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Planning of multi-hub energy system by considering competition issue

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ABSTRACT

Energy hub concept has been emerged as a suitable tool to analyze multi-carrier energy systems. Deregulation and increasing competition in the energy industry have provided a suitable platform for developing the multi-agent energy systems. Planning of energy hubs considering the competition between the hubs has not been sufficiently addressed, yet. A model has been proposed in this study for planning of a multi-hub energy system considering the competition between the hubs. The hubs are interconnected via an electric transmission system. A linear model has been developed to determine the optimal planning/operation strategy for energy hubs in a multi-period planning horizon to meet the heat and electricity demand for the defined load zone. The problem has been formulated and solved using Karush–Kuhn–Tucker (KKT) conditions. The proposed model has been applied to 3-Hub and 5-Hub energy systems. The effect of renewable generation and storage system has also been evaluatedIt has also been observed that inclusion of renewable generation or storage technologies can reduce the conventional electricity generation capacity by 63 percent in HUB2.

Keywords

Energy hub;
Energy market;
Multi-agent planning;
Competitive model;

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1. Introduction

Deregulation and liberalization of energy markets is a strategy taken by many policymakers around the world. Encouraging competition to introduce new technologies and increasing efficiency are the motivation for the liberalization of energy markets in recent years [1, 2]. The restructuring of the power market has increased the competition between different generators. This procedure leads to eliminate expensive technologies of the systems that will reduce the energy cost for the consumers [3]. it should be noted that the operation and planning of energy systems in a centralized system are different from the deregulated system. In a centralized system, an operator plans the system to minimize the total cost. In a deregulated market, however, the energy producers and energy consumers try to maximize their benefits [2]. This procedure has given rise to the emergence of researches in the strategic biding and generation planning areas [2].

Multi-carrier energy system allow for a better integration of volatile renewables and provide the opportunity for an enhanced primary energy efficiency, compared to current energy systems with decoupled energy carriers [4]. Greiml et al. [4] presented general aspects on modelling, designing and operating of MES, coupling the grid bound energy carrier electricity, gas, and heat.

Lazzeroni et al. [5] studying optimization of a polygeneration system that supplying an existing DHC network in the North of Italy. Different possible configurations of technology proposed and optimization

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Nomenclature

Parameter:

ED_{tlr}	Electricity demand for hub (r) at year (t) and load zone (l) (MWh).
HD_{tlr}	Heat demand for hub (r) at year (t) and load zone (l) (MWh).
LL_{rj}	Transmission line loading limit for the line that connects hub (r) to hub (j) (MW).
p_r	Input energy price of hub (r) (USD/m^3).
$tuc_{\tau r}$	The unit cost of technology τ for hub (r) (USD /MW).
$\eta_{elec,\tau r}$	Electrical efficiency of technology for hub (r).
$h_{heat,\tau r}$	Thermal efficiency of technology τ for hub (r).
ΔL_l	Load zone duration for load zone (l) (hr).
NT	Number of technology
NE	Number of energy carrier.
NY	Number of years.
NZ	Number of load zones.

Variable

GCC_r	Cost of gas consumption cost for hub (r) (USD).
E_{tlrj}	Electricity transmission from region (r) to region (j) at year (t) and load zone (l).
F_{tlr}	Total Energy consumption for hub (r) at year (t) and load zone (l) (MWh).
$f_{tl\tau r}$	Energy consumption for technology (τ) at year (t) and load zone (l) in hub (r) (MWh).
G_{tlr}	Total electricity generation for hub (r) at year (t) and load zone (l).
$g_{tl\tau r}$	Electricity generation technology (τ) for hub (r) at year (t) and load zone (l).
H_{tlr}	Total heat generation for hub (r) at year (t) and load zone (l).
$h_{tl\tau r}$	Heat generation technology (τ) for hub (r) at year (t) and load zone (l).
PIC_r	Power import cost for hub (r).
PER_r	Power export revenue for hub (r)
$TC_{t\tau r}$	Capacity added for technology (τ) and hub (r) at year (t).
TIC_r	Technology investment cost for hub (r).
$TTC_{\tau r}$	Total technology capacity for technology (τ) and hub (r).
Z_r	Objective function for hub (r).
λ	Lagrange multiplier for hub (r).
π_{tlr}	Regional market price for region (r) at year (t) and load zone (l).

Superscripts and indices:

l	Load zone index.
r,j	Hub or region index.
t	Year of planning horizon index.
τ	Type of technology index.

model is based on a Mixed Integer Linear Programming (MILP) formulation. Kuriyan et al. [6] present a model for planning district energy systems. The model is formulated as a mixed integer linear program (MILP) and selects the optimal mix of technology types, sizes and fuels for local energy generation, combined with energy imports and exports. The concept of energy hub has been widely used to study, evaluate, and optimize multi-carrier energy systems. Buildings, urban areas, and industrial plants are among the cases that consume both heat and electricity, and they are considered as suitable subjects to study energy hub.

Geidl and Andersson [7–9] introduced the concept of "energy hub" in their work as a modeling method that covers different types of energy flows and enables actual systems analysis. Energy flows in one energy hub includes electricity, thermal flow, and chemical flows [10]. An energy hub receives different energy flows and uses conversion and storage technologies to provide energy demand as its output [11].

Evins et al. [10], for instance, developed an updated model to evaluate the performance of energy hub. The model developed in [10] limits the number of state changes (startups or shutdowns) and uses stepwise approximations of efficiency curves to model part-load behavior accurately. Brahman et al. [12] developed a residential energy hub model with electricity, natural gas, and solar radiation as the inputs that are supposed to supply electrical, heating, and cooling demands. Similarly, Zidan and Gabbar [13] presented an energy hub model for optimizing the cost and CO_2 emissions. The energy hub used natural gas, electricity, and renewable energy to supply electricity and heat demands.

Ma Et al. [14] proposed an energy hub model to optimize the hub operation to minimize daily operational costs. The authors in [14] used a day-ahead dynamic optimal operational model considering the demand response to develop the optimization problems. Renewable energy, combined cooling-heating, and power and energy storage devices were among the considered technologies in the energy hub in [14]. Vahid-Pakdel et al. [15] developed a model to find the optimal operation of an energy hub with wind farms, storage systems, and district heating networks. Authors in [15] have used stochastic programming or modeling demands, market prices, and wind speed.

