Hosting Capacity Evaluation of Renewable Power-to-Ammonia Systems in Distribution Networks

Dongrui Quan, Haipeng Xie*, Lingfeng Tang, Bingkai Huang, Zhaohong Bie
School of Electric Engineering
Xi'an Jiaotong University
Xi'an, China
{qdr2002, lftang, bingkaihuang}@stu.xjtu.edu.cn, {haipengxie@, zhbie}@xjtu.edu.cn

***Abstract*—Renewable Power to Ammonia (RePtA) systems, which couple water electrolysis with green ammonia synthesis, offer a crucial pathway for utilizing renewable energy within distribution networks and fostering industrial decarbonization. However, the large-scale integration of RePtA systems imposes stress on the safe operation of distribution networks, making it essential to determine their hosting limits. To address this issue, this paper proposes a hosting capacity evaluation method for RePtA systems in distribution networks. First, an operational model of grid-connected RePtA is established, and the maximum ammonia load of the distribution network is defined as the hosting capacity indicator. Then, a bi-level evaluation framework is developed, considering user investment costs, where the upper level aims to maximize ammonia load hosting capacity and the lower level minimizes user investment costs. Finally, the effectiveness of the proposed method is verified through a modified IEEE 33-bus test system.**

***Keywords*—renewable power to ammonia (RePtA), hosting capacity, Bi-level optimization, distribution network**

I. INTRODUCTION

The secure and reliable operation of power grids has become a fundamental cornerstone in the digital era. As the segment directly responsible for delivering electricity to end users, the distribution network plays an increasingly critical role in ensuring a clean, efficient, and resilient power supply. However, the large-scale integration of renewable energy sources with intermittent and stochastic output characteristics has introduced substantial uncertainties and operational challenges to the stability, flexibility, and reliability of distribution systems. Ammonia, owing to its low energy storage cost, high transportation and storage safety, and mature infrastructure, serves as a key energy medium linking renewable energy with power systems and as an effective hydrogen carrier. Renewable power-to-ammonia (RePtA) systems based on water electrolysis and the Haber–Bosch process are a critical pathway for achieving life-cycle decarbonization of ammonia production. Accordingly, integrating ammonia synthesis units with electrolyzers is essential for producing a safer, more mature energy carrier while enabling deep decarbonization[1].

Meanwhile, as an important approach for industrial decarbonization and large-scale renewable energy utilization, RePtA has been increasingly deployed worldwide and is experiencing rapid development, which further highlights its significant research relevance. According to the International Renewable Energy Agency (IRENA, 2022), global ammonia demand is projected to rise from approximately 183 Mt yr^{-1} today to nearly 560 Mt yr^{-1} by 2050, with about 80% expected to be supplied as green ammonia[2].

However, while the large-scale integration of RePtA systems facilitates renewable energy utilization and decarbonization, it also imposes stress on distribution network line capacity and flexibility. Consequently, numerous studies have examined the operational characteristics, economic performance, and optimal sizing of RePtA systems within distribution networks.

Reference [3] proposed a power-to-ammonia (P2A) integrated model that exploits the inherent dispatchability of the N_2–NH_3 cycle in highly renewable multi-energy systems. Reference [4] developed an integrated model for modular electrolyzer management in hydrogen–ammonia coupled systems (HCI) to enhance cross-sector flexibility. Reference [5] established a flexible load model for power-to-ammonia considering limited synthesis flexibility and proposed a multi-investor economic model that jointly accounts for external and internal trading modes; a two-stage decomposition method was introduced to address the strong coupling among planning, operation, and market trading. Reference [6] introduced standby and overload operating modes to expand the load adjustment range of ammonia synthesis units in renewable-based virtual power plants, thereby improving system economic performance. Reference [7] analyzed both grid-connected and islanded operation modes and the corresponding economic performance of RePtA systems with different load regulation capabilities. However, existing studies have not addressed the maximum RePtA capacity that can be accommodated by distribution networks, namely the ammonia hosting capacity, which prevents the establishment of a safety boundary for system planning.

