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RESEARCH ARTICLE

Stochastic Expansion Planning Model for a Coordinated Natural Gas and Electricity Networks Coupled With Gas-Fired Generators, Power-to-Gas Facilities, and Renewable Power

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ABSTRACT This paper presents a stochastic expansion planning model for coordinated natural gas and electricity networks, incorporating gas-fired generators, Power-to-Gas facilities, and renewable power sources. The primary objective is to minimize the total cost over the planning horizon, addressing the significant interdependencies between these networks which, if planned independently, can lead to higher overall costs. The originality of this work lies in its comprehensive integration of both systems, leveraging their synergies to optimize infrastructure investment and operational efficiency. Methodologically, the model employs mixed integer linear programming (MILP) within the General Algebraic Modelling System (GAMS), using a Scenario Tree concept to account for the stochastic nature of renewable energy sources (RESs) and load variations. Data from an adapted twenty-node Belgium gas network and a sixteen-bus UK electricity distribution system were utilized. Results demonstrate substantial cost savings and improved system performance with the integrated approach, validating the model's effectiveness.

INDEX TERMS Gas-fired generators, power-to-gas, natural gas network, electricity network, solar and wind energy, expansion planning, uncertainty modeling.

ABBREVIATION

A. INDICES AND SETS

t	Index of hours.
i, j	Index of buses in electricity network.
n, m	Index of nodes in natural gas network.
s	Index of scenarios.
Γ_{GPL}	Set of existing pipelines in the gas network.
Ω_{GPL}	Set of candidate branches for pipelines.
Ω_{Cmpr}	Set of candidate branches for gas compressor.
WT	Index of wind turbine (WTs).
PV	Index of photovoltaic units (PVs).
GFG	Index of gas-fired-units (GFGs).
CFG	Index of coal-fired-units (CFGs).

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P2G	Index of power-to-gas.
BS	Index Battery Storage (BS).
GPL	Index of Gas Pipeline.
GS	Index of Gas storage.
$NGFG$	Number of gas-fired generator.
$NCFG$	Number of coal-fired generator.

B. PARAMETERS

Δt	Duration of time.
ρ_{cur}^{WT}	Penalty price for wind power curtailment.
$\mathrm{Cost}_{\mathrm{i}}^{\mathrm{WT}_{\mathrm{Maint}}}$	Annualized maintenance cost coefficients of WT at node *i*.
$Cost_i^{PV_{Maint}}$	Annualised maintenance cost coefficients of PV at node *i*.
$\mathrm{Cost}_{\mathrm{i}}^{\mathrm{BS}_{\mathrm{Maint}}}$	Annualized maintenance cost coefficients of battery storage.
$Cost_i^{Inv_{PV}^{\frac{New}{exist}}}$	Cost of new Photovoltaics (PVs) and cost of existing PVs.
$Cost_i^{Inv_{BS}^{\frac{New}{exist}}}$	Cost of new Battery storage (BS) and cost of existing BS.
$Cost_n^{Inv_{PL}^{\frac{New}{exist}}}$	Cost of investment of new pipelines/existing pipelines.
$Cost_n^{Inv_{Cmpr}^{\frac{New}{exist}}}$	Cost of investment of new compressors/existing.
$Cost_n^{Inv_{GS}^{\frac{New}{exist}}}$	Cost of investment of new gas storage/existing GS.
$Gf_{mn,t}^{GPL}$	Gas flow through the gas pipelines.
$Gf_{nm,t}^{GS_{Cap}}$	Storage capacity of gas storage.
$\mathrm{Gf}_{\mathrm{n,t,s}}^{\mathrm{in}}$	Gas flow into the gas storage units at node n – m at time t, scenario s.
$\mathrm{Gf}_{\mathrm{n,t,s}}^{\mathrm{in}}$	Gas flow out of gas storage unit at node n – m at time t, scenario s.
$P_{i,t,s}^{ch}$	Charging of power in battery storage.
$P_{i,t,s}^{dch}$	Discharging of power from battery storage.
$P_{i,t,s}^{Cur_{WT}}\ /q_{i,t,s}^{Cur_{WT}}$	Curtailment of active and reactive power for WTs.
$P_{i,t,s}^{Cur_{PV}}\ /q_{i,t,s}^{Cur_{PV}}$	Curtailment of active and reactive power for PVs.
$P_{i,t,s}^{WT}\ /q_{i,t,s}^{WT}$	Active and reactive power of WTs generation before curtailment.
$P_{i,t,s}^{PV}\ /q_{i,t,s}^{PV}$	Active and reactive power of PVs generation before curtailment.
$P_{i,t,s}^{GFG}$	Active and reactive power output from the GFGs at node I, at time t.
$Cost_i^{CFG_{Maint}}$	Maintenance cost coefficient of gas-fired generators at node *i*.
$Cost_i^{CFG_{Maint}}$	maintenance cost coefficient of coal-fired generators at node *i*.
$Cost_i^{Feeder_{Maint}}$	Maintenance cost coefficient for new/existing feeders.
$Cost_n^{GPL_{Maint}}$	Maintenance cost coefficients of natural gas pipelines.
$Cost_n^{Cmpr_{Maint}}$	Annualized maintenance cost coefficients of Gas compressors.
$Cost_n^{GS_{Maint}}$	Annualised maintenance cost coefficients of natural gas storage.
$Cost^{Op_{BS}}$	Operation cost coefficients of battery storage.
$Cost^{Op_{WT}^{Cur}}$	Operation cost coefficients of curtailing wind power.
$Cost^{Op_{WT}^{Cur}}$	Operation cost coefficients of curtailing solar.
$Cost^{Op_{WT}}$	Operation cost coefficients of WTs.
$Cost^{Op_{PV}}$	Operation cost coefficients of PVs.
$Cost^{Op_{GFG}}$	Operation cost coefficient of gas-fired generators (GFGs).
$Cost^{Op_{CFG}}$	Operation cost coefficients of coal-fired generators (CFGs).
$Cost^{Gas_{Stn}}$	Operation cost coefficients gas suppliers from the gas station.
$Cost^{Op_{GS}}$	Operation cost coefficients of gas storage units.
$Cost^{Op_{P2G}}$	Operation cost coefficients of P2G facilities.
$Carbon^{cost}$	Penalty price for carbon emission.
$Gf_{nm,max}^{Cmpr}$	Low limit of the gas compressor.
$Gf_{mn,t,max}^{GPL}$	Ow limit of the gas pipelines.
$Gf_{nm,t,max}^{GS}$	ow limit of the gas storage.
$Gf_{nm,t,max}^{GS_{Cap}}$	Orage capacity limits of adding gas storage.
$\frac{\eta^{in}}{\eta^{out}}$	Efficiency of gas storage in and out.
$\frac{\eta_i^{P2G}}{\eta_i^{GFG}}$	energy conversion efficiency of P2G/GFG.
α_min^(WT/PV)/ α_max^(WT/PV)	minimum/maximum allowable wind and solar permeability.
$\frac{\frac{\beta_{i,max}^{cur_{WT}}}{\beta_{i,max}^{cur_{PV}}}}{}\beta_{i,max}^{cur_{Renew_{load}}}$	curtailment rate of wind/solar/load.
M	Very large number.
$P_{i,max}^{feeder}{}_{i,min}^{feeder}\ /$	min permissible active power flow via existing feeders.
$P_{ij}^{Replace_{Max}^{feeder}}\ /\ P_{ij}^{Replace_{Min}^{feeder}}$	Max/Min permissible active power flow via replacing feeder.
$Q_{i,max}^{feeder}{}_{i,min}^{feeder}\ /$	min permissible reactive power flow via existing feede.
$P_{i,t,s}^{CFG}$	Active and reactive power output from the CFGs at node *i*, at time t.
$\mathrm{P_{i,t,s}}\ /\mathrm{P_{j,t,s}},\ \mathrm{q_{I,t,s}}\ /\mathrm{q_{j,t,s}}$	Active and reactive power flow through the feeders.

$\mathrm{P}_{\mathrm{i,t,s}}^{\mathrm{load}}$ /$\mathrm{q}_{\mathrm{I,t,s}}^{\mathrm{load}}$	Active and reactive power demand at bus *i* at time t (kVAr).
$\mathrm{P}_{\mathrm{i,t,s}}^{\mathrm{P2G}}$ /$\mathrm{q}_{\mathrm{I,t,s}}^{\mathrm{P2G}}$	Active and reactive Power flow in P2G from the network.
$Gf_{nm,t}^{P2G_{Sup}}$	Natural gas supply from the power-to-gas (P2G) unit at node n-m.
$\mathrm{P}_{\mathrm{i,t,s}}^{\mathrm{P2G}}$	Excess power absorbed by the P2G facilities.
$P_{i,t}^{WT_{cur}}$	The wind curtailment power during the period t.
$\frac{P_{i,min}^{Renew_{load}}}{P_{i,max}^{Renew_{load}}}$	um/maximum renewable power load at bus i.
$P_{i,t,s}^{feeder}$ /$q_{i,t,s}^{feeder}$	Active and reactive power flows through feeders.
$P_{nm,t}^{Gas_{GFG}}$	Gas consumed by the gas-fired generators (GFGs).
$\mathrm{P}_{\mathrm{i,t,s}}^{\mathrm{GFG}}$	Electrical power output of gas-fired generators (GFGs).
$P_{i,t,s}^{GFG_{down}}$	The lower ramp rate of GFG.
$P_{i,t,s}^{GFG_{up}}$	The upper ramp rate of GFG.
$P_{i,t,s}^{P2G_{down}}$	Lower ramp rate of P2G.
$P_{i,t,s}^{P2G_{up}}$	Upper ramp rate of P2G.
$Q_{ij}^{Replace_{Max}^{feeder}}$ / $Q_{ij}^{Replace_{Min}^{feeder}}$	Max/Min permissible reactive power flow via replacing feeder.
ξ^{CFG}	Coefficient of carbon emission for coal-fired generator.
ξ^{GFG}	Coefficient of carbon emission for gas-fired generator.

C. VARIABLES

$Cost_i^{Inv_{feeder}^{\frac{New}{exist}}}$	Cost of new distribution feeder and cost of existing feeder.
$Cost_i^{Inv_{GFG}^{\frac{New}{exist}}}$	Cost of new gas-fired generators (GFGs)/existing GFGs.
$Cost_i^{Inv_{CFG}^{\frac{New}{exist}}}$	Cost of new coal-fired generators (CFGs)/existing CFGs.
$Cost_i^{Inv_{WT}^{\frac{New}{exist}}}$	Cost of new wind turbines (WTs) and cost of existing WTs.
$SK_{n,t,s}$	Gas extracted from the gas suppliers at node n – m at time t.
$K^{\cdot}_{\mathrm{max,i,j}}$	Maximum capacity of the branch *i-j* (kWh).
$\mathrm{U}_{\mathrm{GFG,t=1\ or\ 0}}$	The on/off state of GFG.
$\frac{u_{nm,t}^{GS_{in}}}{u_{nm,t}^{GS_{out}}}$	Operation state of charging/release gas for gas storage.
$V_{i,t}$	Voltage magnitude at bus *i* at hour *t* (p.u.).
$\delta_{\mathrm{i,t,s}}^{\frac{\max}{\min}}$	Max/Min voltage angle at bus *i* at hour *t* (radian).
$\mathrm{V}_{\mathrm{i,t,s}}^{\frac{\max}{\min}}$	Max/Min voltage magnitude at bus *i* at hour *h* (p.u).

I. INTRODUCTION

A. BACKGROUND AND MOTIVATION

The current rise in global greenhouse gases (GHG) are a recognized threat to the stability of the earth's climate, and this greenhouse emission continue to rise daily. The prudent response to climate change is to adopt a portfolio of actions aimed at mitigating the rise in greenhouse emission [1].

Reviewing the distribution and sources of greenhouse gas emissions, carbon dioxide CO2 emissions make by far the largest contribution to the greenhouse effect. In turn, the burning of fossil fuels for the production and use of energy contributes to 75% of the world's CO2 emissions. This suggests that the biggest single source of greenhouse gas emissions is the burning of fossil fuels. According to the European Union, roughly one third of CO2 emissions from the combustion of fossil fuels originate from transportation and power generation, while the remaining third is primarily from industry and home heating. Because flue gas streams from thermal power plants are large whereas emission sources in the other sectors are smaller and dispersed, there is an urgent need for technological measures to reduce emissions from power generation both in terms of their efficiency and of the volume of the reduction potential [2] However, compared to natural gas, which primarily consists of methane gas, which emits the least amount of carbon dioxide (CO2) and other harmful substances like nitrogen oxides, Sulphur dioxide, and particulates when burned, fossil fuels like coal and oil produce a higher percentage of CO2 emissions. Directly switching from coal to natural gas for electricity generation has been shown to significantly reduce greenhouse gas emissions [3]. In accordance with the 2015 Paris Agreement, the integration of natural gas and renewable energy sources into power generation ensures energy security and sustainability while significantly reducing greenhouse gas emissions [4] By lowering greenhouse gas emissions, the multilateral pact seeks to keep the rise in average world temperature to below 2° C [5].

