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Levelized cost analysis for renewable ammonia production in Chile

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ABSTRACT

Renewable ammonia production is a crucial step towards decarbonizing energy-intensive industries, but its economic viability is hindered by high capital costs and renewable resource availability. We develop a stochastic optimization framework to estimate the levelized cost of ammonia (LCOA) in any location in the world, accounting for the variability of wind and solar energy. The methodology is based on optimizing the portfolio of renewable sources and the capacity of the ammonia production facility while ensuring the three pillars of renewable fuel production: additionality, temporal matching, and geographic correlation. Formulated as a stochastic linear program, the model also accounts for inter-annual climate variability.

This framework is applied to assess the economic feasibility of renewable ammonia production in Chile, identifying optimal locations for facilities based on renewable energy availability and cost. Our numerical experiments show that, depending on the discount rate utilized, the LCOA in competitive Chilean locations could range from 270 to 380 USD/tNH_3 by 2040, and 250 to 350 USD/tNH_3 by 2050, positioning Chile as a competitive player in the global market. Moreover, our results show that a reduction in the CAPEX of ammonia production has a greater impact on the LCOA than an improvement in electricity-to-ammonia efficiency. This underscores the importance of prioritizing the reduction of investment costs.

1. Introduction

Since 1909, when Fritz Haber and Carl Bosch developed an artificial nitrogen fixation process (now called the Haber-Bosch process) enabling its large-scale production, ammonia has been extensively used in the manufacture of fertilizers and other chemical products. The annual global production of ammonia is above 150 million metric tonnes and is projected to increase by 2.3% per year [1]. The Haber-Bosch process, however, is currently one of the largest global energy consumers and greenhouse gas emitters, responsible for 1.4% of the global anthropogenic CO_2 emissions [2].

Renewable ammonia, a potential game-changer in the global effort to fight climate change, is a low-carbon chemical compound combining hydrogen and nitrogen. This sustainable alternative to traditional ammonia production has gained significant attention due to its potential to serve, in addition to its current uses, as an energy carrier and a key component in various industrial processes. The versatility of renewable ammonia has opened up numerous potential applications, spanning multiple sectors such as energy storage, transportation, and agriculture. As a hydrogen carrier, renewable ammonia can be utilized in power generation, providing a reliable means of storing and transporting renewable energy. This allows for greater integration of renewable sources like solar and wind into the energy grid, mitigating the intermittency challenge they pose. Renewable ammonia is anticipated to play a key role in decarbonizing sectors that are challenging to electrify, such as the maritime and aviation industries [3]. In the agricultural sector, renewable ammonia can serve as a sustainable source of fertilizer, helping to reduce the environmental impact of conventional, fossil-fuel-derived fertilizers. Its wide array of applications positions renewable ammonia as a pivotal player in the global transition toward a more sustainable future.

The economic viability of renewable ammonia production is often constrained by high capital costs and renewable resource variability. This work addresses the need for an advanced methodology to calculate the Levelized Cost of Ammonia (LCOA) using a stochastic optimization approach.

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1.1. Global renewable ammonia context

Renewable ammonia is expected to become the predominant energy carrier for exporting and importing hydrogen via sea transport by 2030 [4]. Although approximately half of the announced worldwide renewable hydrogen projects have yet to express a definitive preference, ammonia accounts for more than 85% of the planned capacity among those who have declared their intentions. The market share for liquefied hydrogen and liquid organic hydrogen carriers is expected to be significant in this decade. Almost every country and region around the world is formulating roadmaps, strategic plans, and committing to renewable hydrogen production to reach fully or nearly carbon-neutral energy systems. Ammonia is recognized as one of the key carriers for this endeavor. The European Union, followed by Japan and South Korea, is expected to be the largest importer of renewable hydrogen (included in the form of ammonia) worldwide [4].

With the overarching goal of achieving climate neutrality by 2050, the European Union (EU) has laid out a strategic roadmap and suite of policies to integrate hydrogen into its energy mix. The European Green Deal [5], introduced in December 2019, serves as the cornerstone of the EU's commitment to transforming its economy into a greener, more sustainable model. Within this broad framework, the Renewable Energy Directive (RED) has been a pivotal legal instrument, steering the development of clean energy within the Union. With RED III coming into force on November 20th, 2023, the EU has set an ambitious target to boost the share of renewable energy in its overall consumption to 42.5% by 2030, with a potential reach of 45% through additional contributions from member states. In May 2022, the European Commission presented the REPowerEU Plan [6]. This initiative seeks to decrease dependence on external fossil fuels and catalyze the green transition. REPowerEU, while not legally binding, provides directional recommendations for the EU's hydrogen strategy, which is a crucial part of the green energy transition.

Hydrogen, with its vast potential for clean energy storage and as a fuel, has gained strategic importance in meeting the EU's climate goals. The REPowerEU plan targets the production of 10 million tonnes of renewable hydrogen domestically and the import of another 10 million tonnes by 2030. This ambitious goal, representing approximately 14% of the EU's total electricity consumption, signals a significant shift from the current hydrogen production, which is predominantly from natural gas, contributing to CO_2 emissions.

The European Union's plans for developing and utilizing hydrogen are framed by the EU's hydrogen strategy [7]. In 2021, the European Commission proposed that by 2030, the industrial and transport sectors within the European Union should consume roughly 11 Mt H_2/year, produced from the electrolysis of water using renewable electricity. In May 2022, the European Commission suggested nearly doubling this target to 20 Mt H_2/year across all end-use and transformation sectors, with half of the total imported into the European Union from other nations [6]. In July 10th, 2023, two Delegated Acts supplementing RED II were adopted, where clear definitions for "renewable fuels" are given as renewable liquid and gaseous transport fuels of non-biological origin (RFNBO) [8]. It was the first definition of its kind and it included three pillars for defining when a fuel can qualify as renewable. The three pillars are: additionality, temporal correlation and co-location.

Japan also aims to achieve zero CO_2 emissions by 2050 [9]. In line with this commitment, Japan is exploring the feasibility of modifying its current coal power plants to facilitate the co-burning of coal and ammonia, in order to decrease carbon dioxide emissions. Japan has set an objective to achieve a 20% co-fire rate of imported ammonia by 2030 and 100% of ammonia firing by 2035. To support this ambition, JERA, Japan's largest thermal power producer, and a major gas trader, has put forth a tender for the provision of up to 0.5 Mt of low-carbon ammonia.

South Korea has set a goal to achieve net zero emissions by 2050. This will involve a substantial increase in renewable energy use, improved energy efficiency, a gradual shift toward electrifying end-use sectors, and the reliance on renewable hydrogen where direct electrification is not feasible [10]. South Korea is also working towards implementing ammonia co-fired power generation. It has set a 20% co-fired target by 2030. Both South Korea and Japan are actively establishing partnerships with potential exporting nations and technology suppliers.

Australia is projected to emerge as a significant player in the global production of low-carbon ammonia and hydrogen. As stated in the World Energy Outlook 2022 [4], by 2030 Australia is expected to be the second largest producer and by 2050 it is expected to take the lead. Hydrogen and ammonia serve as essential components of Australia's energy sector decarbonization strategy for achieving net zero emissions by 2050 [11]. To uphold this trajectory, the Australian Government undertook a review of its National Hydrogen Strategy in February 2023 [12]. Initially established in 2019, the strategy is being reassessed to ensure that Australia remains on course to become a global front-runner in the hydrogen sector by 2030, both regarding exports and in the decarbonization of its domestic industries. A significant number of hydrogen-related projects are already underway in Australia [13]. A standout project is the Asian Renewable Energy Hub, located in an isolated area of Western Australia, which aims to establish a capacity of up to 26 GW from wind and solar power. This renewable energy will be used to produce the equivalent of 1.6 Mt H_2/year or 9 Mt/year of renewable ammonia.

In the United States (US), support for renewable hydrogen and other fuels primarily comes in the form of production and investment tax credits, which are largely facilitated by the US Inflation Reduction Act (IRA) of August 2022 [14]. The IRA encompasses a broad range of US policies, with a central focus on addressing climate change, enhancing energy security, and promoting clean energy production. The qualification as "clean" fuels relies on metrics based on lifecycle greenhouse gas (GHG) emissions, including carbon dioxide released during the production process and the generation of electricity used in the fuel's production.

1.2. Policy landscape shaping Chile's potential for renewable ammonia production

In 2022, the electricity demand in Chile was approximately 83 TWh, reaching a peak demand of 11.9 GW according to statistics of the Chilean National Electricity Coordinator [15]. On the supply side, the total capacity of the generation mix was 33.2 GW, of which 60% consisted of renewable sources, such as wind, solar, biomass, and hydro. The remaining 40% corresponds to thermal power plants using coal, natural gas, and diesel. The share of renewable energy has grown a year-on-year, with particularly significant increases in wind and solar power installations. In 2022, compared to the previous year, the installed capacity of wind and solar power units grew by 22.5% and 31.9% respectively [15].

Chile features a significant solar and wind power generation potential of about 1800 and 38 GW, respectively [16]. With the current decreasing trend in the investment costs of these technologies, their deployments are progressively increasing and seem even more promising in the future. Furthermore, Chile possesses one of the highest irradiances in the world, with values of global horizontal irradiance of up to 1200 W/m^2 [17]. Also, new projects are obtaining attractive power purchase agreements through competitive auctions with prices as low as 13.32 $/MWh [18], presenting significant prospects for supplying internal power demand and using the cheap power to produce renewable hydrogen and ammonia.

