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Dynamic and multi-stage capacity expansion planning in microgrid integrated with electric vehicle charging station

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ABSTRACT

This paper investigates the long-term dynamic capacity expansion planning in the microgrids. The microgrid is supplied by various capacity resources including wind, solar, micro gas turbine, and energy storage system. The microgrid also supplies an electric vehicle charging station. The electric vehicles in the charging station work as vehicle-to-grid and they are able to send energy to the microgrid or regulate their charging time and rate. As a result, the charging station may appear as a flexible load or generating unit. The capacity expansion planning in the microgrid is performed to expand the capacity of micro turbine, solar panels, wind turbine, and battery energy storage system. This capacity expansion is performed for six-years planning horizon through long term plan. The short-term plan is simultaneously conducted to optimize the hourly operation of micro turbine, energy storage system, and electric vehicle charging station. Short-term operation of dispatchable resources reduces the planning cost to 28% and properly contributions to the long-term plan for minimizing the costs. The largest expansion is performed on wind system by 200% expansion that covers about 53% of the expansion cost. The model also needs further resources when facing the uncertainties and such reinforcement increases the cost by about 58%.

1. Introduction

The network expansion planning is one of the conventional methods to deal with load growth in the electrical networks. The expansion may be applied on generation, transmission, or distribution parts of the electrical grids. In the network expansion planning, the available energy resources, lines, and components are expanded or reinforced in order to handling load growth in the future years. The expansion planning is a long-term plan and the planning horizon is often considered between 5 and 20 years [1].

In the generation expansion planning, the capacity of available generating units in the system is expanded and/or the new generating technologies are installed. The generation expansion planning is mathematically presented as an optimization programming and it can be expressed as linear or nonlinear optimization models [2]. This problem determines the site, technology, size, operation pattern, and installation time of new generating systems while it optimizes the objective function including various terms such as investment cost, maintenance cost, operational cost, reliability, and environmental costs [3]. This optimization programming is solved subject to security, technical, and economic constraints of the system. The main challenges facing generation expansion may be referred as integration of transmission networks and role of electricity trade, risk assessment, electric vehicles, role of optimal short-term operation on long-term planning, the mutual impacts of power and natural gas systems, energy storage systems, demand side management programs, environmental impacts, renewable energy integration, and policies-security issues [4]. The generation expansion can be integrated with energy storage systems [3]. The storage technologies shift energy over the hours or days and such operation reduces the planning cost efficiently. Different storage technologies are studied in the expansion planning problems [5].

The transmission expansion planning is an optimization programming that installs new transmission lines or reinforces the existing lines in order to meet the load growth requisites in the next years during the planning horizon [6]. This problem often minimizes the investment cost on new lines while considers the security, reliability, and economic constraints of the network [7]. The main challenges facing transmission expansion may be categorized as renewable energy integration, energy storage systems, demand side management programs, electricity market trades, risk assessment, and electric vehicles [8]. Application of energy storage systems in transmission expansion makes positive impacts on the model and decreases the investment cost significantly. The storage devices supply on-peak loading and reduce the system requirement for installing new lines [9].

The distribution network expansion planning is performed on the distribution grids where the distribution network lines are reinforced or

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Nomenclature

Parameters and variables description

A_1	coefficient to calculate equivalent annual cost
A_2	coefficient to calculate net present value
C_{res}	rated capacity of energy storage (kWh)
C_{rev}	rated capacity of electric vehicle (kWh)
$E_{es}^{s,y,t}$	stored energy in storage system (kWh)
$E_{ev}^{y,n,t}$	stored energy in electric vehicle (kWh)
I_{ces}	energy storage capacity price ($/kWh)
I_{mt}	micro turbine price ($/kW)
I_{pes}	energy storage converter price ($/kW)
I_{sol}	solar system price ($/kW)
I_{win}	wind system price ($/kW)
K_{c1}	limitation on installing new storage capacity at each year
K_{c2}	limitation on installing new storage capacity during consecutive years
K_{m1}	limitation on installing new micro turbine at each year
K_{p1}	limitation on installing new converter at each year
K_{p2}	limitation on installing new converter during consecutive years
K_{s1}	limitation on installing new solar power at each year
K_{s2}	limitation on installing new solar power during consecutive years
K^{y}	limitation on installing new capacity resources at each year
K_{w1}	limitation on installing new wind power at each year
K_{w2}	limitation on installing new wind power during consecutive years
n, N	index of electric vehicles, set of electric vehicles
O_{ces}	operational cost of energy storage capacity ($/kWh)
$O_{mt}^{y,t}$	micro turbine operational cost ($/kW)
O_{pes}	operational cost of energy storage converter ($/kW)
O_{sol}	solar system operational cost ($/kW)
O_{win}	wind system operational cost ($/kW)
$P_{ces}^{s,y,t}$	charged power to energy storage system (kW)
$P_{ccs}^{y,t}$	charged power to electric vehicle charging station (kW)
$P_{cev}^{y,n,t}$	charged power to electric vehicle (kW)
$P_{des}^{s,y,t}$	discharged power from energy storage system (kW)
$P_{dcs}^{y,t}$	discharged power from electric vehicle charging station (kW)
$P_{dev}^{y,n,t}$	discharged power from electric vehicle (kW)
$P_{load}^{s,y,t}$	consumed power by load (kW)
$P_{mt}^{y,t}$	produced power by micro turbine (kW)
$P_{mn}^{s,y,t}$	power between microgrid and upstream network (kW)
P_{rmt}	rated power of micro turbine (kW)
P_{res}	rated power of energy storage converter (kW)
P_{rmn}	limit of power between microgrid and network (kW)
P_{sol}	rated power of solar system (kW)
$P_{sol}^{s,y,t}$	produced power by solar (kW)
P_{win}	rated power of wind system (kW)
$P_{win}^{s,y,t}$	produced power by wind (kW)
R_y	net cash flow
s, S	index of scenarios, set of scenarios
t, T	index of hours, set of hours
TCE_{ins}^{y}	new capacity installed for storage system at each year (%)
$TCET_{ins}^{y}$	available capacity for energy storage at each year (%)
TM_{ins}^{y}	new installed micro turbine at each year (%)
TPE_{ins}^{y}	reinforcement on power of converter at each stage
$TPET_{ins}^{y}$	total available power of converter at each stage
TS_{ins}^{y}	new installed solar power at each year (%)
TST_{ins}^{y}	available solar power at each year (%)
TW_{ins}^{y}	new installed wind power at each year (%)
TWT_{ins}^{y}	available wind power at each year (%)
$u_{ces}^{s,y,t}$	binary variable related to charging state of storage system
$u_{des}^{s,y,t}$	binary variable related to discharging state of storage system
y, Y	index of years, Set of years
z_{inv}^{sol}	investment cost on solar power ($/year)
z_{inv}^{win}	investment cost on wind power ($/year)
z_{inv}^{mt}	investment cost on micro turbine power ($/year)
z_{inv}^{pes}	investment cost on energy storage converter ($/year)
z_{inv}^{ces}	investment cost on energy storage capacity ($/year)
z_{ope}^{sol}	operational and maintenance cost of solar power ($/year)
z_{ope}^{win}	operational and maintenance cost of wind power ($/year)
z_{ope}^{mt}	operational and maintenance cost of micro turbine ($/year)
z_{ope}^{pes}	operational and maintenance cost of storage converter ($/year)
z_{ope}^{ces}	operational cost of energy storage capacity ($/kWh)
Z_{plan}	total cost of expansion ($/year)
η_{es}	efficiency of storage system (%)
θ	discount rate (%)
τ	asset lifetime (year)

