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Optimal Scheduling of Gas and Electricity Distribution Networks in Microgrids: A Decomposition Approach

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***Abstract*— The transition towards increasingly renewables-based energy system is ongoing. During this transition microgrids are seen as a key concept and sub-system which can enable the transition and improve the security of supply at distribution network level. From generation perspective, flexible and rapidly controllable gas-based generation units can be utilized to deal with the variable output of weather-dependent renewable energy resources. Due to these complementary characteristics, it is of interest to study the integrated operation of gas and electricity distribution networks also in future microgrids. In this paper, the optimized scheduling of resources in a microgrid with gas and electricity distribution networks is studied. For this purpose, a mathematical model is first determined. After that, due to the complexity of this model, a decomposition method is developed to solve the optimization problem. This method splits the original problem into two subproblems, which reduces the complexity of solving. In order to validate the efficacy of the proposed model, a case study is derived based on a 15-node gas distribution network and a 13-node electricity distribution network. Based on the results, integrated scheduling improves the costs compared to separated scheduling, and the decomposition method reduces the solving time considerably.**

Keywords—microgrid, scheduling, gas and electricity distribution networks, decomposition

NOMENCLATURE

Sets

Y	Set of sources in gas distribution network ($y \subseteq N$)
N	Set of nodes in gas distribution network ($n \in N$)
P	Set of pipelines in gas distribution network ($p \subseteq (n, n')$)
B	Set of nodes in electricity network ($b \in B$)
T	Set of periods ($t \in T$)
L	Set of distribution lines ($l \subseteq (b, b')$)

Parameters

C^{gas}	Cost of natural gas (\$/km^3)
C^{lp}	Cost of changes in linepack (\$/km^3)
C^{gsh}	Cost of gas not-supplied (\$/km^3)
$F_y^{\text{sup min/max}}$	Minimum /maximum gas injection (km^3)
$D_{n,t}^{\text{gas}}$	Gas demand (km^3)
Le_p	Pipeline length (km)
Dia_p	Pipeline diameter (mm)
$F_p^{\text{pipe min/max}}$	Minimum/maximum gas flow (km^3)
$\pi_{p,t}^{\text{min/max}}$	Minimum/maximum gas pressure (Pascal)
$LP_{p,t}^0$	Initial linepack (km^3)
$\gamma_{b,t}$	Purchased energy prices (\$)
$\gamma'_{b,t}$	Sold energy prices (\$)
α_b	Variable cost of generating power using non-renewable distributed generators (\$/kW)
β_b	Fixed cost of generating power using non-renewable distributed generators (\$)
$Pg_b^{\text{min/max}}$	Minimum/maximum produced power by non-renewable generators or supplied by substations (kW/h)
$R_b^{\text{max up/down}}$	Minimum ramp up/down of non-renewable generating units (kW/h)
υ	Energy conversion coefficient (m^3/W)
η_b	Energy efficiency of non-renewable generators
$Qt_b^{\text{min/max}}$	Minimum/maximum active power of non-renewable generators or substations (kVAr)
$P_{b,t}^{\text{load}}$	Active load (kW)
$Q_{b,t}^{\text{load}}$	Reactive load (KVAr)
R_l	Resistance (Ω)
X_l	Reactance (Ω)
Z_l	Impedance (Ω)
$V_b^{\text{min/max}}$	Minimum/maximum voltage (kV)
I_l^{max}	Maximum current (kA)
$Pw_{b,t}^{\text{max}}$	Maximum available generated power by wind generators (kW)
f	Friction factor for pipelines
S	Specific gravity of natural gas (kg/m^3)
λ	Optimal multipliers of optimization problem