According to [1] electricity generation is now one of the world's largest demands for natural gas. Natural gas accounted for approximately 40% of the UK's electricity generation in 2022. As a result, gas-fired generators which use natural gas to generate electricity play the role of producers in the electricity network and consumers in the natural gas network simultaneously. According to [2] the utilization of gas-fired generators to generate electricity has increased in recent decades. Hence, since gas-fired generators gets its input from the gas network and transmit its output into the electricity network, it will be vital to say that for energy reliability and efficiency the integration of both the electricity and natural gas networks is essential. Also, the benefits of planning both the natural gas and electricity networks simultaneously will be negated when individual networks are planned individually in terms of the overall planning cost because the natural gas network is intimately connected to the electricity network by the gas-fired generators. An efficient planning methodology is therefore essential for an integrated natural gas and electrical networks.

Furthermore, to achieve net zero targets and lessen the use of fossil fuels, the proportion of electricity produced from renewable energy sources like solar and wind have increased in recent years. As a result, the uncertainties associated with electricity generation from Renewable energy like solar and wind, combined with the pre-existing uncertainty of load demands on energy networks require practical solutions [3] Gas-fired generators which uses natural gas to generate electricity has been projected as one of the available solutions to solving Renewable energy uncertainty due to its distinct advantages of low price, fast response capacity and low carbon emissions of up to 60% when compared with coal-fired power plants [4]. These distinct advantages of using natural gas for electricity generation have increased interaction of electricity and natural gas networks through deployment of a wide range of technologies, including gas-to-power technologies (e.g., Combined-Circle gas turbines (CCGTs), Combined heat and power and Gas-fired units) and power-to-gas technologies (e.g., electrolysis and methanation) [5].

Additionally, Power-to-gas technology is presented as a novel idea for energy storage and a method that shows promise for combining the networks for natural gas and electricity to manage the fluctuating supply of solar and wind energy. The power-to-gas technologies can facilitate the integration of high proportion of renewable energy by converting excess renewable energy into green hydrogen which can be used as synthetic natural gas in the gas network. This enables the energy transition policy to fully utilize renewable energy for power generation in the future [6].

The careful coordination between electricity and natural networks can help achieve the net zero targets more cost-efficiently by exploiting the synergies between the two networks to encourage the use of more renewable energy through the use of technologies like the Gas-Fired generators and the Power-to-gas [7]. Hence, there is an urgent need to improve on the coordinated planning of the natural gas and electricity network. One of the ways to decrease natural gas uncertainty concerning the supply of natural gas to the Gas-Fired generators is by the integration of both natural gas and electricity networks simultaneously using modern technologies like Power-to-gas, Gas-fired generators, and Renewable energy [8]. When compared to the traditional practice of planning the natural gas and electricity networks separately, the strategy of planning both natural gas and electricity networks simultaneously will give benefits including cost savings and improved network efficiency and dependability. Hence, this paper proposed an expansion planning model of a coordinated natural gas and electricity networks considering Gas-fired generators, power-to-gas facilities, and renewable power.

B. RELATED LITERATURES AND RESEARCH GAP

Recently, increasing research interest has been channelled towards the expansion planning of integrated natural gas and electricity networks in relation to multi energy systems. For example, with the increasing maturity of power-to-gas and Gas-fired generators technologies, the coupling between the natural gas and electricity network is getting closer with other consideration like application of high shares of renewable power, the authors in [9] provide a dynamic co-planning model of electricity and gas networks while considering uncertainties of renewable energy resources. [10] investigate a low-carbon oriented representation of expansion problem of gas and electricity network which considers profit to-cost maximization as objective function, this is examined by considering market prices of gas and electricity in different price scenarios. According to the authors in [11] and [12], it proposed a robust model of an integrated expansion plan for electricity and natural gas networks considering grid resilience as a set of constraints. Furthermore, [13] presents a model to plan a distribution system in which the investment and operational costs and unsupplied energy risk are considered. The study uses a Monte Carlo simulation to deal with uncertainties from demand, non-renewable operation of distributed generation, and energy prices. However, in this paper the scenario-Tree approach is incorporated in the optimization process to deal with the uncertainties of loads and renewable power. The author in [14] examined a multi-stage co-planning of electricity-gas systems and shows that Power-to-gas plants expansion planning will influence the planning solution of transmission expansion planning. Nevertheless, neither did it consider the uncertainties of load demand and renewable wind energy which was considered in this paper. A long-term, multi-area, multistage, and integrated expansion planning model of electricity and natural gas systems was investigated in [15], These studies examined how an electricity and natural gas network can be integrated at the transmission level.

Also, Power-to-Gas technologies innovations have additionally been examined as a potential system in integrated electricity and natural gas networks to handle the unpredictable nature of wind electricity power supply [16]. When Power-to-gas technology was present, the authors of [17] proposed a reliable method for identifying the best scheduling of coupled electricity and natural gas networks. With evaluations of both low and high-power demands in Great Britain, which has a large penetration of wind electricity power, the authors in [18] investigated the capacity of Power-to-gas in integrated networks to reduce the cost of delivering the gas and electricity loads. Regarding Power-to-gas's effects on the environment, the authors of [19] offered an operational analysis for its incorporation into the network's integrated power and gas operations in Great Britain. They examined the potential for converting extra wind energy into different forms of gas using Power-to-gas technologies, and a model for reducing carbon dioxide emissions was developed to evaluate the system's overall environmental impact.

Despite those thorough studies, there are still gaps that the present study aims to fix. First, most of the material now in circulation focuses on the cost analysis of Power-to-gas technology in power systems. They have not considered the Power-to-gas facility as an indispensable medium to transform the excess wind power into synthetic natural gas. The Power-to-gas technology, however, is very promising in addressing the curtailment cost of wind energy by converting the surplus renewable power into synthetic natural gas to make up for the limitation of gas supply from the conventional gas wells, hence, has a direct influence on the coordinated planning and operation of gas and electricity networks by reducing the total planning costs. In this paper, the Power-to-gas technology is used as an effective tool to address the wind energy curtailment cost in a coordinated gas and electricity networks. The Power-to-gas facility supplies synthetic natural gas to compensate for the limited gas supply from the conventional gas wells as well as providing clean energy in line with the NetZero policies. This paper proposes an expansion planning model for a coordinated natural gas and electricity networks at distribution level considering Gas-fired generators, power-to-gas facilities, and renewable power. In essence, the coordinated expansion planning will solve the numerous challenges both natural gas and electricity networks might face when they are planned independently. For instance, in this paper we have looked at the challenges like wind power curtailment, carbon emission costs and the site and sizing. Coordinated expansion planning might achieve lower investment and operation costs compared to when they are planned separately. The paper is an extension of [7]. To the best of the author's knowledge, this model covers the gaps in recent literatures as stated below: In short, the research gaps are as follows:

- Existing studies did not consider expansion planning of the interdependence between gas-fired generators and Power-to-gas facilities at distribution level.
- Being different from the conventional planning of electricity and natural gas networks separately with more emphasis on minimizing the investment and operation cost, this model focus on expansion planning of a coordinated natural gas and electricity network focusing on not only the investment and operation cost but rather including the cost of both wind curtailment and carbon emission that makes the model more practical when compared with real world approach.
- The coordinated expansion planning of gas and electricity networks is also seen by many utilities operators (which operate in the electricity and natural gas sectors as competitors) as an alternative to offering low-cost service to their customers. In other words, utilities operators that planned and own both gas and electricity networks as an interdependent network could reduce their investment costs using the proposed planning model, hence transferring potential savings to their customers via electricity or gas tariffs.
- Some literature has used demand response programs to solve the challenges of wind curtailment. But to the best of the author's knowledge no study has used Power-to-gas technologies to solve the challenges of wind and solar curtailment in planning coordinated gas and electricity networks at distribution level.

The following are the primary contributions of this paper:

1. This paper modelled an expansion planning of a coordinated electricity and natural gas networks to assess the economic and environmental benefits of planning a coordinated electricity and natural gas networks compared to the traditional independent planning. The piecewise linearization approach was used to simplify the complex nonlinear relationships in the networks into a mixed integer linear programming for more efficient and accurate optimization.
2. To address the cost of wind and solar power curtailment in the electricity network using the Power-to-gas technologies to convert excess renewable power into synthetic natural gas to compensate for the limited gas supplies from the conventional gas wells in the natural gas network.
3. To model the correlated uncertainties associated with wind speed, solar irradiation and load demand using the scenario-Tree approach, in this model uncertainties in electrical loads and renewable power are incorporated in the optimization process.

II. PROPOSED EXPANSION PLANNING MODEL

In this section, the suggested framework expansion planning of coordinated natural gas and electricity network coupled with Gas-fired generators, Power-to-gas infrastructures, and renewable power is modelled, as showed in Fig 1. This study focuses on the evaluation of natural gas and electricity networks steady state. The natural gas network consists of the gas pipelines, gas compressors, gas storage, and gas-wells (gas source). The natural gas network utilises the pipelines to transport natural gas from the gas-wells to the end consumers. The natural gas steady state model is presented in [18]. The Pipelines, compressor stations, gas storage and interconnection sites are the only four main categories of entities included in this study for natural gas network modelling. It is expected that all the compressors are powered by gas energy, and that the natural gas is tapped from each compressor's inlet node. In the electricity network, the AC power flow is employed to represent the electricity network, this study considers both active and reactive power as well as voltage amplitude, feeders, battery storage, wind turbine and photovoltaic units. Also, in this study, the Gas-fired generators, which can be thought converters of two energy systems, connect the natural gas and electricity networks. The Gas-fired generators are treated as natural gas loads by the natural gas network, while they are considered as power suppliers by the electricity network [11]. Furthermore, the

TABLE 1. **Comparison between the proposed model and recent literature reviewed.**

Ref	Planning or Operation Model	Transmission or Distribution level	GFUs & P2G Technologies in linking both Gas & Electricity network	Uncertainty Modelling	Objective Functions*					P2G technologies is deployed to handle the cost of wind curtailment
					1	2	3	4	5	
[14]	Yes	Transmission	GFGs	No	✓	✓	✓	×	×	No
[15]	Yes	Transmission	P2G	No	✓	✓	×	×	×	No
[17]	Yes	Transmission	GFGs & P2G	No	✓	✓	×	×	×	No
[18]	Yes	Transmission	GFGs & P2G	Yes	✓	✓	✓	×	×	No
[19]	No	Distribution	GFGs & P2G	No	×	✓	✓	×	×	No
This model	**Planning**	**Distribution**	**GFGs & P2G**	**Yes**	✓	✓	✓	✓	✓	**Yes**

*1 denote Investment cost, 2 denote Operation cost, 3 denote Maintenance cost, 4 denote Carbon emission cost, 5 wind curtailment cost

Power-to-gas facilities which also link the natural gas and electricity networks, converts excess renewable power into synthetic natural gas and supply to the natural gas network. It is worthy to state that in this study, both the solar and wind power curtailment is considered different from most work that only give priority to wind power curtailment and describe solar power curtailment as negligible. The suggested model's goal is to plan a coordinated energy systems in other to achieve the lowest investment cost while meeting future energy requirements as the Natural gas and electricity loads increase in the planning horizon year.

We anticipate reducing the cost of gas supply and power generation. Also, the assessment considers the uncertainty of solar, wind, and electrical load. The flowchart of the proposed modelling methodology is represented in Fig 3.