the new lines are installed [10]. The model is similar to the transmission expansion planning but the distribution grids are usually radial and the system topology must remain radial during the expansion [11]. The distribution grids are often integrated with distributed generation, energy storage systems, microgrids, and demand response programs [12,13]. Such technologies can be included in the distribution network expansion planning [14]. These local resources can significantly improve the system efficiency [15]. The distributed energy resources are usually controlled and integrated to the grid through interfacing inverters. The operation of inverters makes substantial impacts on the protection scheme, control strategies, and operation of distribution grids. The distribution grids integrated with such devices need to update their protection schemes, control strategies, and operation plans [16].

The microgrids are the efficient parts of the electrical grids that have been broadly developed over the recent years [17]. The expansion planning can also be performed on the other electrical systems such microgrids [18]. In the microgrids, the capacity of lines and energy resources are less than the electric power systems. However, the expansion model for such systems is similar to the large-scale electrical networks. The microgrid is integrated with various energy resources like wind, solar, gas turbine, combined heat and power, diesel generation, and energy storage systems [19]. In the microgrid expansion planning, the capacity of the available energy resources is expanded to supply the load demand in the future years. The capacity of the line connected between the microgrid and the upstream network may also be expanded [20]. The energy storage systems are one of the inseparable parts of the microgrids [21]. Application of hybrid energy storage systems in microgrids provides numerous technical and economic advantages [22]. The hybrid storages are classified as short-term and long-term hybrids. The short-term like battery-flywheel hybrid and the long-term such as compressed air-super capacitor combination. Application of hybrid energy storage systems under unbalanced and nonlinear loads is suggested as future trends [22].

The electric vehicles are the other technologies that operate like energy storage systems. These technologies are able to make substantial effects on the short-term and long-term plans in the electrical networks. The charging facility of the electric vehicles is an important factor and has a great role on the performance and lifetime of vehicle's battery. The modified interfacing inverters and converters are experimented to improve the performance of these chargers. The charging rates are different under winter and summer because of battery temperature. It has verified that simultaneous charging of electric vehicles enhances the charging performance concerning the charging rate [23]. Together with development of electric vehicles, more charging-capacity is required by the society. The key issues related to the charging stations are the energy gap during peak demands and lack of charging infrastructure because of high construction costs. The energy storage systems are able to compensate the energy gap during peak demands [24]. Additionally, the batteries provide the other benefits such as managing peak demands, reliability improvement, and enabling integration of renewable energies to the electrical grids. The main available technologies are sodium-sulfur, redox-flow, lithium-ion batteries [25].

This paper presents an advanced model for dynamic and multi-stage capacity expansion planning in the microgrid integrated with electric vehicle charging station and various energy resources. The microgrid is supplied by micro turbine, solar panels, wind turbine, and battery energy storage system. The microgrid is also connected to an electric vehicle charging station. The electric vehicles are modeled as vehicle to grid technology. The charging station can change its demand for power by optimal charging-discharging of the electric vehicles. As a result, the charging station appears as a flexible load on the microgrid. As well, it appears as a generating unit on the microdot at some hours when the electric vehicles are discharged. The optimal operation of electric vehicle charging station is determined and its impacts on the microgrid expansion planning are investigated and evaluated. In the introduced model for microgrid capacity expansion, the capacity expansion planning is performed to expand the capacity of micro turbine, solar panels, wind turbine, and battery energy storage system. The installed capacity resources need an optimal hourly operation pattern. As a result, the short-term plan is performed to find optimal hourly operation pattern for electric vehicle charging station, micro turbine and battery energy storage system. The long-term capacity expansion is improved by short-term optimal operation of charging station, micro turbine, and storage unit. The investment, maintenance, and operational costs of micro turbine, solar panels, wind turbine, and battery energy storage system are considered in the model. The plan finds optimal capacity, installation time, and operation pattern for all capacity resources in the microgrid. The uncertainty of energy resources and loads are considered in the model through stochastic programming.

The main highlights of the introduced model are listed below:

ü Finding optimal hourly operation pattern for electric vehicle charging station, micro turbine, and energy storage system.

ü Regulating the charging time, charging rate, discharging time, and discharging rate of the electric vehicles in the charging station in order to minimizing the expansion cost.

ü Considering the uncertainty of energy resources and loads through stochastic programming.

ü Considering the investment, maintenance, and operational costs of micro turbine, solar panels, wind turbine, and battery energy storage system.

2. Microgrid structure

The electricity in the microgrid may be generated by renewable energies, gas turbines, or diesel generators [26]. Microgrid can supply the electrical and thermal loads and also be supported by energy storage systems and electric vehicles to have more flexible operation. Microgrid is a single controllable entity with regard to the upstream