El-Zonkoly et al. [16] developed a multi-objective optimization model for optimizing the operation of an energy hub. The objectives of optimization problems were minimizing the capital and operational cost of the energy hub, reducing greenhouse gas (GHG) emissions, and also maximizing the revenue gained from power exporting. Majidi et al. [17] used the weighted sum approach to solve a multi-objective optimization model of the economic operation of an energy hub. The objective function components were operating costs of the hub energy system and greenhouse emissions generated in the energy hub system.

Moghaddam et al. [18] developed a model to find the optimal operation of an energy hub that uses electricity and natural gas as inputs while supplying the electricity, heating, and cooling demand of a residential building. Dolatabadi et al. [19] proposed a model to find the optimal size and configuration of energy conversion technologies to supply thermal and electrical demands. The authors in [19] invented different scenarios based on wind power generation, load forecasting, and random outages of components. Najafi et al. [20] developed a bi-level approach for hub and customer management. The hub problem is considered as the upper-level problem, while the customers' problem forms the lower-level ones. The Karush–Kuhn–Tucker (KKT) condition has been used to solve the problem according to a strong optimality condition.

While the reviewed literature has been focused on developing models for a single hub, Studying the role of each agents is a lacking area in the modeling and design of energy systems. [21]; However, including all decisionmakers in an energy system, is vital for accurate modeling of such systems [22]. As a result, many researchers have analyzed systems, where multi-energy hubs are available, and the energy hubs interact with each other. Huo et al. [23], for instance, developed an optimization model to find the optimal flow between two energy hubs. Heat pump, solar power, and boiler technologies were considered in the hubs, and they were capable of exchanging power and heat. The objective function was developed for the whole system.

Zhang et al. [24] proposed an optimization problem for the expansion planning of an interconnected multi-node energy hub system for over ten years. The objective function of the model was minimizing the total net present value of the system. The analyzed case study in [24] is an energy system with six interconnected hubs. Zhang et al. [25] developed a multi-agent bargaining-learning-model for economic dispatch of energy hubs. Although the authors in this model have considered each hub as an agent, the objectives of their optimization problem were total energy cost and total energy loss.

Yang et al. [26] developed a model for the optimal dispatch of interconnected energy hubs. The case study is a 15-node regional multi-energy prosumer whose energy demands are supplied by the hubs that used CCHP, distributed renewable energy generators, and energy storage technologies. The objectives in the model optimization were the prosumer's cost of purchasing electricity, natural gas, and GHG emissions. Sheikhi et al. [27] stated a game theory approach for modeling the interaction of different energy hubs. The aim of each hub was to reduce the energy bill. The Nash equilibrium concept was used as the sub-gradient optimization method to solve the game theory problem. The proposed model was shown to effectively reduce the peak-to-average ratio in the electricity grid.

Wang et al. [28], presented an energy market framework to analyze microgrid participation in energy trading. In the model developed by Wang et al., microgrid first bid in a distribution electricity market. The electricity could be sold and bought between the distribution electricity market and a day-ahead wholesale market. The distribution electricity market, day-ahead wholesale market, and an additional gas market are then presented in the form of a stochastic equilibrium model.

Badri et al. [29], analyzed the market behavior of electricity generation companies practicing in a market with transmission constraints and when the market power of the participants is taken into account. The model is solved using a bi-level optimization framework with generation companies in one level and independent operator in the other level.

In their work [30], Wang et al, compared the Nash equilibrium and competition equilibrium in the electric power market. The results their comparison showed that Nash equilibrium should be used to achieve mathematical optimization while the economic optimization is achieved by the competition equilibrium. In that sense, competition equilibrium maximizes market efficiency and fairness for market benefit. Kasaei [31] presented a model to optimize energy management of a power plant. The model developed by Kasaei was based on imperialist competitive algorithm and is used to minimize the operating cost of a virtual power plant consisting of aggregated distributed energy resources, energy storage devices, and controllable loads.

A system with renewable energy technologies and battery storage is used as a case study. Gebremedhin and Moshfegh [32] developed a heat market model with seven different participants. The results of the modeling done by Gebremedhin and Moshfegh shows that an integrated system in which players are able to participate in market leads to cost reduction for the system. Investigation of the effectiveness of bid performance by power producer is done by Fatemi Ardestani et al. [33]. The authors used two different methods to investigate the effectiveness of bid performance by power producer. In the first method, power producers submit a first step bid on the meeting point of the bidder's actual bid and the market demand curve. In the second method, the power producers bid based on realized residual demand. Coffey and Kutrowski [34] presented a dispatch strategy for a cogeneration system considering the effect of monthly charges and hourly prices. The authors used three office buildings with different cogeneration size and efficiency characteristics and showed that their proposed model leads to payback periods of 5–10 years for an investment in a cogeneration system.

While multi-hub energy systems have been studied in [24–34], the planning problem of multi hub system has been addressed in [25] and [26] only. On the other hand, the competition among the hubs must be considered in determining optimal planning/operation of each hubs (agents) in deregulated energy system. However, to the authors' best knowledge, no research work is available on planning of multi-hub energy system considering the competition between the hubs.

A model has been proposed in this study for planning/operation of a multi-hub energy system considering the competition between the hubs. Each hub has its own objective function and seeks to minimize the cost of supplying demand. Therefore, each hub picks its optimized strategy regarding demand, market prices and specifications of available technologies. The hubs are interconnected via an electric transmission system. While the heat demand for each hub must be supplied by deploying associated technologies, the electricity demand can be fulfilled by investing in technologies or exchanging through the transmission system considering the market price and line loading limits. Therefore, the decision variables for each hub are built capacity and gas consumption of each technology as well as the amount of electricity exchanged with the market.

A linear model has been developed to determine the optimal planning/operation of heat and electricity generation technologies for energy hubs in a multi-period planning horizon to meet the heat and electricity demand for the defined load zone. The problem has been formulated and solved using Karush–Kuhn–Tucker (KKT) conditions. Solving the model will result in annual built capacity in different technologies for the hubs. Other outputs include electricity exchanges between the hubs, and also gas consumption by technologies for each load zones of the planning horizon for each hub. Market price is obtained from market clearing conditions in the equilibrium problems.

The contributions of the presented work are:

I. Considering the competition in the multi-period planning of a multi-hub energy system,
II. Proposing a linear model for the problem of optimal planning of competing energy hub,
III. Using Multi-period planning with multi load zone demand profiles,
IV. Using KKT conditions to find the optimal solution for the problem.