The Chilean energy policy landscape has undergone significant transformation in recent years, in response to both domestic pledges and global trends. Central to Chile's energy policy is the government's commitment to achieving carbon neutrality by 2050 [19]. In this transformed policy landscape, the state has assumed a more proactive role in energy planning, resulting in accelerated project development, particularly in the field of electricity transmission. Examples of this increased governmental involvement are the unification of the national electricity system in 2017 and the development of national renewable poles [20]. In 2022, the Chilean Ministry of Energy undertook a critical revision of its Long-Term Energy Planning (PELP) [20], first introduced in 2015, making a commitment to attaining net-zero emissions across all sectors of the national economy. This ambitious pledge is underpinned by Chile's remarkable solar and wind energy resources, which put the nation at the forefront of the global clean energy stage.

Chile's revised energy policy has brought renewable hydrogen into a unique spotlight. From as early as 2020, Chile has established its National Hydrogen Strategy [21], setting ambitious production targets for 2030 and 2040. The strategy envisions a progressive reduction in the levelized costs of hydrogen (LCOH) to achieve benchmarks of 2.5, 1.8, and 1.4 USD/kg H_2 for the years 2030, 2040, and 2055, respectively [22].

In summary, Chile presents an exceptional opportunity to apply the proposed stochastic optimization methodology due to its unique renewable energy landscape, offering a cost advantage over other regions. Moreover, Chile's diverse geography, provides an ideal testing ground for the methodology, allowing for comprehensive analysis across different locations and climate conditions.

1.3. Economy of renewable ammonia production

The Haber–Bosch process continues to be the dominant method for ammonia production, accounting for more than 90% of the world's ammonia supply. Primarily used for fertilizers, ammonia has become an essential component of modern agriculture. Ammonia is one of the largest volume industrial chemicals synthesized globally, both in terms of energy use and carbon footprint. Between 2016 and 2020, average ammonia prices hovered around US$500 per ton. From November 2021 to February 2023, the price of ammonia has been above US$1000 per ton, surpassing US$1600 per ton in July 2022 [23].

The environmental impact of ammonia production is significant, releasing around 400 million tons of CO_2 equivalents annually, which contributes to approximately 1.4% of all worldwide greenhouse gas emissions. The Haber–Bosch process is responsible for consuming 3%–5% of the world's natural gas production, corresponding to 1%–2% of the annual global energy supply. Moreover, renewable hydrogen is a key component in the renewable ammonia production. However, of the 60 million tons of hydrogen produced annually for industrial purposes, 95% is derived from fossil fuels such as gas, oil, and coal, while the remaining 5% comes from water electrolysis [2].

The economic feasibility of renewable ammonia production fundamentally depends on its competitiveness with traditional production pathways. Levelized Cost of Ammonia (LCOA) provides a rigorous assessment of the lifetime costs of ammonia production.

These tools are vital for providing trustworthy signals to investors and policymakers, assisting them in making informed decisions. In this paper, we harness the power of modeling and mathematical programming to present a methodology for determining the levelized cost of renewable ammonia.

The calculation of the LCOA can be approached through either *direct* or *indirect* methods. The direct method relies on analytical-based calculations using estimates of key input parameters, such as electricity prices and utilization factors of the ammonia production facility [24]. While this approach is straightforward and easy to compute, it requires strong assumptions regarding certain input parameters and is often based on illustrative projects.

In contrast, the indirect method, which is the most prevalent approach in the scientific domain, utilizes optimization models to simulate the optimal operation of the ammonia production facility. This approach can be further divided into two categories: simple optimization models that aim to simulate the optimal operation of the facility given certain design parameters [25], and more strategic models that optimize not only the operation, but also the sizing of each component of the power-to-ammonia facility, including renewable generation and connections to other infrastructure [26,27]. The level of detail in these models can vary depending on the specific problem being addressed and the research question of interest. In this study, we employ an optimization-based approach to calculate the LCOA, which enables us to determine the optimal capacity portfolio and operating conditions for the ammonia production facility, thereby providing a more detailed understanding of the economic viability of renewable ammonia production.

1.4. Paper objective and contributions

Despite the growing interest and potential for renewable ammonia as a sustainable energy carrier and chemical feedstock, significant challenges remain in making its production economically viable on a large scale. This study addresses the need for a methodology to calculate the LCOA that accounts for the variability and uncertainty of renewable resources while aiming to minimize assumptions due to the renewable ammonia technology's early stage and the challenge of predicting electricity prices in the future.

The main objective of this study is to introduce a methodology for computing the LCOA and assess the economic feasibility of renewable ammonia production in various locations. We selected Chile as a reference country for the application of the proposed methodology.

The contributions of this paper are split into two main tracks.

- *Methodological contribution.* The first main contribution of this paper focuses on creating a model that captures the characteristics of a generic and ideal renewable ammonia facility, allowing for integration into optimization models for comprehensive assessments. A stochastic linear program is proposed for this purpose, offering a novel lens to approach the modeling of renewable ammonia production and paving the way for more nuanced analyses.
  Distinctive aspects of this methodological contribution that set this work apart from general literature on calculating LCOA include: (i) the elimination of the need for electricity price forecasting, as the optimization model leverages investments in renewable sources to enable an endogenous calculation of the value of electricity; (ii) additionally, this approach does not tie to any specific technology of power supply, but rather calculates an optimal portfolio using available renewable resources and capital cost information; (iii) it does not assume fixed capacity factors or equivalent full-load hours for the renewable ammonia production facility. Instead, the model utilizes hourly profiles of wind speed and solar radiation, employing 11 scenarios that correspond to future projections representing different climate scenarios. Our methodology determines the equivalent full-load hour of production in the renewable ammonia facility within the model itself instead of assuming it.
- *Analytical contribution with a focus on Chile.* This paper provides a comprehensive exploration of renewable ammonia production within the context of Chile, extending far beyond mere theoretical considerations. However, the application can be easily extended to other regions.
  Various sensitivity analyses were conducted to assess the impacts of different variables and assumptions on the outcomes; for instance, looking at how improvements in investment cost of new renewable ammonia plants can propagate to LCOA and how the improvement in the efficiency of producing ammonia from electricity impacts the value.

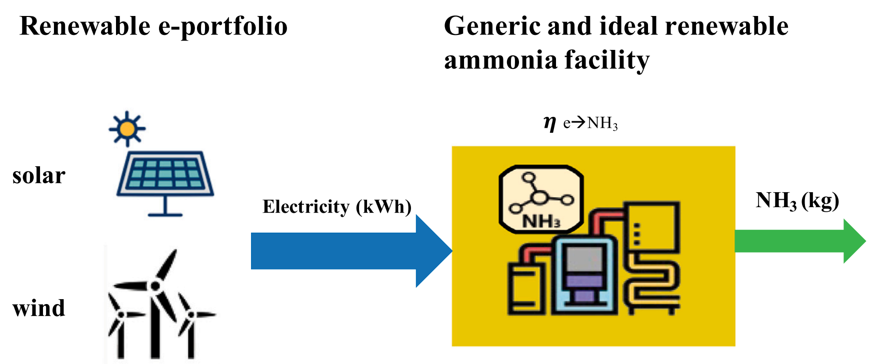

Fig. 1. Generic and ideal renewable ammonia production facility. Renewable electricity from wind and solar power plants feeds the generic and ideal facility for producing ammonia. The conversion from electricity (kWh) to ammonia (kg) is based on a conversion efficiency $\eta_{e \to NH_3}$.

1.5. Paper organization

The remainder of this paper is organized to guide the reader through a comprehensive exploration of renewable ammonia production. Section 2 introduces the subject, detailing various possible facility archetypes and defining what we present as a generic and ideal renewable ammonia facility, complete with the set of equations that characterize it. In Section 3, we delve into the core of the methodology for determining the LCOA, employing a stochastic optimization model as our foundation. Moving on to Section 4, we present an extensive analysis of Chile's LCOA, starting with data collection and assumptions. Actual data from Chile is then employed to present the results of the analysis across 24 nodes, and various sensitivity analyses are explored, including the projection and evolution of LCOA for all the studied locations within Chile. Finally, Section 5 wraps up the paper with a comprehensive discussion of the primary outcomes of this work, conclusions, and an outline of avenues for future research.

2. Renewable ammonia production

Conventionally, ammonia (NH_3) is produced through the Haber–Bosch process, which reacts nitrogen from the air with hydrogen derived from natural gas or coal. This process is energy intensive and generates substantial greenhouse gas emissions, such as carbon dioxide (CO_2). In contrast, renewable ammonia production relies on renewable energy sources, like solar or wind power, to electrolyze water into hydrogen and oxygen. This hydrogen is then utilized in the Haber–Bosch process, yielding a carbon-neutral or even carbon-negative production method.

2.1. A model for a generic and ideal renewable ammonia facility

A *generic renewable ammonia facility* is defined as any facility capable of producing renewable ammonia using renewable energy sources, regardless of the specific archetype and layout used within the production facility. On the other hand, an *ideal renewable ammonia facility* integrates certain simplifications in its technical and economic operations. It adopts a system-level perspective, providing significant advantages in the context of mathematical modeling. It distills the extensive complexity of an ammonia production facility into a simplified, yet comprehensive, reference framework. Furthermore, it enables generalization across a multitude of configurations, establishing a reference point for benchmarking diverse renewable ammonia facility archetypes. Fig. 1 depicts an illustrative configuration of a generic and ideal renewable ammonia facility, along with the modeled conversion from renewable electricity to ammonia.