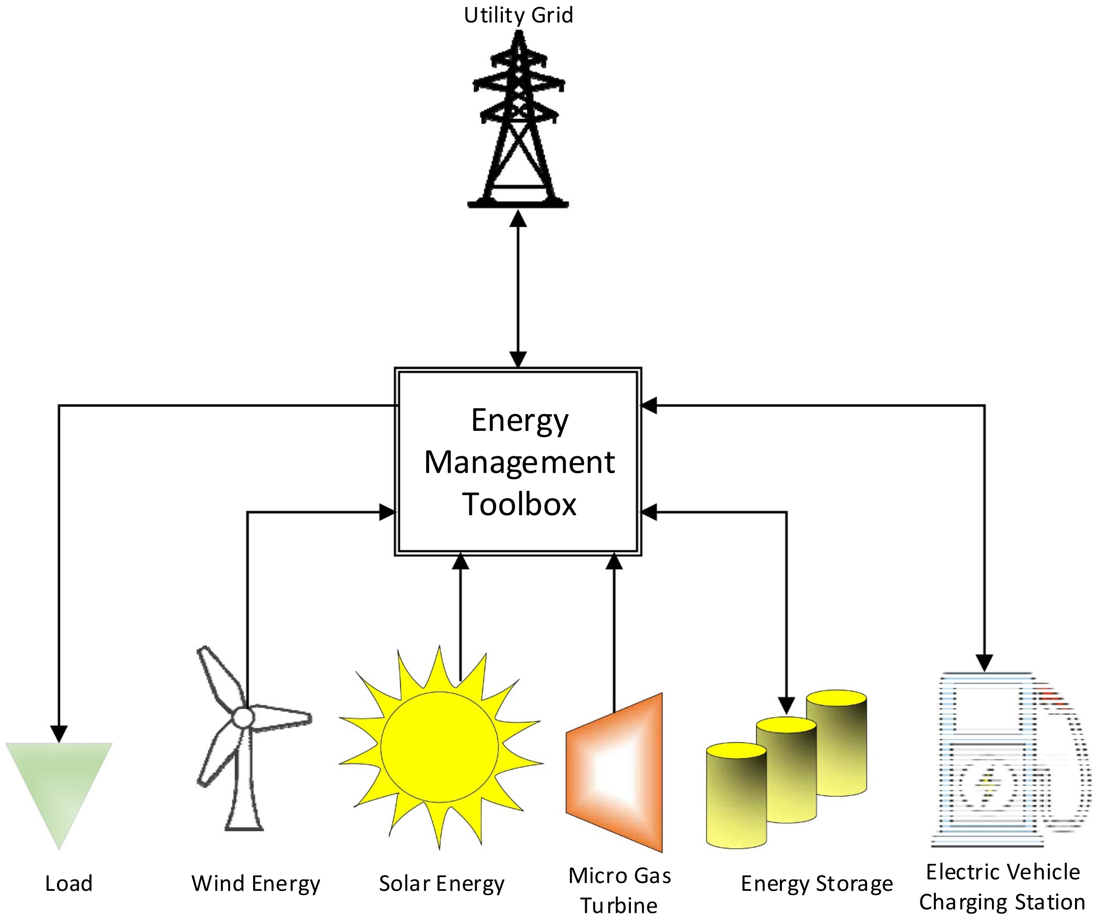

Fig. 1. Structure of microgrid connected to the upstream grid.

utility network [27] and is able to continue its operation when the upstream grid is not available during blackout. The optimal operation of the microgrid is dictated by economic or technical conditions [28].

Fig. 1 shows the structure of a typical microgrid which is connected to the upstream grid and has bidirectional power trade with the network. The wind and solar energy resources are connected to the microgrid as renewables. The micro gas turbine is also connected as nonrenewable and the energy storage system is used to shift energy and adjust the uncertainty of the renewables. Microgrid is connected to the electric vehicle charging station and the plug-in electric vehicles in the changing station can take part in the energy optimization model through either sending energy to the grid or regulating their charging time and rate. The connections to the loads and generating resources are unidirectional, but the connections to the energy storage system and charging station are bidirectional. The control center optimizes the operation of microgrid and this operation is optimized considering the autonomous operation, grid-tied operation, economic condition, and technical restrictions.

2.1. Capacity expansion model

The introduced microgrid in Fig. 1 supplies the load demand by using the local capacity resources as well as the utility grid. However, by growing the load demand in the next years, the microgrid cannot supply the demand properly. As a result, the capacity resources in the microgrid need to be expanded. A capacity expansion planning is required to be conducted on the microgrid to determine the size, time, setting (operation), and technology of new capacity resources that must be installed on the microgrid. This capacity expansion planning must expand the microgrid to supply the demand during next years while it should consider the economic and technical conditions.

In the proposed model for capacity expansion, the wind, solar, micro gas turbine, and energy storage systems are considered as capacity resources for expansion. An annual load growth is applied on the load demand. Then the aforementioned capacity resources are expanded to supply the load growth.

2.2. Short and long term plans

Fig. 2 shows the flowchart of the developed model. The capacity expansion model comprises two plans including long-term optimization programming to install new capacity resources in the microgrid and short-term optimization programming to find optimal operation pattern for dispatchable resources. These two optimization plans are combined to implement a mixed integer linear programming that minimizes the investment, operational, and maintenance costs all together.

The long-term plan installs new capacity resources and calculates the investment cost of the plan over the planning horizon. The new

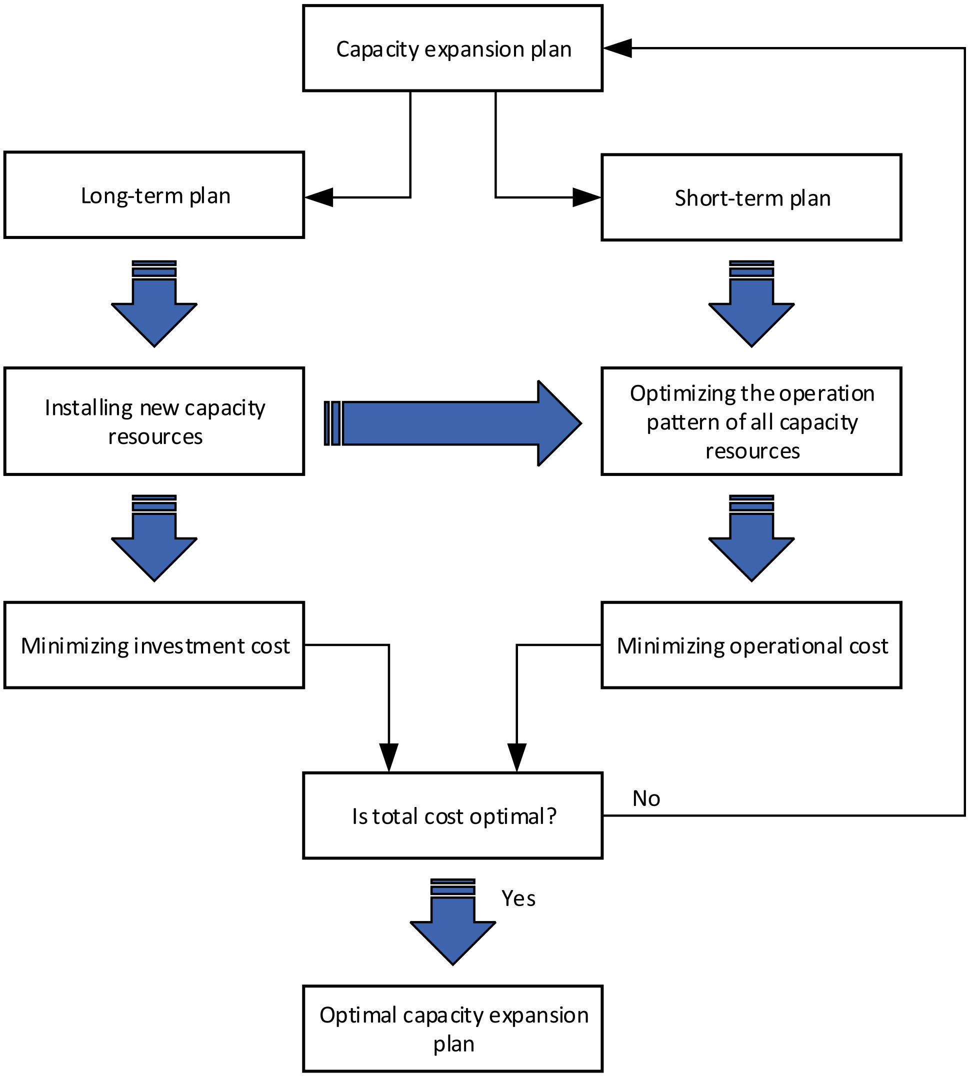

Fig. 2. Flowchart of the introduced model for capacity expansion.

