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Optimal possibilistic-robust operation of multi-energy microgrids considering infrastructure hydrogen storage capability

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ABSTRACT

In sustainable energy transitions, the utilization of hydrogen is crucial, providing flexibility in the operation of net-zero emission renewable-based energy systems. This paper presents a study on the optimal operation of net-zero emission multi-energy future microgrids that utilize hydrogen as an alternative fuel instead of natural gas. The electrolyzers' output is injected into the hydrogen grid to meet demand or converted back to electricity later using generating units, owing to the storage capability of pipes, called linepack. For this purpose, a detailed mathematical model is developed to simulate the main characteristics of grids (e.g., voltage, current, hydrogen flow, and pressure) as well as various components (e.g., renewable systems, electrolyzers, and hydrogen-fired units). To become more realistic, a possibilistic-robust approach is developed to account for the uncertainty arising from the lack of real-world implementation. By representing a case study, a test is performed to evaluate the possibility of employing a low-pressure gas grid to meet the demand for hydrogen. After that, the effects of electrolyzers are analyzed in the presence and absence of the uncertainty consideration approach. The result indicates that, despite hydrogen's lower energy density compared to natural gas, it is still feasible to satisfy the same energy demand level, considering the technical characteristics of the grid. The integration of electrolyzers can reduce wind curtailment by 2 % and supplement hydrogen demand by 50 %. A higher level of conservatism in the possibilistic-robust approach leads to an increase in the mean value of the objective function and a reduction in the standard deviation under the realization of uncertain parameters, which provides the decision-makers with a more realistic insight.

Nomenclature

Indices			
t	Time step	b	Bus in electricity grid
n	Node in hydrogen grid	l	Electric line
p	Pipe		
Parameters			
ψ_t	Import price for electric power	ψ'_t	Export price for electric power
ψ''_t	Shedding cost for electric demand	ϕ	Import price for hydrogen
ϕ'	Cost of linepack management	ϕ''	Shedding cost for hydrogen demand

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$E^{load}_{b,t}/Er^{load}_{b,t}$	Active/reactive power demand	V^{max}_b	Voltage limit
$R_{l,t}/X_l$	Resistance/reactance of electric line	I^{max}_l	Current limit
$E^{dg,min/max}_b$	Minimum/maximum available renewable power	$T^{on/off}$	Minimum up/down time of generating units
$Ramp_b$	Ramp limit	$H^{load}_{n,t}$	Hydrogen consumption
$\pi^{min/max}_n$	Minimum/maximum pressure	$H^{line,\ min/max}_p$	Minimum/maximum flow within pipe
$LP^0_{p,t}$	Initial linepack (stored hydrogen) within pipe	$D_{n,n'}$	Diameter of pipe

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$L_{n,n'}$	Length of pipe	ξ	Hydrogen required for electricity production using generating unit
ζ	Electricity required for hydrogen production using electrolyzer	$f_{n,n'}$	Friction factor
S	Slope or gradient of pipe	c_{ij}	Cost coefficient
$\widetilde{a}_{ij}$	Imprecise constraint coefficients	b_i	Right-side coefficient
ρ_0	Fixed tolerance	$\widehat{c}$	Optimal value of objective function without uncertainty
z	Control parameter of decision maker	γ	Weighted coefficient
Decision Variables			
OF^{MEM}	Operating cost of multi-energy microgrid	OF^{ELC}	Operating cost of electricity grid
OF^{H_2}	Operating cost of hydrogen grid	E_t^{buy}	Purchased power
E_t^{sell}	Sold power	$E_{b,t}^{shed}$	Load shedding
H_t^{buy}	Purchased hydrogen	$\Delta H_{n,t}$	Changes in hydrogen within pipe
$HNS_{n,t}$	Hydrogen-not-supplied	$E_{b,t}^{dg}$	Electric power from renewable resources
$E_{b,t}^{rmw}$	Electric power of gas-fired unit	$E_{l,t}^{line}/Er_{l,t}^{line}$	Active/reactive power within line
$E_{b,t}^{elz}$	Electric power consumption of electrolyzer	$V_{b,t}$	Voltage
Er_t	Reactive power from the main grid	$I_{l,t}$	Current
$\Gamma_{i,t}$	On/off status of generating units	$H_{n,t}^{elz}$	Hydrogen production of electrolyzers
$\pi_{n,t}$	Pressure	$H_{p,t}^{line}$	Hydrogen flow within pipe
$LP_{p,t}$	Linepack (stored hydrogen within pipes)	$H_{p,t}^{pipe,in/out}$	Hydrogen flow to/from pipe
$H_{n,t}^{dg}$	Hydrogen required for generating units	z	Objective function
x_{ij}	Decision variables	Γ_i	Protection level
Abbreviations			
RES	Renewable Energy Systems	MEM	Multi-Energy Microgrids
PRP	Possibilistic-Robust Programming	DICOPT	Discrete and Continuous Optimizer
GAMS	General Algebraic Modeling System	NG	Natural Gas
NGL	Natural Gas-Low Initial Linepack	H2	Hydrogen
mcm	Million Cubic Meter	kcm	Thousand Cubic Meters
H2L	Hydrogen-Low Initial Linepack	MINLP	Mixed-Integer Nonlinear Programming

1. Introduction

Currently, a considerable share of emissions stems from the energy sector as there is still dependency on burning fossil fuels for energy demand provision. To address this concern, governments of different countries set targets to increase their renewable energy share in their final energy consumption [1]. This objective is being pursued through various policies promoting the adoption and development of Renewable Energy Systems (RESs). These policies include financial incentives like feed-in tariffs, investment grants, and tax credits to encourage the installation of RESs [2]. However, despite their efforts, the key challenge still includes the intermittent nature of renewable sources impacting the grid [3]. A solution can be to utilize flexible gas-fired units burning hydrogen to manage intermittency and address supply-demand provisions without emissions [4]. The existing gas grid infrastructure can be repurposed to transport and distribute hydrogen to the gas-fired units, reducing the need for new investments [5]. The hydrogen produced by electrolyzers can also be injected into the grid to supply these units or provide hydrogen demand for other purposes, leading to reduced emissions and moving toward a carbon-neutral energy sector [6].

In order to study the role of hydrogen in the operation of energy systems, it is of great importance to consider the time that it takes to transfer gas from the supply point to the demand point. However, the gas stored within the pipes, known as linepack, can help manage sudden changes in demand by compensating for the mentioned time delay. Linepack also serves as a form of storage, allowing gas to be reserved for later use, which optimizes the need for additional storage systems to provide flexibility [7]. A growing number of studies focus on the incorporation of alternative fuels within natural gas grids, employing steady-state models to inform their analyses with respect to the linepack within pipes. For instance, in [8], the distributed injection of alternative fuels, such as hydrogen and biogas, into transmission gas grids was examined. The findings indicated the potential to supplement demand by injecting alternative fuels up to a 10 % mixture. In [9], a case study in Germany was considered to examine the impact of hydrogen on the supply of energy. This study provided insight into the capacity of electrolyzers, hydrogen storage systems, and fuel cells used in future scenarios, which showed that hydrogen is still expensive due to the high loss factor of conversions. While highlighting the role of hydrogen and linepack management on the supply side of natural gas systems, the above-mentioned studies did not focus on its conversion for use in the power sector.

Some other studies focused on the electricity grid operation, considering the production and/or sale of hydrogen in the market. For instance, in [10], a risk-averse operating model was developed for a grid-connected energy system, which consisted of photovoltaic systems, wind turbines, diesel generators, and hydrogen storage systems. The results indicated the potential cost savings of interactions with electricity and hydrogen markets. In [11], an operating model for a microgrid was developed and optimized to improve the resilience in the islanded mode. It indicated that the capability of the integration of electrolyzers, fuel cells, and hydrogen storage systems to reduce the load shedding in the case of an unexpected failure in the upstream grid. In [12], the role of hybrid hydrogen and battery storage systems in the optimal dispatch of an isolated electricity grid was studied. By analysis of a case study indicated that the hybrid system facilitated the integration of renewable resources. In [13], a stochastic model was developed for the dispatching of energy systems, analyzing the role of power-to-gas systems for seasonal storage. The output demonstrated the seasonal storage capability to improve the operation of the energy system. In [14], the optimal operation of a transmission electricity grid was optimized considering power-to-gas systems. The results addressed the economic and environmental improvement obtained by scheduling the integration of the power-to-gas systems. In [15], the integration of fuel cells into photovoltaic and wind units is studied by developing a model for a multi-microgrid. Developing a heuristic solving approach, this studies reduce the allocation cost by developing a framework for this purpose. In [16], energy management of microgrids that rely on renewable and hydrogen storage is optimized using artificial intelligence. However, in [17], the optimal operation of stand-alone and photovoltaic-based microgrids is examined, which are equipped with hydrogen storage systems. The results of the studies indicate the more efficient and economical energy management through the devised frameworks. The main drawback of the reviewed studies was that they did not model the gas or hydrogen grids, and their mathematical models of the optimization problems were neither detailed nor realistic.

Multiple research efforts have explored both gas and electricity grids, specifically investigating the viability of injecting produced green hydrogen, generated via electrolyzers, into natural gas grids. Notably, in [18], the potential of power-to-hydrogen systems to enhance flexibility within both natural gas and electricity grids was highlighted. This study anticipated future energy scenarios, where surplus RESs' output could be converted into hydrogen using power-to-hydrogen technologies. This surplus hydrogen could also be integrated into the natural gas grid to

meet demand requirements. Alternatively, during instances of demand exceeding supply in the electricity grid, the stored hydrogen could be reconverted into electricity through the fuel cells, offering a flexibility option that provides cost savings. In [19], the planning for flexibility options was conducted to facilitate the operation of natural gas and electricity grids for future energy resources. The outputs indicated that the integration of flexibility options, such as flexible gas-fired units and compressors, provided operating cost savings. Although these studies focused on the operation of multi-energy systems considering flexibility options, they only focused on the natural gas grid. None of them focused on a net-zero emission future grid that fully supplies hydrogen through pipes to meet demand.

Aside from the recapped issues, the development of a method to deal with intermittent and vague parameters makes the output more realistic. For instance, in [20], a planning approach is conducted to allocate a microgrid integrated into a hydrogen grid using a stochastic approach. In [21] and [22], a scenario-based stochastic method is employed to operate multi-microgrids connected to the hydrogen grid. In [23], hydrogen storage planning is implemented to reach peak shaving and valley filling utilizing robust programming. In [24], a possibilistic approach is used to dispatch different parties in a microgrid, such as wind turbines, hydrogen storage systems, and heat storage systems. In [25], the operation and configuration of a microgrid are optimized, which relies on electrolyzers and fuel cells. This study uses robust programming to capture the uncertainty in renewable resources and demand. Although uncertainty has been considered in the existing literature, most proposed approaches are scenario-based according to the reviewed studies, which increases the computational complexity of solving the optimization problem. This underscores the need for non-scenario-based methods to effectively reduce the complexity associated with the optimal operation of MEMs.