The proposed model can be considered as a general model for finding the optimal planning of energy systems where the competition between the agents (hub, generation plants, Virtual Power Plant, etc.) must be considered. In particular, the proposed model can be used for optimal planning of an independent set of energy systems. Large-scale energy systems, interconnected energy systems or even an isolated set of micro grids are among the cases which could be studied by the proposed model.

2. Methodology

As already mentioned, this study aims at developing a model for optimal planning of independent interconnected energy hubs considering the competition between the hubs.

2.1. Proposed Model

Figure 1 shows a multi-hub energy system.

As can be seen in Figure 1, each energy hub (one through *NH*) can buy natural gas from a gas source (that is shown by GS_i) at the price of P_i. Each hub utilizes conversion technologies to convert natural gas into heat and power. The associated heat demand (*HD*) with the hub should be supplied by the heat generation technologies. The hub can supply the electric demand (*ED*) using power generation technologies or power imports from the regional market. The hubs are interconnected via electric transmission lines (shown by dashed lines in Figure 1).

Based on the electricity demand and supply in the hub market, electricity price varies in each load zone. The market is cleared by balancing supply and demand. It is assumed that the price of the imported power is equal to the market price of the importing hub. Exporting hubs only offer the amount of power that they are willing to export, and they do not offer the price. Exporting hubs receive destination hub market price for the power they export.

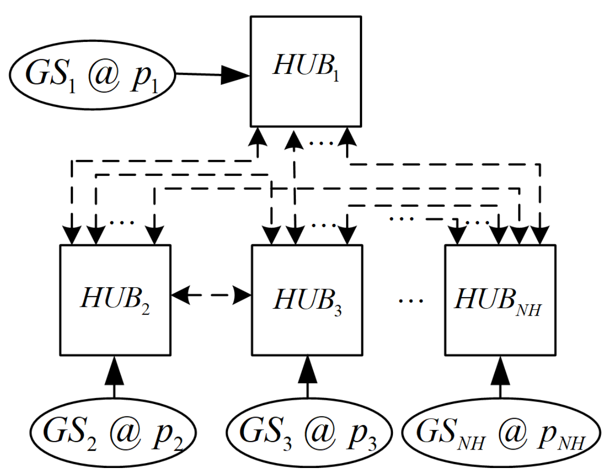

Figure 1: Independent interconnected energy hub

The planning problem for each hub is to determine the optimal size for the technologies in each year (t) of the planning horizon, and optimal operation for each load zone (l) considering the capital cost and efficiency. These elements are associated with the technologies as well as the total energy supply costs during the planning horizon. The energy supply cost includes gas consumption costs and the imported power costs from the importing hub's market. Each hub may make revenue by selling power to other hubs' market.

Each year is divided into *NL* load zones (such as peak, off-peak, … load zones). Gas consumption and electricity exchange, as well as the electricity market price, are then determined for each load zone of the planning years.

For each hub (*r*), the objective function is to minimize the total cost (*Zr*), including technology investment cost (*TICr*), gas consumption cost (*GCCr*) as well as the power import cost (*PICr*) minus the power export revenue (*PERr*) as expressed in Eq. (1).

$$\text{objective function} = \min(Z_r) = TIC_r + GCC_r + PIC_r - PER_r \tag{1}$$

For all hubs, the maintenance cost is assumed to be zero. Also, only the fuel cost is accounted as the operation cost. In Eq. (1), technology investment cost for hub *r* (TIC_r) is calculated according to Eq. (2).

$$TIC_r = \sum_{t=1}^{NY} \sum_{\tau=1}^{NT} TC_{t\tau r} \times tuc_{\tau r} \tag{2}$$

Where $TC_{t\tau r}$ represents added capacity for technology τ in hub *r* at the beginning of year *t* in kW, and $tuc_{\tau r}$ is the unit cost of technology τ for hub r in USD/kW. In Eq. (1), gas consumption cost for hub *r* (GCC_r) is calculated according to Eq. (3).

$$GCC_r = p_r \sum_{t=1}^{NY} \sum_{l=1}^{NZ} F_{tlr} \tag{3}$$

In Eq. (3), F_{tlr} denotes gas consumption for hub *r* at year *t*, load zone *l* in kWh, and P_r gas price in hub (*r*) in USD/

kWh, as shown in Eq. (3). Power import cost for hub r (PIC_r) in Eq. (1) is calculated according to Eq. (4).

$$PIC_r = \sum_{t=1}^{NY} \sum_{l=1}^{NZ} \pi_{tlr} EI_{tlr} \tag{4}$$

Where E_{tlr} is the imported power for hub r at year t, load zone l in kWh, and π_{tlr} is the market price for hub r at the year t, load zone l in USD /kWh. Finally, power export revenue for hub r (PER_r), is calculated according to Eq. (5).

$$PER_r = \sum_{t=1}^{NY} \sum_{l=1}^{NZ} \sum_{j=1, j \neq i}^{NH} \pi_{tlj} E_{tlrj} \tag{5}$$

Where E_{tlrj} represented the exported power from hub r to market of hub $j$at year t, load zone l in kWh, π_{tlr} and market price for hub j at year t, load zone l in USD /kWh (π_{tlr}). In Eq. (2)-(5), NH represents the total number of the hubs, NY indicates the number of planning horizon years and NZ is the number of load zones in each year.

In this work, energy hub operators can invest in two different types for power plants (PP), two types of boilers (B), and two types of combined heat and power (CHP) technologies to fulfill heat and electricity demand, as shown in Figure 2.

In Figure 2, $f_{tl\tau r}$ is the natural gas input of technology τ at year t and load zone l in hub r in terms of kWh, $g_{tl\tau r}$ is generated electricity by technology r at year t and load zone l in hub r in terms of kWh, and $h_{tl\tau r}$ is heat generated by technology τ at year t, and load zone l in hub r in terms of kWh. According to Figure 2, F_{tli}, G_{tlr}, and H_{tlr} represent the total natural gas consumption, total electricity generated and the total heat generated in year t and load zone l in hub r in terms of kWh, respectively. These quantities are calculated as stated in Eq. (6), Eq. (7), and Eq. (8).

$$F_{tli} = \sum_{\tau=1}^{NT} f_{tl\tau r} \tag{6}$$

$$G_{tlr} = \sum_{\tau=1}^{NT} g_{tl\tau r} \tag{7}$$

$$H_{tlr} = \sum_{\tau=1}^{NT} h_{tl\tau r} \tag{8}$$

Where $g_{tl\tau r}$ and $h_{tl\tau r}$ are calculated as the productions of natural gas inputs to the technology and efficiency of the technology shown in Eq. (9) and Eq. (10).

$$g_{tl\tau r} = \eta_{elec,\tau r} \times f_{tl\tau r} \tag{9}$$

$$h_{tl\tau r} = \eta_{\text{heat},\tau r} \times f_{tl\tau r} \tag{10}$$

Capacity constraints shown in Eq. (11) and Eq. (12).