installed capacities and the existing capacities must supply the peak load demand. However, the new and existing resources can be optimally scheduled to supply the peak demand to avoid installing further resources. For instance, the energy storage systems can be discharged under peak load demand to prevent investing on new resources. The optimal operation of all available resources through short-term plan allows the long-term plan to install smaller capacities resulting in less investment cost. Therefore, the long-term plan installs the energy resources and the short-term plan contributions the long-term plan to install less capacities by best utilization of dispatchable resources. The best utilization is carried out through determining the optimal hourly operation of micro gas turbine, energy storage system, and electric vehicle charging station. For instance, the short-term plan can manage the electric vehicle charging station to send energy to the microgrid or regulate its charging time and rate. Such management reduces the necessarily of installing further resources by long-term plan.

3. Formulation

In the introduced model, the microgrid is supplied by wind, solar, and micro turbine resources. It is also equipped with energy storage systems and electric vehicle charging station. The investment, operational and maintenance costs are considered for all capacity resources. The investment cost of solar power is presented by (1). This cost is converted to equivalent annual cost (by using coefficient A_1) and then it is presented as net present value (by using coefficient A_2). The operational-maintenance cost of solar power is given by (2) [9]. In this paper, the discount rate is considered equal to 10% and the salvage value is not included in the model.

$$\begin{cases} z_{inv}^{sol} = \sum_{y\in Y} (TS_{ins}^{y} \times P_{sol} \times I_{sol} \times A_1 \times A_2) \\ A_1 = \theta \times \frac{(1+\theta)^{\tau}}{(1+\theta)^{\tau}-1} \\ A_2 = \frac{R_y}{(1+\theta)^{y}} \end{cases} \tag{1}$$

$$z_{ope}^{sol} = \sum_{y\in Y} (TST_{ins}^{y} \times P_{sol} \times O_{sol} \times A_2 \times 365) \tag{2}$$

The investment and operational costs of wind system are denoted in (3) and (4). The micro turbine costs are presented through (5) and (6), where, the equivalent annual cost is given by (5) and the operational and maintenance costs are shown by (6) [29].

$$z_{inv}^{win} = \sum_{y\in Y} (TW_{ins}^{y} \times P_{win} \times I_{win} \times A_1 \times A_2) \tag{3}$$

$$z_{ope}^{win} = \sum_{y\in Y} (TWT_{ins}^{y} \times P_{win} \times O_{win} \times A_2 \times 365) \tag{4}$$

$$z_{inv}^{mt} = \sum_{y\in Y} (TM_{ins}^{y} \times P_{rmt} \times I_{mt} \times A_1 \times A_2) \tag{5}$$

$$z_{ope}^{mt} = \sum_{y\in Y} \sum_{t\in T} (P_{mt}^{y,t} \times O_{mt}^{y,t} \times A_2 \times 365) \tag{6}$$

The investment cost to install new converters for energy storage system is presented in (7) and the operational-maintenance cost of converters is given by (8).

$$z_{inv}^{pes} = \sum_{y\in Y} (TPE_{ins}^{y} \times P_{res} \times I_{pes} \times A_1 \times A_2) \tag{7}$$

$$z_{ope}^{pes} = \sum_{y\in Y} (TPET_{ins}^{y} \times P_{res} \times O_{pes} \times A_2 \times 365) \tag{8}$$

The investment and operational costs related to expansion of energy storage capacity are presented by (9) and (10).

$$z_{inv}^{ces} = \sum_{y\in Y} (TCE_{ins}^{y} \times C_{res} \times I_{ces} \times A_1 \times A_2) \tag{9}$$

$$z_{ope}^{ces} = \sum_{y\in Y} (TCET_{ins}^{y} \times C_{res} \times O_{ces} \times A_2 \times 365) \tag{10}$$

Eventually, the final cost of network expansion is presented by (11). This cost is the equivalent annual cost of expansion and it is presented as net present value.

$$Z_{plan} = z_{inv}^{sol} + z_{ope}^{sol} + z_{inv}^{win} + z_{ope}^{win} + z_{inv}^{mt} + z_{ope}^{mt} + z_{inv}^{pes} + z_{ope}^{pes} + z_{inv}^{ces} + z_{ope}^{ces} \tag{11}$$

The equilibrium of power in the microgrid is confirmed by (12), where, the capacity resources produce electricity and the consumers appear as load. The difference between generation and consumption is received from the upstream grid or sent to the upstream network. The exchanged power between the microgrid and the upstream grid is modeled by (13).

$$\begin{gathered} P_{mn}^{s,y,t} = P_{load}^{s,y,t} - P_{sol}^{s,y,t} - P_{win}^{s,y,t} - P_{mt}^{y,t} + P_{ces}^{s,y,t} - P_{des}^{s,y,t} + P_{ccs}^{y,t} - P_{dcs}^{y,t} \\ \forall\, s \in S,\, y \in Y,\, t \in T \end{gathered} \tag{12}$$

$$\begin{gathered} |P_{mn}^{s,y,t}| \le P_{rmn} \\ \forall\, s \in S,\, y \in Y,\, t \in T \end{gathered} \tag{13}$$

The installed solar power at each stage of the planning horizon is denoted by (14). The limitations on expansion of solar system can also be considered as introduced in (14).

$$\begin{cases} TS_{ins}^{y} = TST_{ins}^{y} - TST_{ins}^{y-1} \\ TS_{ins}^{y} \le K_{s1} \\ TST_{ins}^{y} \le K_{s2} \\ \forall\, y \in Y \end{cases} \tag{14}$$

The expansion level for wind system is defined by (15). The limitations on expansion of wind energy are also defined in relationship.

$$\begin{cases} TW_{ins}^{y} = TWT_{ins}^{y} - TWT_{ins}^{y-1} \\ TW_{ins}^{y} \le K_{w1} \\ TWT_{ins}^{y} \le K_{w2} \\ \forall\, y \in Y \end{cases} \tag{15}$$

The power and capacity of energy storage system are expanded by the proposed model. The power is related to the rated power of interfacing converter between battery and grid. This rated power is expanded and the power of converter is reinforced. The limitations on such expansion are considered as (16) and the total available power shows the existing power plus to the reinforced power at each stage.

$$\begin{cases} TPE_{ins}^{y} \le K_{p1} \\ TPET_{ins}^{y} \le K_{p2} \end{cases} \quad \forall\, y \in Y \tag{16}$$

The capacity of energy storage system (battery capacity) is also expanded. The new installed batteries are modeled by (17). This expansion is limited by some constrains as modeled by (17).