Following the examination of existing studies in the related subjects (Table 1), the main objectives of this study are as follows:

- Primary Objective: to develop a comprehensive framework for assessing the applicability of existing gas infrastructure for hydrogen distribution, and to investigate the role of electrolyzers, flexible hydrogen-fired units, and the storage capability of pipelines (i.e., linepack) within MEMs. For this purpose, a detailed operating model of the hydrogen grid is developed, considering constraints such as hydrogen pressure limits, hydrogen flow limits, and linepack variations. Additionally, a test is proposed to evaluate the adaptability of previously used low-pressure natural gas grids for hydrogen distribution, taking into account supply-demand balance. The framework is further enhanced to simulate and optimize MEM operation by integrating the electric grid, incorporating parameters, such as voltage at connection points, current flow through lines, and active/reactive power.
- Secondary Objective: to propose a novel Possibilistic-Robust Programming (PRP) approach that captures uncertainty in key parameters and provides a more realistic decision-making environment based on possibility and necessity theories within fuzzy logic and robust optimization. This approach simulates uncertainties to assist decision-makers, whose performance is evaluated through the realization of uncertain parameters and the comparison of mean values and standard deviations.

By representing a case study, the test is conducted to evaluate the capability of the former low-pressure natural gas grid to be used for hydrogen. The role of electrolyzers in producing hydrogen to be injected into the hydrogen grid is examined. The produced green hydrogen can be either used to assist hydrogen supply-demand provision or converted back to electricity by hydrogen-fired units, owing to the linepack. More precisely, the interaction between the grids, the effects of hydrogen on the operation of the electricity grid, and the role of the uncertainty consideration approach are studied in detail.

2. Methodology

In this section, the operating model for the MEM, which consists of an electricity grid and a hydrogen grid utilized for hydrogen transportation, is presented (Step I). Afterward, integrating the uncertainty consideration approach based on possibilistic and robust programming is explained to be more realistic (Step II). Then, the solving approach and the test for the applicability of the natural gas grid to be used for hydrogen are introduced (Step III), as demonstrated in Fig. 1. It should be noted that, after the methodology, the main steps are case study representation and determination of scenarios (i.e., Step IV), represented in Section 3. At the end, the results and analyses are conducted in Section 4 (i.e., Step V).

Before developing an operational model, the definition of a microgrid is introduced in this section. A microgrid is a localized energy system that can operate autonomously or in conjunction with the main grid, integrating various energy sources to meet the needs of a specific community or facility. Microgrids are key components in the transition to resilient and sustainable energy systems because they enhance energy security, reduce transmission losses, and facilitate the integration of renewable energy sources such as wind and solar [26]. In contrast to traditional microgrids, multi-energy microgrids go a step further by incorporating multiple forms of energy, such as electricity, heat, and gas, allowing for a more flexible and efficient energy exchange. These systems leverage diverse energy carriers, like hydrogen, to optimize overall energy efficiency and reliability, while balancing supply and demand across different energy vectors. By coupling sectors and enabling energy storage through systems, such as hydrogen linepack, multi-energy microgrids play a critical role in advancing net-zero emission goals and improving the resilience of future energy infrastructures [27].

The following subsection presents a detailed mathematical model of a multi-energy microgrid that integrates electricity and hydrogen systems. It should be noted that in the hydrogen grid's model, the continuity and momentum equations are employed to represent gas flow, with the primary assumption that variations in kinetic energy along the pipeline resulting from changes in velocity and density are negligible. In the electricity distribution network model, the demand is represented as constant active and reactive power, power losses along each branch are assumed to occur at the sending end, and the network is modeled as a single-phase balanced equivalent. Furthermore, the microgrid is assumed to interact with the main grid within a day-ahead market framework, and renewable generation output is assumed to follow the forecasted day-ahead profile [11].

2.1. Operational model

To optimize the operation of an MEM, the objective function consists of two terms indicated in (1): (i) the operating cost of the electricity grid and (ii) the operating cost of the hydrogen grid. The operating cost of the electricity grid depends on three terms (Eq. (2)), including (a) the expense of buying electricity from the main grid, (b) the earnings from selling surplus electricity back to the main grid, and (c) the cost of load shedding during emergencies. The cost of operating the hydrogen grid is also influenced by three terms (Eq. (3)), including (a) the cost of purchasing hydrogen from the market, (b) the expenses associated with storing hydrogen within pipes, and (c) the cost of hydrogen shedding when it is required. To ensure a cost-effective operation of the MEM, the summation of the objective functions is minimized subject to a set of constraints, which are introduced in the following.

$$OF^{MEM} = OF^{ELC} + OF^{H_2} \tag{1}$$

$$OF^{ELC} = \sum_{t=1}^{T} \psi_t \cdot E_t^{\text{buy}} - \sum_{t=1}^{T} \psi'_t \cdot E_t^{\text{sell}} + \sum_{t=1}^{T} \sum_{b=1}^{B} \psi''_t \cdot E_{b,t}^{\text{shed}} \tag{2}$$

Table 1
A systematic review of previously conducted studies considering various energy carriers.

No.	Ref.	Objective	Solution Method		Grid Consideration			Transmission/ Distribution Level	Solver	Uncertainty Consideration Approach	Components		
			Numerical analysis or simulation	*Exact optimization*	*Electricity*	*Gas*	*Hydrogen*				*Renewable*	*P2G*	*Fuel cell/ gas-fired unit*
1	[8]	-Examining the injection of green hydrogen into gas grids	✓	-	-	✓	-	Transmission	-	-	✓	✓	-
2	[9]	-Examining Germany's hydrogen strategy	✓	-	-	-	✓	Transmission	-	-	✓	✓	✓
3	[10]	-Improve the operation of electricity grids	-	✓	✓	-	-	Transmission	CPLEX	Stochastic	✓	✓	-
4	[11]	-Improve the resilience of microgrids	-	✓	✓	-	-	Distribution (Microgrid)	DICOPT	-	✓	✓	✓
5	[12]	-Improve the integration of renewable resources	-	✓	✓	-	-	Distribution (Microgrid)	GUROBI	-	✓	✓	✓
6	[13]	-Improve the operation of electricity grids	-	✓	✓	-	-	Distribution	CBC	Stochastic	✓	✓	✓
7	[14]	-Improve the operation of electricity grids	-	✓	✓	-	-	Transmission	CPLEX	-	✓	✓	✓
S	[15]	-Improve energy management of microgrids	-	✓	✓	-	-	Distribution (Microgrid)	Huristics	-	✓	✓	✓
9	[16]	-Improve energy management of microgrids	-	✓	✓	-	-	Distribution (Microgrid)	Artificial inteligence	Stochastic	✓	✓	✓
10	[17]	-Improve energy management of microgrids	-	✓	✓	-	-	Distribution (Microgrid)	Huristics	-	✓	✓	✓
11	[18]	-Examining power-to-gas systems from techno-economic aspect	✓	-	✓	✓	-	Distribution	-	-	✓	✓	✓
12	[19]	-Improve the flexibility of gas and electricity grids	-	✓	✓	✓		Transmission	OA/ER	-	✓	✓	✓
13	[20]	-Planning a microgrid with net-zero target	-	✓	✓	-	✓	Distribution (Microgrid)	GUROBI	Stochastic	✓	✓	✓
14	[21]	-Improve the operation of microgrids	-	✓	✓	-	-	Distribution (Microgrid)	CPLEX	Stochastic	✓	✓	✓
15	[22]	-Improve operation and configuration	-	✓	✓			Distribution (Microgrid)	CPLEX	Robust	✓	✓	✓
16	[23]	-Improve the operation of electricity grids	-	✓	✓	-	-	Transmission	CPLEX	Robust	✓	✓	✓
17	[24]	-Improve the operation of electricity grids	-	✓	✓	✓	-	Distribution	CPLEX	Possibilistic	✓	✓	✓

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Table 1 (*continued*)

No.	Ref.	Objective	Solution Method		Grid Consideration			Transmission/ Distribution Level	Solver	Uncertainty Consideration Approach	Components		
			Numerical analysis or simulation	*Exact optimization*	*Electricity*	*Gas*	*Hydrogen*				*Renewable*	*P2G*	*Fuel cell/ gas-fired unit*
18	[25]		-	✓	✓	-	-	Distribution (Microgrid)	GUROBI	Robust	✓	✓	✓
19	*	-Evaluating a net-zero emission multi-energy microgrid	-	✓	✓	-	✓	Distribution (Microgrid)	DICOPT	Possibilistic-Robust	✓	✓	✓

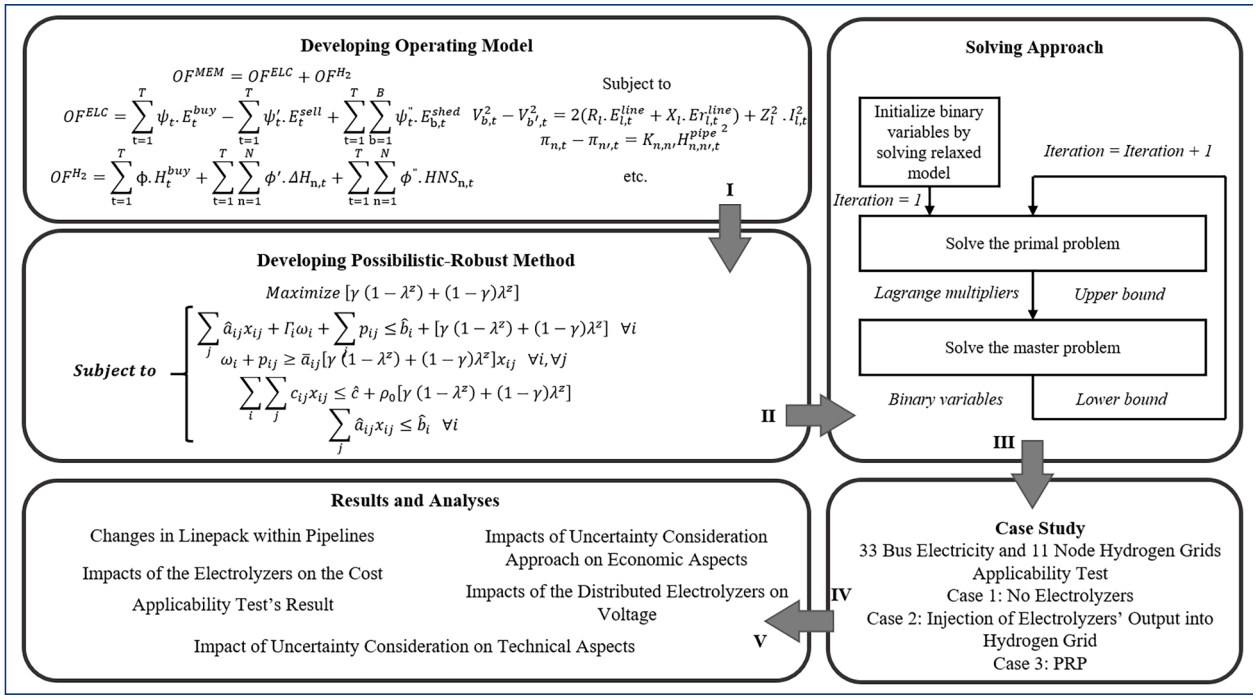

Fig. 1. Overview of the methodology for optimizing microgrid operation with hydrogen energy carrier.

