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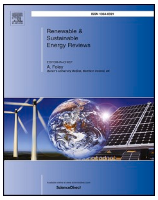

Techno-economic feasibility of centralized and decentralized ammonia production in the United States

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ABSTRACT

Ammonia is a cornerstone of modern agriculture, supplying the nitrogen essential for crops that nourish nearly half the global population. Yet its production is responsible for ~2 % of global greenhouse gas emissions. To meet climate and food security goals, sustainable, low-carbon, and resilient ammonia production systems are needed. Here, we develop a spatially explicit techno-economic model to compare centralized and decentralized ammonia production pathways across the U.S., a major global ammonia producer and consumer, spanning the full supply chain from hydrogen production to fertilizer delivery. We integrate high-resolution supply and demand data and apply linear optimization to estimate delivered ammonia costs, accounting for geographic mismatches and transportation. Our results show that decentralized ammonia production, whether powered by grid electricity or solar energy, is substantially more expensive than centralized production from natural gas or coal. Centralized natural gas-based ammonia has a median production cost of 326 USD/tonne NH_3, compared to 499 USD/tonne for coal. Decentralized grid-powered systems range from 659 to 1634 USD/tonne, and solar-powered systems from 1077 to 2266 USD/tonne. Transportation costs for centralized production range from 7 to 85 USD/tonne, with a median of 40 USD/tonne, resulting in a delivered cost of 343 USD/tonne. Median delivered costs for decentralized grid- and solar-powered systems are 1069 and 1494 USD/tonne, respectively. Decentralized systems require electricity prices below 19 USD/MWh (grid) and 17 USD/MWh (solar) to achieve cost parity, well below 2024 U S. averages of 117 USD/MWh. These results highlight the economic challenges facing decentralized ammonia production and the importance of electricity cost reductions, tax credits, carbon pricing, or further technological breakthroughs for broader viability.

1. Introduction

Ammonia is the primary precursor for all nitrogen-based fertilizers [1], supporting food production for nearly half of the global population [2,3]. Its availability, cost, and environmental footprint are therefore critical factors influencing agricultural productivity and global food security [3]. The United States (U.S.) plays a central role in both ammonia production and nitrogen fertilizer consumption. With an annual ammonia production capacity of ~19 million tonnes (Mt NH_3) [3–5], the U.S. holds the position of the second-largest producer globally, accounting for roughly 9 % of global capacity [3]. The U.S. is home to 33 large-scale ammonia production complexes, including the world's largest single-site ammonia facility, located in Louisiana, with a capacity of 4.3 Mt NH_3 per year [3–5]. On the demand side, the U.S. consumes around 10 Mt of nitrogen annually, making it the third-largest consumer worldwide, after China and India, and accounting for about 10 % of global demand [3,6]. These figures highlight the U.S.' strategic importance in the global fertilizer market and its foundational role in supporting both domestic and international agri-food systems.

The U.S. ammonia supply chain is almost entirely dependent on fossil fuels (92 % natural gas 8 % coal), to produce hydrogen (key step in ammonia production) primarily via steam methane reforming (SMR) and coal gasification [5]. The extensive use of natural gas stems from its dual function as the hydrogen feedstock and as the high-temperature energy source required in the Haber-Bosch synthesis process [7]. Additionally, natural gas is abundant and inexpensive in the U.S. [8,9], further reinforcing its dominance as the preferred input for ammonia production.

On average, producing one tonne of ammonia through SMR requires 28–41 GJ of natural gas depending on plant efficiency [7]. As a result, natural gas typically accounts for more than 60 % of the levelized cost of ammonia (LCOA) [5,10]. This high cost share makes ammonia

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production highly sensitive to fluctuations in global energy markets. For instance, following the 2022 energy crisis, natural gas prices surged, pushing U.S. ammonia prices to as high as 1600 USD per tonne, a more than threefold increase compared to the 2018–2020 market average [11,12]. This volatility poses serious risks to the economic stability of fertilizer producers and farmers, exposing the systemic vulnerability of ammonia supply chains to fossil fuel price shocks [13,14].

Beyond economic impact, the reliance on fossil fuels largely contributes to greenhouse gas emissions [5]. On average, ammonia production in the U.S. emits approximately 2.6 tonnes of CO_2 per tonne of NH_3 [5]. Emissions vary by feedstock and process: the most efficient natural gas-based (SMR) plants emit ~1.6–1.8 tonnes of CO_2 per tonne of NH_3 [7] whereas coal-based production can emit as much as 3.2–4.5 tonnes of CO_2 per tonne of NH_3 [15–17]. This results in an estimated 43 Mt of CO_2 annually [5], equivalent to nearly 10 % of global ammonia-related emissions [1,7] and over 13 % of total emissions from the U.S. petrochemical sector [18].

In addition to its carbon footprint, the highly centralized nature of current ammonia production introduces logistical challenges [3,19,20]. Because production sites are often located far from regions of agricultural demand, ammonia must be transported over long distances, adding cost, increasing emissions, and reducing system efficiency [3,11,20,21]. This issue is particularly pronounced in agricultural hubs such as the Corn Belt, as well as regions like the Pacific Northwest and Minnesota [11,14,21], where farmers depend on ammonia transported from distant facilities. These transportation burdens raise fertilizer costs and amplify price volatility throughout the food supply chain, ultimately affecting both producers and consumers.

Together, these challenges underscore both the urgency and the opportunity for a paradigm shift in ammonia production [3,19]. Given the sector's maturity, the scale of ammonia production, and the need to decarbonize a critical input to global food systems, there is growing momentum toward more sustainable and resilient alternatives. Ammonia is not only central to fertilizer production but is also increasingly recognized as a strategic industrial asset, making its decarbonization a national priority for many countries [17].

Three main decarbonization pathways dominate current discussions: blue ammonia (based on carbon capture and storage - CCS), biomass-based ammonia (from biochemical processes), and green ammonia (via electrolytic hydrogen) [3,5,22]. Blue ammonia involves retrofitting conventional fossil-fuel-based Haber–Bosch plants with CCS to reduce direct CO_2 emissions. While this approach can drastically curb point-source emissions (>90 % capture rate [23]), life-cycle assessments highlight concerns such as methane leakage across the natural gas supply chain and the long-term reliability of carbon storage infrastructure [22,24–26]. Moreover, CCS does not address exposure to fossil fuel price volatility, particularly in natural gas markets [3].

Biomass-based ammonia replaces fossil natural gas with biomethane, typically derived from anaerobic digestion of waste biomass [27]. This biomethane can be used in standard steam methane reforming infrastructure by switching fossil natural gas feedstock in a seamless manner [27,28]. When combined with CCS, the process can achieve net-negative emissions due to the capture of biogenic CO_2 [27]. However, its practical deployment is constrained by the local availability of affordable, sustainable biomass, which is essential for cost-effective and continuous operation [26,27].

Green ammonia substitutes fossil feedstocks with hydrogen produced via water electrolysis, powered by low-carbon or renewable electricity [29]. This pathway eliminates direct fossil fuel use and can reduce by more than 90 % life-cycle emissions if powered by low-carbon energy sources [3,25,30]. However, it presents several challenges: high upfront capital requirements (potentially in the billions of dollars) [3,31], increased natural resources intensity (e.g., water [28,32], land [28,32], and energy [2,3]), and high levelized cost of ammonia (LCOA) compared to conventional production [3,31]. Additionally, when powered solely by grid electricity, emissions can exceed those of fossil-based ammonia if the grid is not fully decarbonized [25,33,34]. Meanwhile, relying exclusively on renewables demands massive land footprints to deploy multi-gigawatt-scale infrastructure, raising feasibility and siting concerns [31,32]. Therefore, low-carbon ammonia should be paired with site-specific assessments that optimize production while accounting for natural resources availability [35].

An emerging alternative is decentralized, small-scale electrolytic ammonia production, which offers several advantages. These systems, based on electrolytic hydrogen and electrically driven ammonia synthesis [29], can be modular [19,36], flexible [37], require smaller land footprints [3], and minimize transportation costs by locating production closer to agricultural demand [29,38]. This approach not only improves resilience and energy security but also reduces capital investment barriers, making entry feasible for smaller-scale operators or cooperatives [3]. Unlike most countries, the U.S. directly applies anhydrous ammonia as fertilizer [24], a practice that accounts for the majority of the ~3 % of global ammonia used in its raw form [39]. This existing familiarity, along with established infrastructure (such as irrigation systems capable of applying aqueous ammonia [40]) positions the U.S. as an ideal testing ground for on-farm ammonia production and application, aiming at net-zero emissions in agriculture [41,42].

While a growing body of literature has examined the techno-economic feasibility of decentralized green ammonia production, most studies fall into two categories: global or generalized assessments with limited spatial resolution, and highly localized case studies. Global studies (e.g., Refs. [3,29,36,38,43,44]) offer valuable insights into the theoretical feasibility, cost trajectories, and system-level trade-offs of decentralized or modular ammonia production. For example, Tonelli et al. [36] underscore the importance of including transportation costs when evaluating decentralized competitiveness, while Comer et al. [43] focus on the food security benefits of distributed, renewable-based systems. Fernández et al. [38] highlight the technical targets and resource constraints, such as water stress, that must be addressed for successful deployment. Smith et al. [29] provide a comprehensive overview of emerging distributed ammonia technologies.

In contrast, case studies (e.g., Refs. [14,20,45,46]) provide more realistic, context-specific evaluations, often incorporating historical energy prices, infrastructure constraints, and localized logistics. For instance, Palys and Daoutidis [14] develop a supply chain optimization model tailored to county-level ammonia demand in Minnesota. Smith and Torrente-Murciano [20] examine the economic and social benefits of green ammonia production in Sierra Leone. These studies offer valuable insights into local deployment challenges and opportunities, yet their limited geographic scope constrains broader applicability and national-scale planning.