A generic and ideal renewable ammonia facility encompasses the following key elements:

(a) *System-level approach*: The emphasis is on evaluating mass and energy balances at the facility level. The model accepts renewable electricity as input and yields ammonia as an output, independent of the specific technologies utilized. The facility is, thus, depicted as technology-agnostic, with a broader focus on the overall energy and mass balance.
(b) *Constant conversion efficiency*: The model assumes constant conversion electricity-to-ammonia efficiencies for energy transformation, irrespective of the facility operating at full or partial load. Only facility-level efficiency is accounted for, expressed in this work as kg/kWh, indicating the amount of NH_3 produced per kWh of electricity consumed.
(c) *Absence of ramps*: The model allows for the facility to switch from offline to full-capacity production within the temporal resolution of the mathematical model (1 h). This assumption can be supported by internal buffering mechanisms such as storage.
(d) *Modular design and constant capital costs*: It is assumed modular construction of any capacity (continuous decision variables). Furthermore, it is assumed that capital costs per kg of ammonia produced remain constant, with no economy of scale.

The generic and ideal renewable ammonia facility model is formulated by (1). For every period h, the ammonia production $p_h^{NH_3}$ (in kg) is determined by the transformation of electricity p_h^e (in kWh) into ammonia by the electricity-to-ammonia efficiency $\eta^{e \to NH_3}$ (typically between 0.125 and 0.067 kgNH_3/kWh). The ammonia production capacity is limited by $\overline{P}^{NH_3}$. Thus, even if electricity is available, the production of ammonia cannot go beyond the facility's production capacity.

$$\left\{ p_h^{NH_3}, p_h^{e} \in \mathbb{R}_{\geq 0} \;\middle|\; p_h^{NH_3} = \eta^{e \to NH_3} p_h^{e}, \quad 0 \leq p_h^{NH_3} \leq \overline{P}^{NH_3}, \forall h \right\} \tag{1}$$

3. Methodology for computing the LCOA

We present a methodology for estimating the LCOA. This approach integrates all crucial cost components related to renewable ammonia production while maintaining a manageable complexity in the proposed mathematical model. This methodology is grounded in an assessment of renewable ammonia production in an islanded facility, disconnected from the main power grid.

To achieve this, we center our efforts on developing a mathematical model that determines the optimal portfolio of renewable assets. This portfolio includes the generation capacity for wind and solar power, in conjunction with the production capacity of renewable ammonia facilities. Our central assumption is derived from the definition of renewable ammonia discussed in this paper, which is produced by considering the following three essential principles:

- *Additionality:* The electricity needed for ammonia production is generated exclusively from renewable sources (wind and solar, in this case). Therefore, it necessitates appropriate investments in renewable energy sources to generate the required electricity for renewable ammonia production.
- *Temporal correlation (simultaneity):* The electricity generated during a specific hour by renewable resources dedicated to ammonia production is the only electricity that can be used for the ammonia production. Thus, it is not feasible to transfer electricity from one period to another. In essence, the electricity produced is used directly for ammonia production.
- *Spatial correlation (co-location):* The electricity must be generated in close proximity to the renewable ammonia facility. This stipulation implies that a direct electricity line connection should be possible to supply the ammonia plant from electric renewable resources.

These three principles are in line with the rules for determining when electricity used for the production of renewable liquid and gaseous fuels can be considered fully renewable in Europe, as was recently established by regulation [28]. The three principles imply that the electricity has to be produced by additional renewable capacity, co-located with the renewable ammonia facility, at the same moment, thus, the grid (if connected) is not used for renewable ammonia production. Consequently, an off-grid renewable ammonia facility should result in a similar LCOA as a grid-connected renewable ammonia facility that satisfies the previously stated principles.

Note that different definitions of renewable ammonia, or low-carbon ammonia, could result in varying LCOA calculations. In this specific case, where additionality, spatial, and temporal correlation must be satisfied simultaneously, we can, without loss of generality, disregard the main power grid in our modeling exercise.

In our proposed framework, we do not make assumptions about future electricity prices. Instead, we consider the Capital Expenditure (CAPEX) associated with the necessary renewable generation technologies for electricity production. This approach enhances the precision of LCOA estimations, as predicting future electricity prices can be quite uncertain. In contrast, estimating the CAPEX for well-established technologies such as solar and wind power benefits from a reliable understanding of learning curves and their estimation.

We calculate the LCOA as the sum of the CAPEX and Operating Expenditure (OPEX) required for ammonia production, divided by the total volume of ammonia produced, as expressed in (2). This holistic method includes all costs associated with renewable generation technologies, such as wind and solar power, as well as the CAPEX and OPEX of the ammonia production facility.

$$\text{LCOA} = \frac{\text{C\&O}^{\text{w}} + \text{C\&O}^{\text{s}} + \text{C\&O}^{\text{NH}_3}}{P^{\text{tot,NH}_3}} \tag{2}$$

To maintain consistency, throughout the paper, all the costs considered in estimating the LCOA are computed in USD using the reference value of 2023. Consequently, all CAPEX and OPEX are annualized and updated to USD of 2023, to facilitate direct comparison and analysis.

3.1. Determining LCOA through a linear optimization model

A Linear Programming (LP) optimization model is used as the basis for calculating the LCOA. The mathematical model formulation is presented in (3). Given the analysis is framed within a single year, we establish an annual NH_3 production target of 1 million tons. All capital costs are correspondingly annualized. Capital costs may change based on the target year of the study. We conduct several sensitivity analyses in the numerical experiments section. However, by default, we use the year 2050 as a reference. The temporal resolution of the model is one hour, so the LP model consists of 8760 periods, representing a full year of operation. Each hour is indexed by h.

For considering the inter-annual variability of renewable resources, we incorporate multiple climatic scenarios, each defined by distinctive wind and solar power profiles. This strategy acknowledges the dynamic nature of renewable resources across various regions over time. The availability of solar and wind resources per climatic scenario is indexed by ω. Wind and solar renewable energy profiles are derived from historical observations, with each historical climatic year representing one scenario. Notably, in Chile, climate variability phenomena such as El Niño and La Niña can alter climate conditions, which in turn affect the availability of renewable resources. This climate variation over the years has shown relevant when addressing long-term capacity planning decisions [29].

While the proposed optimization model pertains to a specific year (with values projected to 2050 by default), it can be applied to different specific locations, as it relies on the profiles of solar and wind renewable resources. Consequently, we run the model described in (3) multiple times to determine the LCOA at different locations and for different target years, as detailed in the following numerical analysis section.

$$\text{minimize} \left(\text{C\&O}^{\text{w}} + \text{C\&O}^{\text{s}} + \text{C\&O}^{\text{NH}_3} + \Gamma\right) \tag{3a}$$

subject to:

Cost terms definition

$$\text{C\&O}^{\text{w}} = \left(c^{\text{inv,w}} + c^{\text{ope,w}}\right) \overline{P}^{\text{w}} \tag{3b}$$

$$\text{C\&O}^{\text{s}} = \left(c^{\text{inv,s}} + c^{\text{ope,s}}\right) \overline{P}^{\text{s}} \tag{3c}$$

$$\text{C\&O}^{\text{NH}_3} = \left(c^{\text{inv,NH}_3} + c^{\text{ope,NH}_3}\right) \overline{P}^{\text{NH}_3} \tag{3d}$$

$$\Gamma = \frac{1}{|\Omega|} \sum_{\omega=1}^{|\Omega|} \sum_{h=1}^{8760} c^{\text{curt}} (\rho_h^{\text{s}}(\omega) + \rho_h^{\text{w}}(\omega)) \tag{3e}$$

Electricity balance

$$p_h^{\text{e}}(\omega) = p_h^{\text{w}}(\omega) + p_h^{\text{s}}(\omega), \qquad \forall h, \omega \tag{3f}$$

$$\rho_h^{\text{w}}(\omega) = \gamma_h^{\text{w}}(\omega)\overline{P}^{\text{w}} - p_h^{\text{w}}(\omega), \qquad \forall h, \omega \tag{3g}$$

$$\rho_h^{\text{s}}(\omega) = \gamma_h^{\text{s}}(\omega)\overline{P}^{\text{s}} - p_h^{\text{s}}(\omega), \qquad \forall h, \omega \tag{3h}$$

Renewable ammonia facility

$$p_h^{\text{NH}_3}(\omega) = \eta^{\text{e}\to\text{NH}_3} p_h^{\text{e}}(\omega), \qquad \forall h, \omega \tag{3i}$$

$$p_h^{\text{NH}_3}(\omega) \le \overline{P}^{\text{NH}_3}, \qquad \forall h, \omega \tag{3j}$$

$$P^{\text{tot,NH}_3} = \frac{1}{|\Omega|} \sum_{\omega=1}^{|\Omega|} \sum_{h=1}^{8760} p_h^{\text{NH}_3}(\omega) \tag{3k}$$

Variable definition

$$p_h^{\text{NH}_3}(\omega), p_h^{\text{e}}(\omega), p_h^{\text{w}}(\omega), p_h^{\text{s}}(\omega), \rho_h^{\text{w}}(\omega), \rho_h^{\text{s}}(\omega) \in \mathbb{R}_{\ge 0}, \qquad \forall h, \omega \tag{3l}$$

$$\overline{P}^{\text{w}}, \overline{P}^{\text{s}}, \overline{P}^{\text{NH}_3} \in \mathbb{R}_{\ge 0} \tag{3m}$$

The optimization model targets minimizing the total capital and operational costs necessary to meet the annual expected ammonia production target, $P^{\text{tot,NH}_3}$, as defined in (3a). The components of this objective function are detailed in the set of equations from (3b) to (3e). The capital cost of new wind and solar power capacity installed ($\overline{P}^{\text{w}}$ and $\overline{P}^{\text{s}}$) and their operational costs are depicted in Eqs. (3b) and (3c), respectively. We assume operational costs to be proportional to the capacity of the wind and solar power plants. The capital and operational costs associated with the new ammonia facility are specified in Eq. (3d). Similarly to wind and solar power, the capital and operational cost is assumed to be proportional to the final ammonia production capacity. Lastly, the term Γ in the objective function represents the expected cost or penalization for curtailment. Since curtailment varies depending on the climatic year, we compute the expected wind and solar curtailment costs for all climate years. Although renewable curtailment does not constitute a direct cost of ammonia production, it is penalized as it represents an opportunity cost, which investors will prefer to reduce. As we will observe in the numerical analysis section, curtailment always occurs.

