capacity. In the worst case scenario, an extremely high LCOA of 70€/kgNH_3 is achieved for a HB reactor restart time of 48h, a 100 MW PEM electrolyzer, a BESS capacity of 5 MWh and a hydrogen tank of 1 ton (Figure 4g).

3.2 Optimization results

Following the sensitivity analysis, the sizing of the main plant components was optimized for each selected location with the objective of minimizing the Levelized Cost of Ammonia (LCOA). The selected case studies encompass a wide range of European climatic conditions, including

Southern (Cagliari and Madrid), central (Milan and Bucharest), and Northern (Glasgow and Warsaw) regions, thereby enabling an assessment of the influence of solar resource availability on the techno-economic performance of the proposed islanded ammonia production system.

Figure 5.a presents the breakdown of the optimized LCOA, assuming a PV plant of 100 MW operating in island mode, and a Haber-Bosch synthesis loop capable of producing a mass flow rate of ammonia equal to 1 ton/h with a minimum restart time of 12h.



(a) (b)

Figure 5. LCOA breakdown (a) and Curtailed Energy (red bars) and Water Usage (blue bars) (b) for the optimized cases in the different locations considered.

Under the adopted assumptions, Cagliari and Madrid exhibit the minimum LCOA values of approximately 4.6 and 4.7 €/kgNH_3, respectively. Moving towards continental climates with lower annual solar irradiation, such as Milan and Bucharest, the LCOA increases to approximately 5.1–5.2 €/kgNH_3, while Northern locations, including Glasgow and Warsaw, reach values exceeding 6 €/kgNH_3. This increase is primarily attributable to the lower annual utilization of the electrolyzer and Haber–Bosch reactor, which leads to a reduced ammonia production while the annualized capital costs remain nearly unchanged.

The cost breakdown further highlights that the photovoltaic plant and the PEM electrolyzer are by far the dominant contributors to the overall ammonia production cost. Although the cost of utility-scale photovoltaic systems has significantly decreased over the past decade, the photovoltaic installation still represents the largest capital investment due to the large installed capacity required to ensure sufficient hydrogen production throughout the year. The second major cost contributor is the PEM electrolyzer, whose impact is amplified by both its high specific investment cost and the limited lifetime of the electrolyzer stack, requiring periodic replacement over the plant lifetime.

Consequently, future reductions in electrolyzer capital costs and improvements in stack durability are expected to have a substantially larger impact on the LCOA than equivalent reductions in the cost of the remaining process units. Conversely, the contribution of the battery energy storage system (BESS), hydrogen storage, hydrogen compressor, air separation unit (ASU), Haber–Bosch reactor, and ammonia storage system remains comparatively limited.

Table 3 reports the optimal sizing of the main plant components for each of the investigated locations, while Figure 5.b summarizes two additional performance indicators of the optimized systems, namely the annual water consumption and the photovoltaic energy curtailed.

As expected, the annual water demand closely follows the ammonia production, since water is the feedstock required for hydrogen generation via electrolysis. Consequently, locations characterized by higher solar irradiation and larger annual ammonia production exhibit the highest water consumption. Cagliari, which achieves the lowest LCOA and the highest annual ammonia output, also records the largest water demand, approaching 40 t/year. In contrast, Northern locations such as Glasgow require approximately 40% less water.

Regarding the curtailed renewable energy, Figure 5 shows that despite the optimization of the plant components, a significant amount of renewable electricity cannot be exploited, particularly in locations with high solar resource availability. In Southern Europe, curtailed energy reaches approximately 40 GWh/year, whereas it decreases to around 18 GWh/year in Northern locations such as Glasgow. This behaviour results from the mismatch between the highly variable photovoltaic generation profile and the operational constraints of the downstream process units. During periods of high solar production, the electrolyzer, hydrogen storage system, battery energy storage system (BESS), and Haber–Bosch reactor all operate at their maximum allowable capacities, leaving any additional photovoltaic generation to be curtailed. Renewable electricity curtailment remains one of the main limitations of stand-alone photovoltaic-powered ammonia plants. Although oversizing the photovoltaic field increases the annual utilization of the electrolyzer and reduces the LCOA, it simultaneously leads to higher renewable energy losses. Future improvements could therefore be achieved via the integration of complementary renewable energy sources such as wind power. These strategies would increase the utilization factor of the installed photovoltaic capacity while simultaneously reducing the specific cost of ammonia production.