A. UNCERTAINTY MODELING

Using the concept of scenario tree, the wind velocity, solar energy, and demand load uncertainties are expected with a similar frequency [13]. Wind velocity model: The Weibull PDF function, which links wind velocity to WT-generated electricity, is depicted in the following equation:

$$\mathrm{PDF\ (Ws)} = \left(\frac{\mathrm{ks}}{\mathrm{Cs}}\right)\left(\frac{\mathrm{Ws}}{\mathrm{Cs}}\right)^{\mathrm{ks}-1} \exp\left[-\left(\frac{\mathrm{Ws}}{\mathrm{Cs}}\right)^{\mathrm{ks}}\right] \tag{1}$$

The wind velocity, indicator of shape, and indicator of scale are represented by the Weibull PDFs of Ws, ks, and Cs, accordingly. he produced power of wind turbine determined by power velocity is thus demonstrated in the following way:

$$\mathrm{P_w\ (Ws)} = \begin{cases} 0, & 0 \le \mathrm{Ws} \le \mathrm{Ws_{ci}} \\ \mathrm{P_{rated}} \times \dfrac{\mathrm{Ws}-\mathrm{Ws_{ci}}}{\mathrm{Ws_r}-\mathrm{Ws_{ci}}}, & \mathrm{Ws_{ci}} \le \mathrm{Ws} \le \mathrm{Ws_r} \\ \mathrm{P_{rated}}, & \mathrm{Ws_r} \le \mathrm{Ws} \le \mathrm{Ws_{co}} \\ 0, & \mathrm{Ws_{co}} \le \mathrm{Ws} \end{cases} \tag{2}$$

As a result, the active power at bus i and scenario s can be expressed as:

$$0 \le \mathrm{P^w_{i,s}} \le \gamma^{\mathrm{w}}_{\mathrm{i,s}} \times \mathrm{P^w_{i,rated}} \tag{3}$$

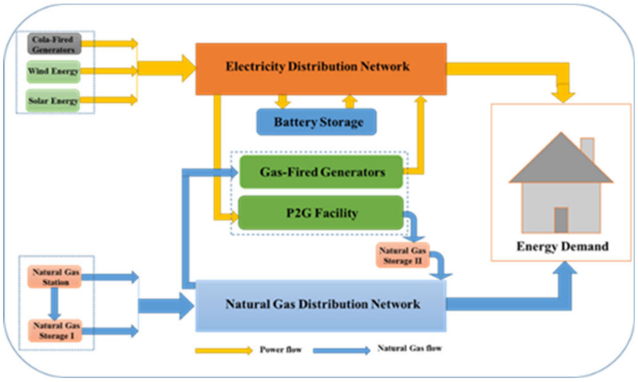


FIGURE 1. **Proposed planning framework of a Coordinated Natural gas and electricity network.**

The percentage active and reactive Wind turbine output is denoted by $\gamma^{w}_{i,s}$.

Solar energy Model: The Beta probability density function (PDF) is provided below [2], [13],

$$PDF\ (Si) = \left\{ \frac{\frac{\Gamma(.\alpha+\beta)}{\Gamma(.\alpha)+\Gamma(.\beta)} \times Si^{\alpha-1} \times (1-Si)^{.\beta-1}\ ; 0 \le Si \le 1; 0 \le \alpha.\beta}{0;\ otherwise} \right\} \tag{4}$$

The Si represents the solar energy, α and β are expressed as showed below:

$$\propto = \frac{\mathrm{ms}-\beta}{1-\mathrm{ms}} \tag{5}$$

$$\beta = (1-\mathrm{ms}) \times \left(\frac{\mathrm{ms} \times (1-\mathrm{ms})}{\mathrm{Vn}^2} - 1\right) \tag{6}$$

The mean and variance are represented by ms and n, accordingly. The power output P^{PV} is calculated as shown below:

$$P^{PV} = \mathrm{P_{SE}} \left\{ \frac{\mathrm{Si}}{1000} \left[1 + \vartheta\ (\mathrm{T_{str-25}})\right] \right\} \tag{7}$$

$$\mathrm{T_{str}} = \mathrm{T_{prev}} + \left(\frac{\mathrm{NOCT}-20}{800}\right) \mathrm{Si} \tag{8}$$

The P_{SE} and P^{PV} accordingly, stand for the evaluation state and output power. The temperature percentage is denoted by ϑ. T_{str} and T_{prev} are structured and prevailing temperature, accordingly. whilst solar energy is Si.

Demand of load: The following is how the load PDF $load_{dm}$ is calculated:

$$\mathrm{PDF}\left(load_{dm}\right)=\frac{1}{\mathrm{Vn_l}\sqrt{2\pi}}\times\exp\left[-\left(\frac{\left(load_{dm}-\mathrm{ms_l}\right)^2}{2\mathrm{Vn_l^2}}\right)\right] \tag{9}$$

The mean and variance arbitrary variable are denoted by $\mathrm{ms_l}$ $\mathrm{Vn_l}$.

B. MODELLING APPROACH

Methodologies for stochastic programming, such scenario tree concepts, are frequently employed to address decision-making issues in the presence of uncertainty [13]. The scenario-tree concept represents potential future possibilities of probability rather than offering an estimate point. The scenarios may only cover the upcoming time step or may travel far further back in time. To model the uncertainty and correlation, duration curves for load demand, wind velocity, and solar energy are provided. As explained below, the combined effects of load demand, wind velocity, and solar energy are modelled. To offer factorized data, The 8,760 hours of previously recorded information are broken down into a few categories, namely solar energy, wind velocity and demand of load. As shown in Fig. 2, Whilst sustaining the link among numerous hourly parameters of solar energy, wind velocity, and demand for loads, information is structured from peak to least levels. The schedules are placed to govern the load size slope, and as the load size expands, so do the schedule increases. To completely analyze the load demand in this model, the historical data for load demand, wind velocity, and solar energy are arranged in descending order for each scheduled. Each block of load demand, solar energy, and wind velocity is used to calculate the cumulative distribution function. The demand level that can be attained in each scheduled is the probability relationship for each segment of a cumulative distribution function. For each time block, various degrees of unclear data are combined to define the scenarios. As a result, each scenario includes the maximum amount of power supplied by PV cells $\mu^{\theta}_{\mathrm{ll,s}}$ for each load level. The maximum level of electricity power generated by WTs $\mu^{\mathrm{W}}_{\mathrm{ll,s}}$, and an average demand factor $\mu^{\mathrm{D}}_{\mathrm{ll,s}}$ for each load level. There are one hundred and eight (108) possible situations to consider when using 4-time blocks, 3 load demand levels, 3 levels of solar energy, and 3 levels of wind velocity ($4\times3\times3\times3=108$).

III. PROBLEM FORMULATION

Formulation of the Stochastic expansion planning model for a coordinated natural gas and electricity networks coupled with GFGs, P2G infrastructures, and Renewable Power has been presented in the following subsections, while the flowchart of the proposed modelling methodology is represented in figure 3.

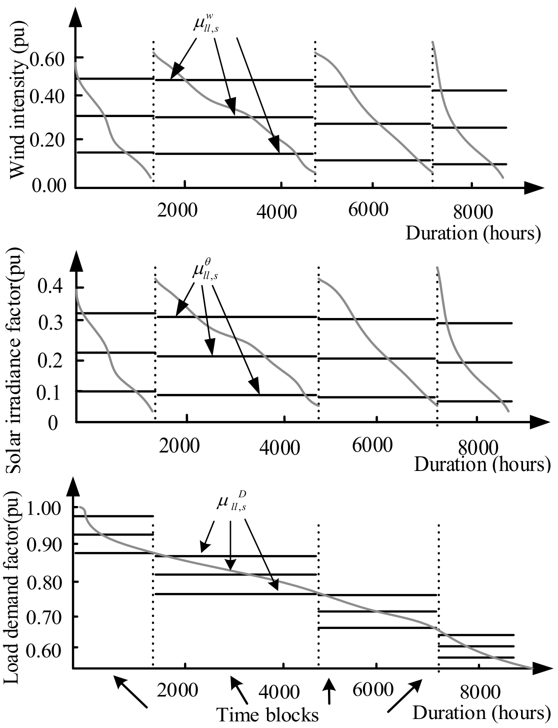


FIGURE 2. Wind velocity, solar energy, and load level of demand variants [2], [13].

A. OBJECTIVE FUNCTION

The aim of this work is to minimize the expected total cost in the planning horizon, which consists of 5 terms: Investment cost, Operation cost, maintenance cost, wind curtailment cost and the carbon emission cost in the planning horizon.

$$\begin{aligned}Min^{Total}_{Cost}&\\ &=Cost^{Inv}+\left[\sum_{y=1}^{NY}\frac{1}{(1+dr)^{y}}\left(Cost^{Maint}_{y}+Cost^{Op}_{y}\right.\right.\\ &\quad\left.\left.+Cost^{WPC}_{y}+Cost^{CM}_{y}\right)\right]\end{aligned} \tag{10}$$

where NY represents the number of years during the whole planning horizon and dr represents annual discounted rate.

B. INVESTMENT COST

The investment cost in this planning horizon is referred to the capital cost of the gas network and equipment, electricity networks and equipment and the power-to-gas (P2G) facilities including the gas storage which in this work is attached to the power-to-gas facilities.

$$Cost^{Inv}=Cost^{Inv}_{Elec}+Cost^{Inv}_{Gas}+Cost^{Inv}_{P2G} \tag{11}$$

As can be observed, the suggested model's investment costs consist of three things: the first is the cost of the electricity network including the upgrade and expansion of feeders, as well as the installation of new WT, PVs, GFGs, CFGs, Battery storage (BS), secondly the gas network including the installation of pipelines, compressors, and gas storage units, and the third is the P2G facilities including its own storage.

1) INVESTMENT COST IN THE ELECTRICITY NETWORK

$$\begin{aligned}Cost_{Elec}^{Inv} = &\sum_{i\in Cfeeder} Cost_i^{Inv_{feeder}^{\frac{New}{exist}}} xfe_i^{\frac{New}{exist}_{feeder}}\\ &+\sum_{i\in CGFG} Cost_i^{Inv_{GFG}^{\frac{New}{exist}}} xfe_i^{\frac{New}{exist}_{GFG}}\\ &+\sum_{i\in CCFG} Cost_i^{Inv_{CFG}^{\frac{New}{exist}}} xfe_i^{\frac{New}{exist}_{CFG}}\\ &+\sum_{i\in CWT} Cost_i^{Inv_{WT}^{\frac{New}{exist}}} xfe_i^{\frac{New}{exist}_{WT}}\\ &+\sum_{i\in CPV} Cost_i^{Inv_{PV}^{\frac{New}{exist}}} xfe_i^{\frac{New}{exist}_{PV}}\\ &+\sum_{i\in CBS} Cost_i^{Inv_{BS}^{\frac{New}{exist}}} xfe_i^{\frac{New}{exist}_{BS}}\end{aligned}\tag{12}$$

2) INVESTMENT COST IN THE NATURAL GAS NETWORK

$$\begin{aligned}Cost_{Gas}^{Inv} = &\sum_{nm\in CGPL} Cost_n^{Inv_{GPL}^{\frac{New}{exist}}}\\ &+\sum_{nm\in CCmpr} Cost_n^{Inv_{Cmpr}^{\frac{New}{exist}}} xfg_n^{\frac{New}{exist}_{Cmpr}}\\ &+\sum_{nm\in CGS} Cost_n^{Inv_{GS}^{\frac{New}{exist}}} xfg_n^{\frac{New}{exist}_{GS}}\end{aligned}\tag{13}$$

3) INVESTMENT COST IN THE POWER-TO-GAS FACILITIES

$$Cost_{P2G}^{Inv} = \sum_{i\in CP2G} Cost_i^{\overset{Inv}{P2G}} Cap_i^{P2G}\tag{14}$$

where $Cost_i^{\overset{Inv}{P2G}}$ represent the investment capital cost of the P2G facilities and the Cap_i^{P2G} represent the installation capacity of P2G facility.

C. MAINTENANCE COST

$$Cost_y^{Maint} = Cost_{Elec}^{Maint} + Cost_{Gas}^{Maint} + Cost_{P2G}^{Maint}\tag{15}$$

Equation (16) models the maintenance costs of newly installed feeders and newly installed WTs, PVs, GFGs, CFGs, and BSs in the electricity network. Equation (17) models the maintenance costs of newly installed gas pipelines, compressors, and gas storage in the gas network, Equation (18) models the maintenance costs of newly installed Power-to-gas (P2G) facilities taking into consideration.