The model accommodates a set of constraints, outlined in Eq. (3f), related to the electricity balance generated from wind and solar resources. It also includes the actual wind and solar curtailments defined in Eqs. (3g) and (3h), respectively. Curtailment is computed as the total available wind or solar production (determined by the final generation capacities $\overline{P}^{w}$ and $\overline{P}^{s}$, along with the respective capacity factors $\gamma_h^{w}(\omega)$ and $\gamma_h^{s}(\omega)$) minus the actual wind or solar production, represented by $p_h^{w}(\omega)$ and $p_h^{s}(\omega)$, which are defined based on the corresponding solar and wind power profiles.

The constraints pertaining to renewable ammonia production and capacity are expressed in the set from (3i) to (3k). For each time period and climate scenario, the ammonia production is proportional to the available electricity used to power the ammonia facility, as depicted in Eq. (3i). The total production for each hour and climate scenario must not exceed the production capacity of the renewable ammonia facility, as shown in Eq. (3j). Lastly, the total production throughout the year must match the target value for ammonia production. Due to the variability of renewable resources over the year, we enforce this constraint in expectation across all climate years, as stated in Eq. (3k). The optimization variables are defined in Eqs. (3l) and (3m).

The optimization model presented in this section is a stochastic linear programming problem. It is specifically designed to be solvable with off-the-shelf LP solvers, like Gurobi, CPLEX, GLPK, or HiGHS. Despite the complexity inherent in addressing the challenges of renewable ammonia production, the model maintains a relatively small size compared to the capabilities of state-of-the-art LP solvers. As such, it does not pose a significant computational challenge, making it a practical tool for real-world applications.

4. Numerical analysis

In this section, we delve into a comprehensive numerical analysis, focusing on the economic aspects of renewable ammonia production in Chile, targeting the year 2050. For this analysis, we have selected 24 distinct locations throughout Chile. These locations were carefully chosen due to their proximity to electric nodes of the country's transmission system, offering a direct and practical linkage to existing infrastructure.

We utilize three capital cost scenarios derived from the Chilean Long Term Energy Planning (PELP from the Spanish) [20]. These scenarios outline varying degrees of technological cost, specifically, *Low*, *Ref*, and *High*, each representing different pathways of capital cost evolution. We will further elaborate on these scenarios in the following subsection and connect them with the renewable ammonia facility capital costs.

For the numerical analysis, computations are performed for each of the 24 selected locations and for each of the PELP scenarios, encompassing a total of 72 separate runs. This extensive range of runs provides a comprehensive view of the varied outcomes that could emerge under different technological and geographic conditions. We evaluate a variety of metrics to provide a well-rounded view of the outcomes. The principal metric of interest is the LCOA, which is the central focus of this paper. Additionally, we analyze the breakdown of the LCOA, the optimal capacities for wind and solar power installations, the capacity of the renewable ammonia facility, the total energy produced by each renewable source and the associated curtailments, full-load equivalent hours, and the overall system-level efficiency achieved, among other parameters.

Beyond this primary analysis, we also perform some sensitivity analyses, examining the impact of changes in the capital cost of the ammonia facility and the renewable-to-ammonia efficiency of the ammonia production process. We project the LCOA under the three PELP scenarios from 2023 through 2050.

The model used for this analysis was implemented using Julia Language and solved with Gurobi 10.0 on a Linux Server with an AMD EPYC 9334 32-core processor and 128 GB RAM. For each of the runs, it is required on average, about 1 min to solve, highlighting the computational effectiveness of the LP model.

4.1. Data collection and sources

4.1.1. Wind and solar power capacity profiles

We selected 11 climatic scenarios for our study, covering the period from 2030 to 2050 and focusing on even years only (every two years). The climatic scenarios utilized in this study are grounded on the projections made in [30]. These climatic scenarios are built based on basic climate information from the IPCC Global Circulation Models (GCM), under the development of the RCP8.5 climate scenario. The rationale for this is that RCP8.5 is the climate scenario that is the closest to the current conditions and the one projecting the highest level of GHG emissions among the IPCC GCM scenarios. Each climatic scenario provides hourly resolution data on wind and solar power capacity factors for every selected location.

It should be noted that these solar and wind power projections are derived using correlation techniques, reflecting the complex relationships between various climatic parameters and renewable energy performance. This allows for a more precise and nuanced understanding of the potential for renewable ammonia production across different locations and future climatic scenarios.

4.1.2. Electricity-to-ammonia efficiency

The efficiency of converting electricity to ammonia is an important factor in the analysis. Note that this efficiency can significantly vary depending on the specific process utilized for ammonia synthesis. Studies reported in the literature present a broad range of efficiencies, spanning from 1/7.9 $kgNH_3/kWh$ to 1/15 $kgNH_3/kWh$ [31,32]. A relatively efficient Haber–Bosch process that uses methane as a feedstock to produce ammonia on a large scale has an efficiency of around 1/8.3 $kgNH_3/kWh$. We adopt this figure as our baseline efficiency for the subsequent analysis. However, acknowledging the potential variability in process efficiencies, we also explore scenarios with different efficiencies to understand their impact on the LCOA.

4.1.3. Wind and solar power capital and operational cost

A critical aspect of the LCOA analysis lies in the values of wind and solar power capital and operational costs, for which we have utilized three distinct scenarios from the PELP [20]. The PELP process, led by the Chilean Ministry of Energy, serves a key role in projecting the nation's energy future over a span of 30 years. The PELP scenarios project diverse trajectories for technological capital cost that are classified as *Low*, *Ref*, and *High*. Each scenario signifies a unique pathway for the evolution of capital costs tied to energy technologies. The annual operational costs for wind and solar power are considered to be 1.5% of the annualized capital cost.

4.1.4. Ammonia production capital and operational costs

As of now, most renewable ammonia projects remain in the pilot stage and thus do not accurately reflect the true capital costs of large-scale renewable ammonia facilities. However, in Chile, there are several planned or feasibility study projects that offer insight into the potential costs. Specifically, five projects have already disclosed their production capacities and overall project costs [33]. These projects are used for projecting ammonia facility CAPEX using a power-law model fitting. See Fig. 2

These projects and their corresponding data are summarized in Table 1.

To estimate the CAPEX of ammonia production over time and ensure alignment with the technological scenarios detailed in the PELP for wind and solar power technologies, we need to estimate learning rates for ammonia investment costs. For this purpose, we have adopted a power-law model, as in (4) and similar to the one applied to six technologies within the PELP, fitting this model to the available data.

$$\text{CAPEX}\,(y) = a \cdot (y - y_0)^{\log_2(b)} \tag{4}$$

Table 1
Relevant renewable ammonia production projects in Chile planned or under feasibility study [33].

Name of the project	Year of commission	Capacity (kt/y)	Total cost (M USD)
Hyex	2024	18	96
AES Andes	2025	250	1500
HNH Energy	2026	850	3000
Selknam	2026	1000	5000
ACH-MRP	2027	500	2000

Table 2
Estimated learning parameter b for three technology development cost scenarios: *Low*, *Ref*, and *High*. The model in (4) is fitted for six technologies taking data points from the PELP cost projections. The average parameter values for each of these three scenarios are utilized to project investment costs for ammonia production.

Technology	*Low*	*Ref*	*High*
Solar PV	0.803110	0.852885	0.892996
Solar CSP 13 h	0.814857	0.866799	0.903875
Wind 140 m	0.823639	0.889325	0.939214
Wind 100 m	0.826589	0.891057	0.940243
Battery 4 h	0.799165	0.883912	0.927239
Battery 2 h	0.799165	0.883912	0.927239
Average	**0.811088**	**0.877982**	**0.921801**

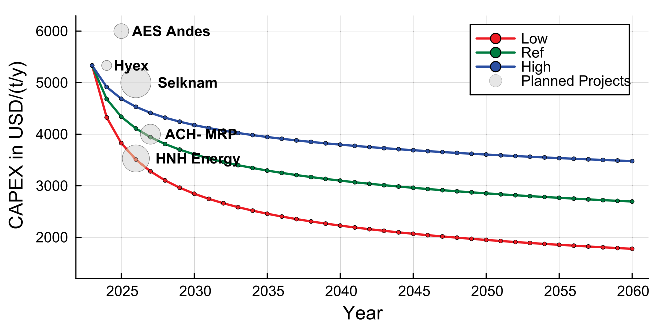

Fig. 2. CAPEX projections for a generic and ideal renewable ammonia production plant in USD/(t/y). Projections are used in conjunction with the wind and solar power CAPEX scenario projections. The monetary reference is USD for year 2023.

Interestingly, we found that the learning rate parameters are quite consistent across all technologies for a specific PELP scenario, but vary significantly among the three scenarios (see Table 2). We have, therefore, decided to use the average parameters from each scenario to project the capital investments needed for ammonia production.

Finally, we present the projected capital costs for ammonia production under the three technology cost scenarios in Fig. 2. For context, we have also included in Fig. 2 the data from the Chilean projects dedicated to renewable ammonia production that were reported in Table 1.