$$\begin{cases} TCE_{ins}^{y} = TCET_{ins}^{y} - TCET_{ins}^{y-1} \\ TCE_{ins}^{y} \le K_{c1} \\ TCET_{ins}^{y} \le K_{c2} \\ \forall\, y \in Y \end{cases} \tag{17}$$

There is a similar methodology for expansion of micro turbine. The new installed micro turbines at each stage of the planning horizon are modeled by (18). The constraints on expansion of micro turbines are also included. The limitation on expansion of all energy resources may also be introduced as (19).

$$\begin{cases} TM_{ins}^{y} \le K_{m1} \\ P_{mt}^{y,t} \le P_{rmt} \\ \forall\, y \in Y,\, t \in T \end{cases} \tag{18}$$

$$[TS_{ins}^{y} + TW_{ins}^{y} + TPE_{ins}^{y} + TCE_{ins}^{y} + TM_{ins}^{y}] \le K^{y} \qquad \forall\, y \in Y \tag{19}$$

In the proposed model, the long-term expansion planning is improved by optimizing the short-term operation of resources such as micro turbines, energy storage system, and electric vehicle charging station. The short-term operation of micro turbine is optimized as shown in (18). Correspondingly, the operation pattern of energy storage system is optimized as given through (20–23). The hourly charging-discharging regime of energy storage system is modeled through (20–23).

$$\begin{cases} P_{ces}^{s,y,t} \times u_{ces}^{s,y,t} \leq P_{res} \\ P_{des}^{s,y,t} \times u_{des}^{s,y,t} \leq P_{res} \\ u_{ces}^{s,y,t} + u_{des}^{s,y,t} \leq 1 \\ \forall\ s \in S,\ y \in Y,\ t \in T \end{cases} \tag{20}$$

$$\eta_{es} = \frac{\sum_{t \in T}(P_{des}^{s,y,t})}{\sum_{t \in T}(P_{ces}^{s,y,t})} \quad \forall\ s \in S,\ y \in Y \tag{21}$$

$$E_{es}^{s,y,t} = E_{es}^{s,y,t-1} + P_{ces}^{s,y,t} - P_{des}^{s,y,t} \quad \forall\ s \in S,\ y \in Y,\ t \in T \tag{22}$$

$$E_{es}^{s,y,t} \leq C_{res} \quad \forall\ s \in S,\ y \in Y,\ t \in T$$

Microgrid is also connected to the electric vehicle charging station. In the electric vehicle charging station, the vehicle-to-grid technology is adopted. As a result, the electric vehicles can receive power from the microgrid or send power to the microgrid. The energy of each electric vehicle in the charging station is modeled by (23) and (24). The total charged power to the charging station and total discharged power from the charging station are modeled by (25).

$$E_{ev}^{y,n,t} = E_{ev}^{y,n,t-1} + P_{cev}^{y,n,t} - P_{dev}^{y,n,t} \quad \forall\ y \in Y,\ n \in N,\ t \in T \tag{23}$$

$$\begin{cases} E_{ev}^{y,n,t} \leq C_{rev} \\ E_{ev}^{y,n,t} = C_{rev} \\ \forall\ y \in Y,\ n \in N,\ t = tl \end{cases} \tag{24}$$

$$\begin{cases} P_{ccs}^{y,t} = \sum_{n \in N} P_{cev}^{y,n,t} \\ P_{dcs}^{y,t} = \sum_{n \in N} P_{dev}^{y,n,t} \\ \forall\ y \in Y,\ t \in T \end{cases} \tag{25}$$

In the introduced expansion model, the long-term plan installs new capacity for wind, solar, micro-turbine, and energy storage system. The short-term plan optimizes the hourly operation for micro-turbine, energy storage system, and electric vehicle charging station. Such coordination between long-term and short-term plans optimizes the model and outputs.

4. Case study

Microgrid shown in Fig. 1 is considered as test case and integrated with 30 kW wind turbine, 30 kW solar panels and 10 kW micro turbine. The peak of load demand is 200 kW. The power and capacity of energy storage system are 10 kW and 30 kWh. The microgrid is connected to the upstream network by a line with 180 kW capacity. The fuel cost for micro turbine is 0.2 $/kWh. The investment and operational costs of all energy resources are listed in Table 1. The life time of solar and wind systems is 8 years. The life time of micro turbine and energy storage system is 6 years. The discount rate is set on 10% [30].

The micro turbine is connected to the electric vehicle charging station. The charging facility of the charging station is able to charge the vehicles by 100 kW charging rate. The capacity of electric vehicles is also considered equal to 100 kWh. The vehicle to grid technology is adopted for the electric vehicles. The capacity of charging station is equal to three vehicles at the same time. In other words, the charging station has three spaces to charge the vehicles. The hourly profiles for wind energy, solar energy, load, and energy price are listed in Table 2.

The planning horizon is 6 years and the load growth and fuel price growth over the planning horizon are considered as shown in Fig. 3. All capacity resources are candidate for expansion over the planning horizon. There are some limitations on the expansion of all capacity resources. Every capacity resource can be expanded to 100% at each stage. Total expansion of every capacity resource over the planning horizon is 200%.

5. Simulation results

The introduced method for capacity expansion is simulated on the given microgrid as case study. All capacity resources of the microgrid are considered as candidate for expansion. The results of the long-term plan for expansion are listed in Table 3. The model installs various capacity resources in different years of the planning horizon to cope with the load growth. The wind energy is expanded more than the solar energy since the wind energy profile is wider than the solar energy profile. As a result, microgrid can harvest more energy from the wind system and better to install more wind turbines in the microgrid. The micro turbine is also installed at the last year of the planning horizon to supply the load growth in this year. Finally, the energy storage system is expanded in different years and both power and capacity of energy storage system are expanded. Energy storage system can properly shift energy over the hours and improve the model by peak-load cutting. Therefore, the model installs more energy storage systems in the microgrid.

Table 4 summarizes the annualized cost of expansion for each component and the total planning cost. All the costs are presented as equivalent annual cost. The most part of cost is covered by investment cost on wind energy. About 53% of the plan cost is related to the wind power, moreover, the large-scale micro turbine is installed at year 6 and it covers about 23% of total cost. The rest of the cost is related to the energy storage system and solar power.

As it was stated, the short-term operation of micro turbine and energy storage system is optimized by the proposed expansion plan in order to minimizing the investment cost on new technologies. Fig. 4 shows the operation of micro turbine at two typical years of the planning horizon (first and last years). The micro turbine only operates at hours 17–22 when the on-peak loading is occurred. At the first year, the operation is not significant because the wind and solar energy are cheaper than the micro turbine and they supply the demand. The micro turbine only produces energy at some hours to supply the shortage of energy. At the last year, the load growth is on the maximum status and the microgrid needs more power. The micro turbine therefore works on the maximum capacity to supply the demand for energy.