$$OF^{H_2} = \sum_{t=1}^{T} \phi.H_t^{buy} + \sum_{t=1}^{T}\sum_{n=1}^{N} \phi'.\ \Delta H_{n,t} + \sum_{t=1}^{T}\sum_{n=1}^{N} \phi''.HNS_{n,t} \tag{3}$$

2.1.1. Operating constraints of the electricity grid

To fulfill the energy demands of consumers and avoid any risk of system overload or underload when operating an electricity grid, it is important to adhere to technical constraints. In (4), active power balance is presented, which means that the total active power generated by distributed energy resources and renewable resources, along with imported power from the main grid, must match the aggregate active power consumed, losses in distribution lines, power consumption of electrolyzers to produce hydrogen, and exported power to the main grid.

$$E_{b,t}^{dg} + E_{b,t}^{rnw} + E_t^{buy} = E_{b,t}^{load} + \sum_{b'=1}^{B}\left(E_{l,t}^{line} + R_{l,t}.I_{l,t}^2\right) + E_{b,t}^{elz} + E_t^{sell}\ \forall b,\ l\epsilon(b,b'),\forall t \tag{4}$$

Apart from maintaining a balance in active power, the reactive power balance is a crucial constraint that must be taken into consideration in the operation of the electricity grid (Eq. (5)). The operating model should guarantee that the reactive power flow from the main grid matches the total reactive power consumed by the loads and the reactive power losses in the distribution lines. This balance of reactive power is essential in maintaining the voltage stability of the grid.

$$Er_t + \sum_{b'=1}^{B}\left(Er_{l,t}^{line} + X_{l,t}.I_{l,t}^2\right) = Er_{b,t}^{load}\ \forall b,\ l\epsilon(b,b'),\forall t \tag{5}$$

Kirchhoff's law presents another fundamental constraint that should be considered in the electricity grid. According to this law, the voltage and current at every node within the grid must comply with the principle of energy conservation (Eqs. (6)-(7)).

$$V_{b,t}^2 - V_{b',t}^2 = 2\left(R_l.E_{l,t}^{line} + X_l.Er_{l,t}^{line}\right) + Z_l^2.I_{l,t}^2\ l\epsilon(b,b'),\ \forall t \tag{6}$$

$$V_{b,t}^2\ .I_{l,t}^2 = E_{l,t}^{line\ 2} + Er_{l,t}^{line\ 2}\ l\epsilon(b,b'),\ \forall t \tag{7}$$

The maximum and minimum limits for voltage at nodes and current within lines are also necessary, as represented in Eq. (8) and Eq. (9), respectively.

$$V_b^{\min} \le V_{b,t} \le V_b^{\max}\ \forall b,\ \forall t \tag{8}$$

$$0 \le I_{l,t} \le I_l^{\max}\ l\epsilon(b,b'),\ \forall t \tag{9}$$

Additionally, dispatchable and renewable generating units must be

operated within their designated or available power limits, as indicated in Eq. (10). However, the ramp-rate limits of dispatchable units constitute another crucial constraint in the operation, indicated in Eq. (11). These limits govern the rate at which the dispatchable units can ramp up or down their power output. Another set of operating constraints that need to be considered is related to the minimum up/down time of these generating units. As proposed in Eq. (12) and Eq. (13), these constraints refer to the minimum amount of time that a dispatchable unit must remain either on or off after being started or stopped.

$$\Gamma_{i,t}E_b^{min} \le E_{b,t}^{dg} \le \Gamma_{i,t}E_b^{max}\ \forall b,\ \forall t \tag{10}$$

$$\left|E_{b,t}^{dg} - E_{b,t-1}^{dg}\right| \le Ramp_b\ \forall b,\ \forall t \tag{11}$$

$$\Gamma_{i,t'} - \Gamma_{i,t'-1} \le \Gamma_{i,t}\ t'\epsilon[t - T^{on} + 1, t-1] \tag{12}$$

$$\Gamma_{i,t'-1} - \Gamma_{i,t'} \le 1 - \Gamma_{i,t}\ t'\epsilon\left[t - T^{off} + 1, t-1\right] \tag{13}$$

2.1.2. Operating constraints of hydrogen grid

To optimize the operation of the MEM, a set of constraints is also considered for the hydrogen grid. These constraints cover various aspects of the hydrogen distribution system, ensuring its safe and efficient operation. A set of constraints is related to the hydrogen flow balance, indicated in Eq. 14. This constraint ensures that the amount of purchased hydrogen from the upstream, besides the distributed production by electrolyzers, must be equal to the consumption at each time step within the microgrid. By maintaining this balance, the constraint guarantees that the hydrogen demand is adequately met.

$$H_{n,t}^{elz} + H_t^{buy} = H_{n,t}^{dg} + H_{n,t}^{load} + \sum_{n'=1}^{N} H_{p,t}^{line}\ \forall n,\ \forall t \tag{14}$$

To maintain the integrity of the hydrogen grid, the maximum and minimum pressure at each node are limited in Eq. (15). These constraints impose limits on the pressure at each node to ensure that the grid is operated within safe pressure levels.

$$\pi_n^{min} \le \pi_{n,t} \le \pi_n^{max}\ \forall n,\ \forall t \tag{15}$$

The maximum and minimum hydrogen flow within pipes is limited in Eq. (16) to avoid overloading.

$$H_p^{line,min} \le H_{p,t}^{line} \le H_p^{line,\ max}\ p\epsilon(n,n'), \forall t \tag{16}$$

Additionally, linepack refers to the amount of gas stored within the pipes. Eq. (17) is also included, which is related to linepack changes to help manage the storage of hydrogen, allowing the system to respond to demand fluctuations effectively.

$$LP_{p,t} = LP_{p,t}^0 + \sum_0^t \left(H_{p,t}^{pipe,in} - H_{p,t}^{pipe,out}\right)\ p\epsilon(n,n'),\ \forall t \tag{17}$$

Lacey's equation plays a significant role in linking hydrogen flow within pipes to the pressure at nodes, enabling accurate modeling of the hydrogen distribution system [28]. In Eq. (18), Lacey's equation is adapted for a low-pressure hydrogen grid, with an operating pressure between 0 and 75 mbar gauge [29]. In the formulation pressure at nodes (π), the diameter of pipes (D), the length of pipes (L), and the hydrogen flow within pipes (H^{pipe}) are measured in mbar gauge, mm, m, cm/h, respectively.

$$H_{n,n',t}^{pipe} = 0.023\sqrt{\left[\frac{(\pi_{n,t} - \pi_{n',t})D_{n,n'}^5}{f_{n,n'}SL_{n,n'}}\right]}\ p\epsilon(n,n'),\ \forall t \tag{18}$$

Unwin's low-pressure formula [30] can be used to determine the value of f, represented in Eq. (19).

$$f_{n,n'} = 0.0044\left(1 + \frac{12}{0.276D_{n,n'}}\right)\ p\epsilon(n,n'), \tag{19}$$

Alternatively, by replacing the value of 0.0065 with $f_{n,n'}$ for all pipes, Eq. (18) can be replaced by Eq. (20), called Pole's equation.

$$H_{n,n',t}^{pipe} = 0.0071\sqrt{\left[\frac{(\pi_{n,t} - \pi_{n',t})D_{n,n'}^5}{SL_{n,n'}}\right]}\ p\epsilon(n,n'),\ \forall t \tag{20}$$

Considering S equal to 0.0695 for hydrogen, the equation can be rewritten in the following (Eqs. (21)-(22)).

$$\pi_{n,t} - \pi_{n',t} = K_{n,n'}H_{n,n',t}^{pipe\ 2}\ p\epsilon(n,n'),\ \forall t \tag{21}$$

$$K_{n,n'} = \frac{1378.69\ L_{n,n'}}{D_{n,n'}^5}\ p\epsilon(n,n') \tag{22}$$

However, for natural gas distribution, as the S is equal to 0.589, the constant is calculated, as indicated in Eq. 23 [27].

$$K_{n,n'} = \frac{11684.19\ L_{n,n'}}{D_{n,n'}^5}\ p\epsilon(n,n') \tag{23}$$

2.1.3. Linking constraints

In Eq. (24) and Eq. (25), the constraints that link the hydrogen and electricity grids are indicated. The former calculates the hydrogen required for distributed generating units, which is added to the hydrogen flow balance. The latter indicates the electricity consumption to produce hydrogen by electrolyzers, added to the load flow balance.

$$H_{n,t}^{dg} = \phi E_{b\to n,t}^{dg}\ \forall n,\ \forall t \tag{24}$$

$$H_{n\to b,t}^{elz} = \psi E_{b,t}^{elz}\ \forall b,\ \forall t \tag{25}$$

2.2. PRP approach

A PRP approach is proposed to handle the uncertainty in the parameters of the optimization problem. This method is based on the combination of the light-robustness counterpart [31] and possibility theory [32]. In robust programming, Soyster's method ensured feasibility within a convex set but was conservative, leading to a significant loss of optimality [33]. Fischetti and Monaci's light robust method addressed this by introducing a protection level to manage conservatism, but it only considered worst-case scenarios [34]. This developed PRP approach extends the interval representation of uncertain parameters using a fuzzy membership function, allowing decision-makers to better balance robustness and optimality, resulting in more practical solutions under various uncertain conditions.

In the context of MEMs, the electricity demand is an uncertain parameter. The electricity demand is subject to epistemic uncertainty when considering the integration of electrolyzers into the future microgrid, a high penetration of renewable resources in the future, which affects the demand profile of prosumers, and the gas grid, which is employed for hydrogen. More precisely, this uncertainty arises from limited data on future RESs' impacts on electricity demand. Integrating electrolyzers, which produce hydrogen from water using electricity, introduces complexity as it depends on variable RESs like solar and wind. The increasing adoption of renewables alters traditional demand patterns, impacting when and how much electricity prosumers consume and generate. Employing hydrogen within existing gas infrastructure

necessitates coordination and adaptation, further complicating future demand forecasting and grid management. To address these challenges, the possibilistic method is efficient in optimizing the microgrid operation under uncertain and evolving energy conditions.