4.1.5. *Annuity, discount factor, and curtailment cost*

In our numerical analysis, we use annual data for all parameters. A commonly employed formula for the Present Value of an Annuity (PVA) is utilized to annualize CAPEX and OPEX values. The PVA formula assumes a constant discount rate, which we have set at 10%, aligning with the standard rate for private investments in Chile. For context, the social discount rate in Chile stands at 6% [34]. We have considered the life of solar and wind power plants to be 25 years. For the renewable ammonia production facility, a lifespan of 20 years is assumed. It is important to note that the lifetimes of many hydrogen-related projects are typically measured in operational hours, and accordingly, a 20-year lifespan is also equivalent to 70,000 h of operation, considering an average of 3,500 full-load hours per year.

Lastly, we also consider the costs associated with curtailment in the case of wind and solar energy production. In our analysis, we assume the cost associated with curtailment to be 25 USD/MWh (which is in the order of current solar-PV-based PPAs in Chile).

4.2. *Results analysis for PELP Ref scenario*

The *PELP Ref* scenario refers to a reference case wherein we solve the model based on a set technology scenario with a targeted year of 2050. The following results are representative of expected values (such as total wind and solar power production) across all climatic years. However, specific outcomes – like the installed capacities of solar, wind, and ammonia plants – are singular values that do not depend on the climatic year.

Fig. 3 provides a comprehensive overview of the total installed capacities of wind and solar power at each location. These capacities are the outcome of the proposed optimization model, detailed in (3). The right side of Fig. 3 reveals the total installed capacity of the generic and ideal renewable ammonia plant at the corresponding study locations. It is noteworthy that solar investments predominantly dominate the North while wind power is the principal technology in the South. Interestingly, the optimal capacity of the NH_3 plants can exceed the energy capacity by more than double, depending on the location. The figure also includes a dashed reference line indicating the ammonia capacity needed if the facility runs continuously (24/7), equating to 1 million tons divided by 8760 h, i.e., 114.15 tNH_3/h.

Fig. 4 presents the LCOA calculated for each location along with its component breakdown. In most cases, the CAPEX of NH_3 accounts for over half of the LCOA, with some cases reaching two-thirds of the total cost. It is important to mention that this calculated LCOA does not factor in any form of subsidies or taxes, nor any transportation cost for delivery to other sites.

Fig. 5 displays the annual energy balances. It illustrates the energy generated by solar and wind power necessary for producing 1 Mt of NH_3 in a year period set as reference. The figure also contains the renewable energy curtailment in every location, which is always a non-zero amount. As a benchmark, we have plotted the energy content in 1 Mt of NH_3 produced using its Lower Heating Value (LHV) (5.17 MWh/tNH_3). This allows us to estimate an end-to-end (i.e., renewable-to-ammonia) efficiency, measured in kWh/$kWhNH_3$, for the transformation of renewable energy into ammonia in values between 0 and 1. It is interesting to note that the renewable-to-ammonia efficiency is remarkably similar across nearly all locations in Chile, with values roughly between 55% and 60%.

Despite having similar renewable-to-ammonia production efficiencies at nearly all locations, the LCOA figures exhibit considerable variation. This discrepancy arises from the differences in wind and solar resources at each location, and the complementarity between wind and solar power found in specific locations, which can help to avoid overestimating the ammonia plant capacity.

4.3. *A close look at Parinacota and Charrua locations*

The previous analysis identified Charrua, located in the south-central region of Chile, as the most cost-effective location in terms of LCOA. In the context of the PELP *Ref* technology scenario projected for 2050, the LCOA in Charrua was calculated to be 458 USD/tNH_3. A remarkable observation from the analysis is that Charrua presents one of the lowest over-investments in ammonia production capacity for harnessing variable renewable resources. In contrast, Parinacota, situated in the northernmost region within the Atacama Desert – a world-renowned location for optimal solar PV electricity production conditions – does not boast the most competitive LCOA. Under the same scenario and target year, the LCOA for Parinacota stands at 674 USD/tNH_3.

In Parinacota, solar power production follows a strong daily pattern, with electricity generation occurring every day and maintaining high solar production factors consistently. This reliability, however, is not mirrored in Charrua, where solar PV electricity production exhibits greater day-to-day variation. Furthermore, in Parinacota, ammonia production is not feasible during nighttime, and even during daylight

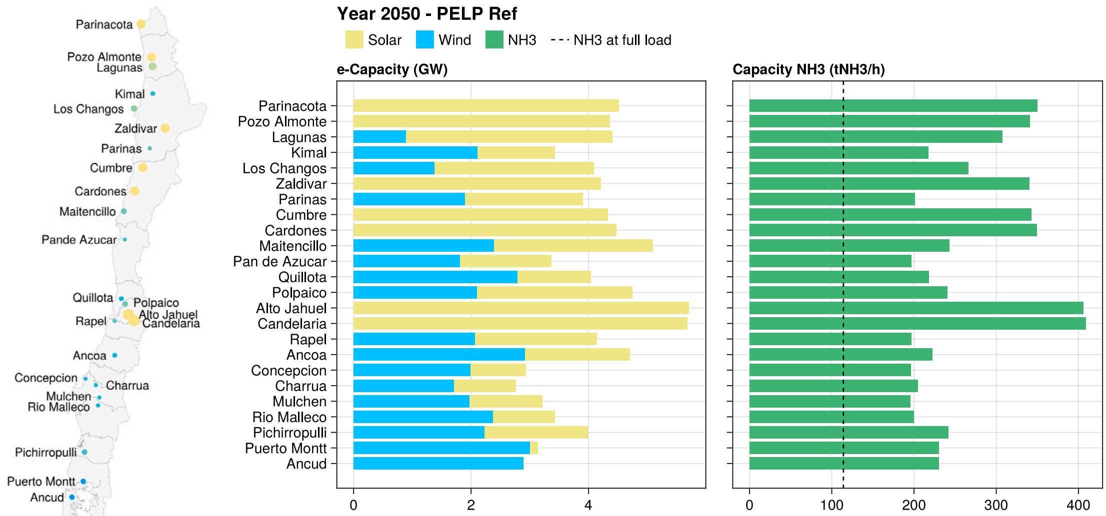

Fig. 3. Total capacity installed by location. *Left:* Partial map of Chile with locations of study. The size of the bubbles is proportional to the ammonia plant capacity while the color is related to the mix of renewable generation. *Center:* Optimal solar and wind power capacity installed (in GW). *Right:* Optimal capacity of the renewable ammonia production facility (in tNH_3/h).

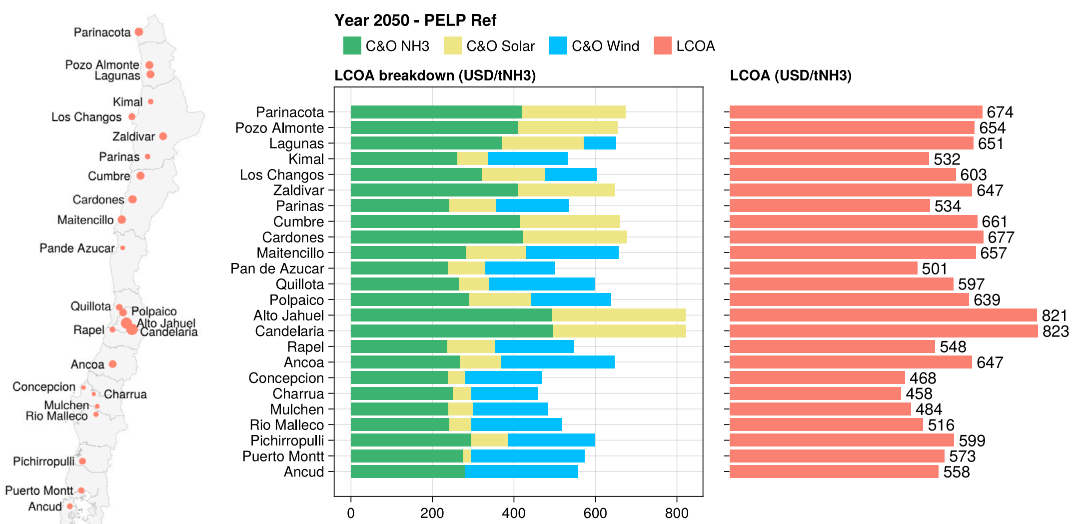

Fig. 4. LCOA by location. *Left:* Partial map of Chile with locations of study. The size of the bubbles is proportional to the LCOA. *Center:* LCOA breakdown. *Right:* LCOA (in USD/tNH_3).

hours, production faces curtailments. Notably, the constant presence of curtailment is observed in both locations—a trend also found across other examined areas.

Fig. 6 offers detailed LCOA breakdown for both sites. Parinacota's LCOA is 216 USD/tNH_3 more expensive than Charrua's. Interestingly, 80% of this cost increase (i.e., 170 out of 216 USD/tNH_3) is attributed to the investment cost associated with the ammonia production plant. It is worth noting that ammonia investment cost accounts for approximately 50% of the LCOA for Charrua and 60% for Parinacota.

The impact of renewable investment costs, including solar and wind, on the total LCOA is not as significant as that of the ammonia capital cost. Disregarding curtailment, i.e., considering only CAPEX & OPEX for solar and wind power, the impact on the total LCOA increase in Parinacota is 46 USD/tNH_3 out of 216 USD/tNH_3. This represents about 20% of the LCOA difference between the two locations.