The exchanged power between the microgrid and the upstream network is shown by Fig. 5 under different years of the planning horizon. The traded power is limited on 180 kW because the capacity of line between the microgrid and the upstream network is 180 kW. It can be realized that the load growth in the microgrid is supplied by the available capacity resources and the new installed resources. Since the traded power between the microgrid and the upstream network is limited, the microgrid should supply the load demand (load growth) by

Table 1
Investment and operation costs of capacity resources.

	Investment cost	Operation and maintenance cost
Solar power	1200 ($/kW)	0.1 ($/kWh)
Wind power	2000 ($/kW)	0.1 ($/kWh)
Micro turbine power	500 ($/kW)	0.2 ($/kWh)
Power of energy storage	500 ($/kW)	0.1 ($/kWh)
Capacity of energy storage	500 ($/kWh)	0.1 ($/kWh)

Table 2
Hourly profile of wind, solar, load powers and energy price.

Hour	Electricity price ($/kWh)	Wind power (%)	Solar power (%)	Load power (%)
1	10	70	0	5
2	10	70	0	5
3	10	80	0	7
4	10	85	0	7
5	10	85	0	9
6	10	80	0	9
7	10	70	10	15
8	15	70	15	25
9	15	65	20	45
10	15	75	45	65
11	15	70	80	85
12	15	55	100	95
13	15	54	100	85
14	15	35	95	75
15	15	25	90	65
16	20	35	75	55
17	20	25	45	60
18	20	40	35	70
19	20	55	10	90
20	20	65	5	100
21	20	75	0	95
22	20	100	0	75
23	20	90	0	50
24	15	80	0	35

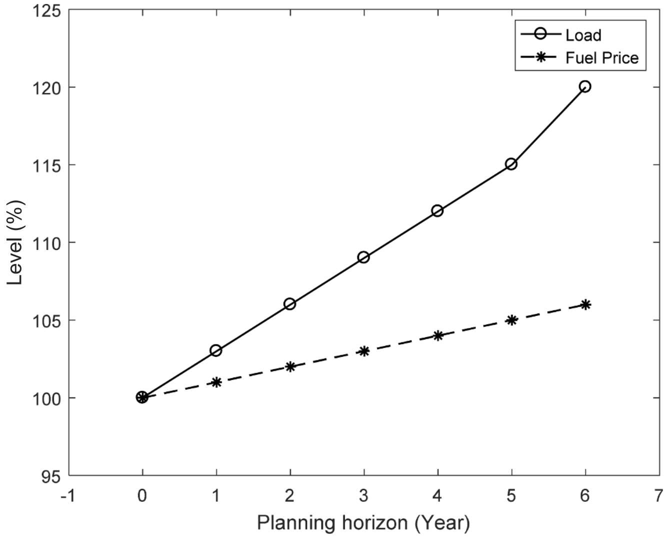

Fig. 3. Load and fuel price growth over the planning horizon.

Table 3
Percentage of expansion for each capacity resource over the planning horizon.

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6
Solar power (kW)	–	–		19.5%	–	–
Wind power (kW)	100%	81.0%	19.0%	–	–	–
Micro turbine (kW)	–	–	–	–	–	58.7%
Power of energy storage (kW)	–	24.9%	29.0%	16.1%	–	–
Capacity of energy storage (kWh)	100%	8.2%	50.0%	41.8%	–	–

Table 4
Annualized cost of expansion for each component and the total cost.

	Annualized cost of expansion ($/year)
Solar power ($/year)	1046.33
Wind power ($/year)	21,242.759
Micro turbine ($/year)	9355.008
Power of energy storage ($/year)	807.302
Capacity of energy storage ($/year)	7434.125
Total cost of expansion ($/year)	39,885.523

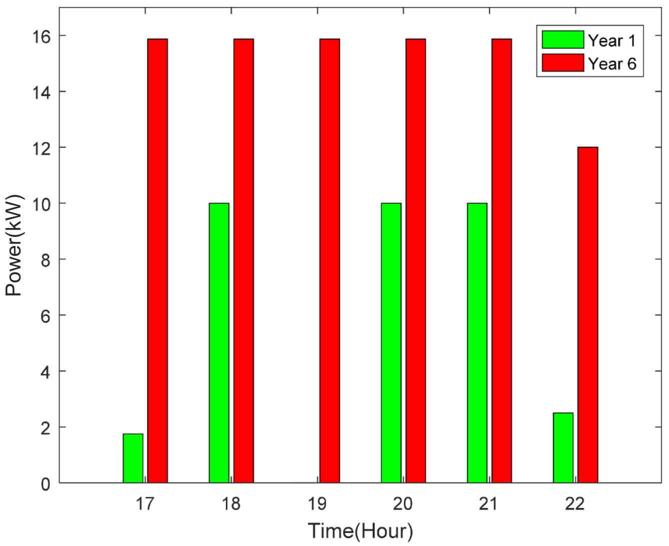

Fig. 4. Operation of micro turbine at the first and last years of the planning horizon.

installing proper and enough capacity resources including wind, solar, micro turbine, and energy storage system.

The model not only installs new capacity resources (i.e., wind, solar, micro turbine, and energy storage system) to supply the load demand but also optimizes the operation of micro turbine and energy storage system at the same time. Fig. 6 shows the operation of energy storage system in different years of the planning horizon. This component shifts energy from the low-price hours to the high-price hours as well as shaves the peak load.

The proposed plan also optimizes the operation electric vehicle charging station. The vehicle to grid technology is adopted for the electric vehicles in the charging station. The operation of electric vehicles is optimized to make the flexible operation for charging station. One of the electric vehicles in the charging station is discussed as an example. For instance, Fig. 7 presents the electric vehicle that arrives to the charging station at hour 19 with initial energy equal to 9 kWh. The vehicle is fully charged at hours 19. Then it is discharged at hour 21 and injects power to the microgrid. It is finally fully charged at hour 21 and leaves the charging station. Such operation is optimized for all electric vehicles that arrive to the charging station and allows electric vehicle charging station to inject power to the microgrid at some hours dictated by economy or technical conditions. The injected powers to the microgrid by electric vehicle charging station are listed in Table 5. The charging station usually injects power to the microgrid when the energy price is high.