Traditionally, hosting capacity is defined as the maximum amount of generation or load that can be connected to a power network without violating equipment loading limits, short-circuit current, voltage deviation, or harmonic constraints[8]. Reference [9] determined the hosting capacity of electric vehicles (EVs) considering voltage violation risk (VVR), line overload, and transformer capacity constraints. Reference [10] incorporated new flexibility indices based on secure grid operation to enhance the hosting capacity of distribution networks for EVs and photovoltaics. Nevertheless, existing hosting capacity assessments have primarily focused on the network perspective, evaluating admissible capacity, economy, and flexibility without considering the impact of user-side equipment sizing. As a result, the obtained results tend to be overly idealized. Therefore, it is necessary to develop a hosting capacity evaluation method for power-to-ammonia systems in distribution networks that incorporates user investment costs to provide more realistic and practical planning guidance.

The main contributions of this study are as follows:

(1) A novel hosting capacity indicator — the maximum ammonia load mass of the distribution network — is proposed to evaluate the RePtA capability, filling the research gap in ammonia hosting capacity assessment for distribution systems.

This paper was supported by the National Natural Science Foundation of China (No. 52307134).

979-8-3315-8138-1

(2) A bi-level ammonia hosting capacity evaluation model incorporating user investment costs, addressing the limitations of traditional methods that neglect user investment preferences and tend to yield idealized results.

(3) An improved IEEE 33 distribution system integrated with RePtA systems is used to validate the proposed method, demonstrating its effectiveness while considering the user's one-time investment cost.

II. Modeling of the Grid-Connected RePtA System

In recent years, mature renewable energy plants have been established within distribution networks. Therefore, this study focuses on a distribution network with known photovoltaic (PV) and wind power installation locations and capacities. Based on ensuring the secure and stable operation of the distribution network, and considering the initial investment cost of the RePtA operator, the ammonia synthesis load hosting capacity is proposed as the evaluation index of the RePtA hosting capacity in the distribution network.

At the nodes where renewable energy plants are connected to the distribution network, a RePtA system is constructed. (as shown in Fig.1) The system consists of an electrolyzer, a hydrogen storage tank, an air separation nitrogen production unit, and an ammonia synthesis unit. In this system, the electrolyzer is powered by wind and photovoltaic generation to produce hydrogen, which is subsequently stored in the hydrogen tank. Nitrogen is obtained from ambient air through cryogenic air separation technology, and ammonia is synthesized from nitrogen and the stored hydrogen via the Haber–Bosch process.

The entire ammonia synthesis process is powered by renewable electricity, while grid power is used to supplement the energy demand when renewable generation is insufficient.

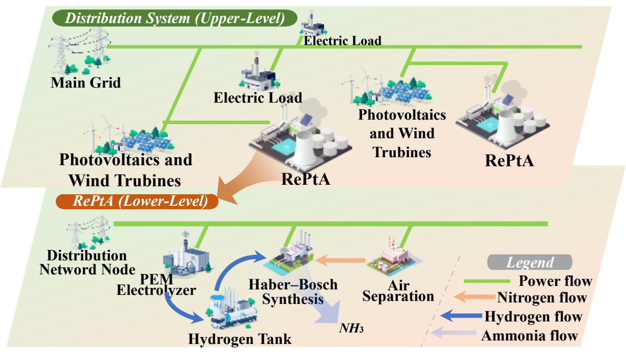

Fig.1 Grid-Connected RePtA in Distribution Network

A. Electrolyzer Model

The water electrolysis section converts electrical energy into hydrogen via a Proton Exchange Membrane (PEM) electrolyzer. The PEM electrolyzer features high current density, high efficiency, and strong operational flexibility. By arranging multiple units in series and parallel, large-scale and stable hydrogen production can be achieved. Hence, the PEM electrolyzer is adopted as the power-to-hydrogen conversion device in the RePtA system. The model of the electrolysis section is expressed as follows:

$$M_{k,t}^{el} = k_{el} p_{k,t}^{el} \tag{1}$$

$$0.05 p_k^{eln} \le p_{k,t}^{el} \le p_k^{eln} \tag{2}$$

$$p_{k,t}^{el} \le p_k^{eln} \le M \tag{3}$$

where $M_{k,t}^{el}$ represents the hydrogen production of the electrolyzer at node k and time t; k_{el} denotes the power-to-hydrogen conversion efficiency; $p_{k,t}^{el}$ represents the electrical power of the electrolyzer at node k and time t; p_k^{eln} denotes the installed capacity of the electrolyzer at node k; and M represents a maximum constant.