Considering an optimization problem presented in Eq. (26), the goal is to minimize the total cost, which is expressed as a double summation over all decision variables (x_{ij}) and their corresponding cost coefficients (c_{ij}).

$$\begin{aligned} &Minimize\ z = \sum_i \sum_j c_{ij} x_{ij} \\ &\quad Subject\ to \\ &\sum_j \widetilde{a}_{ij} x_{ij} \le b_i\ \forall i \\ &x_{ij} \ge 0\ \forall i,\ \forall j \end{aligned} \tag{26}$$

In the above-mentioned optimization problem, as discussed, c_{ij} and x_{ij} indicate cost coefficients and decision variables, respectively. However, imprecise constraint coefficients and the right-hand side of constraints are indicated by $\widetilde{a}_{ij}$ belongs to $\left[\widehat{a}_{ij} - \overline{a}_{ij}, \widehat{a}_{ij} + \overline{a}_{ij}\right]$ and b_i, respectively. The robust counterpart of the above-mentioned optimization problem is indicated in Eq. (27) [35].

$$\begin{aligned} &Minimize\ ||\lambda|| \\ &\quad Subject\ to \\ &\sum_j \widehat{a}_{ij} x_{ij} + \Gamma_i \omega_i + \sum_j p_{ij} \le b_i + \gamma_i\ \forall i \\ &\omega_i + p_{ij} \ge \overline{a}_{ij} x_{ij}\ \forall i,\ \forall j \\ &\sum_j \widehat{a}_{ij} x_{ij} \le b_i\ \forall i \\ &\sum_i \sum_j c_{ij} x_{ij} \le \widehat{c} + \rho_0 \\ &x_{ij},\ p_{ij},\ \omega_i \ge 0\ \forall i,\ \forall j \end{aligned} \tag{27}$$

In the robust formulation, the protection level allowing decision makers to set the level of conservatism is indicated by Γ_i. The price of robustness is limited by a fixed tolerance, indicated by ρ_0. The optimal value of the objective function without uncertainty consideration is represented by $\widehat{c}$. The formulation allows decision-makers to make a tradeoff between the price of robustness and the feasibility of robustness [36]. To develop the possibilistic method, a fuzzy membership function is replaced with the uncertainty interval. The formulation of the fuzzy membership function is indicated in Eq. (28). Decision makers can change the z to reach the most preferred membership function [37].

$$\begin{aligned} &Probability\left(a_{ij}(\lambda)\right) = \overline{a}_{ij}(1 - \lambda^z) \\ &\quad z \ge 0 and \lambda \in (0, 1] \end{aligned} \tag{28}$$

This possibilistic method considers both the most optimistic and pessimistic possible level for data occurrence (*Possibility* in Eq. (29) and *Necessity* in Eq. (30)). A tradeoff between possibility and necessity is developed, which is called *Mean* in Eq. (31) and Eq. (32) [37].

$$Possibility(a) = sup(Probability(a)) \tag{29}$$

$$Necessity(a) = 1 - Possibility(a) \tag{30}$$

$$Mean(a) = \gamma Possibility(a) + (1 - \gamma) Necessity(a) \tag{31}$$

$$Necessity(a) \le Mean(a) \le Possibility(a) \tag{32}$$

Considering *Possibility*, *Necessity*, and *Mean*, the optimization problem in Eq. (26) can be reformulated as shown in Eq. (33) as *Mean* is greater than $[\gamma(1 - \lambda^z) + (1 - \gamma)\lambda^z]$ if and only if $\sum_j \widetilde{a}_{ij} x_{ij} \le b_i$ is maximized.

$$\begin{aligned} &Maximize\ [\gamma\ (1 - \lambda^z) + (1 - \gamma)\lambda^z] \\ &\quad Subject\ to \\ &\sum_j \widehat{a}_{ij} x_{ij} + \Gamma_i \omega_i + \sum_j p_{ij} \le b_i + \varsigma_i\ \forall i \\ &\omega_i + p_{ij} \ge \overline{a}_{ij} [\gamma\ (1 - \lambda^z) + (1 - \gamma)\lambda^z] x_{ij}\ \forall i,\ \forall j \\ &\sum_j \widehat{a}_{ij} x_{ij} \le b_i\ \forall i \\ &\sum_i \sum_j c_{ij} x_{ij} \le \widehat{c} + \rho_0 \\ &x_{ij},\ p_{ij},\ \omega_i \ge 0\ \forall i,\ \forall j \end{aligned} \tag{33}$$

In the case of uncertainty in b_i, optimization problem proposed in Eq. (33) is replaced by Eq. (34), which indicates the generalized formulation of the PRP approach.

$$\begin{aligned} &Maximize\ [\gamma\ (1 - \lambda^z) + (1 - \gamma)\lambda^z] \\ &\quad Subject\ to \\ &\sum_j \widehat{a}_{ij} x_{ij} + \Gamma_i \omega_i + \sum_j p_{ij} \le \widehat{b}_i + [\gamma\ (1 - \lambda^z) + (1 - \gamma)\lambda^z]\ \forall i \\ &\omega_i + p_{ij} \ge \overline{a}_{ij} [\gamma\ (1 - \lambda^z) + (1 - \gamma)\lambda^z] x_{ij}\ \forall i,\ \forall j \\ &\sum_j \widehat{a}_{ij} x_{ij} \le \widehat{b}_i\ \forall i \\ &\sum_i \sum_j c_{ij} x_{ij} \le \widehat{c} + \rho_0 [\gamma\ (1 - \lambda^z) + (1 - \gamma)\lambda^z] \\ &x_{ij},\ p_{ij},\ \omega_i \ge 0\ \forall i,\ \forall j \end{aligned} \tag{34}$$

In the optimal operation of the MEM, the PRP model is written in Eq. (35).

2.3. Solving approach and applicability test

To solve the developed problem in this study, Discrete and Continuous Optimizer (DICOPT) is employed using General Algebraic Modeling System (GAMS) software [37]. Based on the iterative approach described in Fig. 2(a), the solving method involves generating upper and lower bounds in each iteration to tackle the Mixed-Integer Nonlinear Programming (MINLP) problem effectively [38]. The upper bound is derived from the primal problem, utilizing initialized binary variables from the relaxed problem solution in the first iteration and the master problem in subsequent iterations. The lower bound is obtained by solving the master problem, where nonlinear equality constraints are linearized at the current solution to generate a cutting plane. The process iterates between solving the primal and master problems, gradually refining the solution until convergence is achieved. Additionally, a geometrical interpretation of the linearizations in the master problem

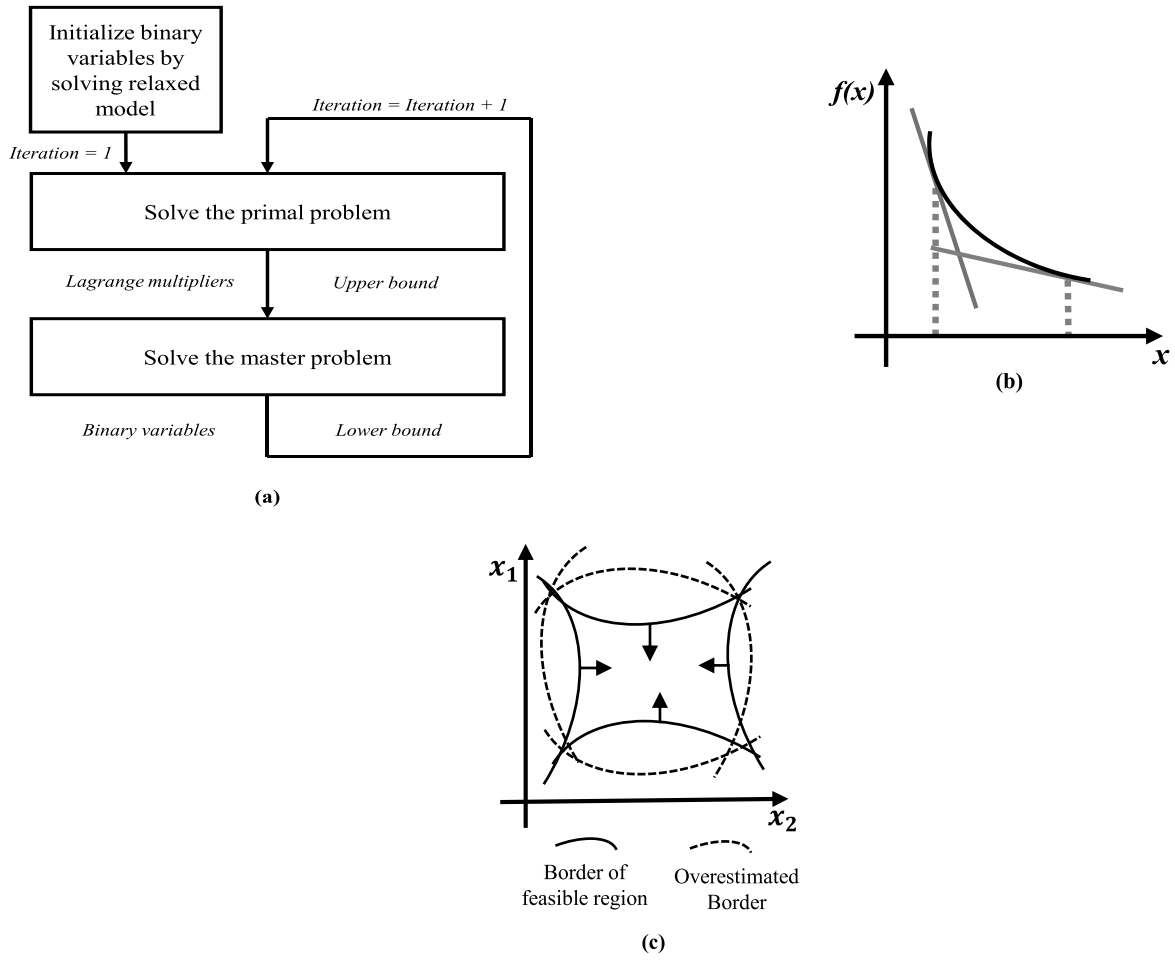

Fig. 2. Solving approach for the operation of MEMs ((a) iterative approach utilized by DICOPT solver, (b) objective function underestimation, and (c) feasible region overestimation).

illustrates how the objective function is underestimated while the feasible region is overestimated, aiding in the efficient solving of the optimization problem (Fig. 2(b) and (c)) [11].

The potential for repurposing the natural gas grid for hydrogen distribution involves evaluating key grid characteristics, such as the pipe's diameter and length. Given the energy density differences, supplying the same load with hydrogen requires three times the volume compared to natural gas. In this study, load shedding for hydrogen demand is tested when the natural gas demand is on the verge of shedding.

$$
\begin{aligned}
&\textit{Maximize } [\gamma\ (1-\lambda^z)+(1-\gamma)\lambda^z]\\
&\textit{Subject to}\\
&-E^{dg}_{b,t}-E^{rnw}_{b,t}-E^{buy}_{t}+\sum_{b'=1}^{B}\left(E^{line}_{l,t}+R_{l,t}.I^2_{l,t}\right)+E^{elz}_{b,t}+E^{sell}_{t}+\Gamma_{b,t}\omega_{b,t}+\sum_{t}p_{b,t}\leq\\
&\overline{E^{load}_{b,t}}+[\gamma\ (1-\lambda^z)+(1-\gamma)\lambda^z]\ \forall b,\forall t\\
&\omega_{b,t}+p_{b,t}\geq\\
&\left(-E^{dg}_{b,t}-E^{rnw}_{b,t}-E^{buy}_{t}+\sum_{b'=1}^{B}\left(E^{line}_{l,t}+R_{l,t}.I^2_{l,t}\right)+E^{elz}_{b,t}+E^{sell}_{t}+\Gamma_{b,t}\omega_{b,t}+\sum_{t}p_{b,t}\right)[\gamma\ (1-\lambda^z)+(1-\gamma)\lambda^z]\forall b,\forall t\\
&-E^{dg}_{b,t}-E^{rnw}_{b,t}-E^{buy}_{t}+\sum_{b'=1}^{B}\left(E^{line}_{l,t}+R_{l,t}.I^2_{l,t}\right)+E^{elz}_{b,t}+E^{sell}_{t}+\Gamma_{b,t}\omega_{b,t}+\sum_{t}p_{b,t}\leq -E^{load}_{b,t}\ \forall b,\ \forall t\\
&OF^{MEM}\leq OF^{MEM*}+\rho_0[\gamma\ (1-\lambda^z)+(1-\gamma)\lambda^z]\\
&\omega_{b,t}\ \textit{and}\ p_{b,t}\geq 0
\end{aligned}
\tag{35}
$$

Eqs. (5)-(17), (21), and (23)-(24).