Decision variables

$F_{y,t}^{\text{sup}}$	Gas injection (km^3)
$\Delta LP_{n,t}$	Change in linepack (km^3)
$GNS_{n,t}$	Gas-not-supplied (km^3)
$F_{p,t}^{\text{pipe}}$	Gas flow within pipelines (km^3)
$F_{p,t}^{\text{pipe in/out}}$	Input/output gas flow of pipelines (km^3)
$\pi_{p,t}^{\text{in/out}}$	Input/output pressure of gas within pipelines (Pascal)
$LP_{p,t}$	Linepack (km^3)
$P_{b,t}^{\text{buy/sell}}$	Purchased/sold energy from/to day-ahead market (kW)
$Pg_{b,t}$	Generated power of non-renewable generators (kW)
$Fg_{b,t}$	Required natural gas of non-renewable generators (km^3)

$Qt_{b,t}$	Reactive power of generating non-renewable generating units or substations (kVAr)
$Pw_{b,t}$	Output power of wind generators (kW)
$Pl_{l,t}$	Active power (kW)
$Ql_{l,t}$	Reactive power (kVAr)
$I_{l,t}$	Electricity current (kA)
$V_{b,t}$	Voltage magnitude (kV)
Binary variables	
$u_{b,t}$	Status of non-renewable generators

I. INTRODUCTION

The increasing proportion of renewable-resource in supplying the amount of energy demand in the world has different benefits, such as decreasing greenhouse emissions and increasing energy supplies diversification, which leads to reduction of dependency on fossil fuels [1]. The worldwide analyses show that transition to a zero-emission energy supply by employing renewable energy resources has been started, and the resources will be the largest sources of energy in the world by 2050 [2]. For instance, the government of the United States of America has set goals to achieve a zero-emission economy by no later than 2050 [3]. The European Union's objective is also to become a zero-emission continent by 2050 to benefit from the sustainable and green transition [4]. Although having significant challenges, such as flexibility requirement and inefficiency resulting from the backup capacity requirement due to the variable output of renewable resources, the electricity sector can accommodate a large share of these recourses by employing an appropriate strategy of scheduling and operation [5].

In moving toward a zero-emission energy system, microgrids can help manage supply-demand balance, reduce energy loss through transmission lines, and improve the resiliency of grids in extreme conditions [6]. Microgrids are local and controllable energy systems composed of a few renewable and non-renewable generating units connected to nearby consumers. The short distance between supply and demand helps manage electricity demand and alleviate congestion and energy loss through lines that reduce the peak demand and energy price. Moreover, microgrids can autonomously operate in island mode when the main grid is off, which enhances resiliency in extreme conditions as well as function as a resource for recovery [7]. A considerable number of previous studies have also investigated scheduling electricity distribution networks in a microgrid. For instance, in [8], a method is proposed to deal with uncertainty in the scheduling microgrids, which is independence in forecasting. The results of this study show cost-saving and being computationally effective in comparison with other approaches which are based on forecasting uncertain data. In [9], this problem is taken into consideration, focusing on the demand response of electric vehicles. It concludes that electric vehicles demand response encourages the owners to participate in the scheduling microgrid that is beneficial in providing supply-demand balance. In [10], the scheduling of microgrids is studied considering a high share of distributed energy resources and energy storage systems. This study shows optimizing this problem considerably contributes to reducing greenhouse gas emissions.

In moving to the producing energy from renewable energy resources, scheduling multi-energy systems is also beneficial. Some components, such as gas-fired units, heat storage systems, and combined heat and power units, integrate gas, electricity, and heat networks and make the integration operation necessary. Therefore, simultaneous scheduling energy systems can lead to cost reduction as a result of finding an optimal solution for the operation of these networks [11]. Among recent studies, in [12], optimal scheduling of integrated heat and electricity microgrids is studied due to a considerable proportion of combined heat and power units. However, in addition to the heat system, cooling system operation is investigated to study the interactions in multi-energy microgrids in [13]. These studies also show the optimal solutions to prevent being exposed to a high scheduling cost. Moreover, in [14] and [15], due to the presence of natural gas-fired units to deal with distributed renewable resources' variable output, scheduling electricity distribution networks coupled with the natural gas network is studied. It is connected to the characteristics of gas-fired units, such as fast-ramping rate, enabling them to cope with the variable output of renewable resources. The results demonstrate cost-saving and the ability of peak shaving when both networks are taken into consideration.