1) MAINTENANCE COST IN THE ELECTRICITY DISTRIBUTION NETWORK

$$\begin{aligned}Cost_{Elec}^{Maint} = &\sum_{i\epsilon CWT} Cost_i^{WT_{Maint}} xfe_i^{\frac{New}{exist}_{WT}}\\ &+\sum_{i\epsilon CPV} Cost_i^{PV_{Maint}} xfe_i^{\frac{New}{exist}_{PV}}\\ &+\sum_{i\epsilon CBS} Cost_i^{BS_{Maint}} xfe_i^{\frac{New/exist}{BS}}\\ &+\sum_{i\epsilon CGFG} Cost_i^{GFG_{Maint}} xfe_i^{\frac{New/exist}{GFG}}\\ &+\sum_{i\epsilon CCFG} Cost_i^{CFG_{Maint}} xfe_i^{\frac{New/exist}{CFG}}\\ &+\sum_{i\epsilon Cfeeder} Cost_i^{Feeder_{Maint}} xfe_i^{\frac{New/exist}{feeder}}\end{aligned}\tag{16}$$

2) MAINTENANCE COST IN THE NATURAL GAS DISTRIBUTION NETWORK

$$\begin{aligned}Cost_{Gas}^{Maint} = &\sum_{nm\epsilon CGPL} Cost_n^{GPL_{Maint}} xfg_n^{\frac{New}{exist}_{GPL}}\\ &+\sum_{nm\epsilon CCmpr} Cost_n^{Cmpr_{Maint}} xfg_n^{\frac{New}{exist}_{Cmpr}}\\ &+\sum_{nm\epsilon CGS} Cost_n^{GS_{Maint}} xfg_n^{\frac{New}{exist}_{GS}}\end{aligned}\tag{17}$$

3) MAINTENANCE COST IN THE POWER-TO-GAS FACILITIES

$$Cost_{P2G}^{Maint} = \sum\nolimits_{i\in CP2G} Cost_i^{P2G_{Maint}} Cap_i^{P2G}\tag{18}$$

D. OPERATION COST

It is important to state that in this paper, the operation cost, wind and solar curtailment cost and the emission carbon cost of GFGs and CFGs are considered individually.

$$\begin{aligned}Cost_y^{Op} = 365\sum_s \rho(s)\sum_{t=1}^{NT} Cost_{s,t}^{Op_{Elec}}\\ + Cost_{s,t}^{Op_{Gas}} + Cost_{s,t}^{Op_{P2G}}\end{aligned}\tag{19}$$

1) OPERATION COST IN THE ELECTRICITY DISTRIBUTION NETWORK

$$\begin{aligned}&Cost_{s,t}^{Op_{Elec}}\\ &= \sum_{i\in CBS} Cost^{Op_{BS}}\left(P_{i,t,s}^{ch} - P_{i,t,s}^{dch}\right)\\ &\quad+\sum_{i\in CWT} Cost^{Op_{WT}^{Cur}} P_{i,t,s}^{Cur_{WT}} + \sum_{i\in CPV} Cost^{Op_{PV}^{Cur}} P_{i,t,s}^{Cur_{PV}}\\ &\quad+\sum_{i\in CWT} Cost^{Op_{WT}} P_{i,t,s}^{WT} + \sum_{i\in CPV} Cost^{Op_{PV}} P_{i,t,s}^{PV}\end{aligned}$$

$$+\sum_{i\in CGFG} Cost^{Op_{GFG}} P_{i,t,s}^{GFG} + \sum_{i\in CCFG} Cost^{Op_{CFG}} P_{i,t,s}^{CFG} \tag{20}$$

2) OPERATION COST IN THE NATURAL GAS DISTRIBUTION NETWORK

$$\begin{aligned} Cost_{s,t}^{Op_{Gas}} &= \sum_{nm\in CGas_{Stn}} Cost^{Op_{Gas_{stn}}} SK_{n,t,s} \\ &\quad + \sum_{nm\in CGS} Cost^{Op_{GS}} \left(Gf_{n,t,s}^{GS_{in}} - Gf_{n,t,s}^{GS_{out}} \right) \end{aligned} \tag{21}$$

3) OPERATION COST IN THE POWER-TO-GAS FACILITIES

$$Cost_{s,t}^{Op_{P2G}} = \sum_{i\in CP2G} Cost^{Op_{P2G}} P_{i,t,s}^{P2G} \tag{22}$$

4) WIND POWER CURTAILMENT PENALTY COST (WPC)

Equation (23) can be used to define the Wind Power Curtailment Penalty Cost (WPC), which is the cost of energy wasted when surplus wind generation is abandoned to preserve the system's power balance.

$$Cost_{y}^{WPC} = \sum_{i\epsilon CCur} \rho_{cur}^{WT} P_{i,t,s}^{cur_{WT}} \tag{23}$$

5) CARBON EMISSION COST

The carbon emission cost is primarily due to the emission of pollutants from the Coal-fired generator and Gas-fired generators. This emission gases considered in this paper are mainly include carbon dioxide (CO2) and Carbon monoxide (CO) which are usually consider large emission obtained from the operation of coal-fire and gas-fired generators, while other emission gases like Nitrogen oxide (NOx) and Sulphur dioxide (SO2) are assumed to be negligible and were not taken into consideration in this paper. The emission carbon cost can be formulated as follows:

$$\begin{aligned} Cost_{y}^{CM} &= \sum_{i=1}^{NCFG} 8760 * Carbon^{cost} * \xi^{CFG} * P_{i,t,s}^{CFG} \\ &\quad + \sum_{i=1}^{NGFG} 8760 * Carbon^{cost} * \xi^{GFG} * P_{i,t,s}^{GFG} \end{aligned} \tag{24}$$

6) INVESTMENT AND USAGE CONSTRAINTS

The following are the restrictions pertaining to the investment and utilization decisions of all facilities in this planning:

$$\sum\nolimits_{i\in Cfeeder} xfe_{i}^{\frac{\frac{New}{exist}}{feeder}} \leq 1, xfe_{i}^{\frac{\frac{New}{exist}}{feeder}} = \backslash\{0, 1\backslash\}, \forall i \in \Omega_{feeder} \tag{25}$$

$$\sum_{i\in CBS} xfe_{i}^{\frac{\frac{New}{exist}}{BS}} \leq 1, xfe_{i}^{\frac{\frac{New}{exist}}{BS}} = \backslash\{0, 1\backslash\}, \forall i \in \Omega_{BS} \tag{26}$$

$$\sum_{i\in CGFG} xfe_{i}^{\frac{\frac{New}{exist}}{GFG}} \leq 1, xfe_{i}^{\frac{\frac{New}{exist}}{GFG}} = \backslash\{0, 1\backslash\}, \forall i \in \Omega_{GFG} \tag{27}$$

$$\sum_{i\in CCFG} xfe_{i}^{\frac{\frac{New}{exist}}{CFG}} \leq 1, xfe_{i}^{\frac{\frac{New}{exist}}{CFG}} = \backslash\{0, 1\backslash\}, \forall i \in \Omega_{CFG} \tag{28}$$

$$\sum_{i\in CWT} xfe_{i}^{\frac{\frac{New}{exist}}{WT}} \leq 1, xfe_{i}^{\frac{\frac{New}{exist}}{WT}} = \backslash\{0, 1\backslash\}, \forall i \in \Omega_{CWT} \tag{29}$$

$$\sum_{i\in CPV} xfe_{i}^{\frac{\frac{New}{exist}}{PV}} \leq 1, xfe_{i}^{\frac{\frac{New}{exist}}{PV}} = \backslash\{0, 1\backslash\}, \forall i \in \Omega_{CPV} \tag{30}$$

$$\sum_{nm\in CGPL} xfg_{n}^{\frac{\frac{New}{exist}}{GPL}} \leq 1, xfg_{n}^{\frac{\frac{New}{exist}}{GPL}} = \backslash\{0, 1\backslash\}, \forall nm \in \Omega_{GPL} \tag{31}$$

$$\sum_{nm\in CCmpr} xfg_{n}^{\frac{\frac{New}{exist}}{Cmpr}} \leq 1, xfg_{n}^{\frac{\frac{New}{exist}}{Cmpr}} = \backslash\{0, 1\backslash\}, \forall nm \in \Omega_{Cmpr} \tag{32}$$

$$\sum_{nm\in CGS} xfg_{n}^{\frac{\frac{New}{exist}}{GS}} \leq 1, xfg_{n}^{\frac{\frac{New}{exist}}{GS}} = \backslash\{0, 1\backslash\}, \forall nm \in \Omega_{CGS} \tag{33}$$

Equation (25)– (33) establishes the pertinent limitations in terms of the binary investment decision x. According to these limitations, only one replacement, addition, or installation is allowed for each component and location.

E. OPERATION CONSTRAINTS

1) THE POWER SYSTEM CONSTRAINTS

Line flow: to satisfy all linear constraints, a linearized AC power flow model proposed in [20] is utilized here. The linearization method has been proven to be equally applicable under extreme events [20]. The linearized AC power flow model can be expressed as:

$$\mathrm{K_{ij_1}} = \frac{\mathrm{x_{ij}}}{\left(\mathrm{r_{ij}^2} - \mathrm{x_{ij}^2}\right)}, \mathrm{K_{ij_2}} = \frac{\mathrm{r_{ij}}}{\left(\mathrm{r_{ij}^2} + \mathrm{x_{ij}^2}\right)} \tag{34}$$

$$\mathrm{P_{ij,t,s}} = \mathrm{K_{ij_1}}.\left(\delta_{\mathrm{i,t,s}} - \delta_{\mathrm{j,t,s}}\right) + \mathrm{K_{ij_2}}.\left(\mathrm{V_{i,t,s}} - \mathrm{V_{j,t,s}}\right) \tag{35}$$

$$\mathrm{Q_{ij,t,s}} = -\mathrm{K_{ij_2}}.\left(\delta_{\mathrm{i,t,s}} - \delta_{\mathrm{j,t,s}}\right) + \mathrm{K_{ij_1}}.\left(\mathrm{V_{i,t,s}} - \mathrm{V_{j,t,s}}\right) \tag{36}$$

$$\mathrm{P_{i,t,s}} = \sum_{\mathrm{i=1,i\neq j}}^{\mathrm{I}} \mathrm{K_{ij_1}}.\left(\delta_{\mathrm{i,t,s}} - \delta_{\mathrm{j,t,s}}\right) + \mathrm{K_{ij_2}}.\left(\mathrm{V_{i,t,s}} - \mathrm{V_{j,t,s}}\right) \tag{37}$$

$$\mathrm{Q_{i,t,s}} = \sum_{\mathrm{i=1,i\neq j}}^{\mathrm{I}} -\mathrm{K_{ij_2}}.\left(\delta_{\mathrm{i,t,s}} - \delta_{\mathrm{j,t,s}}\right) + \mathrm{K_{ij_1}}.\left(\mathrm{V_{i,t,s}} - \mathrm{V_{j,t,s}}\right) \tag{38}$$

$$\left|\mathrm{P_{ij,t,s}}\right| \leq \mathrm{P_{ij}^{Max}}.\mathrm{y_{ij,t,s}} \tag{39}$$

$$\left|\mathrm{Q_{ij,t,s}}\right| \leq \mathrm{Q_{ij}^{Max}}.\mathrm{y_{ij,t,s}} \tag{40}$$

where x_{ij} and r_{ij} are reactance and resistance of the branch ij. The line flow from the sending end is denoted by K_{ij}. $\delta_{i,t,s}$ and $V_{i,t,s}$ are voltage angle and voltage magnitudes at bus i. P_{ij}^{Max} and Q_{ij}^{Max} are maximum active power and maximum reactive power between bus i and j. $y_{ij,t,s}$ is binary variable to indicate the switch status of branch ij, $y_{ij,t,s} = 1$ when the switch is closed, otherwise $y_{ij,t,s} = 0$.

Power flow on each bus: Power is dynamically balanced at each bus in terms of active and reactive power, as represented in equations (41) and (42), respectively. While the active and reactive power limitations of PV, WT, GFG, CFG, P2G, and load demand are represented in equations (43) – (58), respectively:

$$\sum_{i,j,t,s} P_{i,j,t} = P^{GFG}_{i,t,s} + P^{CFG}_{i,t,s} + P^{WT}_{i,t,s} + P^{PV}_{i,t,s} + P^{dch}_{i,t,s} - P^{ch}_{i,t,s} - P^{load}_{i,t,s} - P^{P2G}_{i,t,s} - P^{cur\,WT}_{i,t,s} - P^{cur\,PV}_{i,t,s} \tag{41}$$

$$\sum_{i,j,t,s} Q_{i,j,t} = Q^{GFG}_{i,t,s} + Q^{CFG}_{i,t,s} + Q^{WT}_{i,t,s} + Q^{PV}_{i,t,s} + Q^{dch}_{i,t,s} - Q^{ch}_{i,t,s} - Q^{load}_{i,t,s} - Q^{P2G}_{i,t,s} - Q^{cur\,WT}_{i,t} - Q^{cur\,PV}_{i,t} \tag{42}$$

$$\mathrm{V}^{\mathrm{Min}}_{\mathrm{i,t}} \leq \mathrm{V}_{\mathrm{i,t.s}} \leq \mathrm{V}^{\mathrm{Max}}_{\mathrm{i,t}} \forall \mathrm{i}.\forall \mathrm{t}.\forall \mathrm{s} \tag{43}$$

$$-\pi \leq \theta_{\mathrm{i,t.s}} \leq \pi \forall \mathrm{i}, \forall \mathrm{t}.\forall \mathrm{s} \tag{44}$$