Overall, the findings of this study indicate that, under the assumptions adopted in the analysis, the flexibility of the Haber–Bosch (HB) synthesis loop has a major influence on the economics of green ammonia production. In particular, reducing the reactor restart time to only a few hours would substantially increase the annual ammonia production by allowing the reactor to exploit a larger fraction of the available renewable hydrogen. As a result, the higher utilization factor of the HB reactor is expected to reduce the LCOA by approximately 1–2 € kg/NH_3, bringing the estimated production costs closer to those reported in the literature. Furthermore, the relatively conservative techno-economic assumptions adopted in this study, particularly regarding the electrolyzer capital cost and operational lifetime, also contribute to the higher LCOA values obtained compared with previous studies. These results highlight that improvements in reactor operational flexibility, together with continued reductions in electrolyzer costs and enhancements in durability, could significantly improve the economic competitiveness of stand-alone green ammonia production systems.

Table 3. Optimized component sizes for the selected locations.

Location	Component							
	PV	**BESS**	**PEM**	**H_2 compressor**	**H_2 storage**	**ASU**	**HB**	**HB Utilization**
	MW	**MWh**	**MW**	**tH_2/h**	**t_{H2}**	**t_{N2}/h**	**$kgNH_{3/h}$**	**%**
Cagliari	100	18	40	0.45	9	1.65	1	57.1
Bucharest		18	40	0.45	9	1.65		50.3
Madrid		18	40	0.45	9	1.65		55.6
Glasgow		17	30	0.45	7	1.65		35.4

Location	Component							
	PV	BESS	PEM	H_2 compressor	H_2 storage	ASU	HB	HB Utilization
	MW	MWh	MW	tH_2/h	t_{H2}	t_{N2}/h	$kgNH_{3/h}$	%
Munich		17	30	0.45	7	1.65		39.7
Warsaw		15	30	0.45	8	1.65		37.5
Milan		18	40	0.45	8	1.65		50.3

4. Conclusions

This work presented a techno-economic optimization of an off-grid photovoltaic-powered green ammonia production plant, integrating a PEM electrolyzer, battery energy storage system, hydrogen storage, cryogenic air separation unit, and Haber–Bosch synthesis loop. An energy management strategy accounting for the operational constraints of each subsystem was developed and applied to seven European locations characterized by different climatic conditions.

The results demonstrate that the availability of solar energy is the primary factor determining the Levelized Cost of Ammonia. Southern European locations, benefiting from higher photovoltaic capacity factors, achieve the lowest production costs, with LCOA values as low as 4.6 €/$kgNH_3$, whereas Northern locations exhibit costs exceeding 6 €/$kgNH_3$ due to the reduced utilization of the electrolyzer and Haber–Bosch reactor. The cost analysis further reveals that the photovoltaic plant and the PEM electrolyzer account for the largest share of the production cost, highlighting the importance of further reducing electrolyzer capital costs and extending stack lifetime to improve the competitiveness of renewable ammonia.

The optimization also showed that, despite the inclusion of battery and hydrogen storage, a significant fraction of photovoltaic electricity is curtailed in high-irradiation locations, indicating that additional improvements in process flexibility and renewable energy integration are required. Future work will therefore focus on investigating hybrid renewable energy systems combining photovoltaic and wind generation and more flexible ammonia synthesis technologies to increase renewable energy utilization and further reduce the cost of green ammonia production.

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