Together, these two bodies of work offer complementary insights: global studies help define theoretical boundaries and long-term trends, while case studies ground these findings in real-world contexts. However, what remains largely missing is a spatially explicit, national-scale assessment that integrates real-world data on fertilizer demand, renewable energy potential, energy cost variability, logistics, and existing ammonia infrastructure to evaluate the techno-economic viability of decentralized production and to determine where, and under which conditions, such systems are most feasible and competitive.

Our study addresses these gaps by focusing on the U.S., a context well suited for spatially explicit analysis due to the availability of high-resolution, openly accessible datasets. We develop a techno-economic model of both centralized and decentralized ammonia production pathways across the contiguous U.S., capturing the full supply chain from hydrogen production to end-use fertilizer delivery. The model integrates detailed data on existing ammonia infrastructure (including plant locations and production capacities), county-level nitrogen fertilizer demand, and renewable energy potential based on satellite-derived solar irradiance data. These inputs are combined with more than 20 years of county/state-level energy price data, including natural gas, coal, and electricity, and most recent techno-economic parameters for hydrogen and ammonia production technologies.

We estimate both the LCOA and the cost of delivered ammonia (cost at the demand point), optimizing distribution logistics while accounting for transportation from centralized plants to demand points, infrastructure constraints, and geographic mismatches between supply and demand. This framework enables a robust, spatially resolved comparison of centralized and decentralized production systems under context-specific conditions. Ultimately, we identify where and under what conditions decentralized ammonia production can emerge as a cost-effective, sustainable, and resilient alternative to the existing supply model in the U.S.

2. Methods

2.1. Model description

We model two primary ammonia production pathways: centralized large-scale fossil-based production and decentralized small-scale electrolytic production (Fig. 1). Each pathway includes two alternatives. For centralized production, ammonia is synthesized via the conventional Haber-Bosch process, using either natural gas (via steam methane reforming) or coal (via gasification) as feedstock. For decentralized production, ammonia is generated through an electric Haber-Bosch process using hydrogen from electrolysis, powered either by grid electricity or dedicated renewable installations (e.g., solar PV). For simplicity, we refer to the four configurations as: (i) centralized-gas, (ii) centralized-coal, (iii) decentralized-grid, and (iv) decentralized-renewables.

Our analysis is conducted at the county level across the contiguous U. S. We begin by mapping existing nitrogen demand for agriculture and ammonia production capacity (Fig. 1a), establishing a spatial distribution of supply and demand. For centralized pathways, we first estimate transportation costs required to deliver ammonia from large-scale production facilities to distributed demand points. These are calculated using a cost-minimizing mixed-integer linear programming (MILP) supply chain model that optimally connects production sites to county-level demand, accounting for geographic mismatches and infrastructure constraints. We then estimate production costs using historical data on natural gas and coal, combined with techno-economic parameters for conventional Haber–Bosch plants. The total cost of delivered ammonia (i.e., the cost at the point of use) is calculated as the sum of production and transportation costs.

For decentralized pathways, we assume co-location of production and consumption (e.g., an on-farm unit), which eliminates the need for transportation. In these cases, the LCOA is equal to the delivered cost. For systems powered by dedicated renewables, we calculate the levelized cost of electricity (LCOE) using high-resolution solar capacity factors and techno-economic data for solar PV, while for grid production

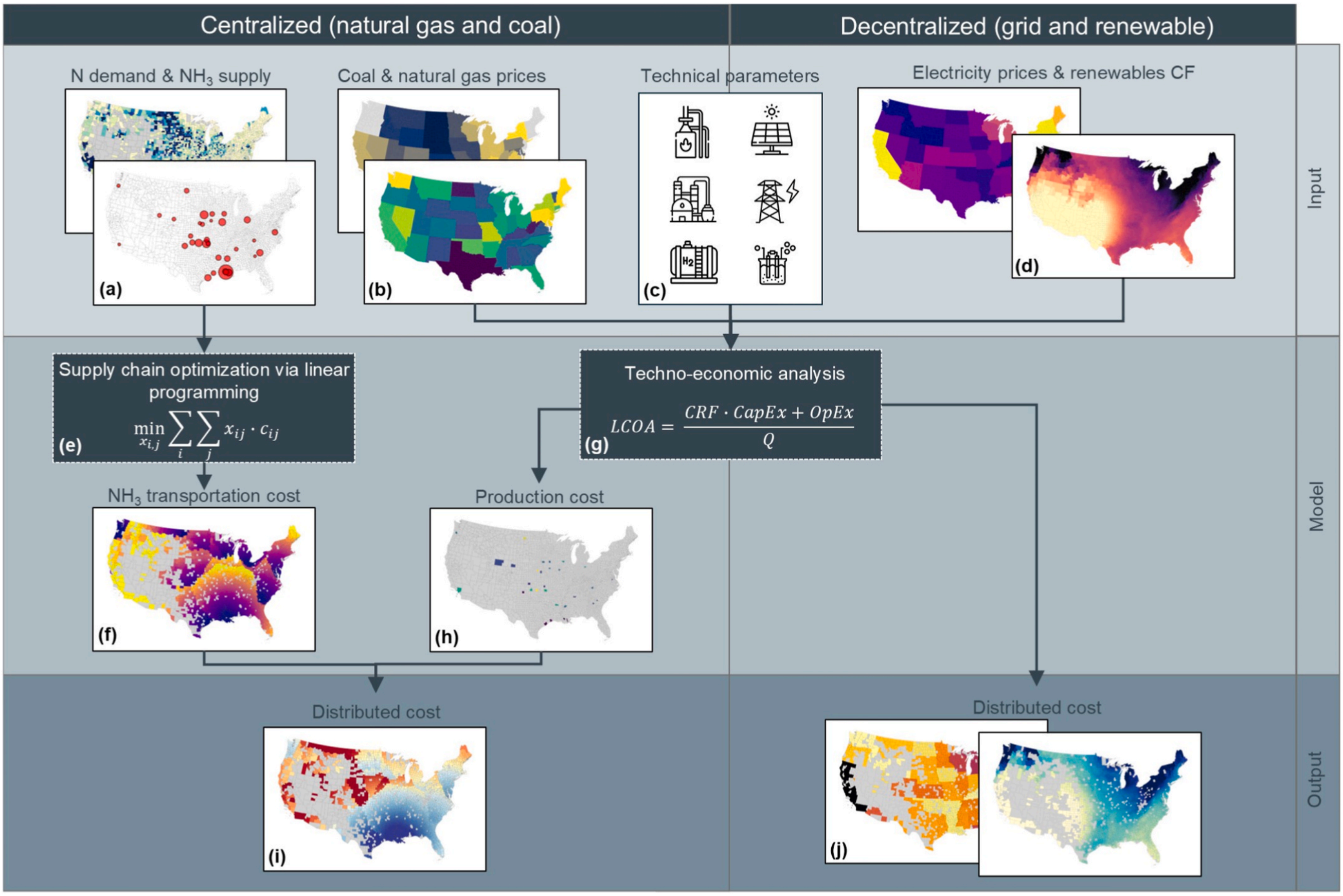


Fig. 1. Graphical overview of methodology. (a) Spatial distribution of agricultural nitrogen demand and existing ammonia production facilities across U.S. counties. **(b)** Historical natural gas and coal prices used in centralized production cost estimation. **(c)** Technology input parameters for centralized and decentralized ammonia production pathways. **(d)** Historical electricity prices and solar PV capacity factors used in decentralized cost modeling. **(e)** Supply chain optimization using a cost-minimizing mixed-integer linear programming (MILP) model. **(f)** Average county-level ammonia transportation costs. **(g)** Techno-economic analysis to calculate levelized cost of ammonia (LCOA) for both centralized and decentralized pathways. **(h)** Map of LCOA for conventional centralized production in counties with local facilities. **(i)** Total delivered cost of ammonia for centralized pathways, including production and transportation. **(j)** Delivered cost of ammonia for decentralized pathways, assuming co-location with demand and no transport costs.

we collected historical state-level retail electricity prices in the U.S for 2001–2024 period.

2.2. Nitrogen demand and ammonia supply

The locations and production volumes of ammonia plants were compiled from dataset of North American facilities, which includes plant coordinates and annual production capacities (kt NH_3) [3–5]. Plant locations were verified through visual inspection using satellite imagery from Google Maps, and latitude–longitude information was collected accordingly. For facilities with multiple production units, data were aggregated by plant name and location, and production capacities were validated using annual company report [4]. This process resulted in a dataset comprising 33 ammonia plants in the U.S., with a combined nominal installed capacity of 18.88 Mt NH_3 per year (Fig. 2a). Assuming an average capacity factor of 90 % [47] and that approximately 70 % of ammonia production is allocated to agricultural uses [7], we estimate an annual agricultural ammonia supply of 11.89 Mt NH_3, equivalent to 9.78 Mt N/year when expressed in terms of nitrogen content. While actual plant utilization can vary due to factors such as plant age, feedstock availability, maintenance schedules, or market fluctuations, this variability does not affect our main conclusions (see Supplementary Text 1 for sensitivity analysis).