If hydrogen can supply the load without shedding, it indicates the feasibility of using the natural gas grid for hydrogen distribution. Further analysis includes checking load shedding when natural gas demand is on the verge of shedding, and there is low linepack within the pipe. The successful supply of hydrogen without load shedding demonstrates the feasibility of utilizing the natural gas grid for hydrogen. Additionally, a more detailed analysis considers initial linepack requirements within the pipe. The absence of load shedding in hydrogen distribution during this assessment further validates the suitability of adapting existing natural gas infrastructure to support hydrogen distribution. It should be noted that, in this study, the risk associated with the leakage of hydrogen and explosion is not considered.

3. Case study

The case study is an MEM, consisting of hydrogen and electricity distribution grids. In this study, the potential for hydrogen to serve as an alternative to natural gas is examined under conditions where the natural gas demand is high. The focus is on evaluating whether hydrogen can maintain the load without requiring load shedding when (i) the natural gas supply is on the verge of shedding (energy demand is high) and (ii) there is a low linepack conditions within the pipeline. In both cases, hydrogen supply without load shedding supports the feasibility of utilizing the natural gas grid for hydrogen from the viewpoint of supply-demand provision. After that, three cases are examined in this study, as follows:

Case 1. In the first case, the operation of the MEM is studied when there is no electrolyzer.

Case 2. In the second case, there are electrolyzers in the microgrid, and the output hydrogen of these systems is injected into the hydrogen grid.

Case 3. In the third case, in addition to the existence of the electrolyzers, the proposed PRP approach is integrated to deal with the uncertainty in electricity demand and output power of renewable resources.

3.1. Hydrogen grid

The hydrogen grid consists of 11 nodes and 14 pipes, connected to the upstream grid through node one, which can import or export hydrogen. An illustration of the hydrogen grid is indicated in Fig. 3. More detailed information about the hydrogen grid under study, such as diameter and length of pipes, pressure and flow limits, supply limit, and costs, can be found in [39]. For natural gas, the purchasing cost is assumed to be $350/kcm, the linepack management cost is $3.5/kcm, and the load shedding cost is $3500/kcm. For hydrogen, the purchasing cost is assumed to be $540.5/kcm, the linepack management cost is $5.25/kcm, with the load shedding cost, assumed to be the same.

3.2. Electricity grid

The electricity grid under study is illustrated in Fig. 4. This grid consists of 33 nodes and 32 electric lines. The flexible generating units and electrolyzers are connected to buses numbered two and nine. The buses are connected to the hydrogen distribution grid. The wind turbines are connected to the buses numbered 15, 29, 30, and 32. The installed capacity of the components installed in the electricity grid is also indicated in Table 2. More detailed data about the electricity system, such as electricity price and characteristics of lines, can be found in [11]. The proposed model for the operation of the MEM, consisting of hydrogen and electricity grids, is solved in the General Algebraic Modeling System, GAMS software, using a computer with an Intel Core i7 processor and 8 GB of RAM.

4. Results and discussions

In Fig. 5(a), the supply curve analysis over 24 h reveals significant insights into the performance of natural gas and hydrogen under varying conditions (Natural gas (NG), Natural Gas-Low Initial Linepack (NGL), Hydrogen (H2), and Hydrogen-Low Initial Linepack (H2L)). Under high demand, the natural gas supply meets demand without experiencing load shedding. In the scenario where the initial linepack is low, the system requires increased injections of natural gas to sustain demand. Conversely, hydrogen supply demonstrates robustness in both normal and low initial linepack conditions. Although the volume of hydrogen required is inherently higher due to its lower energy density, it also meets demand without load shedding. Notably, in the low linepack scenario, the hydrogen supply requires a slight increase compared to normal linepack conditions, but still maintains system stability and demand fulfillment. These findings indicate the potential of repurposing existing natural gas infrastructure for hydrogen distribution, with appropriate adjustments to account for hydrogen's volumetric and linepack characteristics. The linepack within the pipe indicates that, in the case of natural gas supply, more injections are required to compensate for the low initial linepack (Fig. 5(b)). However, for hydrogen supply, the linepack remains lower throughout the entire operating period. Hydrogen transfers faster than natural gas due to its smaller and lighter molecules, resulting in higher diffusion and flow rates. Consequently, even with a lower linepack, hydrogen can maintain a consistent supply, demonstrating the feasibility of using existing natural gas infrastructure for hydrogen distribution.

The obtained results from Case 1 and Case 2 (without and with electrolyzers, respectively), including wind power, purchased power from the main grid, and output of gas-fired units, are indicated in Fig. 6. In Fig. 6(a), it is indicated that there is wind curtailment without electrolyzers, especially from 01:00 to 07:00. In case 2, the total amount of wind curtailment during the operating period is about 800 kW. In Figs. 6 (b) and (c), the power purchased from the main grid and the output power of the gas-fired generating units are indicated. In case 1, a

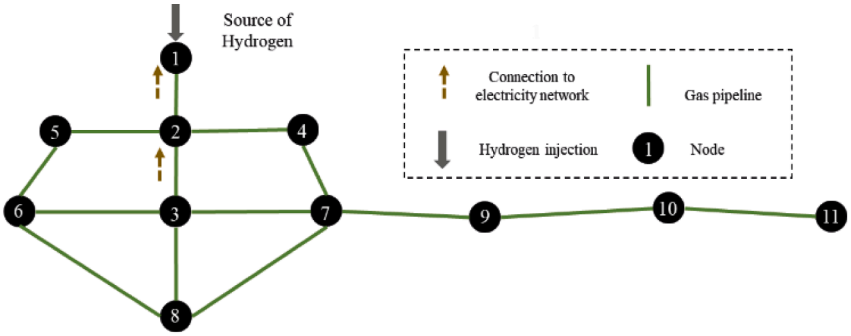

Fig. 3. Case study - hydrogen grid [39].

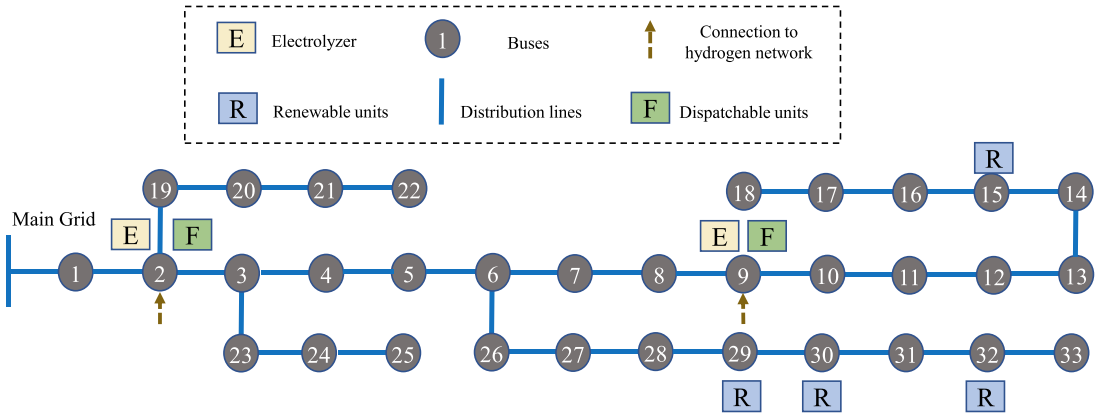

Fig. 4. Case study - electricity grid [40].

Table 2
Characteristics of components in the electricity grid.

Component	Location	Characteristics
Wind	Node 15, Node 29, Node 30, and Node 32	Capacity=2800 kW [41]
Flexible units	Node 2 and Node 9	Capacity=600 kW, Efficiency=55 %, Conversion Rate= 0.00027 MW/mcm, and Ramp rate=50 % [42]
Electrolyzers	Node 2 and Node 9	Capacity=5000 kW and Efficiency=60 % [43]

considerable amount of power is purchased from the main grid, as indicated in Fig. 6(b). The purchased power in Case 1 is about 50 MW more than the purchased power in Case 2. However, in the presence of electrolyzers, more power is produced utilizing gas-fired generating units. The produced power utilizing gas-fired units in Case 2 is around 40 MW more than the generated power in Case 1. The reason is the availability of Hydrogen in the case of the presence of electrolyzers, which assists the transition to a lower-carbon energy system.

In Fig. 7, the maximum voltage deviation in the electricity grid is compared during the operating period in the absence and presence of the electrolyzers (Case 1 and Case 2, respectively). The graph shows the lower voltage deviation in the presence of the electrolyzers. More voltage drops in the absence of electrolyzers are evident from 13:00 to 19:00. When there is a voltage drop, it is possible for various components that use electricity to become overheated. Voltage deviation is an important indicator of power quality and grid stability; excessive deviations can lead to equipment malfunction, reduced efficiency, and potential damage to sensitive electrical devices.

The hydrogen purchased from the market supplied into the hydrogen distribution grid is indicated in Fig. 8. The figure shows a greater dependency on purchasing hydrogen in the absence of electrolyzers. The

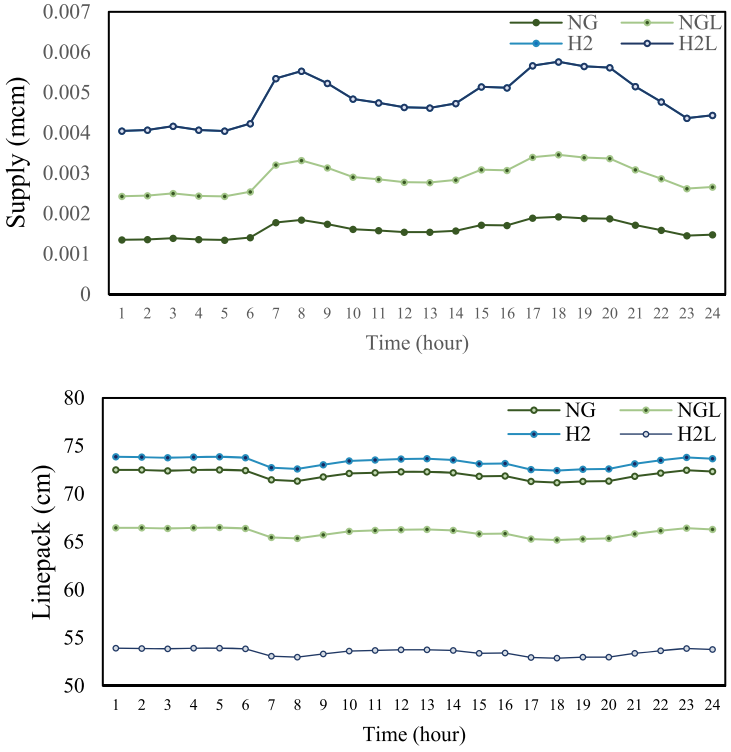

Fig. 5. Supply (a) and linepack (b)-utilization of gas grid for hydrogen (Natural gas (NG), Natural Gas-Low Initial Linepack, Hydrogen (H2), and Hydrogen-Low Initial Linepack (H2L)).