Aside from the already mentioned, solving the integrated operation of energy systems is difficult since the optimization problem is complex. Although linearization [16] and applying heuristic approaches [17] can improve problem solving, decomposition techniques are other options for dealing with the complexity of the optimization. The decomposition method splits the original problem into a few subproblems and solves them iteratively. In recent years, only a few studies have employed decomposition methods to examine the operation of the multi-energy system. For example, in [18], a decomposition method based on Benders Decomposition is developed to solve the complex problem of scheduling multi-energy systems in microgrids considering energy storage systems. In [19], in order to solve the problem of scheduling microgrids quickly and convergently, a relaxation method is employed that provides a convex model. In [20], the problem of scheduling microgrids is examined under a high proportion of distributed renewable energy considering both islanded and grid-connected modes of operation. Furthermore, this study applies Benders Decomposition to solve the optimization problem quickly.

Considering the upsides and downsides of the earlier studies in this field, first of all, a novel mathematical model of gas and electricity distribution networks operation is introduced precisely. In the gas distribution network, constraints such as gas supply limits for the sources, gas flow balance, and linepack and pressure constraints are considered. In the electricity distribution network, an AC model for the scheduling of the electricity distribution network is introduced, which takes into accounts load flow balance, renewable energy resources, and interactions with the market. Then, a decomposition approach is also developed to solve the complex optimization problem. As far as we are aware, it is for the very first time that this method is applied to deal with the complexity of solving the scheduling gas and electricity distribution networks in a microgrid. For validation of the efficacy of the proposed model, a case study is derived based on a 15-node gas distribution network and a 13-node electricity distribution network.

II. MODEL FORMULATION

In this section, at first, a mathematical model is introduced for the integrated scheduling of gas and electricity distribution networks in a microgrid. It is worth noting that, in the gas network's model, continuity and momentum equations are used to show gas flow [21]. The main assumption in the gas distribution network simulation is that the variation in kinetic energy along a pipeline as a consequence of changes in velocity and density is negligible.

The key assumptions in the electricity distribution network's model are also represented as follows:

- The demand is indicated as constant active and reactive power;
- The power loss along a branch is assumed at the beginning of that;
- This network is addressed in a single-phase and balanced equivalent;
- The microgrid interacts with the main grid in a day-ahead market.

A. Gas distribution network model

In this subsection, the operation model of a gas distribution network is indicated (1)-(6). In (1), the objective function of the scheduling gas distribution network is shown, composed of three terms. These terms indicate the cost of natural gas injection through sources, the cost of linepack changes, and the cost of gas not-supplied, respectively. It is important to highlight that linepack refers to the amount of stored natural gas within the pipelines, employed to deal with variation between supply and demand. Linepack is important since it takes a while to transmit natural gas from sources to demand nodes [22].

$$Z_{gas} = \sum_t \sum_y \mathrm{C}^{\mathrm{gas}}.F_{y,t}^{\mathrm{sup}} + \sum_t \sum_n \mathrm{C}^{\mathrm{lp}}.\Delta LP_{n,t} + \sum_t \sum_n \mathrm{C}^{\mathrm{gsh}}.GNS_{n,t} \quad (1)$$

In (2), the gas injection through sources is constrained, and the natural gas balance is shown in (3).

$$F_y^{\mathrm{sup\,min}} \leq F_{y,t}^{\mathrm{sup}} \leq F_y^{\mathrm{sup\,max}} \qquad \forall y, \forall t \qquad (2)$$

$$F_{y,t}^{\mathrm{sup}} - F_{p,t}^{\mathrm{pipe}} = D_{n,t}^{\mathrm{gas}} - GNS_{n,t} \qquad \forall n, \forall t \qquad (3)$$

In (4), Lacey's equation is indicated, employed to simulate the low-pressure gas networks and shows the relation between gas flow and pressure [23].

$$\pi_{p,t}^{\mathrm{out}} - \pi_{p,t}^{\mathrm{in}} = 0.00117\, Le_p.\left(F_{p,t}^{\mathrm{pipe}}\right)^2 / Dia_p^5 \qquad \forall l, \forall t \qquad (4)$$