Nitrogen fertilizer demand (t N/km/year) was obtained from a high-resolution (5 arcminute, ∼10 km at the equator) spatial dataset that reports nitrogen fertilizer use by crop and fertilizer type for the year 2020 [6]. This dataset, applied to the U.S. boundary for our analysis (Fig. 2a), represents the most comprehensive and up-to-date source of spatially explicit nitrogen fertilizer use, accounting for ∼90 % of the global ammonia demand reported by the FAO for 2023 [49]. Although fertilizer application can vary year to year due to crop rotations, weather conditions, and shifts in commodity prices, the use of 2020 data remain a reasonable approximation, as total nitrogen fertilizer demand in the U. S. has remained relatively stable over the past decade, with only modest

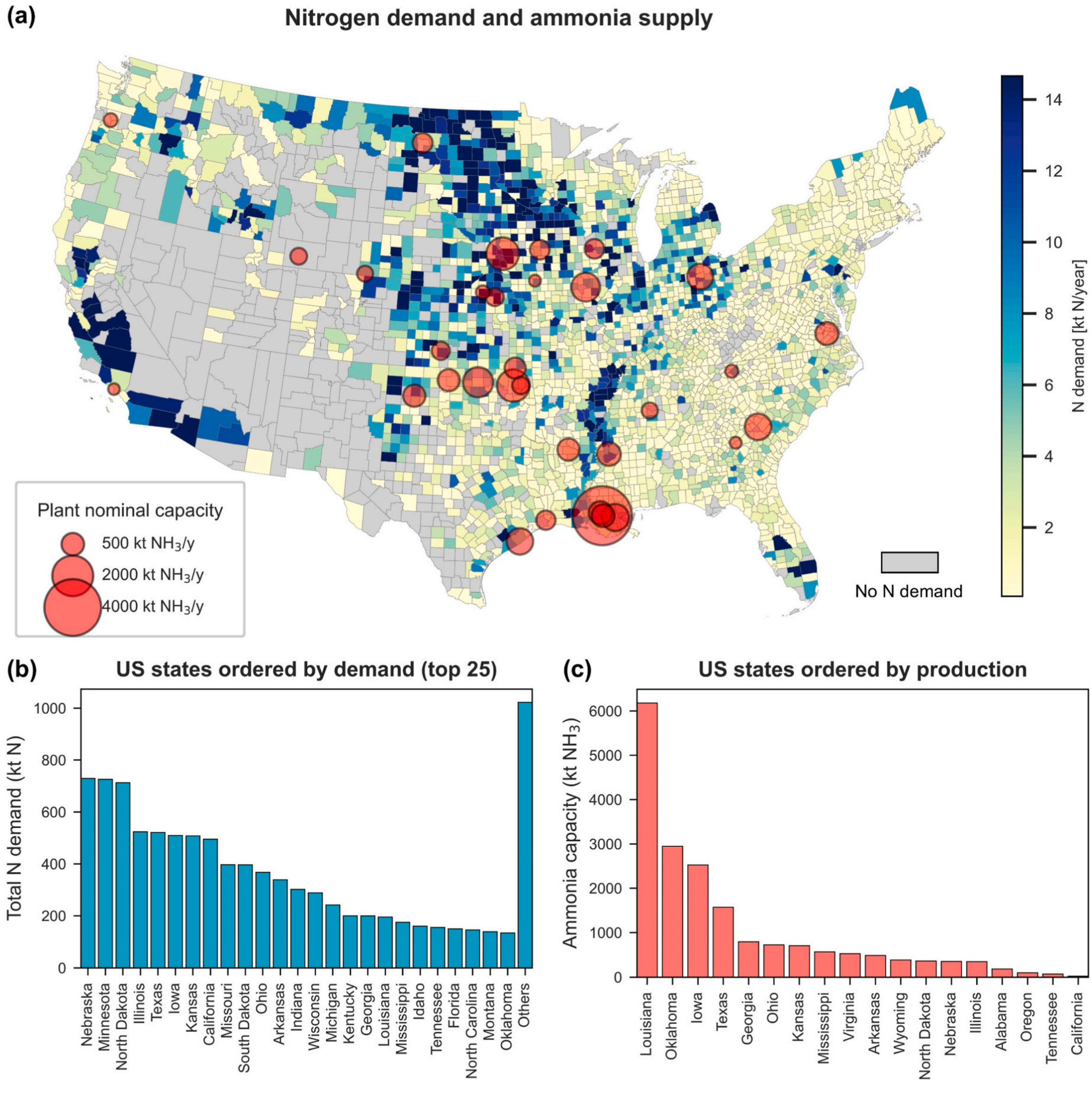


Fig. 2. | **Nitrogen fertilizer demand and ammonia supply in the U.S. (a)** Spatial distribution of agricultural nitrogen demand across contiguous U.S. counties, expressed in kilotons of nitrogen per year (kt N/year), along with the locations and capacities of existing ammonia plants (capacity in kilotons of ammonia per year, kt NH_3/year). **(b)** Top 25 U S. states ranked by annual nitrogen demand, plus others. **(c)** U.S. states ranked by annual installed nominal ammonia production capacity. Shapefiles for U.S. boundaries were obtained from the U.S. Census Bureau's Cartographic Boundary Files [48]. (Colourbar in **(a)** scaled to 5th-95th percentile range for visualization purposes).

interannual fluctuations (see Supplementary Fig. 1). To ensure consistency with ammonia supply data, we spatially aggregated the gridded nitrogen demand values to county boundaries using zonal statistics, yielding county-level nitrogen demand of 9.74 Mt N/year, which closely aligns with our estimated agricultural supply (<0.5 % difference). Fig. 2b shows top 25 U S. states by N fertilizers demand, while Fig. 2c shows U.S. states by ammonia production capacity.

2.3. Ammonia production costs

To compare centralized and decentralized ammonia production, we calculate the delivered cost of ammonia fertilizers, which includes both production and transportation components. Transportation costs apply only to centralized, business-as-usual facilities, where ammonia is produced on a large scale and transported to the point of demand. For small-scale, decentralized production, we assume no transportation cost, as ammonia is assumed to be produced at the point of use.

The production cost is expressed by the LCOA, providing a consistent metric (USD per tonne of NH_3) for comparing different production routes. We assume a constant annual output and annualize capital expenditures using a Capital Recovery Factor (CRF) (used to convert a lump-sum capital investment into an equivalent annual cost over the project's lifetime, assuming a constant output and discount rate [50]), a standard approach in techno-economic assessments of energy systems, particularly when detailed year-by-year cash flow data are not available [51]. We calculate the LCOA for both production pathways: (i) large-scale, fossil-based centralized plants using natural gas or coal for hydrogen production; and (ii) decentralized, small-scale systems using water electrolysis powered by either grid electricity or renewables. The general form of the LCOA for a given technological pathway (p) (i.e., centralized and decentralized) is defined as.

$$\mathrm{LCOA}_p = \frac{\sum_{t\in T_p}\left(CRF\cdot c^{cap}_{t,p}\right) + \sum_{t\in T_p}\left(c^{op}_{t,p} + c^{fuel}_{t,p}\right)}{Q_p} \tag{1}$$

$$CRF = \frac{r(1+r)^L}{(1+r)^L - 1} \tag{2}$$

Where T_p is the set of all technologies and fuels associated with pathway p; $c^{cap}_{t,p}$ is total capital cost of technology t in pathway p; $c^{op}_{t,p}$ is the annual operating expenditure; $c^{fuel}_{t,p}$ is the annual energy or fuel cost; Q_p is the annual ammonia production. CRF is the capital recovery factor (described by (equation (2)); L is project lifetime; r is the discount rate. Input data and assumptions for each case are detailed in Supplementary Table 1.

2.4. Large-scale centralized fossil-based ammonia

Today ammonia is primarily produced in large-scale, centralized plants powered by either natural gas (92 %) or coal (8 %) [52]. In the U. S., approximately 98 % of the natural gas-based production relies on steam methane reforming (SMR) [52]; in the absence of more detailed data, we assume SMR is the default technology. As discussed in Supplementary Text 2, our main conclusions remain robust even when accounting for autothermal reforming (ATR), a more efficient, though currently less common, alternative that is gaining traction in new projects [53]. The notable difference is that under high natural gas price scenarios, ATR performs slightly better (−2.8 % in LCOA) due to its higher efficiency (Supplementary Text 2).

For coal-based ammonia production, we assume coal gasification as the underlying technology. While several gasifier designs exist, the core process (gasification followed by syngas cleanup and ammonia synthesis) is relatively standardized [54]. Therefore, coal-based ammonia systems can be reasonably represented using a single, typical configuration.

2.4.1. Capital and operating expenditures for large-scale centralized plants

Capital cost data for large-scale, conventional ammonia plants are limited, as these facilities are typically designed on a case-by-case basis by technology licensors and engineering contractors to meet specific project requirements, making standardized estimates challenging. Nevertheless, we adopt representative values from industry sources (e.g. ref. [55,56]).

For natural gas-based plants using steam methane reforming, we assume a capital expenditure (CapEx) of USD 1250 per tonne of annual ammonia production capacity, based on recent cost data reported by S&P Global for U.S. projects [55]. For coal-based plants via gasification, we use a CapEx of USD 3134 per tonne, based on a published feasibility study for a new large-scale facility [56]. Although economies of scale typically reduce unit costs for larger plants [57], we focus exclusively on large-scale facilities and therefore apply these unit capital costs uniformly, scaling linearly with plant capacity.

For operating expenditures (OpEx), we assume non-fuel operating costs equal to 5 % of total capital cost per year, consistent with industry practice and standard process plant methodology [55].

2.4.2. Fuel costs

For the natural gas-based ammonia production pathway, energy consumption is estimated at 32.1 GJ per tonne of ammonia [7], which is equivalent to 30.41 MMBtu per tonne of NH_3, using a conversion factor of 0.947817 MMBtu/GJ. Fuel costs are calculated by multiplying the natural gas consumption per tonne of ammonia by the corresponding natural gas price (in USD/MMBtu). State-level industrial natural gas prices are sourced from the U.S. Energy Information Administration (EIA) [58], which provides annual nominal prices at the state level from 1997 to 2024, reported in USD per thousand cubic feet (USD/Mcf). To ensure consistency in energy-based comparisons, prices are converted to USD/MMBtu using the EIA-recommended average heat content of 1 Mcf ≈1.038 MMBtu [59]. To capture uncertainty and historical variability, three scenario values are derived from the converted dataset: the 5th percentile (optimistic), the median (reference), and the 95th percentile (pessimistic) (see Supplementary Fig. 2).

In the coal-based pathway, hydrogen is produced via coal gasification, with an estimated energy requirement of 37.4 GJ per tonne of ammonia [7]. Assuming an average energy content of 24 GJ per tonne of coal [60], this corresponds to a coal consumption rate of approximately 1.56 tonnes of coal per tonne of NH_3. State-level coal prices are obtained from the EIA Coal Data Browser [61], which reports the average annual price of coal received at industrial plants by state from 2000 to 2024, expressed in nominal USD per short ton. To align with other fuel inputs expressed in metric units, prices are converted to USD per metric ton. As with natural gas, three percentile-based price scenarios (5th, 50th, and 95th percentiles) are computed from the historical dataset to represent optimistic, reference, and pessimistic cost conditions, respectively (see Supplementary Fig. 3).