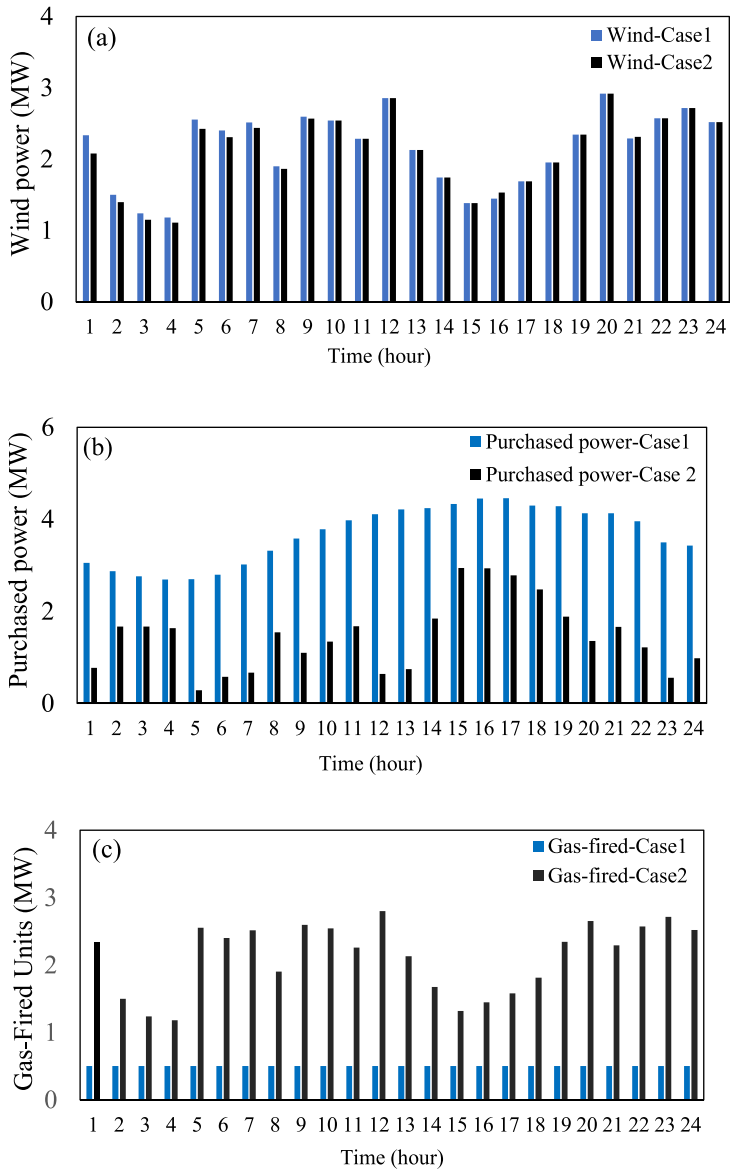

Fig. 6. Output of the optimization problem ((a) wind power, (b) purchased power from the main grid, and (c) gas-fired units' output power, Case 1 without electrolyzer versus Case 2 with presence of electrolyzers).

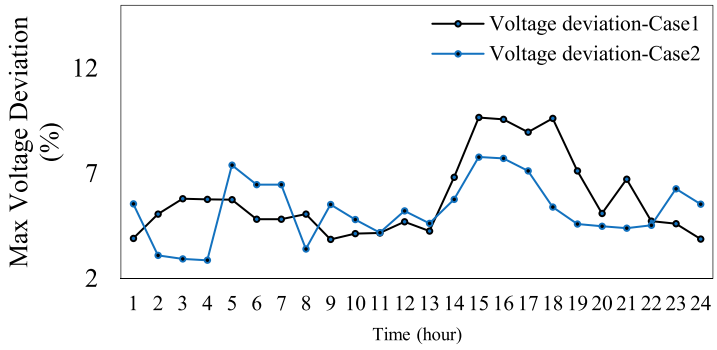

Fig. 7. Maximum voltage deviation - Case 1 (no electrolyzer) versus Case 2 (presence of electrolyzers).

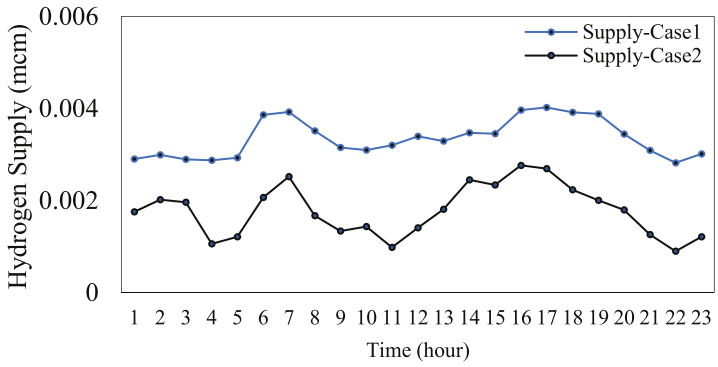

Fig. 8. Hydrogen supply - Case 1 (no electrolyzer) versus Case 2 (presence of electrolyzers).

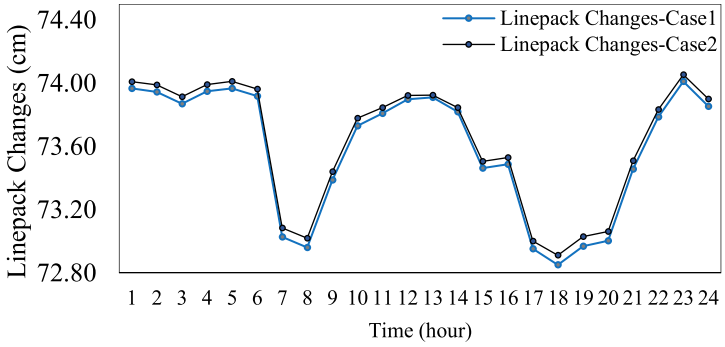

Fig. 9. Linepack changes - Case 1 (no electrolyzer) versus Case 2 (presence of electrolyzers).

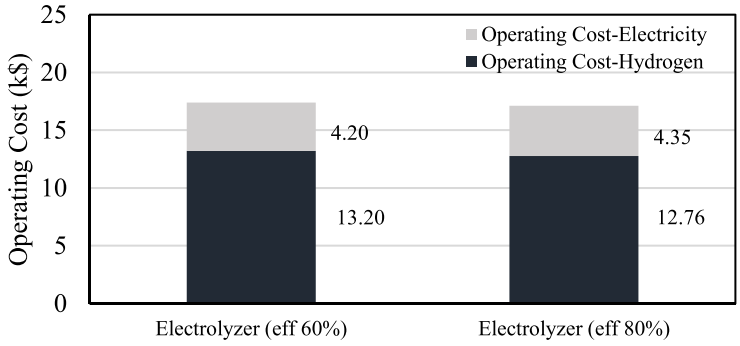

Fig. 10. Analysis of the operating cost of hydrogen and electricity grids when the efficiency increases from 60 % to 80 %.

total amount of purchased hydrogen is about 38,000 cm higher when there are no electrolyzers connected to the grid. Relying on locally generated hydrogen can be advantageous as it increases the reliability of the hydrogen supply. In the event of a failure in the upstream grid, there would be no issues. Moreover, it can lead to cost savings and emission reduction as hydrogen can be produced from accessible renewable sources in the electricity grid. Finally, in Fig. 9, the changes in linepack, which is hydrogen stored within pipes, are indicated during the 24-hour operating period. Based on the results, there are more changes in the linepack in the presence of electrolyzers (or Case 2). It indicates the operation of this grid is more efficient, and the linepack assists supply-demand provision. More precisely, more efficient utilization of the stored hydrogen within pipes has the potential to reduce the operating cost of the hydrogen grid significantly.

In addition to the analysis conducted on the system performance with and without the electrolyzer, a further investigation is performed to examine the sensitivity of system operation to electrolyzer efficiency and the electrification of heat demand supplied through the electricity grid instead of the hydrogen grid. The results show that increasing electrolyzer efficiency from 60 % to 80 % leads to a noticeable shift in the cost distribution between the two energy grids. Specifically, the operating cost of the electricity grid increases due to higher power purchases required to operate the electrolyzers, while the hydrogen grid cost decreases considerably as more hydrogen is generated locally. This trade-off highlights the system's sensitivity to electrolyzer efficiency, emphasizing that higher efficiency improves overall hydrogen production economics but imposes additional stress and cost on the electricity grid, as illustrated in Fig. 10.

Aside from what has already been discussed, in Case 3, the problem of optimal operation of hydrogen and electricity distribution grids is considered utilizing the PRP approach. To evaluate the performance of the proposed method in this study, the costs and standard deviations are compared ten times, generating random values for uncertain parameters (i.e., electricity demand). This ten-time random data generation is

Table 3
Analyses of uncertainty consideration approach.

Conservatism Level	Uncertainty interval (Z)	Operating cost ($)		Mean value	Standard deviation
		Electricity grid	Hydrogen grid		
$\Gamma = 0.1$	2	5675.69	14,720.23	22,231.55	566.86
$\Gamma = 1$	2	5806.23	15,058.79	22,742.87	508.62
$\Gamma = 10$	2	6212.66	15,152.43	23,287.95	475.27
$\Gamma = 0.1$	3	6078.66	14,821.79	20,522.90	565.55
$\Gamma = 1$	3	6305.56	15,171.73	21,094.22	508.01
$\Gamma = 10$	3	6784.22	14,287.29	21,769.08	474.79
$\Gamma = 0.1$	1	5663.69	13,839.21	24,057.78	617.57
$\Gamma = 1$	1	5887.54	14,165.94	24,682.33	553.94
$\Gamma = 10$	1	6334.47	14,273.84	25,460.93	519.77

chosen because, after ten iterations, there are no significant changes in the mean values and standard deviations, indicating the knee point. The output of the examination is indicated in Table 3. Based on the results, by increasing the conservatism level from 0.1 to 10, the mean value increases by around 5 % while the standard deviation decreases by around 16 %, highlighting a better performance in dealing with uncertainty. It is important to recognize that the rise in operating costs is primarily due to the increased purchases of electricity from the main electricity grid, as indicated in Fig. 11. In this figure, as the conservatism level increases from 0.1 to 10, the total purchased power also increases from 37 MW to over 40 MW. Another sensitivity analysis is conducted by changing the uncertainty interval (i.e., changing z). The results indicate that a higher value of z causes the membership function to decline more rapidly, representing a more conservative decision. Conversely, a lower value of z produces a flatter membership function, reflecting more optimistic assumptions. The conservative case yields lower mean values and smaller standard deviations in the realization of uncertain parameters, resulting in more robust but higher-cost operational outcomes.