B. Hydrogen Storage Tank Model

The constraints of the hydrogen storage tank are expressed in (4)–(7). (4)–(5) represent the real-time hydrogen storage constraints, (6) denotes the upper and lower limits of the stored hydrogen, and (7) defines the upper and lower bounds of the installed storage capacity.

$$M_{k,t}^{HT} = M_{k,t-1}^{HT} - M_{k,t}^{Hout} + M_{k,t}^{H} \tag{4}$$

$$M_{k,0}^{HT} = M_{k,T}^{HT} = 0.5 M_k^{HTn} \tag{5}$$

$$0 \le M_{k,t}^{HT} \le M_k^{HTn} \tag{6}$$

$$0 \le M_k^{HTn} \le M \tag{7}$$

where $M_{k,t}^{HT}$ represents the hydrogen stored in the tank at node k and time t; $M_{k,t}^{Hout}$ denotes the hydrogen output from the tank; and M_k^{HTn} denotes the installed capacity of the hydrogen storage tank at node k.

C. Air Separation Nitrogen Production Model

Under standard atmospheric pressure, nitrogen is produced by exploiting the boiling point differences between nitrogen and other gases through air compression, cooling, and liquefaction. The model is given in (8), with (9) representing the operational limits and (10) defining the installed capacity constraints.

$$M_{k,t}^{as} = k_{as} p_{k,t}^{as} \tag{8}$$

$$0 \le p_{k,t}^{as} \le p_k^{asn} \tag{9}$$

$$p_{k,t}^{as} \le p_k^{asn} \le M \tag{10}$$

where $M_{k,t}^{as}$ represents the nitrogen mass at node k and time t; k_{as} denotes the power-to-nitrogen conversion efficiency; $p_{k,t}^{as}$ represents the power of the air separation nitrogen unit at node k and time t; and p_k^{asn} denotes the installed capacity of the air separation nitrogen unit at node k.

D. Haber–Bosch Ammonia Synthesis Model

Ammonia is synthesized from hydrogen produced via water electrolysis and nitrogen obtained from air separation using the Haber–Bosch process. The section is modeled by (11)–(14). (11) represents the power-to-ammonia conversion constraint, (12) defines the installed capacity of the ammonia synthesis unit, (13) represents the operational limits, and (14) defines the mass balance constraint of the produced ammonia.

$$M_{k,t}^{am} = k_{am} p_{k,t}^{am} \tag{11}$$

$$p_{k,t}^{am} \le p_k^{amn} \le M \tag{12}$$

$$0.1 p_k^{amn} \le p_{k,t}^{am} \le p_k^{amn} \tag{13}$$

$$\begin{cases} \dfrac{M_{k,t}^{Hout}}{M_{k,t}^{am}} = \dfrac{3m_{H_2}}{2m_{NH_3}} \\ \dfrac{M_{k,t}^{as}}{M_{k,t}^{am}} = \dfrac{m_{N_2}}{2m_{NH_3}} \end{cases} \tag{14}$$

where $M_{k,t}^{am}$ represents the ammonia mass at node k and time t; k_{am} denotes the power-to-ammonia conversion efficiency; $p_{k,t}^{am}$ represents the power of the ammonia synthesis unit at node k and time t; p_k^{amn} denotes the installed capacity of the ammonia synthesis unit at node k; and m_{H_2}, m_{NH_3}, m_{NH_3} represent the relative molecular masses of hydrogen, ammonia, and nitrogen, respectively.

979-8-3315-8138-1

III. Bi-Level Evaluation Model of RePtA Hosting Capacity Considering Initial Investment

Existing hosting capacity assessments mainly focus on the secure and stable operation of distribution networks, without considering the investment cost of equipment operators, which yields excessively idealized results. Based on ensuring the safe operation of distribution network equipment, reliable load supply, and full utilization of renewable generation, this study proposes a bi-level evaluation model of distribution network hosting capacity for RePtA that incorporates the operator's initial investment cost.

A. Upper-Level Problem: Maximum Ammonia Synthesis Hosting Capacity in the Distribution System

The upper-level model is a distribution network hosting capacity evaluation model for RePtA. Its objective is to maximize the ammonia synthesis hosting capacity of the distribution network, as shown in (15).

$$\max M^{am} \tag{15}$$

$$M^{am} = \sum_k M_k^{am} \tag{16}$$

$$M_{k,t}^{am} = typicalday_t * M_k^{am} \tag{17}$$

where M_k^{am} represents the ammonia load at node *k*, and M^{am} denotes the total ammonia load in the distribution network over the scheduling period; $typicalday_t$ represents the value of the ammonia load typical day profile at time *t*.