2.4.3. Business-as-usual transportation costs

We formulate the allocation of county-level nitrogen fertilizer demand to ammonia production plants as a minimum-cost transportation problem. For each U.S. county i and ammonia production plant j, we define a decision variable x_{ij}, representing the annual flow of ammonia (in tonnes NH_3) transported from plant j to county i. The objective is to minimize the total cost of transportation across all demand-supply pairs:

$$\min_{x_{i,j}} \sum_i \sum_j x_{ij}\cdot c_{ij} \tag{3}$$

Subject to the following constraints. The first is demand satisfaction: the total amount of ammonia delivered to each county i must meet its annual demand D_i (4). The second is supply capacity: no plant j can supply more than its annual production capacity S_j (5).

$$\sum_{j} x_{ij} = D_i \ \ \forall_i \tag{4}$$

$$\sum_{i} x_{ij} \leq S_j \ \ \forall_j \tag{5}$$

The transportation cost (c_{ij}) per tonne of ammonia transported from plant j to county i (6) is calculated based on the great-circle distance d_{ij} and includes a distance-based penalty to reflect higher marginal costs over longer hauls.

$$c_{ij} = d_{ij} \cdot c^t \cdot \left[1 + \alpha d_{ij}\right] \tag{6}$$

Here, d_{ij} is calculated using the Harvesine formula [62] (7).

$$d = 2R \cdot arcsin\left(\sqrt{sin^2\left(\frac{\Delta\phi}{2}\right) + \cos\left(\phi_1\right) \cdot \cos\left(\phi_2\right) \cdot sin^2\left(\frac{\Delta\lambda}{2}\right)}\right) \tag{7}$$

R is the Earth's radius (6371 km), ϕ_1, ϕ_2 are the latitudes of the two locations (in radians), and λ_1, λ_2 are the longitudes (in radians). The parameter c^t represents the base transportation cost per kilometer, set at 0.0365 USD/t NH_3/km for road transport [43]. The term α is the marginal cost penalty for long-distance hauls (e.g. α = 0.0005 km-1), which accounts for increased logistics costs associated with longer trips.

This linear program ensures that all county-level ammonia demand is fully met, while no plant exceeds its annual capacity. The optimization is solved using Gurobi [63,64], a commercial solver for mathematical programming.

2.5. *Small-scale decentralized electrolytic ammonia*

For small-scale decentralized ammonia production, data availability is limited due to the novelty of the pathway and the proprietary nature of emerging technologies developed by a limited number of startups, generally at lower TRL compared to large-scale plants [29]. Nevertheless, we conducted a detailed analysis of the key technological components involved. We assume a modular design approach [36], in which systems are composed of standardized, off-the-shelf components that can be deployed in scalable units [45,57]. For each region, the number of installed modules is determined by local ammonia demand (proportional to the N demand, being ammonia the precursor to N-fertilizers), calculated as the ratio of regional demand to the production capacity of a single module. Due to the scarcity of cost data and the early stage of deployment, we do not assume any economies of scale (i.e., CapEx scales linearly). Each module is assumed to have a production capacity of 4 tonnes per day, consistent with the container-sized systems proposed by several technology startups [65].

The process includes three key components: (i) electrolyzers, which convert water into hydrogen using electricity; (ii) an air separation unit (ASU), which extracts nitrogen from ambient air; and (iii) an electrified Haber-Bosch reactor, which synthesizes ammonia from hydrogen and nitrogen. The entire system is powered by electricity, which can be supplied either from the grid (grid-powered route) or from dedicated renewable energy installations, assumed to be solar photovoltaic (PV) in the context of small-scale decentralized applications.

Electrolyzers are the key technology for water electrolysis, with alkaline (ALK) and proton exchange membrane (PEM) systems representing the most commercially mature options (TRL 9 and TRL 7–9 for ALK and PEM, respectively) [29,66]. Both technologies have distinct technical and economic characteristics, making them suitable for different applications [66], while also being modular [67] and therefore well-suited to decentralized, scalable deployment. ALK electrolyzers are the most technologically mature and are commonly used due to their low capital costs, long operational lifetimes, and reduced maintenance requirements [66,68]. However, they have a higher minimum load, slower dynamic response, and reduced efficiency and durability under frequent cycling, making them less compatible with variable renewable energy inputs [66]. ALK systems typically operate best under steady-state conditions or at loads above 50 %. In contrast, PEM electrolyzers offer superior operational flexibility, including fast ramping capabilities (seconds to minutes), lower minimum load thresholds (as low as 0–10 %), and higher efficiency under part-load conditions, making them well-suited for coupling with intermittent renewable sources [66]. The main drawbacks of PEM systems are their higher capital costs, particularly due to expensive catalysts and membrane materials [66,69]. We assume ALK electrolyzers are powered by grid electricity, while PEM systems are coupled with variable renewable energy sources, aligning with their respective operational strengths.

Due to limited public data precise cost estimates for electrolyzer systems remain uncertain [70]. However, based on published literature and technical report, we estimate total installed CapEx of 842 USD/kW for ALK systems (range: 635–1053 USD/kW) and 1112 USD/kW for PEM systems (range: 780–1697 USD/kW) [66]. These values include the following system components: (i) electrolyzer stack, the core unit where electrochemical water splitting occurs (∼50–60 % of total CapEx); (ii) power electronics (∼15 %): systems for controlling and converting electric power input; (iii) gas conditioning (10–15 %): compression and drying of hydrogen gas to meet purity and pressure specifications, and balance of plant: auxiliary systems including heat exchangers, pumps, control systems, safety equipment, and other supporting infrastructure [66].

While large-scale installations may incur substantial additional indirect costs (e.g., engineering, permitting, infrastructure) [71,72], these are not included in our modeling. We focus on modular, off-the-shelf electrolyzer systems deployed at scale, which are expected to minimize such costs, hence we do not include them in the analysis [69]. We assume fixed annual O&M costs of 2.5 % of CapEx for ALK systems and 3 % for PEM systems. Electrolyzer efficiency is modeled as 72.5 % for ALK (range: 68–77 %) and 75 % for PEM (range: 70–80 %), based on the higher heating value (HHV) of hydrogen [66,68]. Despite PEM electrolyzers are generally considered suitable for dynamic operation, empirical data on the long-term effects of partial load and cycling on efficiency and degradation remain limited, with inconsistent findings across studies [73]. Nevertheless, in our case, the inclusion of batteries is expected to buffer short-term fluctuations, potentially mitigating these potential operational stresses.

To better capture the long-term competitiveness of electrolyzer technologies, we extend our analysis to include industry-aligned cost and efficiency targets, as shown in Supplementary Fig. 4. These targets [66,74], reflect expected improvements in stack components [75], which account for the largest share of total CapEx (50–60 %). The targets assume a CapEx of 460 USD/kW for ALK and 574 USD/kW for PEM, with both technologies achieving 87.5 % efficiency (HHV basis). Integrating these values into our LCOA model reveals that reaching such targets would reduce ammonia production costs by 17.6 % for ALK and 15.2 % for PEM compared to current reference values, and by 11.4 % (ALK) and 8.3 % (PEM) relative to today's optimistic scenarios (see Supplementary Text 3 and Supplementary Fig. 4).

We assume nitrogen is supplied by a cryogenic air separation unit, which is the most commercially mature technology for high-purity, nitrogen production [76]. The air separation unit is modeled with a capital cost of 1697 USD per kg N_2/h of production capacity [76,77], which implies, for example, that supplying nitrogen for a 4 tonne/day ammonia plant (requiring approximately 3.3 tonnes/day of N_2) would correspond to a capital cost of around 233,000 USD for the ASU. We assume an electricity consumption of 250 kWh per tonne of N_2 produced [76–79] and fixed annual operation and maintenance costs of 2 % of the installed capital cost [77].

The ammonia synthesis loop is based on a fully electric Haber–Bosch system, including the synthesis reactor, gas compressors, heat exchangers, mixing units, ammonia separation system, and refrigeration. Achieving operational flexibility in the Haber–Bosch loop is challenging due to the system's thermal inertia and sensitivity to pressure and temperature variations [19]. To improve part-load operability, we consider strategies such as the use of advanced catalysts, improved process control, and electric heating to maintain reactor temperatures under reduced loads. We assume a specific CapEx of 3510 USD per kg NH_3/h of synthesis capacity [77], fixed operation and maintenance costs of 2 % [77], and an electricity demand of 450 kWh per tonne of NH_3 produced under reference conditions [78].

2.5.1. Grid-powered production

For grid-powered decentralized plants, we assume the usage of grid electricity. Electricity price data were sourced from the U.S. EIA Electricity Data Browser [80], providing average retail prices of electricity at the state level from 2001 through 2024. As with natural gas and coal, three percentile-based price scenarios, 5th, 50th, and 95th percentiles, are computed from the historical dataset to represent optimistic, reference, and pessimistic cost conditions, respectively (Supplementary Fig. 5).

In our model, we assume no transmission losses for grid-powered decentralized systems, although some losses could occur depending on factors such as the distance from the grid connection point, type of transmission lines, and local infrastructure. These losses are challenging to model at a national level, as they depend heavily on the specific location of each farm and how remote the site is. Nevertheless, such losses could effectively increase the cost of energy input, as more electricity would need to be purchased to deliver the same useable energy to the system [81].

2.5.2. Renewable-powered production

To calculate the levelized cost of renewable electricity (LCOE) for solar PV systems (SI – fig. iv), we used county-level solar capacity factors derived from high-resolution PV power potential data provided by the Global Solar Atlas [82]. This dataset reports long-term average daily solar output in kilowatt-hours per kilowatt-peak (kWh/kWp/day) at a spatial resolution of approximately 1 km × 1 km. These capacity factors represent a normalized measure of solar output as a fraction of maximum possible generation. We aggregated these data to the county level by averaging PV potential across each county's area (Supplementary Fig. 6).