Where $TC_{t\tau r}$ represents the capacity of technology τ in hub r at year t. Δl in Eq. (11) and (12) is the load zone duration.

$$\sum_{t=1}^{t} TC_{t\tau r} \geq \frac{g_{tl\tau r}}{\Delta l} \tag{11}$$

$$\sum_{t=1}^{t} TC_{t\tau r} \geq \frac{h_{tl\tau r}}{\Delta l} \tag{12}$$

As mentioned before, each energy hub is supposed to supply its own heat and electricity demand. Figure 3 shows the heat and electricity balance at each hub. The electricity demand of hub r at year t and load zone l

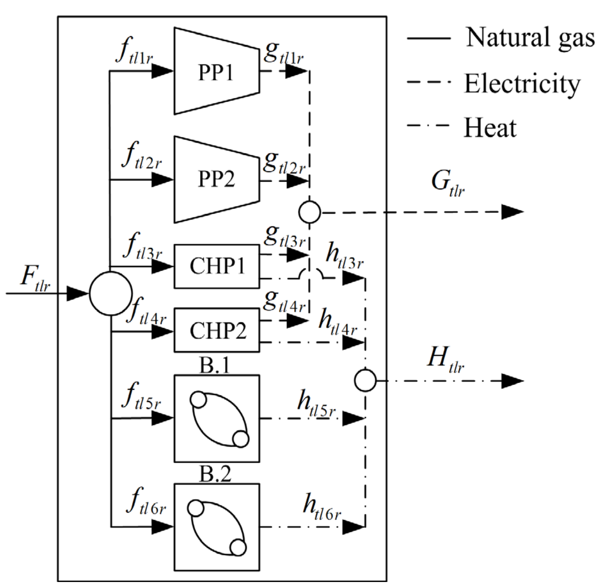

Figure 2: Available Technologies for energy hubs

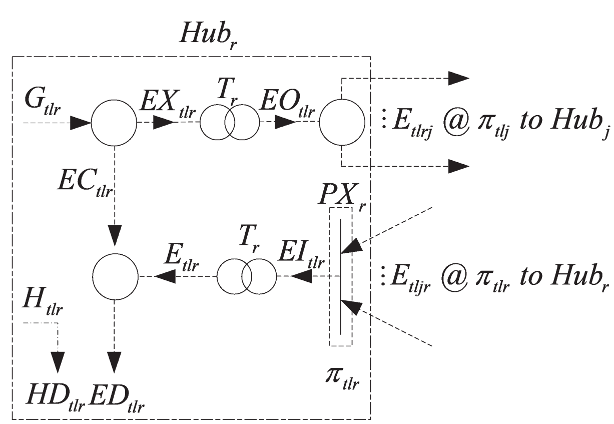

Figure 3: Heat and electricity balance for an energy hub

(ED_{tlr}) should be supplied either by the generated electricity in the hub (G_{tlr}) or by imported power from the market (E_{tlr}). Besides, each energy hub has an option of exporting power, which is depicted as E_{tlrj} in Figure 3. Heat demand (HD_{tlr}), however, is merely supplied by the generated heat in the hub (H_{tlr}).

As expressed in Eq. (13), the sum of the generated power in the energy hub and the imported power minus the amount of the exported power should be equal to or greater than the electricity demand, based on the introduced constraints in Figure 3.

$$G_{tlr} + E_{tlr} - EX_{tlr} \geq ED_{tlr} \quad (13)$$

In Eq. (13), E_{tlr} indicates the electricity energy received by the importing hub from the market. The heat generated by the energy hub r at year t and load zone l should be able to supply the heat demand in hub $r$at year t and load zone l, as shown in Eq. (14).

$$H_{tlr} \geq HD_{tlr} \quad (14)$$

Electricity received by an importing hub r at year t and load zone l (E_{tlr}) equals to the product of electricity imported by hub r at year t and load zone l (EI_{tlr}) and the transformer efficiency of the hub r ($\eta_{trans,r}$) as expressed in Eq. (15).

$$E_{tlr} = \eta_{trans,\mathrm{r}} \times EI_{tlr} \quad (15)$$

The sent electricity to the transmission line by hub r at year t and load zone l (EO_{tlr}) equals the product of electricity exported by hub r at year t and load zone l (EX_{tlr}) and the transformer efficiency of hub r as stated in Eq. (16).

$$EO_{tlr} = EX_{tlr} \times \eta_{trans,\mathrm{r}} \quad (16)$$

The total sent power to the transmission line from hub r at year t and load zone l (EO_{tlr}) equals the sum of sent power from hub r to other hubs j, (E_{tlrj}) as shown in Eq. (18).

$$EO_{tlr} = \sum_{j \neq r}^{NH} E_{tlrj} \quad (18)$$

PX_r in Figure 3, shows the electricity market at hub r. The market-clearing condition for each hub should also be considered:

The total imported power by hub r at year t and load zone l (EI_{tlr}), equals the sum of received power by hub r from other hubs j, (E_{tljr}) as expressed in Eq. (19).

$$EI_{tlr} = \sum_{j \neq r}^{NH} E_{tljr} \quad (19)$$

The transmission line between the hubs has a limited capacity. In other words, according to Eq. (20), the transmitted power between any two hubs over a particular load zone cannot exceed a specific value.

$$\frac{E_{tlrj}}{\Delta l} \leq LL_{rj} \quad (20)$$

Where LL_{rj} is a line capacity limit for transmitting power from hub r to hub j in kW.

The objective function in Eq. (1) and the set of constraints shown in Eq. (2) to (2) 0 form the optimization problem associated with hub r.