The evaluation of the distribution network ammonia synthesis hosting capacity considers constraints of the power-to-chemical conversion devices, distribution network power flow, bus voltage limits, line capacity, load shedding, and renewable energy availability.

1) Power-to-Chemical Conversion Constraints: The power-to-ammonia conversion constraints and the operational upper and lower bounds of the equipment have been provided in Section II, (2), (9), (11), and (13). (18) represents the ramping constraints of the equipment.

$$\begin{cases} P_{i,t}^{am,H,as} - P_{i,t-1}^{am,H,as} \le U^{am,H,as} \\ P_{i,t-1}^{am,H,as} - P_{i,t}^{am,H,as} \le D^{am,H,as} \end{cases} \tag{18}$$

where $U^{am,H,as}$ $D^{am,H,as}$ and denotes the upward/downward ramping limits of the ammonia synthesis equipment, electrolyzer, and air separation nitrogen equipment.

2) Power Flow Constraints: The DistFlow model is adopted to describe the power flow constraints of radial distribution networks, as shown in (19)–(21).

$$\sum_{i\in\Omega(i)} P_{ij,t} - \sum_{i\in\Pi(i)} P_{ki,t} = p_{i,t}^{grid} + p_{i,t}^{wind} + p_{i,t}^{pv} - p_{i,t}^{load} - p_{i,t}^{am} - p_{i,t}^{H} - p_{i,t}^{as} \tag{19}$$

$$\sum_{i\in\Omega(i)} Q_{ij,t} - \sum_{i\in\Pi(i)} Q_{ki,t} = q_{i,t}^{grid} - q_{i,t}^{load} \tag{20}$$

$$u_{i,t} = u_{j,t} - (r_{ij}P_{ij,t} + x_{ij}Q_{ij,t}) \tag{21}$$

where $P_{ij,t}$ and $Q_{ij,t}$ represent the active and reactive power flows on line *ij* at time *t*, respectively; $p_{i,t}^{grid}$ and $Q_{i,t}^{grid}$ denote the active and reactive power supplied from the upstream grid to node *i* at time *t*, respectively; $p_{i,t}^{load}$ and $Q_{i,t}^{load}$ represent the actual active and reactive loads supplied at node *i* at time *t*, respectively; $p_{i,t}^{wind}$ and $p_{i,t}^{pv}$ denote the wind and photovoltaic generation at node *i* and time *t*; $u_{i,t}$ represents the squared voltage at node *i* and time *t*; and $r_{ij} + jx_{ij}$ denotes the impedance of line *ij*.

3) Voltage Constraints:

$$V_{\min} \le u_{ij,t} \le V_{\max} \tag{22}$$

where $V_{\max}$ and $V_{\min}$ denote the upper and lower limits of the squared voltage.

4) Branch Capacity Constraints:

$$\begin{cases} -P_{\text{line}} \le P_{ij,t} \le P_{\text{line}} \\ -Q_{\text{line}} \le Q_{ij,t} \le Q_{\text{line}} \end{cases} \tag{23}$$

where P_{line} denotes the capacity limits of the branch active power, and Q_{line} denotes the capacity limits of the branch reactive power.

5) Load Shedding Constraints: To ensure the secure power supply of the distribution network, the load shedding must not exceed the maximum allowable limit.

$$p_{i,t}^{load} = p_{i,t}^{LOAD} - p_{i,t}^{load\_shed} \tag{24}$$

$$0 \le p_{i,t}^{load\_shed} \le \sigma p_{i,t}^{Load} \tag{25}$$

where $p_{i,t}^{load\_shed}$ represents the load shedding at node *i* and time *t*, $p_{i,t}^{LOAD}$ denotes the load demand at node *i* and time *t*, and σ is the maximum allowable load shedding coefficient.

6) Renewable Generation and Curtailment Constraints: (26)–(27) represent the output constraints of wind and photovoltaic generation. To ensure effective utilization of renewable energy in the distribution network, the curtailed renewable energy generation must not exceed 5% of the total renewable generation.