PV system cost data were sourced from the U.S. Department of Energy's (DOE) Solar Energy Technologies Office (2024 Q1 benchmarks) [83]. We used cost estimates for commercial-scale agrivoltaics systems, which align with our assumptions for farm-scale ammonia production. The DOE benchmark system includes a 3 MW_{dc} PV array paired with a 6 MWh lithium-ion battery, consistent with our assumption that decentralized renewable systems are coupled with energy storage [83]. We adopted the reported capital cost range of 1990–2280 USD/kW_{dc}, which includes both PV and storage system costs [83]. The average value within this range is used as the reference case in our analysis. Operation and maintenance costs (covering module cleaning, inspections, component replacement, land lease, property taxes, insurance, and management) are estimated at 43 USD/kW_{dc} per year [83]. We assume a 30-year system lifetime and evaluate LCOE across discount rates of 4 %, 6 %, and 8 %. To account for energy losses in the storage system, we apply a 6 % increase to the base LCOE, in line with DOE methodology [83].

We assume no transmission losses, as we model co-located, behind-the-meter solar PV installations, where the PV system and the ammonia production unit are located on the same site, typically within a few hundred meters (e.g., <500 m). In such configurations, transmission losses are minimal and can be reasonably considered negligible, particularly when using low-voltage (LV) AC, which is the most cost-effective solution for short distances [81].

If decentralized renewables systems were implemented in a shared configuration, for example, a solar farm supplying multiple, spatially distributed farms through a consortium or cooperative, then transmission distances would increase, and losses could no longer be neglected, resulting in higher ammonia production cost.

3. Results

3.1. Ammonia production costs

Decentralized ammonia production pathways, whether powered by grid electricity or renewables, exhibit substantially higher production costs than centralized pathways based on natural gas or coal prices within the U.S. context (Fig. 3). This pattern persists across almost all scenarios of fuel price historical ranges (Supplementary Fig. 7). For centralized natural gas-based production, the median LCOA is 326 USD per tonne NH_3 in the reference scenario, with a range from 223 USD (5th percentile, optimistic) to 483 USD per tonne (95th percentile, pessimistic). Coal-based production is less common in the U.S. (accounting for only 3 of 33 plants) and is generally more expensive, with a median LCOA of 499 USD per tonne (ranging from 379 to 642 USD/tonne NH_3) (Fig. 3). Both centralized natural gas and coal cost estimates align with previous ranges from IEA [7,84] and previous research [5]. In contrast, decentralized grid-powered ammonia is considerably more costly, with LCOA values of 659 USD (optimistic), 1048 USD (reference), and USD 1634 (pessimistic) per tonne NH_3, surpassing even the highest-cost coal scenario. Decentralized renewables-powered production is the most expensive pathway, with a reference LCOA of 1553 USD per tonne (ranging from 1077 to 2266 USD) (Fig. 3a).

Although the primary cost drivers differ by pathway, energy feedstock (natural gas, coal, or electricity) are the main components affecting LCOA (Fig. 3b). For centralized natural gas plants, natural gas feedstock accounts for 40–64 % of total costs. In decentralized pathways, electricity is the dominant contributor, comprising 86–89 % of costs for grid-powered systems and 89–91 % for renewables-based systems. Renewable electricity refers to the amortized (i.e., annualized over the project lifetime) cost of PV installations and their associated balance-of-plant components, including batteries and auxiliary systems, and their operation and maintenance. For coal-based production, the largest cost component is CapEx of the coal gasification plant itself, representing 43–48 % of the total cost (Fig. 3b).

Overall, due to the high cost of electricity—particularly for decentralized systems—decentralized ammonia production does not appear economically competitive with centralized fossil-based pathways under historical (1997–2024) U.S. market conditions and with today's technologies.

3.2. Ammonia transportation costs

Ammonia transportation costs differ substantially across the U.S., primarily because not all states have local production facilities, requiring long-distance transport to supply counties distant from production sites (Fig. 4). For counties hosting ammonia plants, transportation costs are set to zero. In all other counties, transportation costs range from 7 to 85 USD per tonne of NH_3 (corresponding to the 5th and 95th percentiles, respectively), with a median transportation cost of 40 USD per tonne, an amount that must be added to the production cost (Fig. 4). It is important to note that these estimates reflect only direct transportation costs. Other potential cost drivers such as transaction fees, import tariffs, market markups, or broader supply chain inefficiencies [11], are not included, but may influence the final market price of distributed ammonia. Prior studies, often focused on specific case studies or project-level analysis, report transportation costs typically in the range of 50–150 per tonne of NH_3 in the U.S., depending on distance, mode of transport, and regional infrastructure [14,85].

Outliers exist, particularly in California, where some counties face transportation costs as high as 187 USD/tonne NH_3, due to the limited in-state production, despite California ranking as the eighth-largest state by demand (Fig. 4b). Notably, California has the lowest production capacity among states with production facilities. As a result, transportation

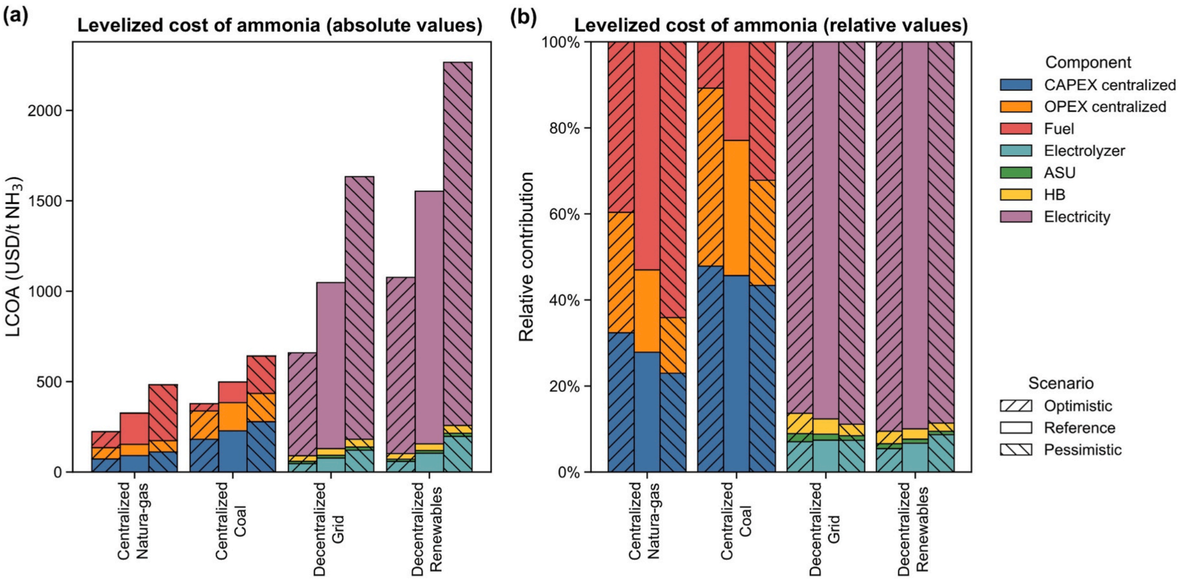


Fig. 3. Centralized and decentralized ammonia production costs. (a) Levelized cost of ammonia (LCOA) in USD per tonne of NH_3 for two centralized pathways (natural gas and coal) and two decentralized pathways (grid-connected and renewables-based). Results are shown for three scenarios: (i) optimistic, (ii) reference, and (iii) pessimistic, which correspond to the 5th, 50th, and 95th percentiles of historical fossil fuel and electricity price distributions across U.S. counties (Supplementary Fig. 7). Results in Fig. 3 are not tied to any specific plant location but instead represent a generic plant operating under varying input cost assumptions derived from historical price data. **(b)** Relative contribution of individual cost components to the LCOA. ASU = air separation unit; HB = Haber-Bosch synthesis loop. For input data see Supplementary Table 1.

can represent a large portion of the total ammonia cost: averaging around 12 % nationwide and reaching as high as 50 % in California (Fig. 4b).

The states with the highest median transportation costs are Nevada (though with minimal demand and only one importing county), followed by California, Arizona, Idaho, Utah, Indiana, Illinois, Oregon, Maine, and Kentucky (Fig. 4b). In these states, transportation costs represent a substantial component of the overall ammonia supply chain.