The natural gas through distribution pipelines is constrained in (5), and the variation of linepack through distribution pipelines is demonstrated in (6).

$$F_p^{\mathrm{pipe\,min}} \leq F_{p,t}^{\mathrm{pipe}} \leq F_p^{\mathrm{pipe\,max}} \qquad \forall p, \forall t \qquad (5)$$

$$LP_{p,t} = LP_{p,t}^0 + \sum\nolimits_0^t (F_{p,t}^{\mathrm{pipe\,in}} - F_{p,t}^{\mathrm{pipe\,out}}) \qquad \forall p, \forall t \qquad (6)$$

B. Electricity network model

In this subsection, the operating model of an electricity distribution network is indicated (7)-(18). The objective function, which consists of three terms, is presented in (7). The first two terms show the cost of interactions with the main grid, and the last one indicates the cost of generating power from non-renewable distributed generators (e.g., combined heat and power units).

$$Z_{elec} = \sum_t \sum_b \gamma_{b,t}.P_{b,t}^{\mathrm{buy}} - \sum_t \sum_b \gamma'_{b,t}.P_{b,t}^{\mathrm{sell}} + \sum_t \sum_b (\alpha_b\,.Pg_{b,t} + \beta_b.u_{b,t}) \quad (7)$$

In (8), the active power balance is represented, and available wind generation and maximum/minimum limitation of non-renewable generators are shown in (9)-(10), respectively.

$$Pg_{b,t} + Pw_{b,t} + P_{b,t}^{\mathrm{buy}} - (Pl_{l,t} + R_{l,t}.I_{l,t}^2) = P_{b,t}^{\mathrm{load}} + P_{b,t}^{\mathrm{sell}} \qquad \forall b, l\epsilon(b,b'), \qquad (8)$$

$$Pw_{b,t} \leq Pw_b^{\mathrm{max}} \qquad \forall b, l\epsilon(b,b'), \forall t \qquad (9)$$

$$u_{b,t}.Pg_b^{\mathrm{min}} \leq Pg_{b,t} \leq u_{b,t}.Pg_b^{\mathrm{max}} \qquad \forall b, \forall t \qquad (10)$$

The ramping rate of the none-renewable generating units is also indicated in (11)-(12).

$$Pg_{b,t} - Pg_{b,t-1} \leq u_{b,t-1}.R_b^{\mathrm{max\ up}} \qquad \forall b, \forall t \qquad (11)$$

$$Pg_{b,t-1} - Pg_{b,t} \leq u_{b,t}.R_b^{\mathrm{max\ down}} \qquad \forall b, \forall t \qquad (12)$$

The reactive power balance is demonstrated in (13), and the limitation of reactive power from the generating units and substations is demonstrated in (14).

$$Qt_{b,t} + Qw_{b,t} + (Ql_{l,t} + X_{l,t}.I_{l,t}^2 = Q_{b,t}^{\mathrm{load}} \qquad \forall b, l\epsilon(b,b'), \forall t \qquad (13)$$

$$Qt_b^{\mathrm{min}} \leq Qt_{b,t} \leq Qt_b^{\mathrm{max}} \qquad \forall b, \forall t \qquad (14)$$

In (15)-(16), the application of Kirchhoff's voltage law is presented [24]. In (17)-(18), the limitations of voltage and current are also indicated.

$$V_{l,t}^{\mathrm{in}^2} - V_{l,t}^{\mathrm{out}^2} = 2(R_l.Pl_{l,t} + X_l.Ql_{l,t}) + Z_l^2\,.I_{l,t}^2 \qquad l\epsilon(b,b'), \forall t \qquad (15)$$

$$V_{l,t}^2\,.I_{l,t}^2 = Q_{l,t}^2 + P_{l,t}^2 \qquad l\epsilon(b,b'), \forall t \qquad (16)$$

$$V_b^{\mathrm{min}} \leq V_{b,t} \leq V_b^{\mathrm{max}} \qquad \forall b, \forall t \qquad (17)$$

$$0 \leq I_{l,t} \leq I_l^{\mathrm{max}} \qquad l\epsilon(b,b'), \forall t \qquad (18)$$