$$P^{Min}_{i,j} \leq \mathrm{P}_{\mathrm{i,j.t,s}} \leq P^{Max}_{i,j} \tag{45}$$

$$Q^{Min}_{i,j} \leq \mathrm{Q}_{\mathrm{i,j.t,s}} \leq Q^{Max}_{i,j} \tag{46}$$

$$P^{PV,min}_{i,t,s} \leq P^{PV}_{i,t,s} \leq P^{PV,max}_{i,t,s} \tag{47}$$

$$Q^{PV,min}_{i,t,s} \leq Q^{PV}_{i,t,s} \leq Q^{PV,max}_{i,t,s} \tag{48}$$

$$P^{WT,min}_{i,t,s} \leq P^{WT}_{i,t,s} \leq P^{WT,max}_{i,t,s} \tag{49}$$

$$Q^{WT,min}_{i,t,s} \leq Q^{WT}_{i,t,s} \leq Q^{WT,max}_{i,t,s} \tag{50}$$

$$P^{GFG,min}_{i,t,s} \leq P^{GFG}_{i,t,s} \leq P^{GFG,max}_{i,t,s} \tag{51}$$

$$Q^{GFG,min}_{i,t,s} \leq Q^{GFG}_{i,t,s} \leq Q^{GFG,max}_{i,t,s} \tag{52}$$

$$P^{CFG,min}_{i,t,s} \leq P^{CFG}_{i,t,s} \leq P^{CFG,max}_{i,t,s} \tag{53}$$

$$Q^{CFG,min}_{i,t,s} \leq Q^{CFG}_{i,t,s} \leq Q^{CFG,max}_{i,t,s} \tag{54}$$

$$P^{P2G,min}_{i,t,s} \leq P^{P2G}_{i,t,s} \leq P^{P2G,max}_{i,t,s} \tag{55}$$

$$Q^{P2G,min}_{i,t,s} \leq Q^{P2G}_{i,t,s} \leq Q^{P2G,max}_{i,t,s} \tag{56}$$

$$P^{load,min}_{i,t,s} \leq P^{load}_{i,t,s} \leq P^{load,max}_{i,t,s} \tag{57}$$

$$Q^{load,min}_{i,t,s} \leq Q^{load}_{i,t,s} \leq Q^{load,max}_{i,t,s} \tag{58}$$

2) FEEDER OPERATION CONSTRAINTS

$$\begin{cases} -P^{feeder}_{i,min} \leq P^{feeder}_{i,t,s} \leq P^{feeder}_{i,max} \\ -Q^{feeder}_{i,min} \leq q^{feeder}_{i,t,s} \leq Q^{feeder}_{i,max} \end{cases} \forall i \in \Gamma_{feeder}, \forall t, \forall s \tag{59}$$

$$\begin{aligned} &-P^{feeder}_{i,max}\left(1 - \sum_{i\in\Omega_{feeder}} xfe_{ij}^{\frac{New}{feeder}}\right) \\ &\quad - \sum_{i\in\Omega_{feeder}} P_{ij}^{Replace^{feeder}_{Max}\, xfe_{ij}^{\frac{New}{feeder}}} \leq P^{feeder}_{i,t,s} \\ &\leq P^{feeder}_{i,max}\left(1 - \sum_{i\in\Omega_{feeder}} xfe_{ij}^{\frac{New}{feeder}}\right) \\ &\quad + \sum_{i\in\Omega_{feeder}} P_{ij}^{Replace^{feeder}_{Max}\, xfe_{ij}^{\frac{New}{feeder}}} \quad \forall i \in \Gamma_{feeder}, \forall t, \forall s \end{aligned} \tag{60}$$

The initial fixed feeders' maximum power ratings ($\forall i \in \Gamma\_feeder$) are shown in equation (59) whereas equation (60) states the replacement and addition of new ones.

3) OPERATION CONSTRAINTS FOR ELECTRICAL BATTERY STORAGE

$$u^{BS_{ch}}_{i,t,s} + u^{BS_{dch}}_{i,t,s} \leq 1, u^{BS_{dch}}_{i,t,s} = 0, \forall i \in \Omega_{BS} \tag{61}$$

$$0 \leq P^{BS_{ch}}_{i,t,s} \leq \sum_{i\in\Omega_{BS}} P^{BS}_{i,t,max} xfe_{i,t,s}^{\frac{New}{BS}} u^{BS_{ch}}_{i,t,s}, \forall t \tag{62}$$

$$0 \leq P^{BS_{dch}}_{i,t,s} \leq \sum_{i\in\Omega_{BS}} P^{BS}_{i,t,max} xfe_{i,t,s}^{\frac{New}{BS}} u^{BS_{dch}}_{i,t,s}, \forall t \tag{63}$$

$$P^{BS_{Cap}}_{i,t,s} = \begin{cases} 0 + P^{BS_{ch}}_{i,t} \eta^{ch} \Delta t - \frac{P^{BS_{dch}}_{i,t,s}}{\eta^{dch} \Delta t} t = 1 \\ P^{BS_{Cap}}_{i,t-1} + P^{BS_{ch}}_{i,t} \eta^{ch} \Delta t - \frac{P^{BS_{dch}}_{i,t,s}}{\eta^{dch} \Delta t} t \geq 2 \end{cases} \tag{64}$$

$$0 \leq P^{BS_{Cap}}_{i,t,s} \leq \sum_{i\in\Omega_{BS}} P^{BS_{Cap}}_{i,t,max} xfe_{i,t,s}^{\frac{New}{BS}}, \forall t \tag{65}$$

Simultaneously discharging and charging of power in a BS are not allowed and first stage discharge of BS are also not allowed (t=1), which equation (64) can be used to enforce. Each BS unit can only charge or release electricity when the criteria are met, as represented by constraint (65) $\sum_{i\in BS} xfe_{i,t,s}^{\frac{New}{BS}} = 1$ *and or* $u^{BS_{dch}}_{i,t,s} = 1$ are both satisfied. $sgn\left(\omega^2_{nm,t} - \omega^2_{mn,t}\right) Gf^{GPL^2}_{mn,t} = \varphi_{nm}\left(\omega^2_{nm,t} - \omega^2_{mn,t}\right) \sum_{nm\in CGPL} xfg_n^{\frac{New}{\frac{exist}{GPL}}}, \forall nm \in \Omega_{GPL}, \forall t\, \eta^{ch}$ *and* η^{dch} in constraint (64) denote the efficiencies of battery storage charge and discharge respectively. $P^{BS_{Cap}}_{i,t,s}$ represents the capacity at time t and it is related with the capacity in the former time stage ($P^{BS_{Cap}}_{i,t-1}$), the charge and discharged in current time stage ($\frac{P^{BS_{ch}}_{i,t}}{P^{BS_{dch}}_{i,t}}$), charged/ discharged efficiency of battery storage ($\frac{\eta^{ch}}{\eta^{dch}}$) and the duration Δt. And for each battery storage unit, its initial capacity $\left(P^{BS_{Cap}}_{i,0}\right)$ is imposed to be 0.

4) CONSTRAINTS OF COUPLING TECHNOLOGIES (GFGs AND P2G FACILITIES) IN THE COORDINATED NATURAL GAS AND ELECTRICITY NETWORKS

The natural gas and electricity networks are integrated with each other in this paper by two technologies, the GFGs and the P2G facilities. According to [15], the rate of generation and consumption of energy in the GFG and P2G facilities installed at node and bus $\frac{m}{l}$ can be calculated below. The gas-fired generators consumed natural gas as its input and generated electricity as its output. Hence the natural gas consumption of GFGs can be expressed in equation (66), equation (67) shows that there is a limitation in the output power of GFGs as formulated. Equation (68) shows that the output power of GFGs should meet ramp-up and down constraints. The P2G consumed excess renewable power as its input and produced synthetic natural gas as its output, hence the relationship between the input and output of the P2G facilities is shown in equation (69) Equation (70) shows that the power consumed by P2G units should meet ramp-up and down constraints.

$$P_{nm,t}^{Gas_{GFG}} = \left(\frac{3.412}{GHV}\right)\frac{P_{i,t,s}^{GFG}}{\eta_i^{GFG}} \tag{66}$$

$$U_{GFG,t}P_{i,t,s}^{GFG,min} \le P_{i,t,s}^{GFG} \le U_{GFG,t}P_{i,t,s}^{GFG,max} \tag{67}$$

$$P_{i,t,s}^{GFG_{down}} \le P_{i,t,s}^{GFG} - P_{i,t-1}^{GFG} \le P_{i,t,s}^{GFG_{up}} \tag{68}$$

$$Gf_{nm,t}^{P2G_{\mathrm{sup}}} = \left(\frac{3.412 \times \left(\eta_i^{P2G}P_{i,t,s}^{P2G}\right)}{GHV}\right) \tag{69}$$

$$P_{i,t,s}^{P2G_{down}} \le P_{i,t,s}^{P2G} - P_{i,t-1}^{P2G} \le P_{i,t,s}^{P2G_{up}} \tag{70}$$

η_i^{GFG} and η_i^{P2G} indicate the efficiencies of GFG and P2G facilities installed at bus and node $\frac{m}{i}$, respectively. GHV represents the amount of gross heating value per volume. As the unit of GHV is BTU/m^3, we used a coefficient of 3.142 to convert W to BTU/h, which makes the gas flow units in terms of SCM/h for the natural gas network.

F. CONSTRAINTS RELATED TO THE NATURAL GAS NETWORK

1) GAS FLOW BALANCE CONSTRAINT

$$\sum_{(n\,|\,(m,n)\in\Omega_A)} Gf_{mn,t}^{GPL} = \sum_{(n\,|\,(m,n)\in\Omega_A)} Gf_{nm,t}^{GPL} + SK_{nm,t} - Gf_{nm,t}^{Gas_{load}} + Gf_{nm,t}^{P2G_{Sup}} - P_{nm,t}^{Gas_{GFG}} + Gf_{nm,t}^{GS_{out}} - Gf_{nm,t}^{GS_{in}} \tag{71}$$

$$sgn\left(\omega_{nm,t}^2 - \omega_{mn,t}^2\right) Gf_{mn,t}^{GPL^2} = \varphi_{nm}\left(\omega_{nm,t}^2 - \omega_{mn,t}^2\right), \quad \forall nm \in \Omega_{GPL}, \forall t \tag{72}$$

$$sgn\left(\omega_{nm,t}^2 - \omega_{mn,t}^2\right) Gf_{mn,t}^{GPL^2} = \varphi_{nm}\left(\omega_{nm,t}^2 - \omega_{mn,t}^2\right) \sum_{nm\in CGPL} xfg_n^{\frac{New/exist}{GPL}}, \forall nm \in \Omega_{GPL}, \forall t \tag{73}$$

$$\varphi_{nm}\left(\omega_{nm,t}^2 - \omega_{mn,t}^2\right) \le sgn\left(\omega_{nm,t}^2 - \omega_{mn,t}^2\right) Gf_{mn,t}^{GPL^2} + M \sum_{nm\in CCmpr} xfg_n^{\frac{New}{\frac{exist}{Cmpr}}} ;\forall nm \in \Omega_{Cmpr}, \forall t \tag{74}$$

$$\varphi_{nm}\left(\omega_{nm,t}^2 - \omega_{mn,t}^2\right) \le sgn\left(\omega_{nm,t}^2 - \omega_{mn,t}^2\right) Gf_{mn,t}^{GPL^2} - M \sum_{nm\in CCmpr} xfg_n^{\frac{New}{\frac{exist}{Cmpr}}} ;\forall nm \in \Omega_{Cmpr}, \forall t \tag{75}$$

The gas flow balance was created by equation (71), which shows that the total gas inflows and outflows in each node at any moment are equal. Furthermore, the steady state power flow constraints of Weymouth [21] are represented as expressed in equation (72)-(73) where φ_{nm} represents the distribution coefficient through pipeline nm and $sgn\left(\omega_{nm,t}^2 - \omega_{mn,t}^2\right)$ is a sign function (for $sgn\,(a)$, *if* $a >$ 0, the value of $sgn\,(a)$ is 1; if $a = 0$, the value of $sgn\,(a)$ is 0 and otherwise, the value of $sgn\,(a)$ is -1). It is worthy to note that the flow through pipeline nm ($Gf_{mn,t}^{GPL}$) is imposed to be 0 if no pipeline is added (that is $\sum_{nm\in CGPL} xfg_n^{\frac{New}{\frac{exist}{GPL}}} = 0$) in equation (73). Constraints (74)-(75) guarantee that compressors can be added to the pipeline that have been previously built. Given that M is a very large enough number [22]. Equation (74)-(75) will be equivalent to equation (72) if not to add the compressor ($\sum_{nm\in CCmpr} xfg_n^{\frac{New}{\frac{exist}{Cmpr}}} = 0$), unrestricted otherwise.