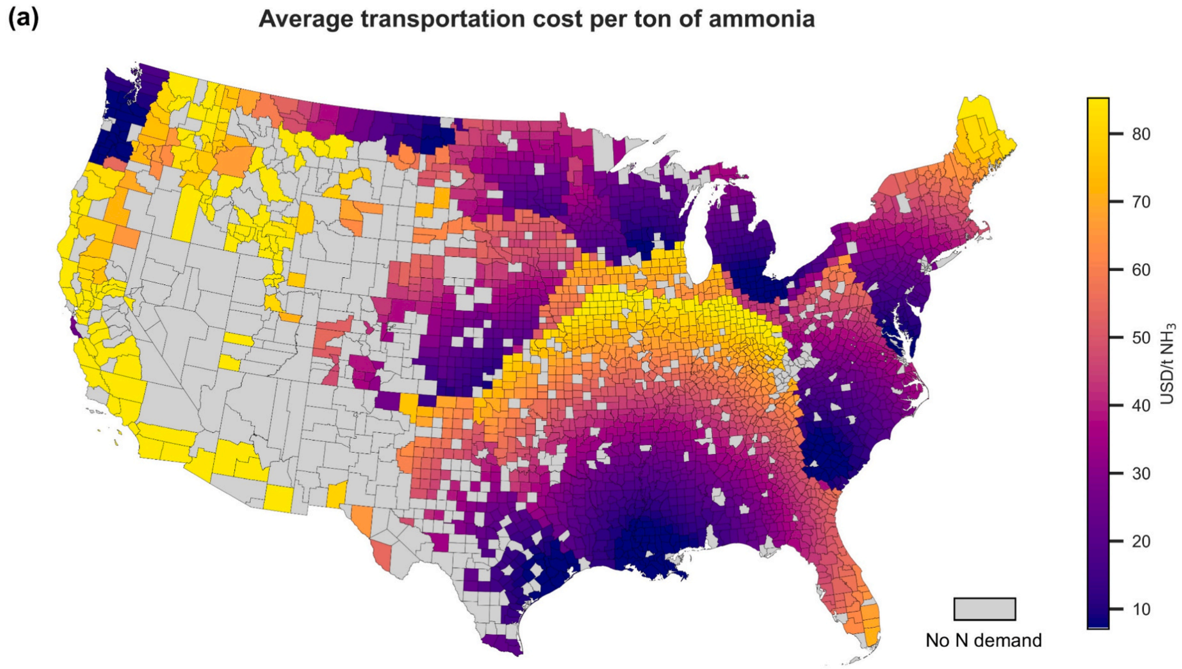
3.3. *Ammonia costs at point of demand*

Centralized ammonia production exhibits a median cost of delivered ammonia (cost at the point of demand, including both production and transportation) of 343 USD/tonne NH_3, with a 5th percentile of 242 USD/tonne NH_3 and a 95th percentile of 529 USD/tonne NH_3 (Fig. 5a–c). Under reference assumptions for fuel costs (Fig. 5b), states with the highest average ammonia costs at the demand point include Nevada (519 USD/tonne NH_3), Utah (451 USD/tonne NH_3), Nebraska (443 USD/tonne NH_3), Montana (435 USD/tonne NH_3), and California (433 USD/tonne NH_3) (Fig. 5b–j). The most extreme cases illustrate the geographic disparity in delivered ammonia costs. Brazoria County, Texas, shows exceptionally low costs (as low as USD 203 per tonne of NH_3 under optimistic assumptions) due to its proximity to production facilities and access to low-cost energy inputs (Fig. 5a). In contrast, Perkins County, South Dakota, reaches much higher costs (up to USD 731 per tonne under pessimistic assumptions) driven by long transport distances and reliance on coal-based production under high fuel price scenarios (Fig. 5c).

Decentralized ammonia remains more expensive at the point of use, even after accounting for transportation costs associated with centralized production (Fig. 5d–i). The median cost of decentralized grid-based ammonia is over three times higher than the delivered cost of centralized ammonia, while renewables-based decentralized production is more than four times higher. Nationally, the median cost of grid-powered decentralized ammonia production is USD 1069 per tonne of NH_3, with a range from USD 633 (5th percentile) to USD 1567 (95th percentile) (Fig. 5j). These variations largely reflect differences in electricity prices across the country: high-cost states like California drive-up production costs. At the extremes, costs range from USD 508 per tonne in Ballard County, Kentucky (Fig. 5d), to USD 2868 per tonne in Alameda County, California (Fig. 5f). For renewables-powered decentralized ammonia (based on solar energy), the median cost is even higher, at USD 1494 per tonne NH_3, with a 5th percentile of USD 1047 and a 95th percentile of USD 2143 (Fig. 5j). These differences are primarily driven by local solar resource quality and system efficiency. For example, Luna County, New Mexico, benefits from strong solar irradiance and achieves the lowest observed cost (USD 871 per tonne) (Fig. 5g), while Snohomish County, Washington, with limited solar potential, faces much higher costs—up to USD 2618 per tonne NH_3 (Fig. 5i).

At the state level, the most expensive decentralized grid-based production under reference assumptions occurs in the Northeast, with Connecticut (1917 USD/tonne NH_3), Massachusetts, and New York topping the list, while the cheapest states include Washington (854 USD/tonne NH_3), Idaho, and Wyoming (Fig. 5j). For renewable-powered production, the Pacific Northwest and Northeast again dominate the high end, led by Washington (1713 USD/tonne NH_3) and Vermont, whereas the Southwest—notably New Mexico (1205 USD/tonne) and Arizona—offers the lowest costs (Fig. 5j). These findings underscore the enduring cost advantage of centralized ammonia production in the U.S., with decentralized options only achieving partial cost effectiveness under few and extreme conditions with high fossil fuel prices.

Transportation costs can account for up to 40 % of the total distributed cost in states like California, yet centralized ammonia remains more cost-effective overall, even when transportation is included, except in rare cases (Fig. 5j). Specifically, only 47 counties (less than 2 % of the U.S. total), primarily located in Nebraska, South Dakota, Colorado, Idaho, and Wyoming, show instances where grid-powered decentralized ammonia under optimistic electricity cost assumptions is cheaper than centralized ammonia under pessimistic fossil fuel scenarios, particularly where long-distance transport and high coal prices increase centralized costs (Fig. 5j). These cases represent outliers where a combination of low-cost electricity (mainly grid-based) and high fossil fuel prices renders decentralized production temporarily competitive.



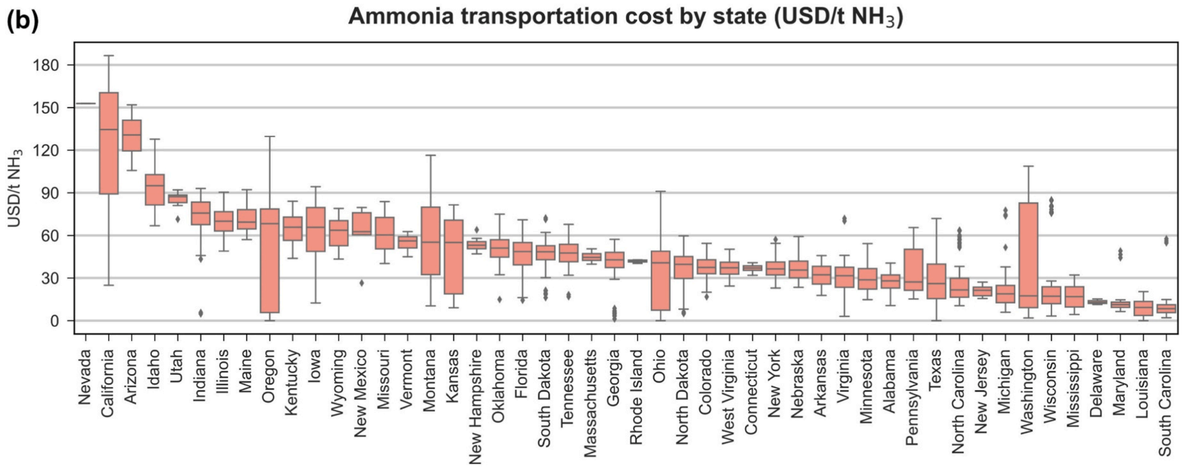


Fig. 4. | **Centralized ammonia transportation costs. (a)** Spatial distribution of average ammonia transportation cost per county, measured in USD per tonne of NH_3 delivered from supply points to demand points (i.e., transportation cost by road from producing counties to user counties). **(b)** Box plots of ammonia transportation costs aggregated by state, ordered from highest to lowest median transportation cost. Shapefiles for U.S. boundaries were obtained from the U.S. Census Bureau's Cartographic Boundary Files [48]. (Colourbar in **(a)** scaled to 5th-95th percentile range for visualization purposes).

Conversely, renewable-powered decentralized production is consistently more expensive than centralized production under all scenarios.

3.4. *Price of electricity for cost-effectiveness between centralized and decentralized ammonia*

Electricity (from grid or renewables) and fossil feedstocks (natural gas and coal) are the primary cost drivers in decentralized and centralized ammonia production pathways, respectively (Fig. 3b). Understanding the relationship between these inputs is essential to determine under what conditions decentralized production can achieve cost parity with centralized alternatives (Fig. 6). Under reference (median) historical fossil fuel prices, decentralized ammonia production powered by grid electricity reaches cost parity with natural gas-based centralized production only when electricity prices fall to 19 USD/MWh (Fig. 6a). For renewable-powered decentralized production, the breakeven electricity price is slightly lower at 17 USD/MWh, primarily due to the higher capital costs of PEM electrolyzers compared to alkaline systems used in grid-based scenarios (Fig. 6a). Compared to centralized coal-based production, the breakeven electricity prices for decentralized ammonia production increased to 36 USD/MWh for grid-based systems and 34 USD/MWh for renewable-based systems (Fig. 6b). However, these breakeven prices are still 70–85 % lower than the historical average retail electricity price in the U.S., which was 117 USD/MWh in 2024 (Supplementary Fig. 5), making decentralized production economically uncompetitive under historical (2001–2024) conditions.