C. Coupled gas and electricity distribution networks

The non-renewable distributed generators couple the electricity and natural gas distribution networks. The distributed generators mainly burn natural gas to produce electricity (e.g., combined heat and power units). The amount of natural gas that these units need to produce electricity is calculated in (19). This is noteworthy to mention that the amount of required natural gas should be added to the gas flow balance (3) when the operation of both networks is considered. Furthermore, the integrated operation is optimized subject to all constraints ((2)-(6) and (8)-(19)) whose objective function is the sum of electricity and natural distribution networks' objective functions [25]. However, in the separated operation (Fig. 1), the scheduling electricity distribution network is optimized at the first stage. Secondly, the required amount of natural gas in the electricity distribution network is considered in addition to natural gas demand. After that, the problem of gas distribution network operation is optimized, and if there is any problem with supply-demand, the maximum output of gas-fired units is constrained [26].

$$Fg_{b,t} = \frac{Pg_{b,t}}{\eta_b}.\upsilon \qquad \forall b, \forall t \qquad (19)$$

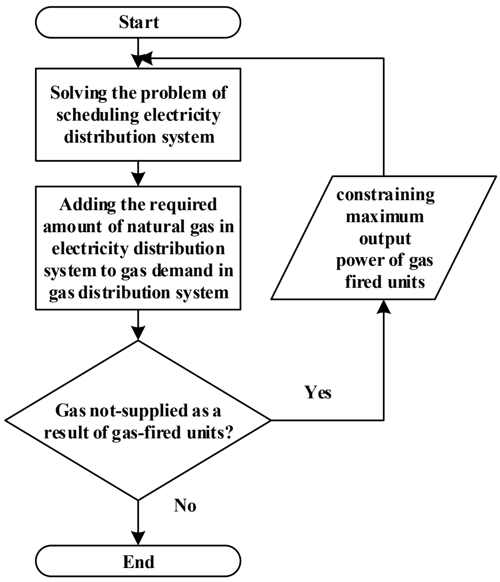

Fig. 1. Separated operation of natural gas and electricity distribution networks

III. Decomposition Method

In this section, the key steps of the decomposition method, called Outer Approximation/Equality Relaxation, are explained (Fig. 2). This should be mentioned that this method was introduced to cope with the nonlinear equality constraints in the form of $f(x) = 0$ in optimization problems [27].

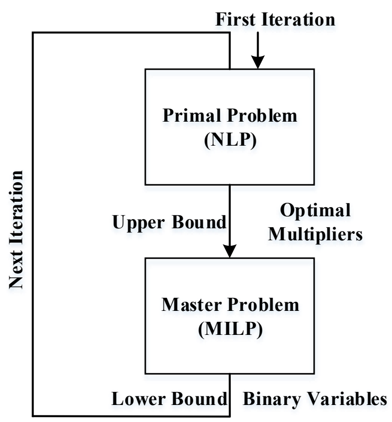

Fig. 2. Structure of Outer Approximation/Equality Relaxation based on [25]

In this method, firstly, the primal problem is solved by initializing binary variables (nonlinear problem). Solving this problem provides upper bound as well as optimal multipliers for the equality constraints. After that, the master problem is solved by relaxing the nonlinear equality constraints and using the optimal multipliers (mixed-integer linear problem). The outputs of the master problem give binary variables for the next iteration as well as a lower band. When the upper band and lower band converge, this is an optimal solution. Therefore, the method splits the main problem into two subproblems, which reduces the complexity of solving. This is noteworthy to mention that, in the problem of scheduling electricity and gas distribution networks in a microgrid, the nonlinear constraints include Lacey's equation in the gas distribution network (4) and the constraint related to Kirchhoff's voltage law in the electricity distribution network (16) that must be relaxed as indicated in (20).

$$sgn(\lambda)(f(x^k) + \nabla f(x^k)(x - x^k)) \leq 0 \qquad (20)$$

In the aforementioned formulation, $f(x)$, λ, and x^k indicate the nonlinear constraints, the optimal multipliers, and the optimal solution of primal problem in kth iteration, respectively. Moreover, $sgn()$ shows the sign function.