2) GAS PIPELINE OPERATION CONSTRAINTS

$$-Gf_{mn,t,max}^{GPL} \le Gf_{mn,t}^{GPL} \le Gf_{mn,t,max}^{GPL}, \forall nm \in \Gamma_{GPL}, \forall t \tag{76}$$

$$-\sum_{nm\in GPL} Gf_{mn,t,max}^{GPL} xfg_{nm,t}^{\frac{New}{GPL}} \le Gf_{mn,t}^{GPL} \le \sum_{nm\in GPL} Gf_{mn,t,max}^{GPL} xfg_{nm,t}^{\frac{New}{GPL}}, \forall nm \in \Omega_{GPL}, \forall t \tag{77}$$

$$-Gf_{mn,t,max}^{GPL} - M \sum_{nm\in Cmpr} xfg_{nm,t}^{\frac{New}{Cmpr}} \le Gf_{mn,t}^{GPL} \le Gf_{mn,t,max}^{GPL} + M \sum_{nm\in Cmpr} xfg_{nm,t}^{\frac{New}{Cmpr}}, \forall nm \in \Omega_{Cmpr}, \forall t \tag{78}$$

The gas flow in previously constructed gas pipes is limited by Equation (76). It can be observed from equations (77) and (78) that the gas flow via newly installed pipelines or potential pipelines for compressors depends on both the upper flow limit $Gf_{mn,t,max}^{GPL}$ ilt also on the investment decision $xfg_{nm,t}^{New/GPL}/xfg_{nm,t}^{\frac{New}{Cmpr}}$.

3) GAS COMPRESSOR OPERATION CONSTRAINTS

$$-Gf_{nm,t,max}^{Cmpr} \le Gf_{nm,t}^{Cmpr} \le Gf_{nm,t,max}^{Cmpr} \forall mn \in \Gamma_{Cmpr}, \forall t \tag{79}$$

$$-Gf_{nm,t,max}^{Cmpr} - M\left(1 - xfg_{nm,t}^{\frac{New}{Cmpr}}\right) \le Gf_{mn,t}^{GPL} \le Gf_{nm,t,max}^{Cmpr} + M\left(1 - xfg_{nm,t}^{\frac{New}{Cmpr}}\right), \forall nm \in \Omega_{Cmpr}, \forall t \tag{80}$$

The operation of the existing gas compressor ($\forall mn \in \Gamma\_(Cmpr)$) is modelled in equation (79) and equation (80) represent the operation of a possible newly installed gas compressor ($\forall nm \in \Omega_{Cmpr}$) that are related with the investment decision on them ($xfg_{nm,t}^{\frac{New}{Cmpr}}$).

4) GAS SUPPLY CONSTRAINTS (GAS-WELL)

$$0 \leq SK_{n,t} \leq SK_{n,max}, \forall n \in \Omega_{SK}, \forall t \tag{81}$$

where $SK_{n,t}$ represent the gas supplied from the gas-well source at node n at time t and $SK_{n,max}$ notes the corresponding maximum value.

5) PRESSURE INEQUALITY CONSTRAINTS

$$\omega_{n,min} \leq \omega_{n,t} \leq \omega_{n,\max}, \forall n, \forall t \tag{82}$$

where $\omega_{n,t}$ denotes nodal pressure at node n and at time t. The lower and upper pressure limits are represented by $\omega_{n,min}$nd $\omega_{n,\max}$, respectively.

6) GAS STORAGE OPERATION CONSTRAINTS

Like the same way the battery storage was model, the Gas storage can be modelled as shown in equation (83) - (87).

$$u_{nm,t}^{GS_{in}} + u_{nm,t}^{GS_{out}} \leq 1, u_{nm,t}^{GS_{out}} = 0, \forall nm \in \Omega_{GS} \tag{83}$$

$$0 \leq Gf_{nm,t}^{GS_{in}} \leq \sum_{nm \in \Omega_{GS}} Gf_{nm,t,max}^{GS} xfg_{nm,t}^{\frac{New}{GS}} u_{nm,t}^{GS_{in}}, \forall t \tag{84}$$

$$0 \leq Gf_{nm,t}^{GS_{out}} \leq \sum_{nm \in \Omega_{GS}} Gf_{nm,t,max}^{GS} xfg_{nm,t}^{\frac{New}{GS}} u_{nm,t}^{GS_{out}}, \forall t \tag{85}$$

$$Gf_{nm,t}^{GS_{Cap}} = \begin{cases} 0 + Gf_{nm,t}^{GS_{in}} \eta^{in} \Delta t - \frac{Gf_{nm,t}^{GS_{out}}}{\eta^{out} \Delta t} t = 1 \\ Gf_{nm,t-1}^{GS_{Cap}} + Gf_{nm,t}^{GS_{in}} \eta^{in} \Delta t - \frac{Gf_{nm,t}^{GS_{out}}}{\eta^{out} \Delta t} t \geq 2 \end{cases} \tag{86}$$

$$0 \leq Gf_{nm,t}^{GS_{Cap}} \leq \sum_{nm \in \Omega_{GS}} Gf_{nm,t,max}^{GS_{Cap}} xfg_{nm,t}^{\frac{New}{GS}}, \forall t \tag{87}$$

Simultaneously storing and supplying of gas from the gas storage is not allowed and the gas storage not allowed to supply gas at initial stage (t=1), this is represented in equation (83). Limitation (84) denotes that each gas storage unit stores or supply gas only when the conditions $\sum_{nm \in GS} xfg_{nm,t}^{\frac{New}{GS}} = 1 \; and \; or \; u_{nm,t}^{GS_{out}} = 1$ are both satisfied. $\eta^{in} \; and \; \eta^{out}$ in constraint (86) denote the efficiencies of gas storage and supply respectively. $Gf_{nm,t}^{GS_{Cap}}$ denote the capacity at time t and it is related with the capacity in the initial time stage ($Gf_{nm,t-1}^{GS_{Cap}}$), the flow of gas storage/release in current time stage ($\frac{Gf_{nm,t}^{GS_{in}}}{Gf_{nm,t}^{GS_{out}}}$), storage/ supply efficiency of gas storage ($\frac{\eta^{in}}{\eta^{out}}$) and the duration Δt. And for each gas storage unit, its initial capacity $\left(Gf_{nm,0}^{GS_{Cap}}\right)$ is imposed to be 0.

G. *WIND TURBINE AND PHOTOVOLTAIC OPERATION CONSTRAINTS*

The constraint of solar and wind curtailment power is represented in equation (88) where α_min^(WT/PV) and α_max^(WT/PV) represent the maximum and minimum permissible of renewable power penetration rate.

$$\begin{aligned} \alpha_{min}^{WT/PV} \sum_{i \in \Omega_{Renew_{load}}} P_{i,min}^{Renew_{load}} \leq & \sum_{i \in \Omega_{WT}} P_{i,max}^{WT} \eta_i^{WT} \\ & + \sum_{i \in \Omega_{PV}} P_{i,max}^{PV} \eta_i^{PV} \leq \alpha_{max}^{WT/PV} \\ & + \sum_{i \in \Omega_{Renew_{load}}} P_{i,max}^{Renew_{load}} \end{aligned} \tag{88}$$

1) WIND CURTAILMENT CONSTRAINTS

$$P_{i,t,s}^{WT} = \sigma_{i,t,s}^{WT} \sum_{i \in \Omega_{WT}} P_{i,max}^{WT} \eta_i^{WT}, \forall i \in \Omega_{WT}, \forall t, \forall s \tag{89a}$$

$$0 \leq P_{i,t,s}^{cur\,WT} \leq \beta_{i,max}^{cur\,WT} P_{i,t,s}^{WT} \tag{89b}$$

$$P_{i,t,s}^{WT''} = P_{i,t,s}^{WT} - P_{i,t,s}^{cur\,WT} \tag{89c}$$

$$q_{i,t,s,max}^{WT)=P\_(i,t,s)^\wedge([WT]^\wedge} \tan\left(cos^{-1} \lambda^{WT}\right) \tag{89d}$$

$$-q_{i,t,s,max}^{WT''} \leq q_{i,t,s}^{WT''} \leq q_{i,t,s}^{WT''} \tag{89e}$$

2) SOLAR CURTAILMENT CONSTRAINTS

$$P_{i,t,s}^{WT} = \sigma_{i,t,s}^{WT} \sum_{i \in \Omega_{WT}} P_{i,max}^{WT} \eta_i^{WT}, \forall i \in \Omega_{WT}, \forall t, \forall s \tag{90a}$$

$$0 \leq P_{i,t,s}^{cur\,PV} \leq \beta_{i,max}^{cur\,PV} P_{i,t,s}^{PV} \tag{90b}$$

$$P_{i,t,s}^{PV''} = P_{i,t,s}^{PV} - P_{i,t,s}^{cur\,PV} \tag{90c}$$

$$q_{i,t,s,max}^{PV''} = P_{i,t,s}^{PV''} \tan\left(cos^{-1} \lambda^{PV}\right) \tag{90d}$$

$$-q_{i,t,s,max}^{PV''} \leq q_{i,t,s}^{PV''} \leq q_{i,t,s}^{PV''} \tag{90e}$$

The real WT and PV generation ($P\_(i,t,s)$^$WT/P\_(i,t,s)$^WT) is written in terms of the upper output limit for the renewable power using ($P\_(i,max)$^$WT/P\_(i,max)$^PV), multiplied by the installation number at bus $i \left(\eta_i^{WT}\right)$ and the coefficient output at time stage t of scenario $\sigma_{i,t,s}^{WT}$. The curtailment of wind and solar is subject to equations (89a)-(89e) and (90a)-(90e), respectively. In this set of constraints, $\frac{\beta_{i,max}^{cur\,WT}}{\beta_{i,max}^{cur\,PV}}$ sents the maximum curtailment rate. $\frac{\lambda^{WT}}{\lambda^{PV}}$ represents the power factor of wind and solar power. $\frac{P_{i,t,s}^{WT''}}{P_{i,t,s}^{PV''}}$ and $\frac{q_{i,t,s}^{WT''}}{q_{i,t,s}^{PV''}}$ represents the renewable power active and reactive after curtailment.

IV. CASE STUDIES AND SIMULATION RESULTS

A. *TEST SYSTEM AND DATA*

An expansion planning model of coordinated natural gas and electricity networks is proposed to investigate the lowest feasible total planning cost while fulfilling future energy demand. To assess the performance and applicability of the proposed expansion planning model, a modified UK 16-bus electricity distribution network coupled with a modified Belgian 20-node natural gas network are used in the proposed model as shown in figure 5 and 6, respectively. While the

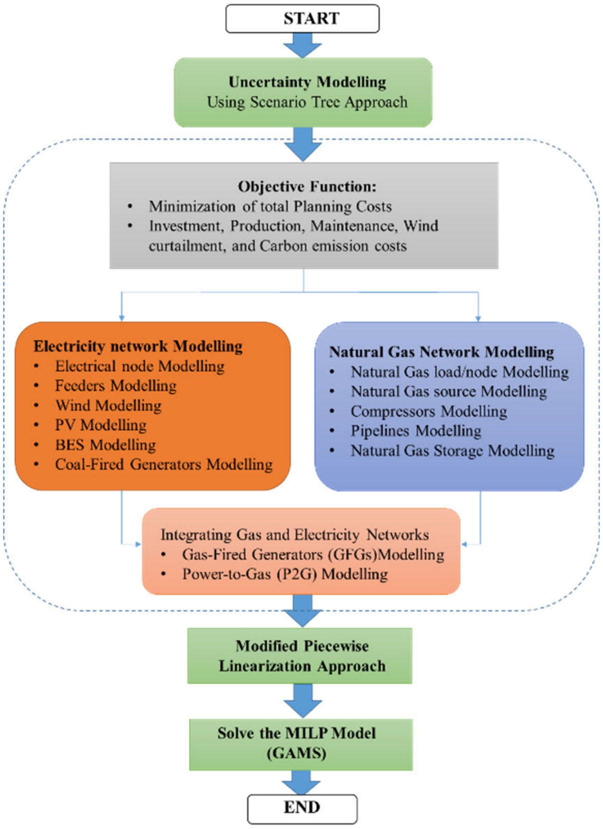


FIGURE 3. Flowchart of the proposed modelling methodology.

data used in this study was adapted from [13]. We assume that the future load growth demand will be met completely by installing more gas-fired generators to replace the current coal-fired generators, while also building P2G facilities to solve the challenges of wind power curtailment by converting excess renewable energy into synthetic natural gas (SNG). The modified UK 16-bus distribution network initially has 5 coal-fired generators with each individual notional output of 200MW, 2 gas-fired generators with each individual notional output of 200MW, 2 wind turbines with each notional outputs of 150MW, and 2 solar PVs with each notional outputs of 50MW, 1 battery storage and about 20 existing distribution corridors. Figure 4 displays the forecasted hourly information pattern of WTs and PVs, figure 7 shows the hourly power generation of the GFGs and CFGs, respectively. 10 years planning horizon is studied, with 5 load blocks in each year. Electrical load, wind power, PV power, and natural gas load in the first planning year are 1800MW, 300MW, 100MW, and 10000 kcf/h with average growth rates of 3%, 8%, and 5%.