$$\begin{cases} p_{i,t}^{wind} = p_{i,t}^{wind\_pre} - p_{i,t}^{wind\_shed} \\ 0 \le p_{i,t}^{wind} \le p_{i,t}^{wind\_pre} \end{cases} \tag{26}$$

$$\begin{cases} p_{i,t}^{pv} = p_{i,t}^{pv\_pre} - p_{i,t}^{pv\_shed} \\ 0 \le p_{i,t}^{pv} \le p_{i,t}^{pv\_pre} \end{cases} \tag{27}$$

$$\begin{cases} 0 \le \sum_{i,t} p_{i,t}^{wind\_shed} \le 5\% \sum_{i,t} p_{i,t}^{wind\_pre} \\ 0 \le \sum_{i,t} p_{i,t}^{pv\_shed} \le 5\% \sum_{i,t} p_{i,t}^{pv\_pre} \end{cases} \tag{28}$$

where $p_{i,t}^{wind\_pre}$ and $p_{i,t}^{pv\_pre}$ represent the wind and photovoltaic generation; $p_{i,t}^{wind}$ and $p_{i,t}^{pv}$ denotes the wind and photovoltaic power injected into the grid; $p_{i,t}^{wind\_shed}$ and $p_{i,t}^{pv\_shed}$ represents the curtailed wind and photovoltaic power.

B. Lower-Level Problem: Capacity Sizing of the RePtA

The lower-level model is the capacity planning model of the RePtA system. Its objective is to minimize the initial investment cost of the user, as shown in (29).

$$\min F = \sum_{k\in K} c_{el} p_k^{eln} + c_{HT} M_k^{HTn} + c_{am} p_k^{amn} + c_{as} p_k^{asn} \tag{29}$$

where c_{el}, c_{HT}, c_{am}, and c_{as} denote the initial investment cost coefficients of the electrolyzer, hydrogen storage tank, ammonia synthesis unit, and air separation unit, respectively.

The capacity planning model of the ammonia synthesis system considers the constraints of the electrolyzer, hydrogen storage tank, ammonia synthesis unit, and air separation nitrogen unit.

(1) Electrolyzer Constraints: The capacity sizing constraints of the electrolyzer are given in Section II, (1)-(3).

(2) Hydrogen Storage Tank Constraints: The capacity sizing constraints of the hydrogen storage tank are given in Section II, (4)-(7).

(3) Ammonia Synthesis Unit Constraints: The capacity sizing constraints of the ammonia synthesis unit are given in Section II, (11)-(14).

(4) Air Separation Nitrogen Unit Constraints: The capacity sizing constraints of the air separation nitrogen unit are given in Section II, (8)-(10).

979-8-3315-8138-1

C. Bi-Level Evaluation Model and Solution

The bi-level hosting capacity evaluation model is formulated as follows:

$$\begin{aligned}
&\min_{\{\mathbf{P},\mathbf{M}\}} -M^{am} \\
&\quad s.t.(18-28) \\
&\quad x^L \in \arg\min_{x^L}\{F(\mathbf{P},\mathbf{M}) : s.t.(1-14)\} \\
&\quad \left\{\begin{matrix} p_k^{amn}, p_k^{eln}, p_k^{asn}, \\ H_k^{HTn}, H_{k,t}^{HT}, H_{k,t}^{Hout} \end{matrix}\right\} \in x^L
\end{aligned} \tag{30}$$

where $\mathbf{P}$ is the set of power-related variables in the bi-level model, $\mathbf{M}$ represents the set of gas mass-related variables, and x^L denotes the set of lower-level model variables.

The bi-level hosting capacity evaluation model consists of the upper-level capacity assessment model and the lower-level capacity planning model. Both levels have their respective objective functions and constraints. However, as both problems are linear optimization models with certain coupling relationships, they cannot be solved directly. The ammonia load hosting capacity depends on the capacity sizing of the ammonia synthesis system, which in turn must satisfy the ammonia load determined by the hosting capacity assessment. Therefore, the Lagrangian function of the lower-level model is constructed, and the lower-level model is transformed into constraints of the upper-level model through the KKT complementarity conditions, as shown in (31). By linearizing the nonlinear terms in the single-level nonlinear model using the Big-M method, a single-level linear optimization model is obtained and solved on MATLAB R2022b using Gurobi 11.0.1. (Fig.2)

$$\begin{aligned}
&\min_{\{\mathbf{P},\mathbf{M}\}} -M^{am} \\
&\quad s.t.(18-28) \\
&\quad L=\nabla_{x^L} F(\mathbf{P},\mathbf{M}) + \nabla_{x^L} G(\mathbf{P},\mathbf{M})\mathbf{u} + \nabla_{x^L} H(\mathbf{P},\mathbf{M})\boldsymbol{\lambda} = 0 \\
&\quad \mathbf{u} > 0,\ G(\mathbf{P},\mathbf{M}) \le 0,\ H(\mathbf{P},\mathbf{M}) = 0,\ \mathbf{u}^{\mathrm{T}} G(\mathbf{P},\mathbf{M}) = 0
\end{aligned} \tag{31}$$

where L is the Lagrangian function of the lower-level model, $\mathbf{u}$ and $\boldsymbol{\lambda}$ are the Lagrange multipliers, $G(\mathbf{P},\mathbf{M}) \le 0$ denotes the lower-level inequality constraints, and $H(\mathbf{P},\mathbf{M}) = 0$ represents the lower-level equality constraints.