When considering pessimistic (95th percentile) fossil fuel prices, representing scenarios of historically high natural gas and coal costs, breakeven electricity prices are higher: 28 USD/MWh (grid) and 21 USD/MWh (renewables) for parity with natural gas (Figs. 6a), and 42 USD/MWh and 36 USD/MWh, respectively, for parity with coal (Fig. 6b). Notably, transportation costs can help close this gap. Including a maximum observed transportation cost of 187 USD/tonne NH_3 (recorded in California), decentralized production becomes more competitive. Under these conditions, breakeven electricity prices increase to 37 USD/MWh (grid) and 36 USD/MWh (renewables) for natural gas (Figs. 6a), and 54 USD/MWh and 53 USD/MWh, respectively, for coal (Fig. 6b). While these adjusted thresholds are more attainable,

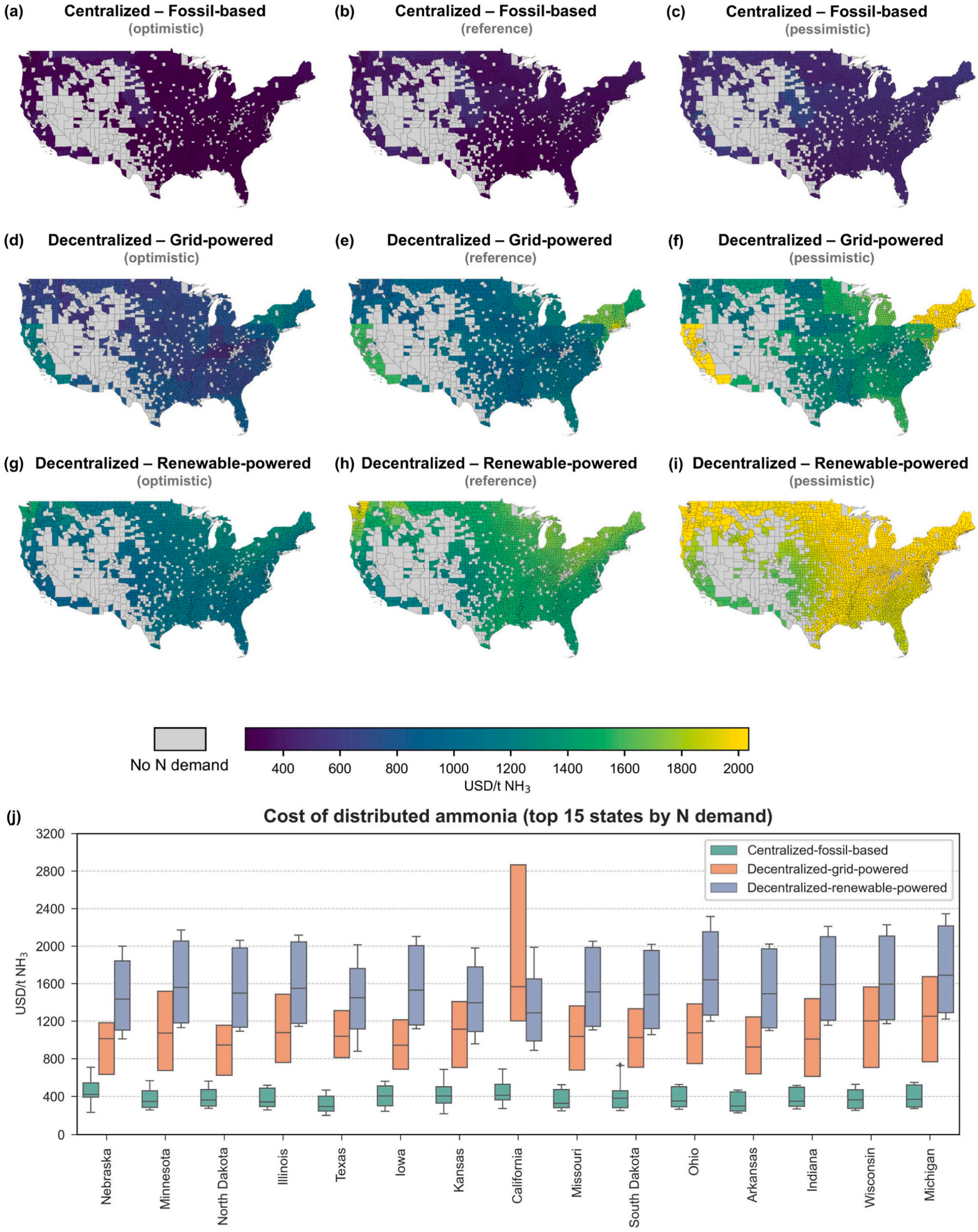


Fig. 5. Geographic distribution of demand-point ammonia cost. Maps showing the cost of ammonia delivered at the demand point: for centralized pathways, costs include both the levelized cost of ammonia (LCOA) and transportation; for decentralized pathways, only the LCOA is included. **(a–c)** Centralized pathways under the optimistic, reference, and pessimistic scenarios, respectively. **(d–f)** Decentralized, grid-powered pathways under optimistic, reference, and pessimistic scenarios, respectively. **(g–i)** Decentralized, renewables-powered pathways under optimistic, reference, and pessimistic scenarios, respectively. **(j)** Box plots showing the cost of distributed ammonia for the top 15 states by agricultural nitrogen demand. Shapefiles for U.S. boundaries were obtained from the U.S. Census Bureau's Cartographic Boundary Files [48]. (Colourbar in **(a–i)** scaled to 5th-95th percentile range for visualization purposes).

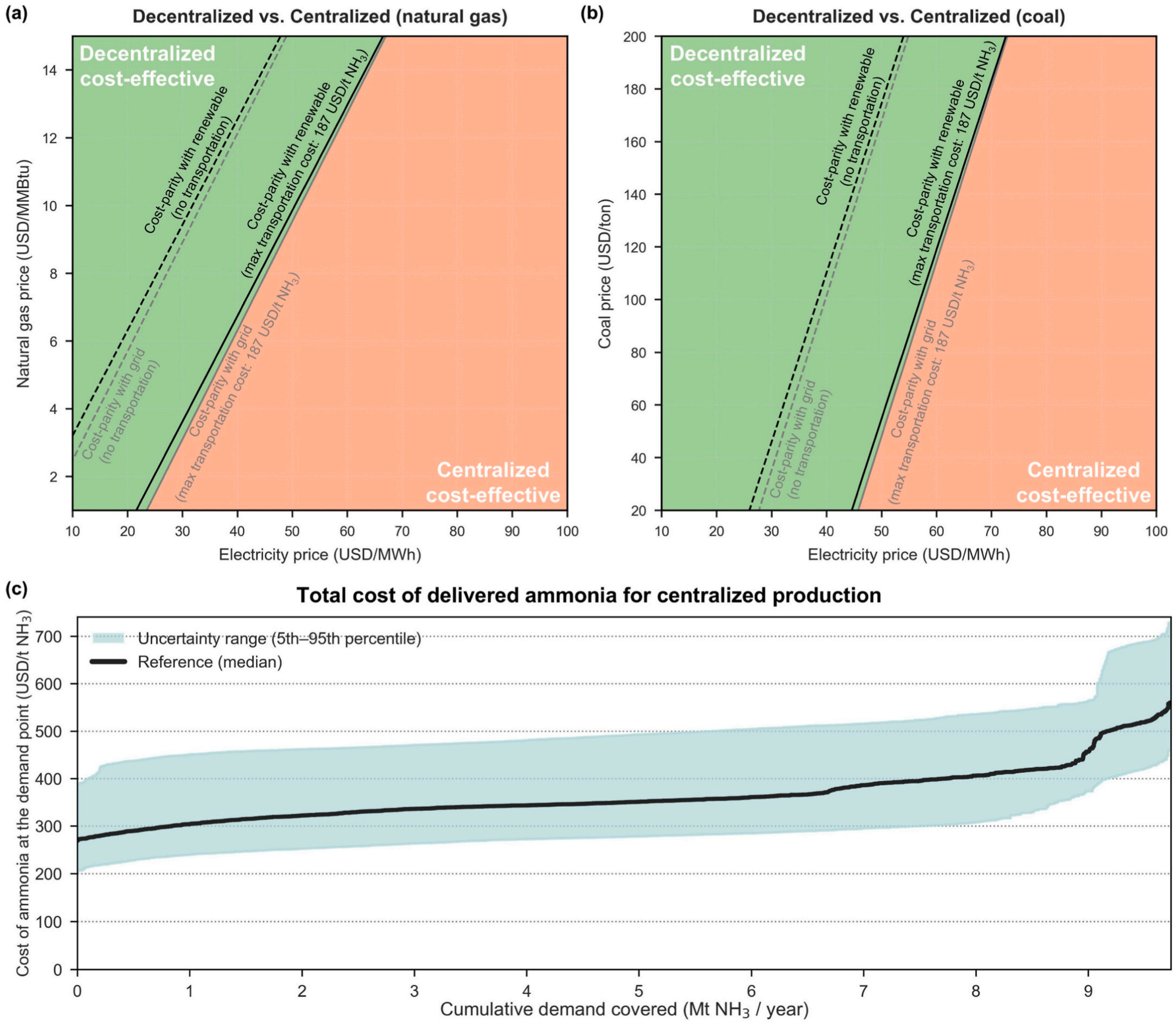


Fig. 6. | **Cost parity between centralized and decentralized ammonia. (a)** Heatmap showing under which combinations of electricity price (USD/MWh) and natural gas price (USD/MMBtu) centralized (natural gas-based) or decentralized (grid- and renewables-based) ammonia production pathways are more cost effective (i.e., have a lower delivered cost). The parity lines for decentralized grid and renewables differ due to different electrolyzer technologies. **(b)** Same as **(a)** but comparing centralized coal-based pathways (with coal price in USD/t) to decentralized pathways. **(c)** Total cost of delivered ammonia for centralized, fossil-based production (natural gas and coal), including both production and transportation costs. The x-axis shows cumulative demand covered, and the y-axis is the cost at the demand point (USD/tonne NH_3).

they still require very low-cost electricity to make decentralized production economically viable. This highlights the challenge of scaling decentralized ammonia production under current market conditions, unless supported by exceptionally low electricity prices or high fossil fuel and transportation costs.

Considering the U.S. case, a decentralized technology aiming to supply 50 % of current domestic ammonia demand competitively would need to achieve a production cost of less than 345 USD/tonne NH_3 (277–491, based on the range of natural gas and coal-based centralized production costs) (Fig. 6c). To cover 95 % of domestic demand competitively, the production cost would need to be less than 289 USD/tonne NH_3 (227–238). These cost targets translate into corresponding electricity price thresholds for decentralized electrolysis-based production systems. For grid-connected production, the electricity price would need to be around 21 USD/MWh (19–28) to supply 50 % of demand competitively, and around 16 USD/MWh (14–23) to reach 95 % coverage (Fig. 6c). For renewable-powered systems, the electricity price should be around 19 USD/MWh (19–22) for 50 % coverage and approximately 13 USD/MWh (13–17) to meet the 95 % threshold (Fig. 6c). For comparison, the average retail electricity price in the U.S. from 2001 to 2024 was 90 USD/MWh (Supplementary Fig. 5).