4.4. Sensitivity analysis on efficiencies and CAPEX for Parinacota and Charrua locations

We conducted a sensitivity analysis varying the CAPEX of ammonia production from 1000 $USD/(tNH_3/y)$ to 6000 $USD/(tNH_3/y)$, and varying the electricity-to-ammonia efficiency, $1/\eta_{e\to NH_3}$, from 7.9 to 15 MWh per tNH_3. The results of this analysis are shown in Fig. 7. The reference values used in the previous analysis of Parinacota and Charrua are indicated by a gray dot. LCOAs above 1000 USD/tNH_3 are not represented, while LCOAs below 500 USD/tNH_3 are depicted in light green. Each 100 USD/tNH_3 interval from 500 to 1000 is differentiated by colors.

From a general perspective, it is noticeable that for the same electricity-to-ammonia efficiency, a reduction in the CAPEX of ammonia production can significantly lower the LCOA. This observation aligns with the insights collected in the previous section.

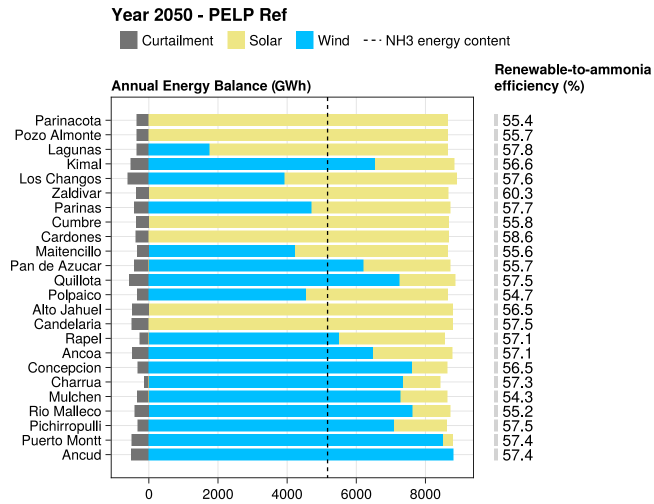

Fig. 5. Annual energy balance by source and whole renewable-to-ammonia efficiency.

On the other hand, electricity-to-ammonia efficiency improvements can also reduce the LCOA. However, for the same CAPEX of ammonia production, an improvement in the electricity-to-ammonia efficiency just slightly lower the LCOA. Moreover, it is essential to consider that if new processes for ammonia production are discovered or developed, the CAPEX would probably be larger due to the processes being in the early stages of development. Consequently, the impact of a reduction in CAPEX significantly outweighs the impact of electricity-to-ammonia efficiency improvement. This conclusion underscores the importance of prioritizing the reduction of investment costs while seeking to improve electricity-to-ammonia efficiency.

4.5. Seasonal production sensitivity for Parinacota and Charrua locations

We take a deeper look into seasonal ammonia production and investigate how it can be influenced by different climatic scenarios.

Fig. 8 illustrates the monthly production of ammonia, as well as wind and solar power and curtailment for the two locations under consideration—Parinacota and Charrua. A first observation to make from this figure is the actual seasonal variation in ammonia production. This is more pronounced in Parinacota, where solar energy solely is used to power the renewable ammonia facility. The ammonia production noticeably drops during June and July (winter) and increases as the months approach summer. This effect is less substantial in Charrua due to the combination of solar and wind resources available for producing ammonia. In both cases, the expected annual ammonia production remains constant at 1 $MtNH_3$, as we established in our analysis.

Moreover, we notice considerable year-on-year variations in ammonia production. Once again, this variation is attributed to the renewable resources' year-by-year variability. This variation can be quite significant. For instance, observe the ammonia production in July at the Charrua location. For a particular year, the ammonia production in July could be around 62 $ktNH_3$, while in another year, the production for the same month could soar to 110 $ktNH_3$, an increase (or decrease) of over 40%. This remarkable variation clearly emphasizes the substantial impact of annual renewable resource availability on ammonia production.

4.6. Analysis and evolution of the LCOA for the three PELP scenarios

We have derived insights into the formation of LCOA at different locations and ways to improve it from the previous analysis. For all the analysis, we chose the year 2050 due to Chile's commitment to achieving zero emissions by this target year [19]. We selected the PELP *Ref* scenario as a reference for technology costs. In this section, we analyze the evolution of the three prospective energy cost paths in line with the PELP scenarios [20].

Fig. 9 illustrates the evolution from 2023 to 2050 of the LCOA for the three PELP cost scenarios: *Low* (depicted in red), *Ref* (depicted in green), and *High* (depicted in blue). The colored intervals represent the range for all 24 locations in Chile analyzed. Both Parinacota and Charrua locations were selected to understand the LCOA evolution at these specific locations. The density functions for the LCOA distributed along all locations in the year 2050 are represented on the right-hand side.

A first observation we can make from the colored interval bands is that location significantly influences the optimal LCOA. Note that the intervals overlap among the three PELP scenarios for 2050 (and many other years). This means that even with a scenario of low technology cost (red), the LCOA for the worst location is higher than the best location for the most expensive technology scenario (blue). This clearly indicates that the location matters significantly in determining the LCOA.

A second observation is that in 2030, an LCOA below 500 USD/tNH_3 would be attainable in Charrua for the PELP *Low* scenario. This LCOA further decreases to fall to 342.8 USD/tNH_3 by 2050.

The third observation is that even in 2050, no location would be able to achieve an LCOA below 500 USD/tNH_3 if the cost of technology progresses with the least of the learning rates (PELP *High* scenario). This underscores the importance of advancing the technology costs at a more accelerated pace to reach competitive LCOA levels.

To extend the analysis of the evolution of the LCOA, we also computed the corresponding full-load equivalent hours (FLH). The FLH is a capacity factor metric, expressed in hours per year, and is widely used in the production context. The FLH illustrates how many hours per year should be required in the ammonia production facility if the ammonia plant were operating at full capacity.

Fig. 10 presents a comparison of the LCOA versus FLH for the three PELP scenarios: *High* (depicted with blue triangles), *Ref* (depicted with green circles), and *Low* (depicted in red squares). Each of the dots represents one of the 24 locations analyzed. The fill color of each dot signifies the mix of renewable energy that powers the ammonia plant. Light blue symbolizes the locations where only wind capacity is installed while yellow represents locations relying exclusively on solar energy. The size of the dots is proportional to the power-to-ammonia plant's capacity. Two snapshots in time, 2030 (left) and 2050 (right), are juxtaposed for a more comprehensive understanding.

Our first observation based on this figure is the negative correlation between the FLH and LCOA. Locations with higher FLH, meaning those that can operate their ammonia plants for more hours per year at full capacity, typically have a lower LCOA. This negative correlation is expected, as more operating hours allow for more ammonia production and a higher level of equipment utilization, thereby spreading the fixed costs over a greater quantity of output and reducing the LCOA.

The second observation relates to the importance of the renewable capacity mix. The geographical renewable resource diversity in Chile strongly influences the optimal renewable technology mix. The northern regions, with abundant sunlight, tend to favor solar-only investment. Conversely, the southern areas, known for their consistent wind patterns, find wind-only investment to be the optimal strategy. In central Chile, where neither solar nor wind is overwhelmingly dominant, hybrid projects that utilize both resources can provide a balanced and efficient solution.

The third observation sheds light on the temporal evolution of LCOA across different locations. In 2030, only a limited number of locations manage to achieve an LCOA under the threshold of 500 USD/tNH_3, and that too primarily under the PELP *Low* scenario. This

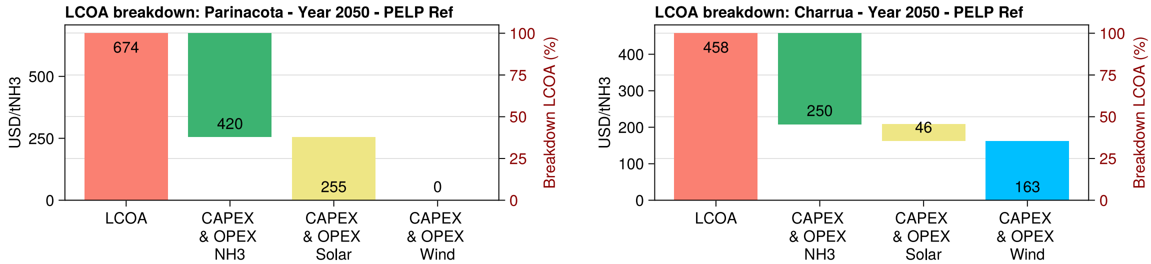

Fig. 6. LCOA and its breakdown for Parinacota location (left), and Charrua location (right).

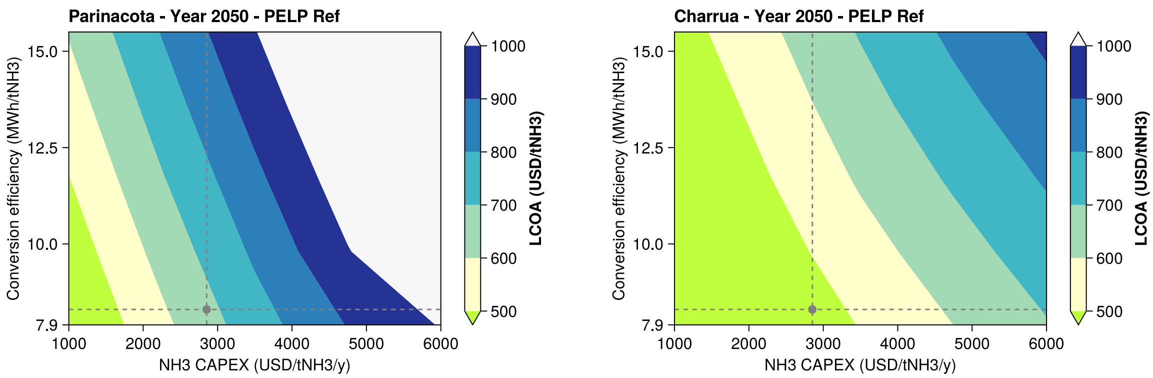

Fig. 7. Sensitivity analysis on efficiencies and CAPEX for Parinacota location (on the left), and Charrua location (on the right). The gray dot is the reference electricity-to-ammonia efficiency and CAPEX used in the simulations presented in the previous subsections. The light green color is used for LCOA below 500 USD/tNH$_3$.

highlights the existing challenges and constraints in reaching cost-competitive levels of renewable ammonia production in the near future. However, by 2050, the landscape changes significantly. Numerous locations can produce ammonia under this threshold, particularly for the PELP *Ref* and PELP *Low* scenarios. This transformation indicates the potential for technological advancement, cost reduction, and improved electricity-to-ammonia efficiency that may occur over the coming decades.