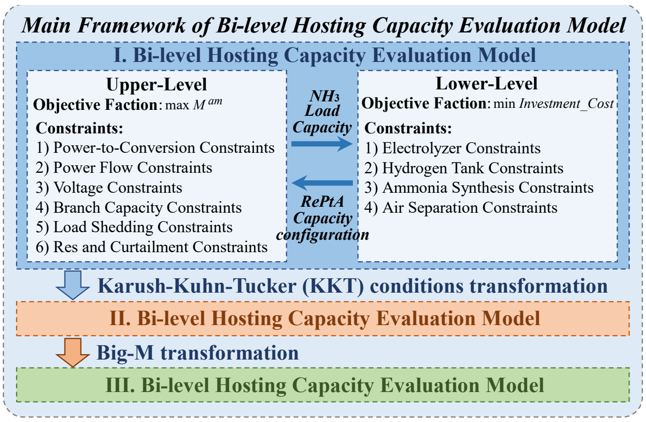

Fig.2 Bi-level evaluation model solution framework

IV. Case Study

A. Case settings

The effectiveness of the proposed evaluation method is verified using a modified IEEE 33 distribution network system. The voltage level of the IEEE 33 system is 12.66 kV, and the maximum line capacity is set to 4 MW. Renewable energy sources and RePtA systems are connected at buses 14, 21, 24, and 31. Annual typical daily profiles for electric load, ammonia load, wind, and photovoltaic generation fluctuations are employed, with a scheduling period of 8,760 hours and a time step of 1 hour. Other parameters are listed in Table 1.

TABLE I. PARAMETERS CONFIGURATION

	Variables	Values	Units
Distribution System	P_{inv}^{wind} , P_{inv}^{pv}	4	MW
RePtA	k_{el} , k_{as} , k_{am}	20, 380, 2907	kg/MW
cost coefficient	c_{el} , c_{as} , c_{am}	80, 200, 200	10^4 CNY/MW
	c_{HT}	0.8	10^4 CNY/kg

B. Ammonia Hosting Capacity and Operation Analysis

The proposed method yields an ammonia host capacity of 2.523 t for the modified IEEE 33 distribution system, with a total annual ammonia production of 12,773.6 t and a total initial construction investment of 57.59 million CNY. The installed ammonia capacity and total annual ammonia production at each node are listed in Table 1, while the installed equipment capacities and the corresponding initial investment costs are presented in Tables 2 and 3, respectively.

TABLE II. AMMONIA CAPACITY & ANNUAL AMMONIA PRODUCTION

Bus	Ammonia Capacity (t)	Annual Ammonia Production (t)
14	0.304	1,541.0
21	0.884	4,481.7
24	0.761	3,854.8
31	0.571	2,896.1
Total	2.523	12773.6

TABLE III. INSTALLED EQUIPMENT CAPACITIES

Bus	p_k^{eln} (MW)	p_k^{asn} (MW)	p_k^{amn} (MW)	M_k^{HTn} (kg)
14	4.37	0.09	0.82	43.13
21	8.86	0.26	2.39	1318.00
24	8.22	0.22	2.05	470.21
31	8.18	0.17	1.54	520.97
Total	29.63	0.74	6.80	2352.31

TABLE IV. INITIAL INVESTMENT COSTS (10^4 CNY)

	p_k^{eln}	p_k^{asn}	p_k^{amn}	M_k^{HTn}
Cost	2369.80	146.31	1361.00	1881.90

As shown in Fig. 3, in the distribution network integrated with ammonia synthesis, the total power demand of ammonia production and local loads matches the sum of renewable generation and electricity purchased from the upper-level grid, ensuring overall power balance. The electricity for electrolyzers, air separation units, and ammonia synthesis units is primarily supplied by renewables, with grid power supplementing production when renewables are insufficient. During spring, autumn, and winter, the ammonia load demand is lower than in summer, and from 00:00 to 08:00, almost no electricity is purchased from the upper grid, with minor curtailment of wind and solar power. The total curtailed energy remains below 5% of the forecasted indicating that grid-connected RePtA enhances renewable energy utilization. In summer, the power purchased from the upper grid remains close to 4 MW, which corresponds to the line capacity limit. Therefore, expanding the line capacity can further improve the ammonia production hosting capability of the distribution network.