The total generation capacity of the based electricity network is 1800MW, while the total electricity load demand is 1550 MW. It is expected that the voltage limitations are 1.06 and 0. 9pu. Taking the year 2030 as the level year, the total power load of the proposed model is expected to double

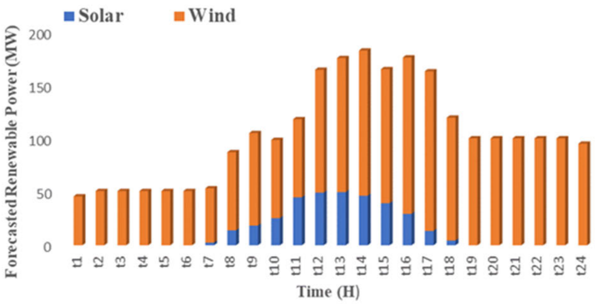


FIGURE 4. The forecasted hourly data of WTs and PVs Power.

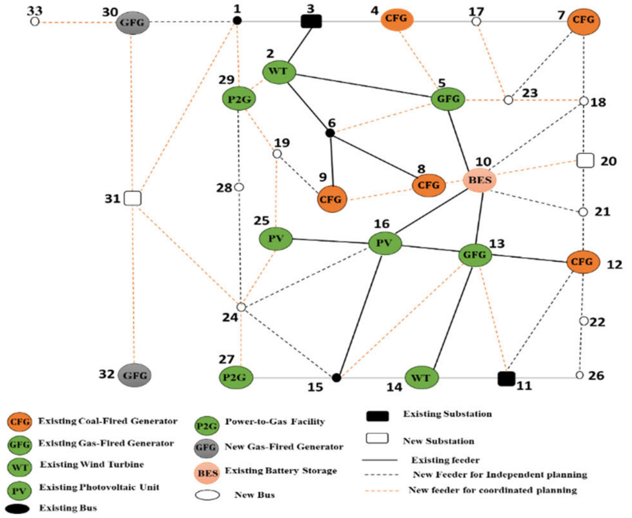


FIGURE 5. Initial topology of the Modified UK 16-bus Electricity distribution network utilized in the proposed model.

the base year generation capacity. The 20-node natural gas network initially has 2 gas-well (gas source), 2 existing compressors, 1 gas storage system and 24 gas pipelines corridors, 20 gas load nodes already in place and 23 additional nodes and gas pipelines corridors. The forecasted natural gas and electricity price used in this study is shown in figure 8. In both figures 5 and 6, solid black lines represent existing elements at the beginning of the planning period, dashed black lines represent potential network expansions for the independent networks, and dashed red lines represent potential network expansions for the coordinated networks. The black circles are the electrical nodes (Fig. 5) and gas nodes (Fig. 6) that exist. White circles are the electrical nodes (Fig. 5) and gas nodes (Fig. 6) that will be connected at the expansion planning stage. All nodes might have power demand or gas demand. If they have demand. Potential locations of new GFGs are shown in bus 30 and 32, respectively. Noting that the system planned attributes these future expansions mostly to the city's growth projections is crucial.

To meet the growing demand for clean natural gas and electricity, there is need for an expansion investment in both networks. Hence, 23 new candidate gas pipelines (marked with black dashed and red dashed lines), 2 new candidate compressors are selected to be available investment options for the natural gas network as shown in figure 5, while for the electricity network, new candidates gas-fired generators were used to replace the existing coal-fired generators, 2 new candidate P2G facilities were installed to solve the problem of wind curtailment and 17 candidate feeders (new feeders) are added to the modified electricity distribution network. The efficiency of the P2G facilities is assumed to be 64% and the investment cost of P2G facility is $1,000,000/MW [23]. It is worthy to note that the investment cost of the P2G facility covers both the electrolyser and the methanation, all other civil and control system work of the P2G facilities were not included in this study. In the meantime, the network has various marked potential places (such as feeders or buses) for the installation of prospective active equipment. Each gas compressor has a yearly investment cost of $25,000,000. The gas pipelines have an annual investment expenditure of $1,000,000/KM. The electricity line (feeders) annual investment expenditure is $350,000/KM. To implement the simulation, the resulting mixed integer linear programming (MILP) problem was addressed on a 8GB-1.4GHz Read only memory (RAM), Core i7 intel personal computer (PC) using generalised algebraic modelling systems (GAMS) software [24]. The uncertainties in the electricity demand load, wind and solar electricity power output are analysed with a scenario-tree based stochastic technique. 108 situations are considered when modelling uncertainty. To model the combination of 4-time blocks, 3 levels of demand load, 3 levels of wind velocity, and 3 levels of solar energy are considered, resulting in one hundred and eight possible scenarios. Normal and Weibull PDFs are utilised.

B. SIMULATION AND ANALYSIS OF RESULTS

It is important to note that the scenario-tree technique has considered the association between the demand load, wind velocity, and solar energy uncertainty. In this study, 4-time blocks, 3 levels of demand load, 3 levels of wind velocity, and 3 levels of sun energy are combined to create one hundred and eight different situations. The same link between demand load and wind and solar electricity power output is examined at all system sites.

To analyse the benefits of the proposed methodology, two case studies are analysed. The first case which is referred to as case 1, calculate the expansion planning cost of the natural gas and electricity networks as two independent networks that are planned and operated separately without any form of connection or the use of any technologies to couple both networks. The second case study is referred to as case 2, is the coordinated expansion planning that was formulated in section III. Where the natural gas and electricity networks are coupled via the gas-fired generators, P2G facilities and renewable power. These two cases compared the effectiveness of planning independently or planning interdependently in terms of total expansion cost.

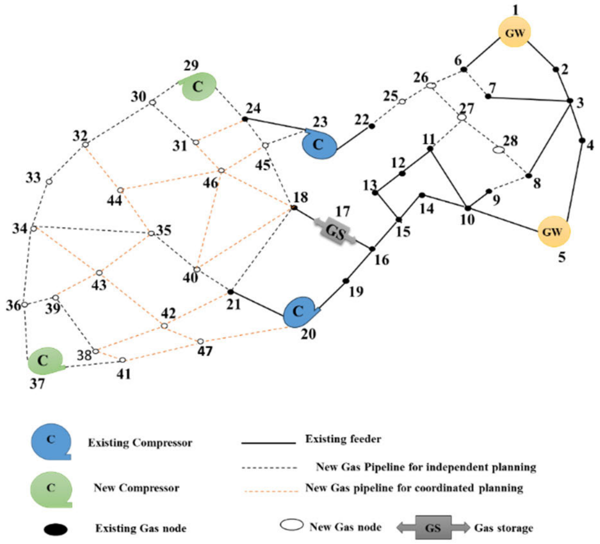


FIGURE 6. Initial topology of the modified natural gas distribution network utilized in the proposed model.

Case 1: Determining the total expansion planning cost of an independent system.

Case 2: Determining the total expansion planning cost of a coordinated system.

Case 1

Electricity and natural gas networks were planned independently in this case. In the electricity network, there was more consideration made for more investment in the installation of more coal fired generators to meet up with the required load demand in the electricity network. In fact, as can be seen from figure 9, 2 more coal-fired generators of 200MW each were installed at buses #18 and #28, respectively to meet the load demand. One of the reasons for the added coal-fired generators were due to the variation and uncertainty nature of the power generation from wind and the photovoltaic systems to meet the load demand and, the limitation of natural gas supply from the gas suppliers. However, apart from the high investment cost of coal-fired generators, the more coal-fired generators that were added in this case, the more penalty were paid for carbon emission and wind curtailment as shown in table 2. Hence, the total planning cost of the electricity network in case 1 will increase as shown in figure 9 and in table 2, respectively.

In the gas network, since the gas network was planned separately, there was need to invest more on the installation of new compressors in other to increase the pressure of the gas supply because it is assume that the natural gas network location in an independent planning is far away from the location of the gas-fired generators and other gas consumers, hence due to the distance of the natural gas network to its consumers, investment into more compressor than gas pipelines

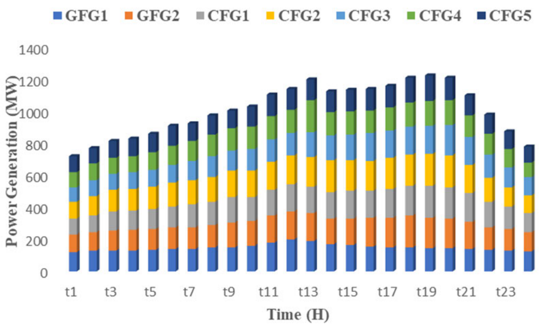


FIGURE 7. Hourly electricity generation from gas-fired and coal-fired generators.

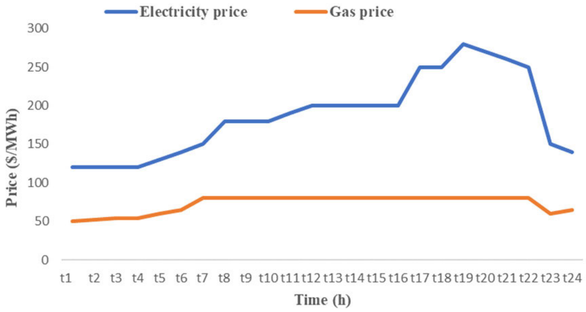


FIGURE 8. The forecasted natural gas and electricity price.

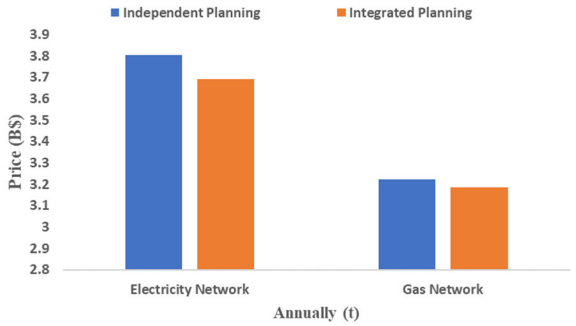
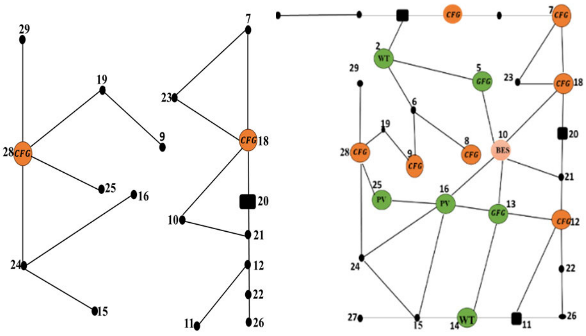


FIGURE 9. Comparison of total planning cost on case 1 and 2.



(a) (b)

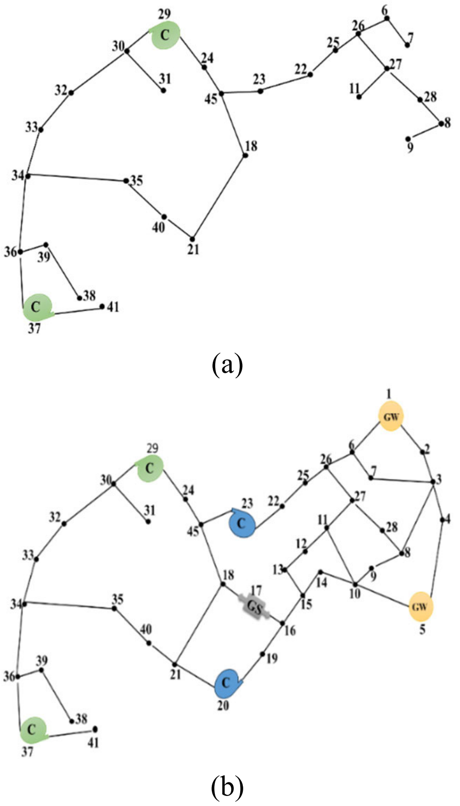
FIGURE 10. Case 1 – independent electricity distribution network topology stage 1 and 2 respectively.

is required to increase the pressure of gas flow to the required consumers. Figure 11 shows that 2 newly gas compressors were installed in this case at node J29 and J37, respectively. While 10 new gas pipelines were installed between node J29 and J37 to serve as a back-up for the existing gas pipelines in handing the increased pressure of the gas flow from the newly installed compressors. However, as discussed earlier, the investment cost of gas compressor is way higher than the investment cost of gas pipelines. Hence, the total investment cost of planning an independent natural gas network is increased due to the investment in more gas compressors than the pipelines to increase the pressure of the gas flow as shown in figure 9.