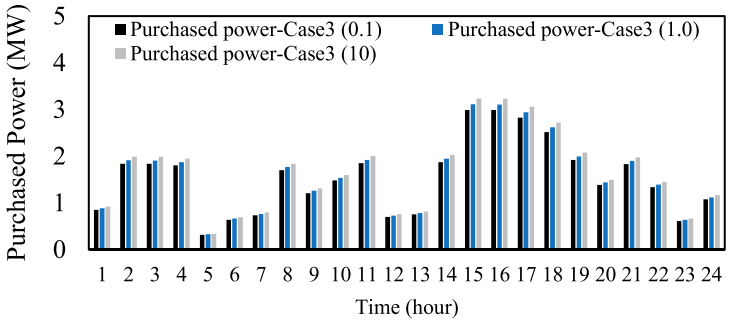

Fig. 11. Purchased power - Case 3 (with uncertainty consideration $z = 2$).

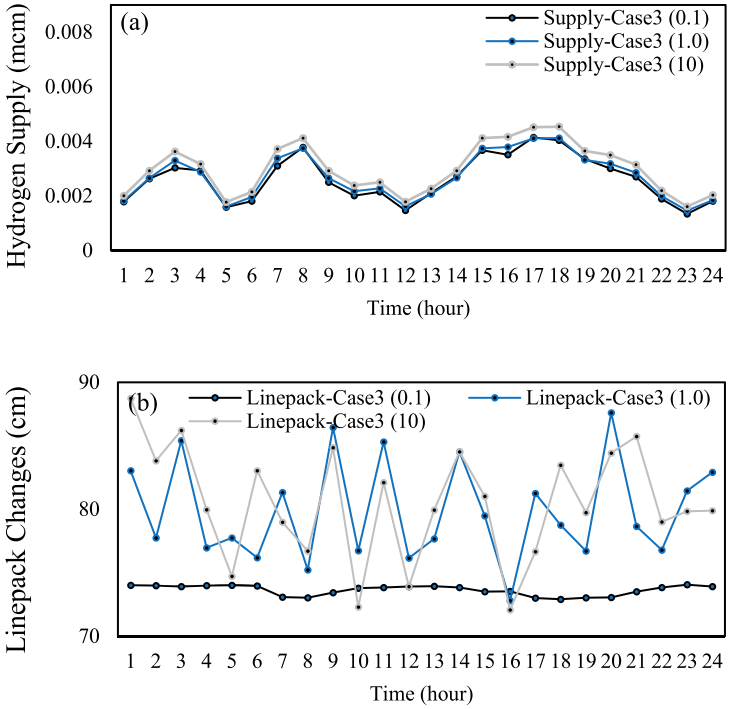

Fig. 12. (a) Hydrogen supply and (b) linepack changes - Case 3 (with uncertainty consideration).

As illustrated in Fig. 12(a) and (b), another reason for the increase in operating costs is related to a greater hydrogen supply and linepack within the pipes. During the operational period, as the level of conservatism increases from 0.1 to 1, there is a corresponding increase of approximately 8000 cm in the hydrogen supply and 1600 cm in the linepack. Although this increases the cost of operations, it is a necessary measure to adapt to changes in demand. For example, having more linepack enables a quicker supply of hydrogen during times of varying demand, as well as meeting the demand for gas-fired units that assist with varying electricity demand provision. The reason for this is that the transfer of hydrogen within pipes from supply nodes to demand nodes takes time. Moreover, a higher linepack requires more injection of hydrogen from supply nodes, which in turn increases operating costs. In the case of increased linepack (Case 3 (1.0) and (10)), the stored hydrogen is used to supply demand, causing oscillations in linepack levels, as indicated in Fig. 12(b). For these two conversion levels, the oscillations are in the same direction, while the total changes in linepack are greater at a conversion level of 10, indicating more efficient use of linepack.

Overall, the findings of this study have significant practical implications for microgrid owners, particularly those considering the integration of hydrogen into their energy systems. In relation to the primary objective of this research, the results demonstrate the robustness of hydrogen supply in maintaining supply-demand balance even under low initial linepack conditions. Hydrogen's ability to transfer faster than natural gas due to its smaller and lighter molecules results in higher diffusion and flow rates, which allows for faster response to the changes. This efficiency can be advantageous for microgrid operators, as it allows for a consistent supply even with lower linepack levels. Consequently, microgrid owners can consider investing in hydrogen infrastructure without the need for significant increases in storage capacity, thus optimizing the use of existing pipes and linepack management that reduces capital expenditure. Furthermore, the role of electrolyzers, also central to the primary objective, is shown to be crucial in integrating RESs into the microgrid. Electrolyzers reduce wind curtailment and enhance the utilization of locally generated hydrogen, thereby improving both the reliability of hydrogen supply and the overall energy efficiency of the system. This integration supports a stable and flexible operation of the MEM while facilitating progress toward a net-zero emission energy system.

In relation to the secondary objective, which introduces the PRP approach to capture uncertainties, the findings highlight the stability of system performance under uncertain operating conditions. The PRP-based model ensures robust decision-making despite fluctuations in renewable generation and demand, resulting in consistent operational outcomes and reduced standard deviation under the realization of uncertain parameters as key performance indicators. This confirms the effectiveness of the proposed approach in managing uncertainty and enhancing the reliability and resilience of MEM operations.

Overall, these results collectively demonstrate that the developed framework and uncertainty modeling approach successfully meet the primary and secondary objectives of this study, offering a practical, adaptable, and robust solution for the integration of hydrogen in multi-energy microgrids.

5. Conclusion

This research aimed to optimize microgrid operations for a cleaner energy future by examining hydrogen as a substitute for natural gas. In line with the primary objective of this research, a comprehensive mathematical framework was developed to evaluate the applicability of existing gas infrastructure for hydrogen distribution and to assess the roles of electrolyzers, gas-fired units, and linepack within Multi-Energy Microgrids. The developed applicability test demonstrated that existing low-pressure natural gas pipelines can be effectively repurposed for hydrogen transport from demand provision aspect. This finding confirms the technical feasibility of hydrogen integration with minimal additional investment in new infrastructure, though our work extends prior findings by incorporating both the electrical and gas subsystems in a unified optimization model. The results further revealed that incorporating electrolyzers significantly improved renewable energy utilization, reducing wind curtailment by approximately 2 % and enhancing system voltage stability by about 8 %. These outcomes directly address the primary objective's focus on evaluating electrolyzers' contributions to flexible operation. The observed efficiency gains are consistent with earlier findings on electrolyzer-based grid balancing. However, this model also highlighted the unique advantage of leveraging linepack as a temporary hydrogen storage mechanism, an aspect that remains underexplored in previous studies. Addressing the secondary objective, the proposed Possibilistic-Robust Programming approach effectively managed uncertainties in renewable generation and demand, yielding solutions with reduced standard deviation and improved cost stability under varying conditions. This demonstrates the approach's capacity to provide realistic and reliable decision-making under uncertainty, complementing and extending previous PRP-based studies by explicitly incorporating hydrogen-related variability. Overall, this study successfully meets both its primary and secondary objectives, demonstrating that repurposing existing gas infrastructure for hydrogen use, supported by robust optimization techniques, can enable a cost-effective, reliable, and sustainable energy transition.

The findings contribute to the growing body of research advocating for hydrogen-integrated microgrids and provide actionable insights for policymakers, energy planners, and microgrid operators seeking to advance toward net-zero energy systems. While these findings are promising, the study acknowledges several limitations and assumptions. The current model does not explicitly address hydrogen leakage or explosion risks, which could affect both system safety and economic feasibility. In addition, uncertainties related to infrastructure retrofitting costs, material compatibility of existing pipelines, and hydrogen purity requirements were not explicitly modeled. These aspects, along with the simplified representation of renewable variability and aggregated operational constraints, present important directions for future work. Incorporating these real-world constraints and cost uncertainties will enhance the robustness and applicability of the proposed framework in practical planning contexts.

Declaration of generative AI and AI-Assisted technologies in writing process

During the preparation of this work, the authors used ChatGPT in order to improve the readability and language. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

CRediT authorship contribution statement

Vahid Shahbazbegian: Writing – original draft, Software, Methodology, Investigation, Data curation. **Hossein Ameli:** Writing – original draft, Visualization, Methodology, Investigation, Data curation. **Goran Strbac:** Writing – review & editing, Supervision. **Hannu Laaksonen:** Writing – review & editing, Validation, Conceptualization. **Miadreza Shafie-khah:** Writing – review & editing, Validation, Conceptualization.

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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Data availability

Data will be made available on request.

References

[1] A. Shrestha, Y. Rajbhandari, F. Gonzalez-Longatt, Day-ahead energy-mix proportion for the secure operation of renewable energy-dominated power system, Int. J. Electr. Power Energy Syst. 155 (2024) 109560, https://doi.org/10.1016/J.IJEPES.2023.109560.

[2] F. Dehghani, M. Mohammadi, M. Karimi, Age-dependent resilience assessment and quantification of distribution systems under extreme weather events, Int. J. Electr. Power Energy Syst. 150 (2023) 109089, https://doi.org/10.1016/J.IJEPES.2023.109089.

[3] A. Ali Dashtaki, S. Mehdi Hakimi, Arezoo Hasankhani, G. Derakhshani, B. Abdi, Optimal management algorithm of microgrid connected to the distribution network considering renewable energy system uncertainties, Int. J. Electr. Power Energy Syst. 145 (2023) 108633, https://doi.org/10.1016/J.IJEPES.2022.108633.

[4] A. Rabiee, A. Keane, A. Soroudi, Green hydrogen: a new flexibility source for security constrained scheduling of power systems with renewable energies, Int. J. Hydrog. Energy 46 (2021) 19270–19284, https://doi.org/10.1016/J.IJHYDENE.2021.03.080.

[5] N.S. Muhammed, A.O. Gbadamosi, E.I. Epelle, A.A. Abdulrasheed, B. Haq, S. Patil, et al., Hydrogen production, transportation, utilization, and storage: recent advances towards sustainable energy, J. Energy Storage 73 (2023) 109207, https://doi.org/10.1016/J.EST.2023.109207.

[6] I. Saedi, S. Mhanna, P. Mancarella, Integrated electricity and gas system modelling with hydrogen injections and gas composition tracking, Appl. Energy 303 (2021) 117598, https://doi.org/10.1016/J.APENERGY.2021.117598.

[7] C. Wang, S. Chen, J. Zhao, Y. Zhou, Z. Wei, S. Zheng, Coordinated scheduling of integrated electricity, heat, and hydrogen systems considering energy storage in heat and hydrogen pipelines, J. Energy Storage 85 (2024) 111034, https://doi.org/10.1016/J.EST.2024.111034.