IV. Case Study

The proposed methodology is examined on a 15-node gas distribution network and 13-node electricity distribution network, depicted in Fig. 3 and Fig. 4, respectively. As depicted, the gas distribution network consists of one injection node, 15 nodes, and 17 pipelines. The electricity distribution network also consists of one gas-fired unit, three renewable distributed energy resources, 13 nodes, and 13 lines. It should be mentioned that gas-fired units connect node two in the electricity distribution network to node five in the gas distribution network. For this purpose, the operation of the microgrid is optimized through the integrated and separated strategies with and without employing the decomposition method during a day (24 hours). The results of the study are presented in the next section, and analyses are conducted to validate the results.

It is noteworthy to mention that, the characteristics of the gas and electricity distribution networks have been presented in [28] and [29], including the maximum injection through the terminal, and the length and diameter of pipelines, the capacity of lines, the characteristics of generating units, and gas and electricity demand.

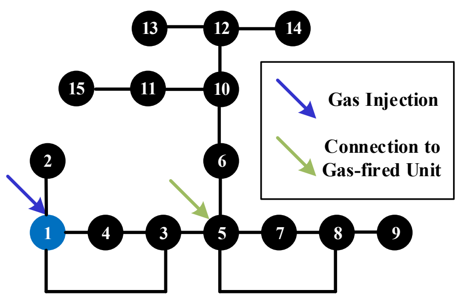

Fig. 3. Representation of natural gas distribution network

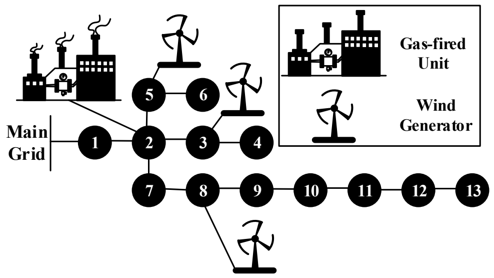

Fig. 4. Representation of electricity distribution network

V. RESULTS AND ANALYSES

In this section, the analytical findings of the proposed methodology are analyzed using the fifteen-node gas distribution network and the thirteen-node electricity distribution network.

A. *Gas distribution network analysis*

The injection of natural gas through the sources and the variation of linepack within the pipelines are depicted in Fig. 5. It is evident that maximum natural gas injection in the separated strategy of operation is higher compared to when the integrated strategy of operation is employed (from 17:00 to 22:00). Therefore, the natural gas distribution network can supply more demand in peak hours as a result of choosing the integrated strategy (from 06:00 to 09:00 and from 17:00 to 22:00). On the other side, when the integrated strategy of operation is conducted, the amount of linepack within the pipelines is higher in comparison with applying the separated strategy. Therefore, it increases the ability of this network to supply changes in demand (e.g., the growth in the required amount of natural gas for gas-fired units). It is worth noting that it takes a while to transmit natural gas from sources to demand nodes, and a higher level of linepack allows to address the supply-demand balance in the gas distribution network effectively. Due to these reasons, employing the integrated strategy to optimize the problem, the natural gas distribution network is more flexible in dealing with changes and supplying excess demand.