4.7. Sensitivity analysis on the impact of the discount rate

In Chile, private projects are conventionally governed by a discount rate of 10%. This figure would naturally be the expectation for ammonia projects, which are anticipated to be financed predominantly by private capital within the nation. However, a contrasting value, known as the social discount rate, plays a key role in the governmental domain. This rate is used by governments to translate the future societal benefits and costs into present value, serving as a metric for how the present generation values welfare relative to future generations. Unlike the private discount rate, the social discount rate takes into account broader societal considerations. The Chilean government has set this value at 6% [34].

The results of the same simulations made before, but now using the 6% discount rate, are summarized in Fig. 11. It shows a substantial decrease in LCOA under the social discount rate. This decrease is not merely a numerical shift; it represents a profound change in how the projects' costs and benefits are evaluated. By adopting a social discount rate, the emphasis shifts from narrow financial returns to broader considerations of social welfare.

By 2030, irrespective of the technology cost scenario, the production of ammonia at a cost under 500 USD/tNH$_3$ becomes achievable in the best-suited locations of Chile, Charrua being a prime example.

Fast-forwarding to 2050, the landscape shifts even more favorably. Under the PELP *Low* scenario, all locations across Chile exhibit the capacity to produce ammonia below the critical threshold of 500 USD/tNH$_3$. Even in the more moderate PELP *Ref* scenario, by the year 2050, two-thirds of the locations fall below the 500 USD/tNH$_3$ threshold. This considerable proportion emphasizes the substantial impact that the social discount rate can have on the economic feasibility of ammonia projects across the country.

5. Discussion and conclusions

The evolution of renewable ammonia projects and the trajectory toward achieving favorable LCOA remains complex and multifaceted challenges, particularly in the context of Chile's commitment to zero emissions by 2050. Factors such as fluctuations in ammonia and energy markets, advancements in relevant technologies, and varying availability of renewable resources, like solar and wind, contribute additional layers of uncertainty.

This paper takes a new and practical perspective by introducing a methodological framework for LCOA by using a generic and ideal model for renewable ammonia production plants. This tool is not merely a theoretical construct, it serves as a concrete foundation for assessing LCOA at different locations.

Our analysis of various scenarios for ammonia production in Chile has led to clear insights. Rather than simply highlighting challenges, this paper offers tangible solutions and economic quantification for the development of renewable ammonia projects in Chile. The findings within this research can significantly inform decision-making, leading to more effective and efficient ammonia production in alignment with Chile's ambitious environmental commitments. Below, we describe the main insights.

(i) *Geographical considerations for technology selection.* Projects in the north of Chile exhibit superior performance using solar power technology due to abundant sunlight. Conversely, the southern regions, exposed to stronger and more consistent winds, benefit more from wind power technology. In between these extremes, hybrid portfolios that combine solar and wind power technologies emerge as optimal. These findings emphasize the need to tailor technology choices to local geographical and climatic conditions.

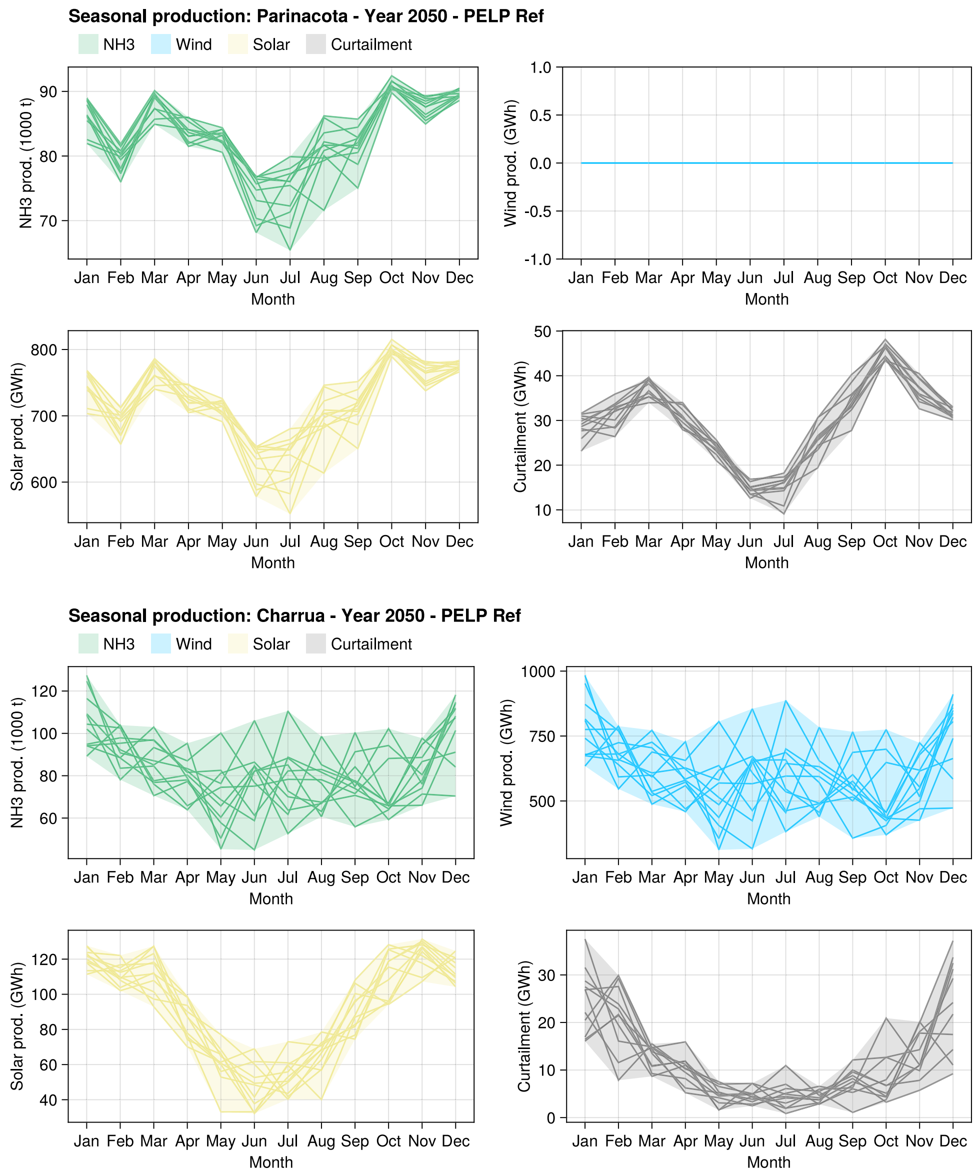

Fig. 8. Seasonal profiles for production of NH_3, wind and solar power, as well as curtailment, in Parinacota location (top) and Charrua location (bottom).

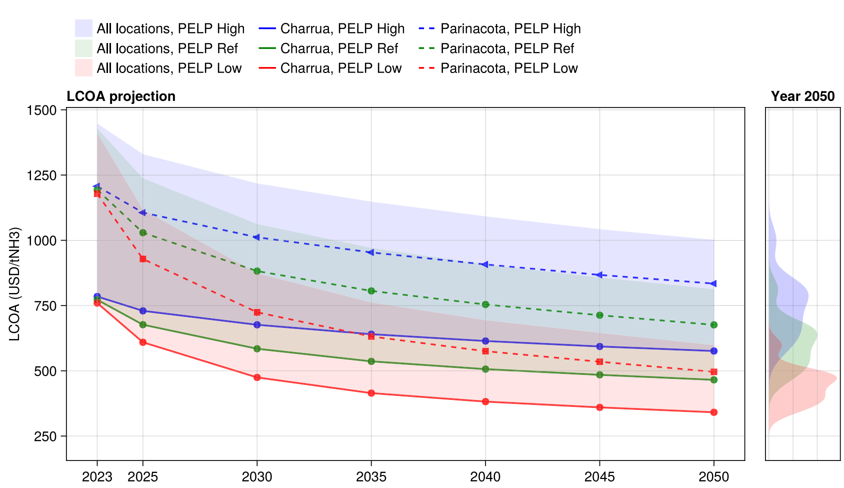

Fig. 9. LCOA projections for the three PELP scenarios analyzed.