5.1. *Impacts of charging station on expansion plan*

By optimizing the charging process of the electric vehicles, the electric vehicle charging station appears as a flexible load on the microgrid. The vehicle to grid technology also allows the charging station to appear as a generating unit at some time intervals. In order to signifying the influence of electric vehicle charging station on the expansion plan, the model is simulated again but the vehicle to grid technology is not considered for the electric vehicles. In other words,

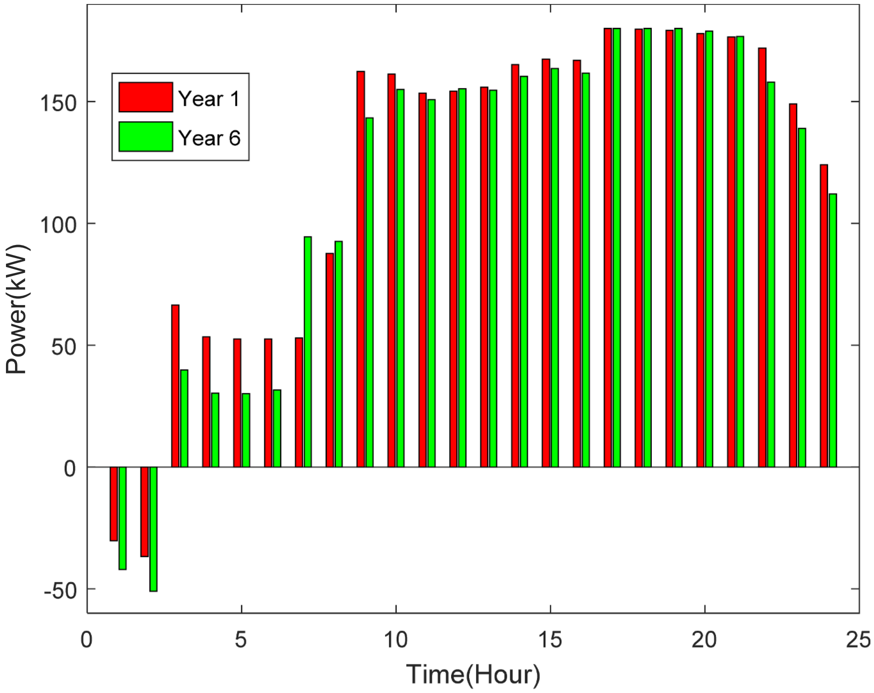

Fig. 5. Exchanged power between microgrid and upstream network in different years.

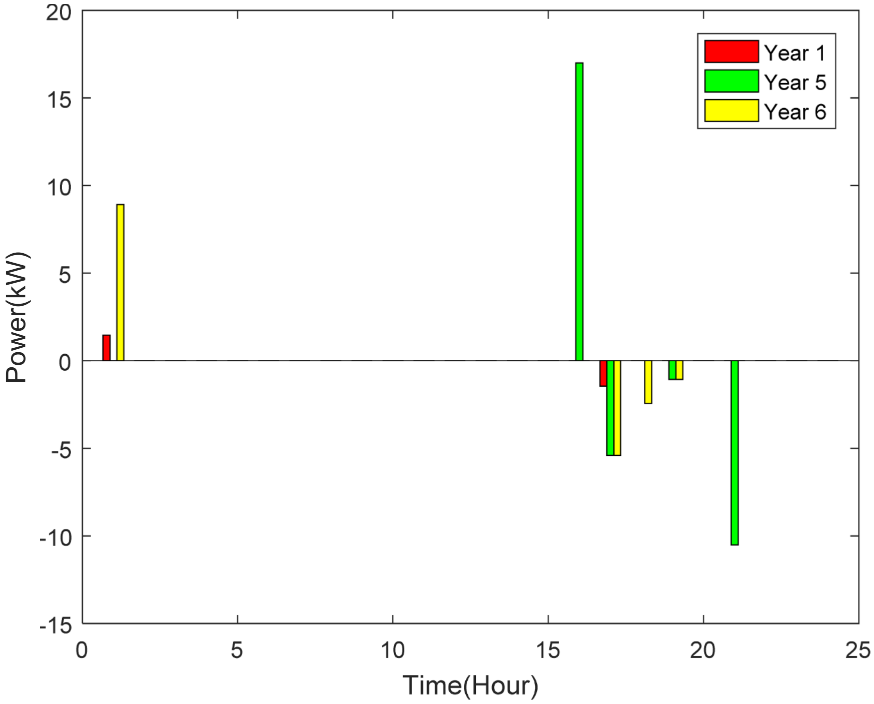

Fig. 6. Operation of energy storage system in different years of the planning horizon.

the charging station can not inject power to the microgrid. The results for this case are listed in Table 6. The total cost of expansion is increased by about 28%. The expansion of resources is listed in Table 7. It reveals that the microgrid needs large capacity resources to cope with load growth. Specially, the larger expansion is planned for micro turbine.

The results with and without vehicle to grid technology are presented and compared in Table 8. The results clearly verify that the microgrid without vehicle to grid technology needs about 74 MW (127%) larger micro turbine.

5.2. The parametric uncertainty

The parametric uncertainty is considered for several parameters in

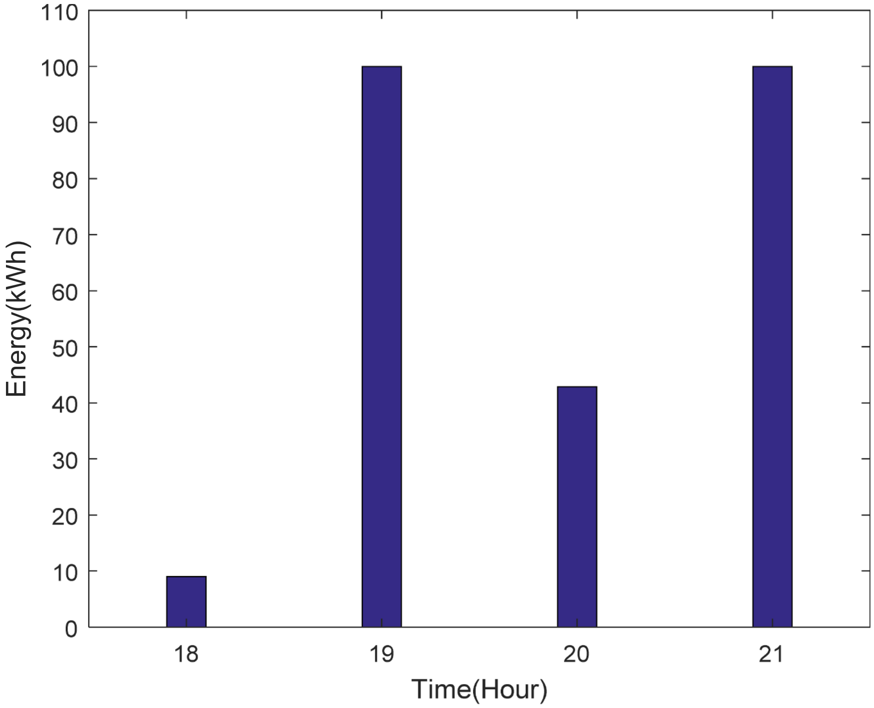

Fig. 7. Electric vehicle that arrives at hour 19 with initial energy 9 kWh.

Table 5
Injected power to the microgrid by electric vehicle charging station.

Hour	2	11	12	14	17	19	20	21	22
Year 1	5	0	0	0	0	69.1	100	64.2	20
Year 2	0	8.1	0	0	0.93	0	0	25	20
Year 3	0	0	0	0	0	61.27	60.54	25	20
Year 4	0	0	17.571	1.897	0	0	0	50.205	20
Year 5	0	0	0	0	0	53.84	60.75	25	20
Year 6	0	0	0	0	0	57.052	57.12	25	20

Table 6
Expansion plan without vehicle to grid technology for electric vehicles.