According to Eq. (21), for each hub r, the optimization problem can be rearranged:

$$\begin{cases} Min \quad Z_r = f_r(x) \\ s.t. \\ g_r(x) \geq RHS_r \end{cases} \quad (21)$$

Where x represents the decision vector for hub r, $f_r(x)$ indicates the objective function, and $f_r(x)$ is the set of constraints. It should be noted that the decision vector for each hub includes:

I. Yearly added technology capacity
II. Power exchange for all load zones in each year
III. Gas consumption of technologies for all load zones in each year

Since hubs are independent, each hub tries to make a suitable decision by solving Eq. (21) to minimize its own cost. However, the power market price at each hub depends on the decisions of all hubs. As a result, the market-clearing condition is a condition that expresses the interaction among the hubs.

Oligopolistic Competition is a competitive condition in which there are only a few producers (in this paper 3 hubs). Each hub has a high percentage of the market and cannot afford to ignore the actions of the other hubs. The set of optimization problems are expressed in Eq. (21) for all hubs. Besides, the market-clearing condition in

Eq. (19) makes an equilibrium problem that represents a Cournot competition model for oligopoly games. The Nash Equilibria is determined by solving the equilibrium problem.

The Karush–Kuhn–Tucker (KKT) conditions for the equilibrium problems should be determined and solved simultaneously in order to find the Nash equilibria. KKT condition for the equilibrium problem is associated with the hubs that can be obtained by Eq. (22)–(26) [35]:

$$\nabla_x F(x) - \lambda^T \nabla_x g(x) \geq 0 \tag{22}$$

$$\left[\nabla_x F(x) - \lambda^T \nabla_x g(x)\right] \cdot x = 0 \tag{23}$$

$$g(x) - RHS \geq 0 \tag{24}$$

$$\lambda^T \left[g(x) - RHS\right] = 0 \tag{25}$$

$$x \geq 0 \quad , \quad \lambda \geq 0 \tag{26}$$

In KKT condition equations, λ indicates the dual variable associated with the inequality constraint in Eq. (21). As the hub problem in Eq. (21) is a convex and linear optimization problem, the KKT conditions in Eq. (22)–(26) are both necessary and sufficient to obtain the optimal solution for Eq. (21). Once the KKT condition is determined for the problem of all hubs, the set of resulting equations along with the market clearing condition represented in Eq. (22)–(26) for all hubs can be solved to find optimal hub planning considering the competition among the hubs.

3. Results

The result section has been arranged as follows: Section 3.1 presents the result of applying proposed model to a 3-Hub system. Investigation and Verification of Nash Equilibrium have been discussed in Section 3.2. Impact of Renewable and Energy Storage have been summarized in Section 3.3.

3.1. Appling proposed model to a 3-Hub system

The proposed model has been applied to a 3-Hub test system, namely HUB1, HUB2, and HUB3. Table 1 summarizes the cost and efficiency of technologies. Power plant technologies only possess electricity efficiency, while boiler technologies only have heating efficiencies. CHP technologies inherit both heating and electricity efficiency, as depicted in Table 1.

A 5-year planning horizon has been considered with two load zones, i.e. peak and off-peak load zones. Table 2 presents the forecasted heat and electricity demand for the hubs for the load zone of the planning horizon.

The maximum heat demand for HUB1 and HUB2 is illustrated with bolded numbers, and the heat demand for these hubs is decreased after the third year. The gas price in HUB1, HUB2, and HUB3 is 52.7, 47.4, and 55.3 cents per cubic meter, respectively. Therefore, the most expensive gas source is available in HUB3, while the cheapest gas source is available for HUB2.

The loading limit associated with the transmission line that connects HUB2 to HUB3 is assumed to be 60 MW. For the lines that connect HUB1 to HUB2 and

Table 1: Cost and efficiency of energy conversion technologies

		***PP*1** ($\tau = 1$)	***PP*2** ($\tau = 2$)	***CHP*1** ($\tau = 3$)	***CHP*2** ($\tau = 4$)	***B*1** ($\tau = 5$)	***B*2** ($\tau = 6$)
HUB1	Electrical efficiency	0.3	0.4	0.3	0.2	NA*	NA
	Heating efficiency	NA	NA	0.5	0.5	0.75	0.6
	Investment cost (USD /kW)	700	840	1400	980	504	336
HUB2	Electrical efficiency	0.35	0.45	0.3	0.25	NA	NA
	Heating efficiency	NA	NA	0.4	0.5	0.8	0.65
	Investment cost (USD /kW)	840	980	1260	1120	560	392
HUB3	Electrical efficiency	0.25	0.5	0.3	0.2	NA	NA
	Heating efficiency	NA	NA	0.5	0.4	0.75	0.5
	Investment cost (USD /kW)	560	1120	1400	840	504	280

* Not Applicable

Table 2: Heat and electricity load (MWh) for different hubs at each year and each load zone

Year	Load zone	HUB1		HUB2		HUB3	
		ED	HD	ED	HD	ED	HD
1	Peak	800	100	600	60	240	400
	Off-peak	500	400	240	300	200	440
2	Peak	840	110	660	70	300	500
	Off-peak	530	430	260	400	260	520
3	Peak	890	110	700	70	320	520
	Off-peak	550	**450**	270	440	300	**560**
4	Peak	920	100	760	80	400	480
	Off-peak	590	360	280	500	340	500
5	Peak	950	110	800	90	600	360
	Off-peak	630	380	290	700	520	400

Table 3: Objective function and its associated components for the energy hubs

	Z (1000 USD)	TIC (1000 USD)	GCC (1000 USD)	PIC (1000 USD)	PER (1000 USD)
HUB1	1151.9	158.2	755	249.1	10.4
HUB2	820	168.3	835.6	9	193
HUB3	653.3	120.2	587.9	56	110.7

HUB3, the loading limit is assumed 120 MW and 100 MW, respectively.

The mathematical model has been solved using the General Algebraic Modeling System (GAMS) platform for the MCP problem on a Pentium N3700 computer with 4 GB of RAM. The problem has been solved and the optimal hub planning, electricity purchase from market and electricity export to another hub, gas consumption by each technology, and the market price for the load zones of the planning horizon have been obtained.

Table 3 demonstrates the objective function and its associated components for the energy hubs. According to Table 3, Z represents the objective function of each hub, which is the sum of technology investment cost (*TIC*), gas consumption cost (*GCC*), power import cost (*PIC*) minus the power export revenue for hub (*PER*) (as shown in Eq. (1) to Eq. (5) respectively).