4. Discussion

Providing nutrients to grow food that feed 3.8 billion people [2,3], ammonia is not only the backbone of global food production through its role in fertilizers but is also emerging as a key player in the low-carbon transition as a hydrogen carrier and potential clean fuel [7,86]. The U.S., with its abundant natural gas reserves and large-scale ammonia infrastructure, stands at the forefront of global production and consumption

[5]. However, as the world seeks more sustainable and resilient supply chains, decentralized ammonia production, particularly small-scale, electrolytic systems, is receiving growing attention. Several startups, many based in the U.S., are now actively developing distributed technologies powered by grid or renewable electricity [11].

In this study, we developed a spatially detailed techno-economic framework to assess where and under what conditions decentralized ammonia production could become a viable alternative to centralized systems. Even when accounting for transportation costs in the centralized supply chain, our results show that decentralized production remains substantially more expensive in nearly all cases. Under reference conditions, grid-powered decentralized ammonia is more than three times more expensive than conventional centralized ammonia at the demand point, while renewable-powered systems are over four times as expensive. These high costs are primarily driven by the energy intensity of the electrolytic process, which, given current electricity prices, renders decentralized systems economically uncompetitive. Electricity cost is the dominant factor (as also underlined by other studies [36,87]), and the breakeven point between centralized and decentralized production remains far out of reach without major shifts in market conditions.

In this work, we considered both grid and solar-powered systems. However, other configurations may help reduce costs and narrow the cost gap between centralized and decentralized production. These include hybrid renewable portfolios, grid backup, and demand-flexible electrolyzers. For example, integrating wind into the generation mix could reduce storage requirements and improve load matching [31,88]. While wind energy typically involves larger-scale infrastructure and may be less suitable for small, farm-scale systems, it could be feasibly incorporated into district-level decentralized systems serving multiple units. Future research should explore this possibility.

Grid backup and semi-islanded configurations have also been investigated in prior studies [81], particularly for large-scale plants, and represent promising options for reducing costs. Modeling such systems would require an optimization framework to dynamically balance the use of grid electricity and renewable generation based on time-varying electricity prices and renewable output [34,81]. This, in turn, would necessitate high-resolution temporal data. Nevertheless, even with these more flexible and hybrid system designs, it remains challenging to bridge the substantial cost gap (often 3 to 4 times higher) compared to centralized fossil-based ammonia production systems [31].

That said, policy support and technological innovation could alter this landscape. In particular, the U.S. Inflation Reduction Act (IRA) [89] offers unprecedented subsidies through Section 45V, providing up to USD 3 per kilogram of hydrogen produced under stringent carbon intensity thresholds [89]. These incentives can reduce the levelized cost of electrolytic ammonia and, under favorable conditions, make it cost-competitive with centralized fossil-based production [5,87]. Yet, several critical limitations remain. First, only systems powered by near-zero-carbon electricity, such as dedicated renewables, are eligible for full credit, excluding most grid-connected configurations due to residual emissions [90]. Second, the scale and duration of support raise questions of long-term feasibility: decarbonizing the U.S. ammonia sector would require over 1.8 Mt of hydrogen annually, implying USD 50–60 billion in subsidies over a decade, assuming full eligibility. Third, policy uncertainty, including future changes to tax credit implementation or matching rules, adds significant investment risk, potentially delaying deployment [91,92]. Lastly, a recent paper shows that IRA subsidies may not be sufficient to make grid-based electrolytic ammonia competitive, as high electricity demand, upfront capital costs, and transaction complexities reduce project viability [90]. For off-grid systems, the subsidies often fail to offset near-term cash flow constraints, and the actual financial support is typically lower than nominal values due to transaction costs and credit conversion inefficiencies, especially for high-risk technologies [90]. Therefore, while the IRA is a powerful enabler, its current structure may require complementary reforms to unlock the full potential of decentralized systems.

In parallel, advancements in electrolyzer efficiency and modular design [67] could reduce both energy use and capital costs [93]. Achieving target performance for ALK and PEM electrolyzers could reduce costs by ~10 % and alternative technologies such as solid oxide are promising (see Supplementary Text 3). Yet, due to the thermodynamic limitations of the Haber–Bosch process, ammonia synthesis will always require large amounts of energy, meaning that access to cheap, low-carbon electricity remains a baseline requirement for economic viability [29,94]. Alternative small-scale ammonia synthesis routes (e.g., electrochemical, non-thermal plasma, and photocatalytic methods) are being actively explored. However, these technologies are still at very early stages of development (TRL 1–3 [29]) and lack sufficient data to support robust modeling, in contrast with proposed startups relying on the Haber–Bosch process that are generally around TRL 6 [95], meaning they are closer to pilot-scale validation and allow for more realistic performance and cost assumptions.

The U.S. is a unique case. It benefits from low-cost natural gas, high-capacity centralized infrastructure, established domestic supply chains, major import/export ports, and access to capital for large-scale investments. In many other regions, these advantages do not exist. Countries with high fossil fuel prices, limited domestic ammonia production, or long and vulnerable import routes face a very different set of challenges.

In such contexts, decentralized ammonia production may not be cost-competitive in absolute terms, but it can offer strategic value, enhancing energy security, reducing dependence on volatile fossil fuel markets, and strengthening food system resilience [3]. This is particularly relevant for low- and middle-income countries, where fertilizer access is already constrained and food represents a major share of household expenditures [43,96]. In these regions, long supply chains and high transportation costs exacerbate the price and restrict availability of fertilizers, limiting agricultural productivity and deepening food insecurity [3,29,43]. For example, in remote parts of Sub-Saharan Africa, Latin America, and South-East Asia, ammonia often travels thousands of kilometers from production centers or ports to end users [3,97].

Fertilizer prices are often substantially higher at the farm gate, as seen in country like Rwanda, Uganda, Mozambique, Ghana, due to a combination of small-scale purchasing, limited economies of scale, inefficient logistics, and, in some cases, political instability [43,98]. Similar structural challenges exist in import-dependent Asian economies such as Bangladesh, Vietnam, Thailand, and the Philippines, where limited domestic ammonia production and reliance on distant suppliers expose markets to international price volatility and logistical disruptions [3,49,97]. Comparable vulnerabilities are observed in parts of Latin America, including Brazil (one of the world's largest fertilizer importers) where dependence on external suppliers contribute to elevated costs and market exposure [3,99,100].

In such settings, decentralized ammonia production, even if more expensive per unit, could serve as a resilient alternative, particularly if supported by international finance, technology transfer, and deployment-focused policy frameworks [3]. While decentralized systems may face higher levelized costs, they typically require much lower upfront capital investment, thereby reducing financial barriers and investment risk [19]. By contrast, large-scale fossil-based ammonia plants typically demand capital expenditures between USD 2–4 billion [57–60], while green ammonia facilities can exceed USD 7–8.4 billion [101,102]. In comparison, modular decentralized units (e.g., 5–50 MW) are proposed at USD 3–5 million per unit [65,103]. This stark difference underscores the potential of decentralized systems to support more accessible and scalable deployment, particularly in developing regions or as first-mover demonstration projects.

However, distribution and handling remain key challenges. Ammonia is a gas at ambient conditions and requires pressurized or refrigerated storage, making on-site handling complex [104]. While the U.S. is one of the few countries that directly applies anhydrous ammonia as fertilizer, most countries rely on solid derivatives like urea or ammonium nitrate [39]. Converting ammonia into liquid or solid forms can simplify distribution and application but adds cost and operational complexity at the farm level [3]. Additionally, although we assumed co-location between production and consumption (e.g., an on-farm unit), as this is the model currently being pursued by several emerging startups [11], some level of transportation may still occur, for example, in scenarios where small regional hubs serve multiple nearby users or farms. In such cases, a "last-mile" distribution network could introduce additional costs. Nevertheless, since these distances are smaller than in centralized systems (where the average transportation distance by truck is approximately 200 km [105]), such costs can be considered relatively minor.

Agribusinesses and project developers should carefully factor in these local distribution and handling costs when examining specific case studies. While such granular considerations are challenging to incorporate into a country-scale, system-level analysis like ours, they are critical for real-world implementation and investment decisions. Moreover, while decentralized systems may incur some local transport and distribution costs, the centralized production paradigm could also involve additional expenses (such as markups, intermediaries, and supply chain handling [98]) that were not included in this analysis and could further increase the total cost of delivered ammonia.

5. Conclusions

Our findings highlight that the relative effectiveness of centralized, fossil-based ammonia production versus decentralized, electricity-based alternatives is highly context-dependent. While centralized production remains the most cost-effective pathway in the U.S., where decentralized systems are currently 3–4 times more expensive, this is not universally the case. In regions facing high energy prices, limited infrastructure, or vulnerable supply chains, decentralized ammonia production may offer strategic advantages, particularly in enhancing energy security, climate resilience, and food system sovereignty.

Rather than treating centralized and decentralized approaches as mutually exclusive, a more nuanced understanding is needed, one that recognizes the complementary roles each can play in a diversifying global landscape. Expanding this analysis beyond the U.S. to a global perspective will help identify geographies where decentralized production may already make sense today, such as areas with long, inefficient supply chains or acute food security concerns. As clean energy technologies mature and decarbonization efforts intensify worldwide, the role of decentralized ammonia production may shift from marginal to essential in certain regions.

Future work should also consider the potential of emerging ammonia synthesis technologies (such as electrochemical, plasma-catalytic, and photocatalytic methods) which, though currently at lab or pilot scale, may overcome the limitations of the Haber-Bosch process and improve the cost-effectiveness and scalability of small-scale production. These innovations, together with supportive policy and financing mechanisms, could unlock new pathways for sustainable, localized ammonia supply systems aligned with broader energy and agricultural transition.

Author contributions

SM and LR conceived and designed the study. SM collected and analyzed data, developed the modeling framework, and wrote the study with inputs from LR.

Data statement

All data required to replicate the results of this study, including input parameters, modeling assumptions, and output data, are provided in the main manuscript, the Supplementary Information, and the accompanying Supplementary Data file.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT-4o (OpenAI) for grammar checking and proofreading. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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 A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2025.116486.

Data availability

Data are available at: https://zenodo.org/records/17574824

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