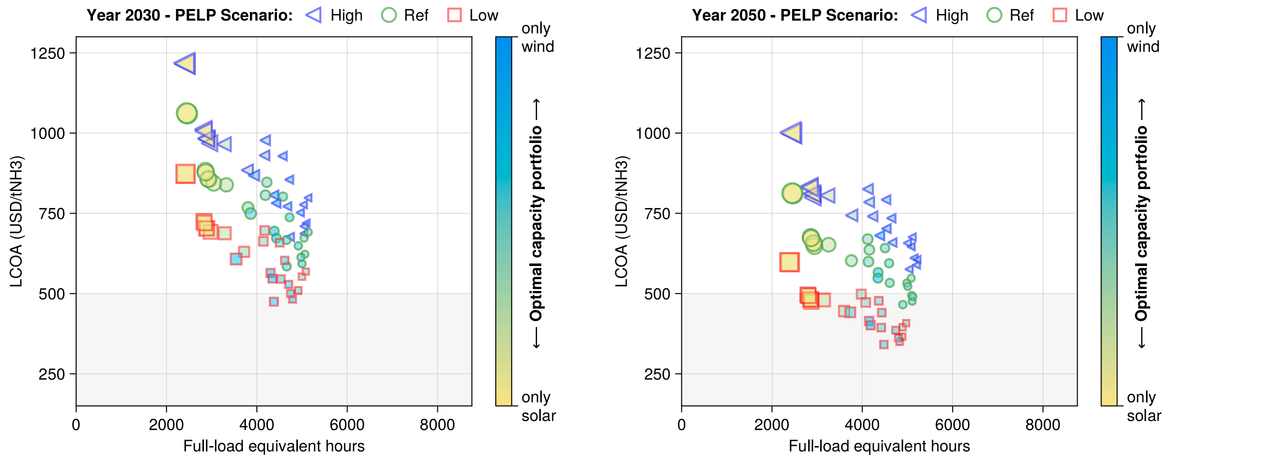

Fig. 10. LCOA vs. FLH. The size of the symbols is proportional to the size of the ammonia production capacity. The color is related to the optimal portfolio of renewable sources. *Left:* case for year 2030. *Right:* case for year 2050.

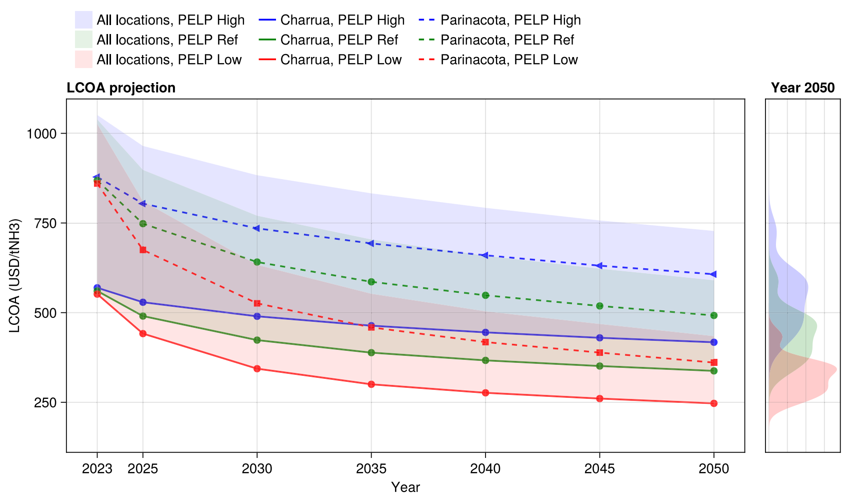

Fig. 11. LCOA projections for the three PELP scenarios analyzed, using a social discount rate of 6%.

(ii) *The role of hybrid portfolios.* Despite excellent solar power production conditions in the north, solar-only projects do not always yield the best outcomes. Instead, hybrid portfolios of wind and solar power can provide more favorable results in terms of LCOA, demonstrating the value of diversification in energy sourcing.

(iii) *Optimal capacity for ammonia production plants.* The optimal capacity of an ammonia production plant is 2 to 3 times the average hourly production rate. This oversizing allows the facility to effectively harness intermittent renewable energy sources. This insight may guide the design and scaling of grid-connected ammonia plants, optimizing electricity-to-ammonia efficiency and performance.

(iv) *Inverse relationship between LCOA and FLH hours.* Our simulations confirm the expected inverse relationship between LCOA and equivalent full-load hours (FLH). As FLH hours increase, the ammonia plant size can be reduced, leading to a corresponding decrease in LCOA. This trend illustrates the critical role of renewable resource complementarity and aligns with the geographic considerations mentioned earlier.

(v) *CAPEX's significant share in LCOA.* The capital expenditure (CAPEX) for the ammonia production plant consistently forms a substantial portion of the overall LCOA, always constituting more than 50%.

(vi) *The unavoidability of curtailment.* The unavoidable nature of curtailment in renewable ammonia production contradicts some literature on the subject. Oversizing the ammonia production plant to utilize the last watt of peak renewable power production is suboptimal, particularly considering the substantial influence of ammonia production CAPEX on the final LCOA. Instead, our analysis shows the optimal strategy that has a lower ammonia production capacity combined with a larger renewable production capacity. This approach not only aligns with the inherent variability of renewable energy resources, but also optimizes the LCOA, reflecting a more nuanced and practical understanding of the production dynamics.

(vii) *Renewable-to-ammonia efficiency considerations.* The overall renewable-to-ammonia efficiency ranges between 55% and 60% in Chile, using the lower heating value (LHV) of ammonia. The remaining energy is lost in curtailment and ammonia production, with curtailment accounting for less than 1%–5% in all cases.

(viii) *Prioritizing CAPEX over process electricity-to-ammonia efficiency.* Given the cost structure and technological considerations, improving the ammonia production CAPEX may yield more substantial economic benefits than enhancing the process efficiency. Accordingly, our quantification of the trade-off between the impacts of CAPEX and process efficiency improvements can inform not only investment, but also research funding decisions for applied versus basic research and development in this field.

Table A.1
Nomenclature of parameters and variables used in the model.

Symbol	Definition
Parameters	
$c^{\text{inv,NH}_3}$	Investment cost of ammonia production facility
$c^{\text{inv,s}}$	Investment cost of solar power capacity
$c^{\text{inv,w}}$	Investment cost of wind power capacity
$c^{\text{ope,NH}_3}$	Operational cost of ammonia production facility
$c^{\text{ope,s}}$	Operational cost of solar power capacity
$c^{\text{ope,w}}$	Operational cost of wind power capacity
c^{curt}	Curtailment cost
$\eta^{e\to\text{NH}_3}$	Electricity-to-ammonia efficiency
$\gamma_t^{\text{s}}(\omega)$	Capacity factor of solar power at time h for scenario ω
$\gamma_t^{\text{w}}(\omega)$	Capacity factor of wind power at time h for scenario ω
Variables	
$\text{C\&O}^{\text{NH}_3}$	Total cost of ammonia production
$\text{C\&O}^{\text{s}}$	Total cost of solar power capacity
$\text{C\&O}^{\text{w}}$	Total cost of wind power capacity
Γ	Expected curtailment cost
$P^{\text{tot,NH}_3}$	Total ammonia production
$p_h^{\text{e}}(\omega)$	Electricity input for ammonia production at time h for scenario ω
$p_h^{\text{NH}_3}(\omega)$	Ammonia production at time h for scenario ω
$p_h^{\text{s}}(\omega)$	Solar power production at time h for scenario ω
$p_h^{\text{w}}(\omega)$	Wind power production at time h for scenario ω
$\rho_h^{\text{s}}(\omega)$	Solar power curtailment at time h for scenario ω
$\rho_h^{\text{w}}(\omega)$	Wind power curtailment at time h for scenario ω
$\overline{P}^{\text{NH}_3}$	Production capacity of ammonia facility
$\overline{P}^{\text{s}}$	Installed solar power capacity
$\overline{P}^{\text{w}}$	Installed wind power capacity

(ix) *The impact of the social discount rate.* The adoption of a social discount rate can significantly foster investments in ammonia production. By aligning private investment with social welfare goals, LCOA would become highly competitive within the Chilean context.

In conclusion, while our study provides valuable insights into the economic viability of renewable ammonia production in Chile, we acknowledge several limitations that highlight the need for further research. Notably, our analysis relies on ideal assumptions, such as the availability of water, infrastructure to deliver ammonia and inputs, and simplifications of the facility's overall operation. Additionally, our model does not account for the potential benefits of optimizing with energy storage systems, such as batteries, which could further improve the economic feasibility of renewable ammonia production. Furthermore, our study focuses on a specific definition of "renewable ammonia" that requires temporal correlation between ammonia production and renewable resource generation, which may not be the only viable pathway to sustainable production.

Despite these limitations, we recognize the vast potential for further investigation in the field of this paper. Foremost among the avenues for future research is the comprehensive analysis of other renewable fuels. These encompass not only ammonia, but also other fuels like hydrogen, and other synthesized chemicals. An interesting area for investigation would be to look at alternative definitions of "renewable ammonia". For instance, by decoupling the temporal correlation between ammonia production and its corresponding renewable resource generation, we might uncover alternative pathways to sustainable production. Moreover, understanding the impact of renewable ammonia production on the power grid is of paramount importance, especially when such production is interlinked with the grid's operational dynamics. Lastly, by examining the design of renewable ammonia production facilities, we can better understand key parts of the process, including storage, transport, and production. As we continue to study these areas, we expect to discover connections and valuable information that will help us improve how we understand and work with renewable ammonia production.

CRediT authorship contribution statement

David Pozo: Writing – review & editing, Validation, Visualization, Methodology, Conceptualization, Software, Data curation, Writing – original draft, Formal analysis. **Enzo Sauma:** Visualization, Writing – review & editing, Funding acquisition, Methodology, Writing – original draft, Validation, Conceptualization, Investigation, Formal analysis. **Ricardo Bolado-Lavín:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix. Nomenclature

The nomenclature used in the mathematical model is summarized in Table A.1.

Data availability

Data will be made available on request.

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