As depicted in Table 3, technology investment cost forms a major share of the objective function associated with each hub. Table 3 also shows that HUB1 has 28 and 4.4 times power import costs higher than HUB2 and HUB3, respectively. HUB2 has the highest revenue from selling power, as shown in Table 3. The reason behind the cost difference in power import between the hubs is the low gas price in HUB2 and also high gas prices in HUB1.

Table 4: Aggregated capacity development in different hubs and for different technologies (MW)

	HUB1	HUB2	HUB3
PP2	606.2	710.9	195.92
CHP1	258	224.1	312
CHP2	8	45	20
B2	0	191.8	0

The aggregated (5 years) capacity development for all hubs and technologies is summarized in Table 4. Zero capacity technologies are not depicted in Table 4. In all three hubs, power plant technologies with high efficiency (PP2) are selected by the model.

All hubs invest in co-generation technologies in order to supply their heating demand. As a result, no boiler capacity is developed except in the 5th year and in HUB2. HUB2 faces an increase in heating demands in the last years. Since heat demand increase is not simultaneous with electricity demand increment, HUB2 invests in boiler technology to supply the heating demand.

Figure 4 depicts each modeling year's share in PP2 capacity development. HUB1 invests in PP2 technology in years 1-3. However, investing in PP2 technology with a higher capital cost becomes less feasible as we move to the last planning year. When new PP2 technology is not developed, Developed CHP technology is used to supply the electricity demand.

Initially, HUB2 invests in tur2 technology to supply the electricity demand. In the following years, due to the higher heat demand increase rate compared to the electricity demand increase rate, HUB2 has invested in CHP1 technology. HUB3 has the lowest PP2 technology capacity due to high CHP capacity in HUB3.

Figure 5 shows co-generation capacity development in all planning years. HUB1 and HUB3 invest in CHP1 technology (with higher electric efficiency) in years 1 and 2. Surplus capacity in year three is supplied by CHP2 technology.

HUB2 had the lowest gas price. As a result, HUB2 exports electricity by investing in PP2 technology while using it as a supplier of its own demands. Although HUB2 has surplus electricity generation in off-peak hours, HUB2 invests in CHP1 technology (lower electric efficiency, higher heating efficiency) and uses PP2 to supply the electricity demand at off-peak hours.

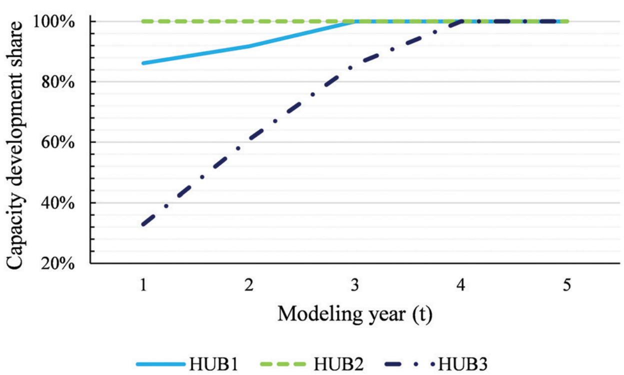

Figure 4: Each modeling year's share in PP2 capacity development

Table 5 demonstrates the market price for all hubs in different years and load zones. In this work, the model is used for planning and operation modeling. To reduce the number of decision variables, load zone based modeling has been used instead of using hourly modeling. Therefore, the results of the proposed model can be used in the time-of-use electricity pricing system. HUB1 has the highest market price. Compared to HUB2, HUB1 has a higher gas price and lower efficiency that leads to a higher cost for HUB1. Compared to HUB3, HUB1 has a lower gas price and lower-cost power plant technology. However, electricity generation cost in HUB1 is higher than HUB3 due to the higher PP2 technology efficiency in HUB3.

Additionally, as shown in Figure 5, most of the generated electricity in HUB3 is produced by using CHP technology. The utilization of co-generation technology for generating electricity lowers electricity generation costs in HUB3.

Table 6 shows the imported electricity to HUB1 from HUB2 and HUB3 in different years and load zones.

Considering KKT conditions, the price difference between the regions with different exchanged power should equal to zero. According to Table 5, similar prices are bolded. When the prices of HUB1 load zones are higher than HUB2 and HUB3, all the electricity transmission capacities can be used. When the price difference between HUB1 load zones and HUB2 and HUB3 is zero, transmitted electricity may take any value between zero and the line capacity. The value of the

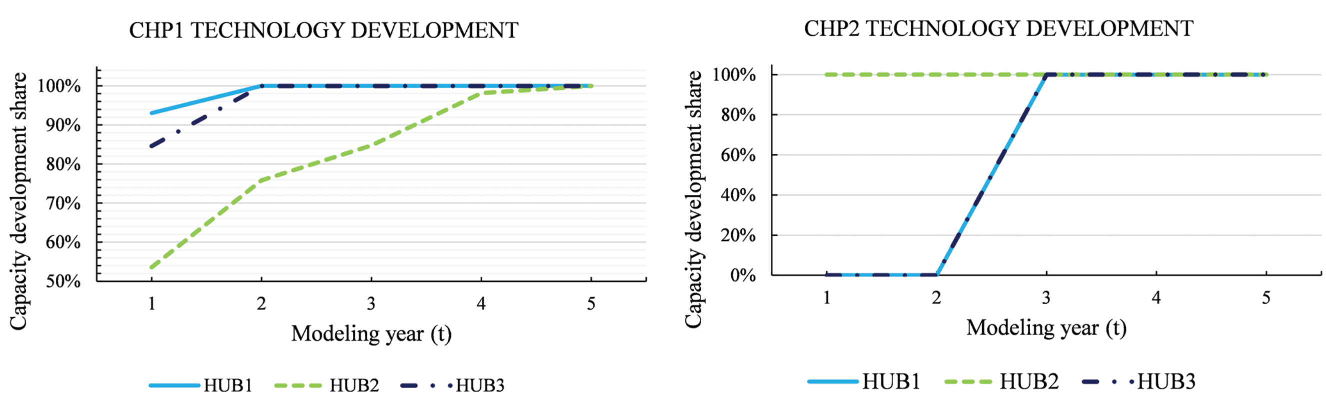

Figure 5: Co-generation capacity development in all planning years

Table 5: Electricity market price for all hubs

Year	$t = 1$		$t = 2$		$t = 3$		$t = 4$		$t = 5$	
Load zone	$l = 1$	$l = 2$	$l = 1$	$l = 2$	$l = 1$	$l = 2$	$l = 1$	$l = 2$	$l = 1$	$l = 2$
Market price at HUB1 (cent/kWh)	12.49	12.49	12.49	12.5	13.5	12.5	**16.7**	12.5	**22.3**	**12.5**
Market price at HUB2 (cent/kWh)	10.5	10	10.5	10	11.68	10.5	**16.7**	10.5	18.15	10
Market price at HUB3 (cent/kWh)	10.5	10	10.5	10	11.68	10.5	**16.7**	10.5	**22.3**	**12.5**