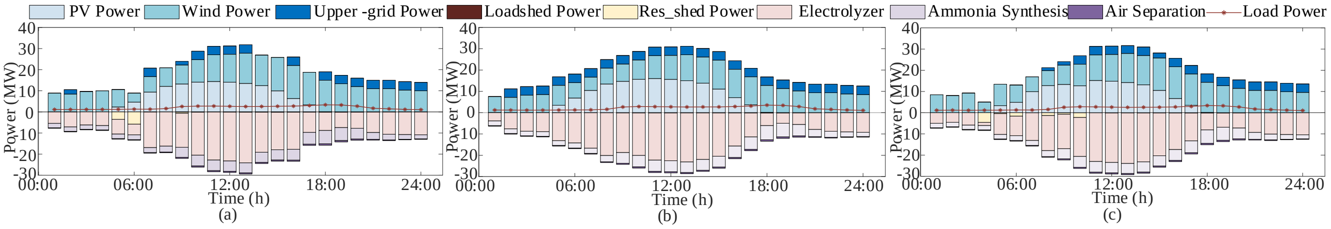

Fig.3 Power balance of the distribution network integrated with RePtA in (a) winter, (b) summer, and (c) spring & autumn

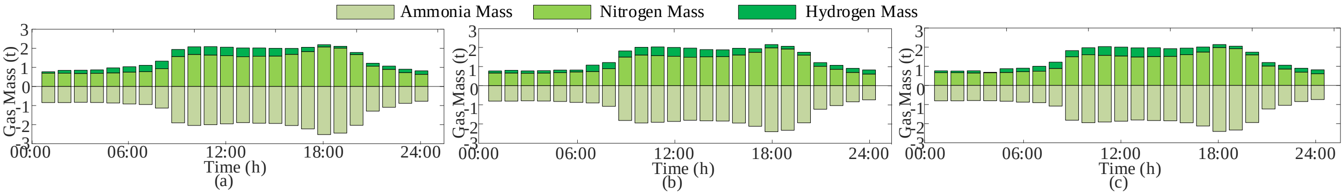

Fig.4 Gas mass scheduling results of the RePtA in (a) winter, (b) summer, and (c) spring & autumn

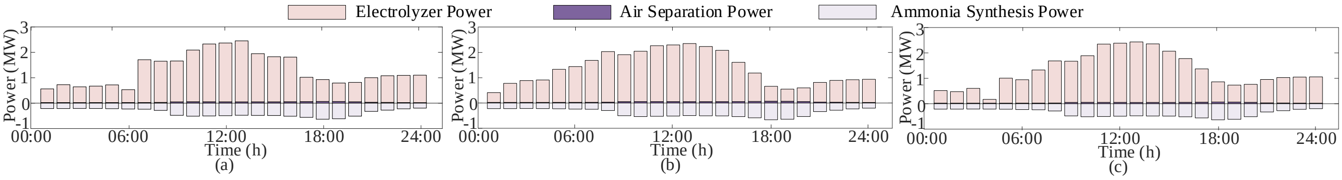

Fig.5 Power scheduling results of each stage of the RePtA in (a) winter, (b) summer, and (c) spring & autumn

The gas mass balance of the RePtA system is shown in Fig. 4. The ammonia mass equals the sum of the nitrogen mass and the hydrogen stored in the hydrogen tanks, demonstrating that the mass distribution of the ammonia synthesis system satisfies the principle of mass balance and that all process units operate in a coordinated and stable manner. The power balance of the RePtA system is shown in Fig. 5. The electricity consumption of each unit is positively correlated with the mass of the produced gases. Across the entire ammonia production process, the electrolyzers account for the majority of power consumption. Therefore, improving electrolyzer efficiency can reduce total electricity consumption for ammonia synthesis and enhance the hosting capacity of the distribution network for ammonia production.

C. *Model Accuracy and Performance*

Three representative scenarios (summer 19:00, spring/autumn 02:00, and winter 05:00) are evaluated using MATPOWER. Nodal voltages and line power flows show a maximum voltage error of about 5%, a mean absolute percentage error below 3%, and closely matched power flow profiles, validating the proposed model.