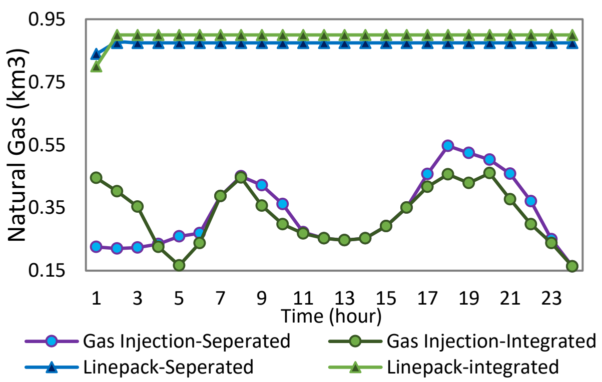

Fig. 5. Amount of gas injection and sum of linepack in gas distribution network

B. *Electricity distribution network analysis*

The power output of distributed renewable generators and gas-fired units as well as the imported power from the main grid is demonstrated in Fig. 6. It is evident that when the integrated strategy is employed to solve the problem, more wind power can be used to supply the demand by 2293 kW. It is due to the flexibility of the natural gas distribution network that facilitates employing gas-fired units to deal with variable output of the renewable distributed generators in peak hours (from 06:00 to 09:00 and from 17:00 to 22:00). On the other side, the imported power from the main grid and power output of gas-fired units is higher when the separated strategy is employed by 100 kW and 1956 kW, respectively, which increases the cost of operation and emissions.

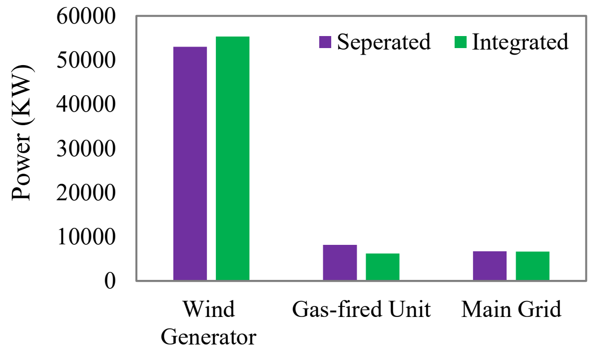

Fig. 6. Output power of different generating units and interactions with the main grid

C. *Cost and decomposition method analyses*

In this subsection, the scheduling cost of natural gas and electricity distribution networks are examined under both strategies of operation. Furthermore, the solving time is compared considering solving by GAMS solvers and Outer Approximation/Equality Relaxation method. Table I shows the economic analyses of the operation of electricity and natural gas distribution networks. It is a fact that employing the integrated strategy decreases the operating costs in natural gas and electricity distribution systems by $60.69 and $125.82, respectively. The reason is to use more renewable distributed energy resources to address supply-demand balance.

TABLE I. ECONOMIC ANALYSIS AND SOLVING TIME OF OPTIMIZATION PROBLEM

Solver		Operating cost ($)		Time (Sec)
		Gas Network	***Electricity Network***	
GAMS Solvers	Separated Operation	2797.691	1787.971	452.23
	Integrated Operation	2737.022	1662.156	770.13
Decomposition Method	Separated Operation	2797.691	1787.971	150.21
	Integrated Operation	2737.021	1661.993	370.85

On the other side, the solving time decreases by 51.8% when Outer Approximation/Equality Relaxation decomposition is employed to solve the problem. The reason is that this decomposition method solves the optimization problem iteratively and splits the original problem into the primal problem and the linearized master problem. This is noteworthy to mention that the GAMS solvers, employed to conduct this comparison, are SBB and BARON. Both solvers are based on the Branch and Bound method, improved with some constraints, such as interval analysis and duality techniques [30].

VI. Conclusion

In reaction to the growing proportion of distributed energy resources in electricity systems, such as photovoltaic systems and wind turbines, this study investigates the operation of gas and electricity distribution systems in a microgrid. In this context, gas-fired units are employed to cope with the variable output of renewable resources and dependence on the operation of these networks. For this purpose, in the first step, a mathematical model is introduced for the operation of natural gas and electricity distribution systems. In the electricity system, AC load flow is employed, and Lacey's equation is considered to simulate the low-pressure gas systems. Furthermore, a decomposition method known as Outer Approximation/Equality Relaxation is developed to solve the proposed mixed-integer non-linear model. This approach reduces the solving time by splitting the original problem into two subproblems. The obtained results of this study demonstrate the increase in the participation of renewable distributed generators by about 5% as a result of the integrated scheduling of both natural gas and electricity distribution systems. It concludes cost reduction by 2.3% and 7.5% in the gas and electricity distribution systems, respectively. Moreover, the decomposition method reduces the solving time by 52% in the integrated scheduling of these networks.

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