Table 6: Electricity import for HUB1 in different years and load zones

Year (t)	$t = 1$		$t = 2$		$t = 3$		$t = 4$		$t = 5$	
Load zone (l)	$l = 1$	$l = 2$	$l = 1$	$l = 2$	$l = 1$	$l = 2$	$l = 1$	$l = 2$	$l = 1$	$l = 2$
Import from HUB2 (MWh)	120	120	120	120	120	120	6	120	120	120
Import from HUB3 (MWh)	100	100	100	100	100	100	84	100	0	0

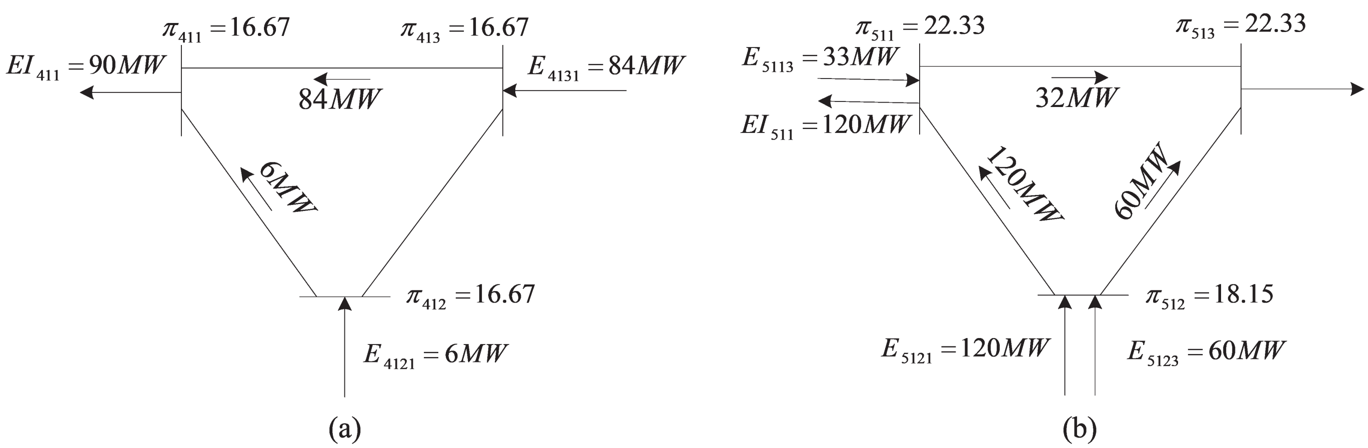

Figure 6: Electricity exchange between hubs for peak-load zone in year 4 and 5

transmitted electricity is determined by using the system equilibrium in this case.

Figure 6 depicts the electricity exchange between the hubs for the peak-load zone in years 4 and 5. According to Figure 6 (in the 4th year of the planning), the exported power by HUB3 to HUB1 is higher than the power HUB2 exports to HUB1. HUB3 has a high heating demand, and it uses CHP to supply the heating demand. As a result, it has an extra capacity to produce electricity besides PP2 technology.

In the on-peak load zone, HUB3 faces an increase in electricity demand in year 5. Available technology capacities in HUB3 are unable to supply the electricity demand. As a result, HUB3 has to buy electricity from other hubs as shown in Figure 6.b. Due to the constraints in electricity transmission lines between HUB2 and HUB3, it can be inferred that HUB1 exports some of the purchasing power from HBU2 to HUB3, taking advantage of the transmission capacity between HUB1 and HUB3.

3.2. Investigation and Verification of Nash Equilibrium:

Nash equilibrium is an equilibrium, in which no agents can increase their profit by changing their strategy after knowing all agents' strategies. Therefore, once the strategies of all agents have been determined, no individual agent is interested in violating or changing its own strategy.

In order to investigate and verify the Nash equilibrium, the calculated regional prices are applied to the

HUB2 model as specified input parameters. The planning model for HUB2 with the new data is solved independently using the Simplex method, and the optimized strategy has resulted as the output. Table 7 demonstrates HUB2 capacity development in both the proposed model and single-HUB model.

Although the capacity development is different in the proposed model and single-HUB model, the value of the objective function is the same in both of them. Hence, HUB2 has no interest in changing its selected strategy in the proposed model.

3.3. Impact of Renewable and Energy Storage

This section is devoted to studying the impact of renewable and storage technologies on the planning of multi-hub system. As demonstrated in Figure 7, a 5-Hub Energy System is assumed. The system is modified version of IEEE 5-Bus Test System [36]. HUB1 and HUB3 have the same structures as HUB1 and HUB3 in the system depicted in Figure 2. HUB2 contains electricity storage(Lithium-ion-battery) as well as the other 6 technologies that have been mentioned before.

As depicted in Figure 8, it is assumed that HUB4 is capable of using a solar panel as well as the gas turbine for electricity generation. Besides, this hub can manage the produced electric energy by building capacity on Lithium-ion storage. It is presumed that HUB5 possesses wind turbine and solar panel. Therefore, all produced power in HUB5 has a renewable sources. Hydro storage has been utilized in this hub.

The amount of the produced energy in the wind turbine and the solar panel is obtained by using the capacity factor. According to [37], the capacity factor for the wind turbine and solar panel are assumed as 0.34 and 0.18, respectively. The regional prices for the five hubs, which are summarized in Table 8, can be obtained by calculating the equilibrium problem.

As renewable energies have negligible operation costs (that has been assumed 0 in this study), it is observed that the electricity price is decreased to zero in the off-peak hours, in which the electricity demand is reduced. Renewable energies are unmanageable, and their penetration rate in the energy system has been increased. Hence, in off-peak hours, when the power supply overtakes the power demand in the network, it is probable to observe negative prices - to stimulate the consumers to consume more- to prevent the network instability.