A single-level model without investment costs yields an ammonia hosting capacity of 2.5203 t, an annual production of 12,774 t, and an initial investment of 4.0e13 CNY, resulting in highly unrealistic total costs. By accounting for investor capital costs, the proposed bilevel model provides more practically relevant guidance for ammonia deployment while assessing hosting capacity.

V. Conclusion

This paper presents an evaluation method for the hosting capacity of RePtA systems in distribution networks. An operational model of grid-connected RePtA is established, where the maximum ammonia load is defined as the hosting capacity indicator. A bi-level evaluation framework is then developed, with the upper level maximizing the ammonia load hosting capacity under network security constraints, and the lower level minimizing user investment cost subject to RePtA sizing constraints. Simulation results based on the modified IEEE 33-bus system show an ammonia load hosting capacity of 2.523t, an annual ammonia production of 12,774t, and a total investment of 57.589 million CNY, demonstrating the effectiveness of the proposed method. Future work will investigate the effects of line capacity expansion and equipment efficiency improvement on hosting capacity, and extend the analysis to larger-scale networks.

References

[1] A. Valera-Medina, H. Xiao, M. Owen-Jones, W. I. F. David, and P. J. Bowen, “Ammonia for power,” Prog. Energy Combust. Sci., vol. 69, pp. 63–102, 2018.

[2] IRENA, Global Hydrogen Trade to Meet the 1.5 °C Climate Goal: Par t I - Trade Outlook for 2050 and Way Forward, Abu Dhabi: Internatio nal Renewable Energy Agency, Jul. 2022, p. 59. [Online]. Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Jul/IRENA_Global_hydrogen_trade_part_1_2022_.pdf

[3] D. Xu, B. Zhou, Q. Wu, C. Chung, C. Li, S. Huang, and S.Chen, “Integrated Modelling and Enhanced Utilization of Power-to-Ammonia for High Renewable Penetrated Multi-Energy Systems,” IEEE Trans. Power Syst., vol. 35, no. 6, pp. 4769–4780, Nov. 2020.

[4] A. Firdous, C. P. Barala, P. Mathuria, and R. Bhakar, “Short-Term Operation Flexibility in Modular Power to Hydrogen Based Ammonia Industries,” IEEE Trans. Sustain. Energy, vol. 16, no. 1, pp. 601–612, Jan. 2025.

[5] Z. Yu, J. Lin, F. Liu, J. Li, Y. Zhao, Y. Song, Y. Song, and X, Zhang, “Optimal Sizing and Pricing of Grid-Connected Renewable Power to Ammonia Systems Considering the Limited Flexibility of Ammonia Synthesis,” IEEE Trans. Power Syst., vol. 39, no. 2, pp. 3631–3648, Mar. 2024.

[6] S. Wu, J. Li, J. Lin, F. Liu, Y. Qiu, Y. Song, X. Cheng, and Z. Yu, “A Dispatchable Region-Guided Adaptive Mode-Switching Regulation for Renewable Power to Ammonia Virtual Power Plants,” IEEE Trans. Sustain. Energy, vol. 16, no. 1, pp. 32–44, Jan. 2025.

[7] J. Lin, Z. Yu, X. Zhang, and J. Li, “On-grid/Off-grid Operation Mode and Economic Analysis of Renewable Power to Ammonia System,” Proceedings of the CSEE, vol. 44, no. 1, pp. 117–126, Jan. 2024.

[8] R. Gong, H. Li, L. Li, “Optimal Allocation Method of Energy Storage Systems for Improving the Comprehensive Carrying Capacity of Distribution Network,” Power System Technology, vol. 49, no. 9, pp. 3860–3869, Sep. 2025.

[9] C. D. W. W. Mudiyanselage, K. N. Hasan, A. Vahidnia, and M. T. Rahman, “Spatio-Temporal and Correlation Modeling of EV Charging Data for Hosting Capacity Analysis,” IEEE Trans. on Ind. Applicat., vol. 61, no. 6, pp. 8722–8735, Nov. 2025.

[10] L. Liu, N. Shi, Z. Wang, M. J. Reno, and J. A. Azzolini, “Probabilistic Estimation of PV Hosting Capacity in DER-Rich Feeders Using Smart Meter Data,” IEEE Trans. Smart Grid, vol. 16, no. 5, pp. 4293–4296, Sept. 2025

979-8-3315-8138-1