[8] S. Pellegrino, A. Lanzini, P. Leone, Greening the gas network – The need for modelling the distributed injection of alternative fuels, Renew. Sustain. Energy Rev. 70 (2017) 266–286, https://doi.org/10.1016/J.RSER.2016.11.243.

[9] B. Lux, G. Deac, C.P. Kiefer, C. Kleinschmitt, C. Bernath, K. Franke, et al., The role of hydrogen in a greenhouse gas-neutral energy supply system in Germany, Energy Convers. Manage 270 (2022) 116188, https://doi.org/10.1016/J.ENCONMAN.2022.116188.

[10] J. Wang, X. Xu, L. Wu, Q. Huang, Z. Chen, W. Hu, Risk-averse based optimal operational strategy of grid-connected photovoltaic/wind/battery/diesel hybrid energy system in the electricity/hydrogen markets, Int J Hydrog. Energy 48 (2023) 4631–4648, https://doi.org/10.1016/J.IJHYDENE.2022.11.006.

[11] V. Shahbazbegian, M. Shafie-khah, H. Laaksonen, G. Strbac, H. Ameli, Resilience-oriented operation of microgrids in the presence of power-to-hydrogen systems, Appl. Energy 348 (2023) 121429, https://doi.org/10.1016/J.APENERGY.2023.121429.

[12] A. Martinez Alonso, G. Matute, J.M. Yusta, T. Coosemans, Multi-state optimal power dispatch model for power-to-power systems in off-grid hybrid energy systems: a case study in Spain, Int. J. Hydrog. Energy 52 (2024) 1045–1061, https://doi.org/10.1016/J.IJHYDENE.2023.06.019.

[13] E. Marzi, M. Morini, C. Saletti, S. Vouros, V. Zaccaria, K. Kyprianidis, et al., Power-to-Gas for energy system flexibility under uncertainty in demand, production and price, Energy 284 (2023) 129212, https://doi.org/10.1016/J.ENERGY.2023.129212.

[14] H. Chen, H. Wu, T. Kan, J. Zhang, H. Li, Low-carbon economic dispatch of integrated energy system containing electric hydrogen production based on VMD-GRU short-term wind power prediction, Int. J. Electr. Power Energy Syst. 154 (2023) 109420, https://doi.org/10.1016/J.IJEPES.2023.109420.

[15] D.B. Aeggegn, G.N. Nyakoe, C. Wekesa, Optimal sizing of grid connected multi-microgrid system using grey wolf optimization, Results Eng. 23 (2024) 102421, https://doi.org/10.1016/J.RINENG.2024.102421.

[16] I. Elabbassi, M. Khala, N. Elyanboiy, O. Eloutassi, Y. El hassouani, Evaluating and comparing machine learning approaches for effective decision making in renewable microgrid systems, Results Eng. 21 (2024) 101888, https://doi.org/10.1016/J.RINENG.2024.101888.

[17] R.A. Younis, E. Touti, M. Aoudia, W. Zahrouni, A.I. Omar, A.H. Elmetwaly, Innovative hybrid energy storage systems with sustainable integration of green hydrogen and energy management solutions for standalone PV microgrids based on reduced fractional gradient descent algorithm, Results Eng. 24 (2024) 103229, https://doi.org/10.1016/J.RINENG.2024.103229.

[18] G. Fambri, C. Diaz-Londono, A. Mazza, M. Badami, T. Sihvonen, R. Weiss, Techno-economic analysis of Power-to-Gas plants in a gas and electricity distribution network system with high renewable energy penetration, Appl. Energy 312 (2022) 118743, https://doi.org/10.1016/J.APENERGY.2022.118743.

[19] H. Ameli, M. Qadrdan, G. Strbac, Coordinated operation strategies for natural gas and power systems in presence of gas-related flexibilities, IET Energy Syst. Integr. 1 (2019) 3–13, https://doi.org/10.1049/IET-ESI.2018.0047.

[20] X. Sun, X. Cao, B. Zeng, Q. Zhai, X. Guan, Multistage dynamic planning of integrated hydrogen-electrical microgrids under multiscale uncertainties, IEEe Trans. Smart. Grid. 14 (2023) 3482–3498, https://doi.org/10.1109/TSG.2022.3232545.

[21] N. Rezaei, Y. Pezhmani, Optimal islanding operation of hydrogen integrated multi-microgrids considering uncertainty and unexpected outages, J. Energy Storage 49 (2022) 104142, https://doi.org/10.1016/J.EST.2022.104142.

[22] L. Li, C. Ning, G. Pan, L. Zhang, W. Gu, L. Zhao, et al., A risk-averse just-in-time scheme for learning-based operation of microgrids with coupled electricity-hydrogen-ammonia under uncertainties, IEEe Trans. Sustain. Energy (2025), https://doi.org/10.1109/TSTE.2025.3561067.

[23] Y. Qiu, Q. Li, T. Wang, L. Yin, W. Chen, H. Liu, Optimal planning of Cross-regional hydrogen energy storage systems considering the uncertainty, Appl. Energy 326 (2022) 119973, https://doi.org/10.1016/J.APENERGY.2022.119973.

[24] G. Zhang, Y. Ge, Z. Ye, M. Al-Bahrani, Multi-objective planning of energy hub on economic aspects and resources with heat and power sources, energizable, electric vehicle and hydrogen storage system due to uncertainties and demand response, J. Energy Storage 57 (2023) 106160, https://doi.org/10.1016/J.EST.2022.106160.

[25] R. Xu, Z. Hong, G. Wang, T. Zhu, D. Li, Z. Li, et al., Two-stage robust optimization of hydrogen microgrid in plateau tourist cities —Taking Yunnan Lijiang as an example, Carbon Neutrality 4 (2025) 1–21, https://doi.org/10.1007/S43979-025-00121-2/TABLES/4.

[26] V. Shahbazbegian, H. Ameli, M. Shafie-Khah, H. Laaksonen, M.T. Ameli, G. Strbac, Optimal scheduling of gas and electricity distribution networks in microgrids: a decomposition approach, in: 2022 IEEE International Conference on Environment and Electrical Engineering and 2022 IEEE Industrial and Commercial Power Systems Europe, EEEIC /I and CPS Europe 2022, 2022, https://doi.org/10.1109/EEEIC/ICPSEUROPE54979.2022.9854624.

[27] V. Shahbazbegian, F. Dehghani, M.A. Shafiyi, M. Shafie-khah, H. Laaksonen, H. Ameli, Techno-economic assessment of energy storage systems in multi-energy microgrids utilizing decomposition methodology, Energy 283 (2023) 128430, https://doi.org/10.1016/J.ENERGY.2023.128430.

[28] Z. Hafsi, A. Ekhtiari, L. Ayed, S. Elaoud, The linearization method for transient gas flows in pipeline systems revisited: capabilities and limitations of the modelling approach, J. Nat. Gas. Sci. Eng. 101 (2022) 104494, https://doi.org/10.1016/J.JNGSE.2022.104494.

[29] M. Ketabdar, M. Ketabdar, K. Gregorian, S. Oruji, Evaluation of flooding potential on gas pipelines in tulare county, California, in: Lifelines 2022: 1971 San Fernando Earthquake and Lifeline Infrastructure - Selected Papers from the Lifelines 2022 Conference 1, 2022, pp. 111–120, https://doi.org/10.1061/9780784484432.011.

[30] A. Osiadacz, Simulation and Analysis of Gas Networks, 1986. https://www.osti.gov/biblio/5141539.

[31] R.K. Ahuja, R.H. Möhring, C.D. Zaroliagis (Eds.), Robust and Online Large-Scale Optimization, 2009, p. 5868, https://doi.org/10.1007/978-3-642-05465-5.

[32] M. Inuiguchi, J. Ramík, Possibilistic linear programming: a brief review of fuzzy mathematical programming and a comparison with stochastic programming in portfolio selection problem, Fuzzy. Sets. Syst. 111 (2000) 3–28, https://doi.org/10.1016/S0165-0114(98)00449-7.

[33] A.L. Soyster, F.H. Murphy, Data driven matrix uncertainty for robust linear programming, Omega (Westport) 70 (2017) 43–57, https://doi.org/10.1016/J.OMEGA.2016.09.001.

[34] M. Fischetti, M. Monaci, Light Robustness, in: Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), 5868, LNCS, 2009, pp. 61–84, https://doi.org/10.1007/978-3-642-05465-5_3.

[35] M. Fischetti, M. Monaci, Light Robustness, in: Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), 5868, LNCS, 2009, pp. 61–84, https://doi.org/10.1007/978-3-642-05465-5_3.

[36] Bertsimas D., Sim M. The Price of Robustness. 101287/Opre10300065 2004;52: 35–53. https://doi.org/10.1287/OPRE.1030.0065.

[37] I.E. Grossmann, J. Viswanathan, A. Vecchietti, R. Raman, E. Kalvelagen, GAMS/DICOPT: A Discrete Continuous Optimization Package, GAMS Development Corporation, Washington, DC, USA, 2002. May 10, 2002, https://www.math.ucdavis.edu/~deloera/MISC/LA-BIBLIO/trunk/gams-dicopt-a-discrete.pdf.

[38] G.R. Kocis, I.E. Grossmann, Computational experience with dicopt solving MINLP problems in process systems engineering, Comput. Chem. Eng. 13 (1989) 307–315, https://doi.org/10.1016/0098-1354(89)85008-2.

[39] G. Strbac, D. Pudjianto, R. Sansom, P. Djapic, H. Ameli, N. Shah, N. Brandon, A. Hawkes, M. Qadrdan, Analysis of Alternative UK Heat Decarbonisation Pathways: Extended Executive Summary for the Committee on Climate Change, Imperial College London and Cardiff University, London, UK, 2018. https://www.theccc.org.uk/wp-content/uploads/2018/09/Imperial-College-2018-Analysis-of-Alternative-UK-Heat-Decarbonisation-Pathways-Executive-Summary.pdf.

[40] M. Mahdavi, H.H. Alhelou, P. Cuffe, Test distribution systems: network parameters and diagrams of electrical structural, IEEE Open Access J. Power Energy 8 (2021) 409–420, https://doi.org/10.1109/OAJPE.2021.3119183.

[41] Z. Li, Z. Zheng, L. Xu, X. Lu, A review of the applications of fuel cells in microgrids: opportunities and challenges, BMC Energy 1 (2019) 1–23, https://doi.org/10.1186/S42500-019-0008-3, 2019 1:1.

[42] A. Albaker, A. Majzoobi, G. Zhao, J. Zhang, A. Khodaei, Privacy-preserving optimal scheduling of integrated microgrids, Electr. Power Syst. Res. 163 (2018) 164–173, https://doi.org/10.1016/J.EPSR.2018.06.007.

[43] A. Rezvani, M. Gandomkar, M. Izadbakhsh, A. Ahmadi, Environmental/economic scheduling of a micro-grid with renewable energy resources, J. Clean. Prod. 87 (2015) 216–226, https://doi.org/10.1016/J.JCLEPRO.2014.09.088.