Table 7: Capacity development for hub2 in proposed and single-hub model (MW)

	Proposed model	Single-HUB model
PP2	710.9	708.5
CHP1	224.1	226.8
CHP2	45	34.7
B2	191.8	200

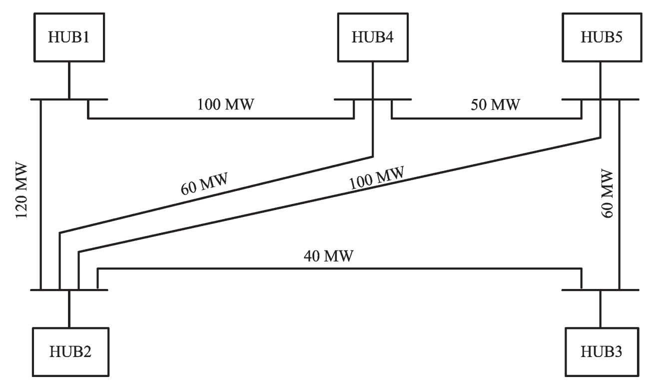

Figure 7: 5-Hub Energy System

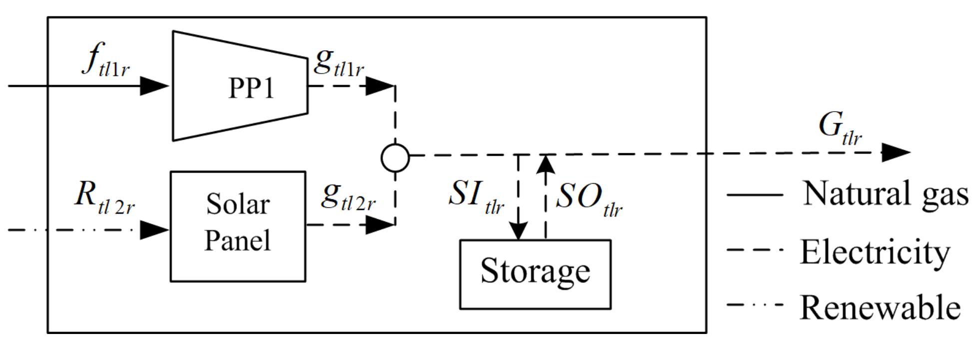

Figure 8: Internal structure of HUB4

Table 8: Electricity market price for all hubs (5-hub system)

Year	$t = 1$		$t = 2$		$t = 3$		$t = 4$		$t = 5$	
Load zone	$l = 1$	$l = 2$	$l = 1$	$l = 2$	$l = 1$	$l = 2$	$l = 1$	$l = 2$	$l = 1$	$l = 2$
Market price at HUB1 (cent/kWh)	12.4	12.4	13.4	12.4	16.5	12.4	16.5	12.4	18	12.4
Market price at HUB2 (cent/kWh)	10.1	10	10.1	10	11.3	11.3	13.3	12.3	17.9	10.6
Market price at HUB3 (cent/kWh)	5.8	0	6.4	0	10.4	4.8	10.4	10.4	29.9	10.6
Market price at HUB4 (cent/kWh)	10	9.9	10	10	11.3	11.2	13.2	12.1	17.9	10.6
Market price at HUB5 (cent/kWh)	5.8	0	6.4	0	10.4	4.8	10.4	10.4	17.9	10.6

Energy storage equations shown in Eq. (27) and Eq. (28).

$$\sum_{l=1}^{NL} SI_{tlr} - \sum_{l=1}^{NL} SO_{tlr} \geq 0 \tag{27}$$

$$\sum_{l=1}^{NL} SI_{tlr} - \sum_{l=1}^{NL} SO_{tlr} \leq TC_{t\tau r} \tag{28}$$

It is assumed that during off-peak load zone, electricity is stored in the storage while during peak load zone, electricity is taken from the storage. The amount of capacity development is summarized in Table 9.

Due to the presence of renewable energy and the accessibility of HUB2 to the produced electricity by renewable energy resources, which have smaller costs, HUB2 uses the cheap electricity of HUB4 and HUB5 by decreasing the capacity-building in turbine technology. In addition, as HUB1 and HUB3 have access to the cheap produced electricity (that has been produced by renewable energy resources), the demand for buying the produced electricity by HUB2 is decreased, and the need for capacity-building in turbine technology have also been reduced. In the first two years, it is expected that the price of the produced electricity by HUB3 be zero in off-peak hours. Therefore, CHP technology electricity generation using natural gas will no longer be justifiable. So, it can be observed that investment in CHP technology is reduced in HUB3.

Storage capacity-building has only happened in HUB2. As HUB4 and HUB5 use their total transmission capacities in the peak and off-peak load zones, no additional capacity for transmitting the stored energy is accessible for them. Hence, there have been no investments for storage technology in these two hubs.

Table 9: Aggregated capacity development in different hubs and for different technologies (MW)

	HUB1	HUB2	HUB3
PP2	556.2	264.1	212.9
CHP1	240	321.2	288.1
CHP2	20	43.2	0.0
B1	0	0.0	79.9

4. Conclusion

The proposed model in this paper aims at determining the optimal planning/operation of the competing hub in a multi-hub energy systems. The problem has formulated as an oligopoly Cournot game. Solving the model will result in annual built capacity in different technologies for the hubs. Other outputs include electricity exchanges between the hubs, and also gas consumption by technologies for each load zones of the planning horizon for each hub. Market price is obtained from market clearing conditions in the equilibrium problems.

The proposed model has been applied to 3-Hub and 5-Hub energy systems. The effect of renewable generation and storage system have also been evaluated. The results have been presented and discussed to evaluate the validity of the results as well as the capabilities of the proposed model. By increasing the load zones, better modeling of demand profile and photovoltaic power generation, which is a function of the solar irradiation, can be achieved. Besides, the accuracy of the modeling can be improved.

The gas market, together with the electricity market, can be studied in this model to obtain the market price of gas in various load zones. The impact of the applied policy on energy market can be investigated by studying the proposed model. However, bi-level modeling is needed for finding the optimized policy for the policymaker. In this type of modeling, the objective function of the policymaker is the upper level of the model, and the selected policy of the policymaker is prior to the chosen strategy of the agents. Therefore, market agents can optimize their strategy after determining the selected strategy by the policymaker. The bi-level model should be used to find the optimized capacity development in the energy grid.

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