Case 2

As illustrated from case 2, the coordinated planning result is shown in figure 6. In the natural gas network, it can be observed that new gas pipelines were installed at node J31, J32, J34, J35, J38, J39, J40, J41, J42, J43, J44, J45, J46, J47. Unlike the planning result in case 1 for the natural gas network, in this case, apart from the 2 existing compressors no new candidate compressors were added during the planning in this case rather more new pipelines were added as shown in figure 13. This is because it is assumed that in a coordinated planning both natural gas and electricity networks are sited in a close location for high efficiency. Additionally, from an economic perspective. The investment cost of new compressors is relatively higher than new gas pipelines. Hence, it would be wise to use gas pipelines instead of installing more new compressors since the distance between the two networks is sited closer and the natural gas in the pipeline will not require too much pressure to deliver gas to each gas load. To ensure continuous flow of natural gas 14 new gas pipelines are added through the path from the gas suppliers to the gas demand as shown in figure 13. Hence the simulation result in figure 9 and table 2 shows that the planning cost of natural gas network is less compared to the result obtained in case 1.

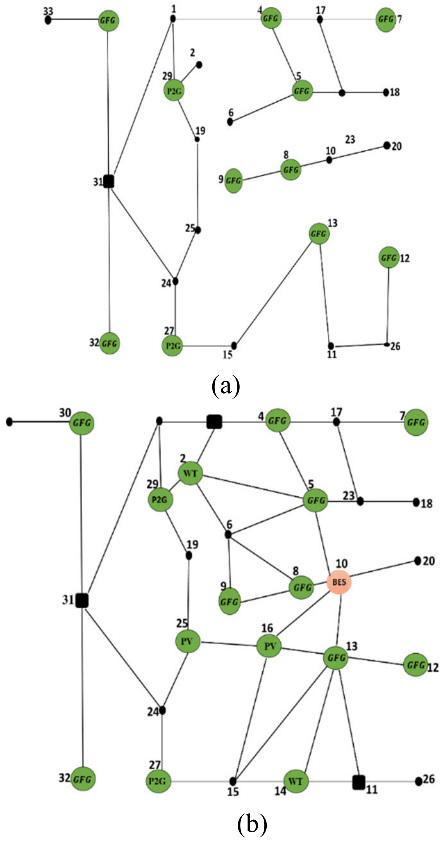
For the electricity network in case 2, seven new gas-fired generators are installed at #3, #5, #7, #6, #8, #9, #12 to replace the five CFGs. The reason for the replacement or retirement of the CFGs with the GFGs is that both the production cost, investment cost and carbon emissions cost of GFGs are lower than the CFGs. Another reason for the replacement of the CFGs with the GFGs is in line with the Paris Agreement adopted in 2015 [25] which states that Direct replacement of coal with natural gas for power generation has proven to reduce GHG emissions tremendously in the energy sector. It can also be seen in figure 12 that newly distribution lines (feeders) are mostly installed/added around the GFGs so that the capacity of the electricity lines around the GFGs are improved, the cleaner power energy with lower price can be delivered as much as possible to meet the electricity load demands. Furthermore, around the electricity buses connected to the wind farms and photovoltaic systems in bus #2, #14, #16, and #25, respectively.



(a)

(b)

FIGURE 11. Case 1 – independent natural gas network topology stage 1 and 2 respectively.



(a)

(b)

FIGURE 12. Case 2 – coordinated electricity distribution network topology stage 1 and 2 respectively.

A lot of electricity lines are expected to be expanded because of the total distribution capacity of the existing electricity lines is insufficient to ensure that the wind farm, photovoltaic systems, and the newly installed gas-fired generators supplies enough excess renewable power to the newly installed P2G facilities at bus #27 and #29. Also, the installation of two new P2G facilities in this case, will reduce the problem of gas limitation from the natural gas suppliers and the cost of production will greatly reduce in this case since the P2G facilities will also be producing synthetic natural gas to supply to both the gas-fired generators and the natural gas network.

Furthermore, the result in table 2 Shows that the independent planning for case 1(electricity network) shows that the owners of the planned network considered the penalty cost they will pay to the wind farm owner to shot down their farms during high-capacity generation to avoid the excess renewable power from causing instability on the network. From the result of the simulation in table 2, it shows that the cost paid to the wind and PV farm owners is about \$400,000 p.a. in case 1, while in case 2. Due to the installation of P2G facility to absorb excess renewable power the penalty cost of wind curtailment is zero as shown in table 2. Hence the simulation result in figure 9 shows that the planning cost of the electricity network is lesser compared to the result obtained in case 1.

1) COMPARISON AND DISCUSSION

The results of the two case studies are compared in terms of expansion planning of independent networks and coordinated networks considering investment, operation, wind curtailment and carbon emission costs. Figure 9 and table 2 shows that the coordinated planning can strengthen both electricity and natural gas networks to improve the energy transfer capability to deliver more gas from the P2G facilities for balancing load demand since the production cost of gas is relatively lower than coal. Figure 12 shows that all the coal-fired generators used in figure 10 were all replaced with a gas-fired generators since in case 2, both the gas and electricity network were planned simultaneously and there will be available gas supply from both the gas-well and the P2G to supply the gas-fired generators, thereby reducing the total planning cost of case 2 as compared to case 1 in table 2. Additionally, from the result in table 2, it shows that coordinated planning of gas and electricity network will reduce the cost of both wind curtailment and carbon emission cost, hence providing clean renewable power and reducing CO2 in the environment.

2) THE MODIFIED IEEE 118-BUS POWER NETWORK AND THE 134-NODAL NATURAL GAS NETWORK

The developed model is further applied to a bigger test system in this section to gauge its computing efficiency and

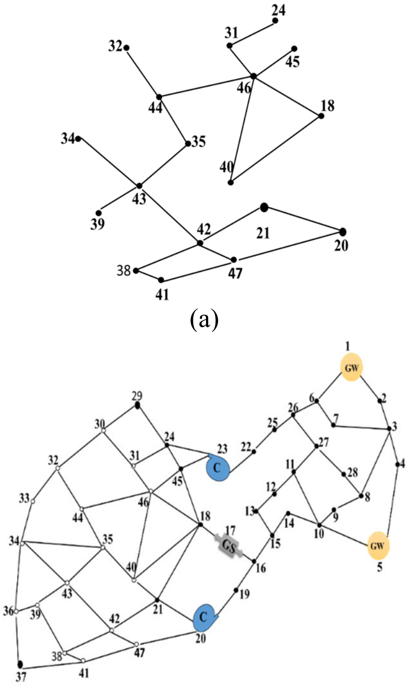


FIGURE 13. Case 2 – coordinated natural gas network topology stage 1 and 2 respectively.

determine its applicability. The 134-nodal Natural Gas and a modified IEEE 118-bus power system make up the test setup. The test system specifically consists of 186 lines, 91 electrical loads, 3 gas wells, 24 pipelines, 2 compressor stations, and 9 non-power gas loads, as well as 46 coal-fired generators and 8 gas-fired generators, 7 wind farms, and 3 solar systems. Candidate assets include 30 gas pipelines, 3 P2G stations, 12 coal-fired generators, 9 gas-fired generators, 15 transmission lines, and 21 producing generators [26]. The stochastic coordinated optimization model without uncertainty was solved in 60 seconds with a threshold on relative MILP gap of 0.1%. In the suggested model, the same case studies 1 and 2 are examined here, and their computational times are listed in Table 3. Case 1 is unable to derive a workable independent planning strategy, indicating that if all less expensive gas-fired generators were built when the network was independently planned, the natural gas network would not be able to supply the necessary amount of gas to run all the installed gas-fired generators due to limitations in the gas supply from the gas well. Additionally, the suggested coordinated optimization planning model's heterogeneous computing cost on a bigger test system depends on the following two key elements:

(a) The intricate and accurate modelling of the natural gas network, which includes the strict modelling of the natural gas compressors and nonlinear Weymouth gas flow equations. In particular, (1) the huge number of binary variables introduced by the linearized Weymouth gas flow equations and (2) the need for big-M constraints as well as additional binary investment and operating variables in gas compressor modelling. The coordinated optimization planning in case 2 takes more time (about 60s) to compute than the independent planning method in case 1, which calculates the independent electricity network planning in 6s.

(b) When electrical load, wind, and PV generation uncertainties are considered, the computational efficiency of the coordinated optimization approach remains a problem for realistic large-scale systems, increasing the running time from the 60s in case 2 to roughly 240s.

TABLE 2. Comparison of the planning cost in both independent and coordinated networks.

Annual cost (10^8\$)	Case 1 (Independent expansion planning cost (10^8\$)		Case 2 (Coordinated expansion planning cost (10^8\$)		Percentage of total cost reduction (%)
	Electricity Network	Gas Network	Electricity Network	Gas Network	
Investment cost (\$)	2.4539	2.1000	2.3886	2.0968	8%
Annual Production cost	1.3482	1.1232	1.2997	1.0878	10%
Annual Maintenance cost	0.0013	0.0011	0.0010	0.0001	11%
Annual Renewable curtailment cost	0.0004	0.0000	0.0000	0.0000	100%
Annual Carbon emission cost	0.0003	0.0000	0.0001	0.0000	60%
Total planning cost (\$)	7.0284		6.8729		12%

Note: that the annual operation cost represents the sum of operation excluding cost of wind curtailment, carbon emission cost, and maintenance costs.

TABLE 3. Computation time of cases studies 1 and 2.

Cases	Time (s)
Case 1	6
Case 2	60
With Uncertainties	240

V. CONCLUSION

In this paper, a stochastic expansion planning model for a coordinated natural gas and electricity network, integrating gas-fired generators, power-to-gas (P2G) facilities, and renewable power sources, has been presented. The study compared the benefits of planning integrated natural gas and electricity networks simultaneously against the traditional approach of planning these networks separately. The final planning solution identified the optimal type, location, and size of all infrastructures to achieve the best operation strategy, minimizing overall costs over the planning horizon. The simulation results and analysis reveal several key insights:

(1) Cost Reduction: Coordinated expansion planning can significantly reduce the total cost of managing natural gas and electricity networks.

(2) Interdependent Investment Decisions: Investment decisions in a coordinated planning framework are highly interdependent. For instance, retiring all seven coal-fired generators in one scenario triggers investments in additional gas-fired generators.

(3) Role of Power-to-Gas (P2G): P2G technology can accommodate excess renewable energy, preventing curtailment, and supplementing natural gas production.

(4) System Synergies: The combined modeling of P2G, wind farms, photovoltaic systems, gas storage, and gas-fired generators provides a promising approach to alleviating challenges from natural gas limitations at gas wells.

(5) Balancing Gas Demand: P2G construction can balance temporal gas demand, potentially influencing the installation of more gas-fired generators and the retirement of coal-fired generators.

The benchmarked of the current model against current research, was far outperformed the competition. Similar to Zhang et al. [18], the proposed model demonstrates even more significant cost reductions by coordinating the development of gas and electricity networks, building on the work that emphasizes the cost savings from integrating renewable energy sources with traditional power systems. Moreover, the findings align with the conclusions of Tao et al. [23] on the critical role of P2G in enhancing system flexibility and renewable energy integration, but the present approach goes further by optimizing the entire network's infrastructure investments and operations simultaneously. Additionally, a stochastic approach was employed to account for uncertainties associated with wind speed, photovoltaic irradiance, and load demand, utilizing the scenario tree method.

Regarding limits and areas for further study, the present model provides significant advantages but also has certain constraints. For instance, the existing model fails to account for the impact of line pack on the efficiency of integrated gas-electricity networks. Subsequent studies might explore this element in order to enhance the precision of the planning model. Incorporating more detailed data and real-time analytics might improve the accuracy and usefulness of the model in dynamic operating contexts.

In terms, the efficiency and policy implications of the model, the proposed model is more efficient than others due to its holistic approach to integrated network planning, which reduces redundancy and optimizes resource allocation across both networks. The algorithm's capability to handle large-scale, complex systems and its consideration of various uncertainties make it a robust tool for planners. The advantages of proposed model extend beyond technical efficiency by providing a comprehensive framework for integrated network planning, in which the model informs policy and management decisions in several ways:

(1) Investment Prioritization: Helps policymakers identify critical infrastructure investments that maximize overall network efficiency and resilience.

(2) Renewable Energy Integration: Supports the development of policies promoting renewable energy sources and technologies like P2G.

(3) Cost Management: Assists in formulating strategies to minimize costs and enhance economic viability.

(4) Environmental Impact: Guides the transition from coal-fired to gas-fired generation, aligning with environmental regulations and sustainability goals.

In summary, the stochastic expansion planning model in this paper represents a significant advancement in the coordinated management of natural gas and electricity networks. It offers a robust framework for minimizing costs, optimizing resource use, and enhancing the overall sustainability and resilience of integrated energy systems.

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