	Annualized cost of expansion ($/year)
Solar power ($/year)	1151.67
Wind power ($/year)	21,419.377
Micro turbine ($/year)	19,696.032
Power of energy storage ($/year)	705.861
Capacity of energy storage ($/year)	7551.472
Total cost of expansion ($/year)	50,524.413

Table 7
Percentage of expansion without vehicle to grid technology for electric vehicles.

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6
Solar power (kW)	0	0	19.5	0	0	0
Wind power (kW)	100	100	0	0	0	0
Micro turbine (kW)	30.8	0	0	0	12.4	88.8
Power of energy storage (kW)	0	30.9	28.1	0	0	0
Capacity of energy storage (kWh)	69.2	69.1	61.8	0	0	0

the model. The expansion of capacity resources with uncertainty and without uncertainty is presented in Fig. 8. In the model excluding uncertainty, the microgrid needs less and smaller capacity resources to cope with load growth. On the other hand, the model with uncertainty installs more and larger capacity resources in the microgrid. These capacity resources are installed to handle the load growth and uncertainty.

Table 8
Comparing the results with and without vehicle to grid technology.

	Installed capacity		Cost ($/year)	
	With V2G	Without V2G	With V2G	Without V2G
Solar power (kW)	19.5	19.5	1046.33	1151.67
Wind power (kW)	200	200	21,242.759	21,419.377
Micro turbine (kW)	58.7	132	9355.008	19,696.032
Power of energy storage (kW)	70	59	807.302	705.861
Capacity of energy storage (kWh)	200	200.1	7434.125	7551.472
Total cost of expansion ($/year)			39,885.523	50,524.413

The expansion cost including and excluding the parametric uncertainty is given in Table 9. The expansion cost is increased by about 58% because of uncertainty. This cost is used to install more and larger capacity resources in the microgrid to handle the uncertainty.

Fig. 9 shows share of powers to supply the demand in the microgrid at one typical hour. The load of microgrid is supplied by cogeneration of all capacity resources. For instance, at hour 20, about 30% of the required energy is supplied by capacity resources and rest of the energy is received from the upstream grid. At this hour, the solar power is close to zero and it does not play a significant role in the microgrid.

6. Conclusions

This paper addressed an advanced model for capacity expansion in the microgrid. The microgrid was connected to the upstream grid and supplied by solar, wind, and micro turbine. Microgrid was connected to the energy storage system and electric vehicle charging station and the expansion model was planned for six-year planning horizon. The proper load growth was modeled and the capacity resources were expanded to

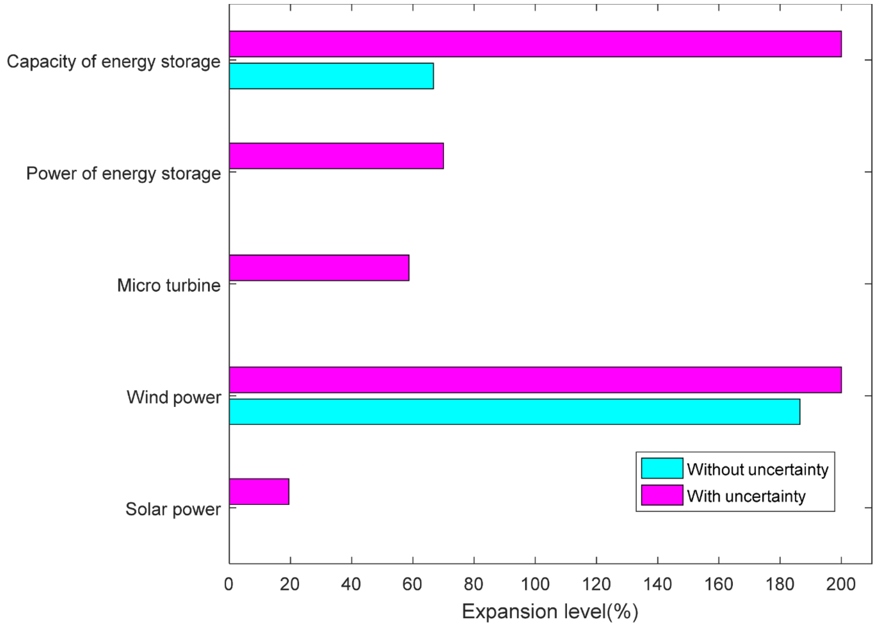

Fig. 8. The expansion of capacity resources with and without uncertainty.

Table 9
Comparing the results with and without vehicle to grid technology.

	With parametric uncertainty	Without parametric uncertainty
Total cost of expansion ($/year)	39,885.523	23,687.778

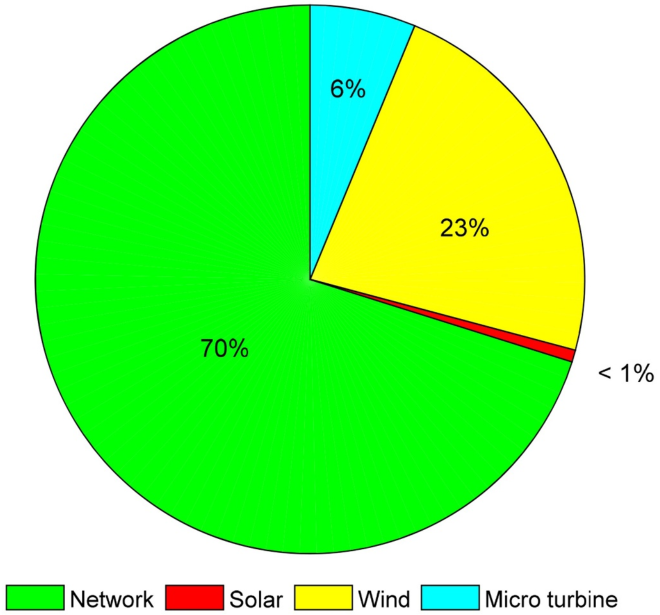

Fig. 9. Share of powers to supply demand in the microgrid at hour 20.

handle the load growth. The objective function of the plan was to minimize the investment cost of new capacity resources and the operational cost of all capacity resources over the planning horizon. The results demonstrated that the plan installs various capacity resources at different years of the planning horizon to cope with the load growth. According to the results, the most expansion is occurred on the wind energy because wind profile is wider than the solar energy profile. The expansion of wind energy is about 180% more than the solar energy. The new installed wind resources take about 53% of the total expansion cost and the micro turbine covers about 23% of the total cost. The short-term operation pattern of micro turbine and energy storage system are also optimized and it is demonstrated that the micro turbine operates at hours 17–22 when the on-peak loading is occurred.

The exchanged power between the microgrid and the upstream network is limited to 180 kW at all years of the planning horizon. As a result, the load growth cannot be supplied by the upstream grid and the microgrid has to install sufficient capacity resources to handle the load growth. The operation and charging rate of the electric vehicle charging station is also optimized by the introduced plan. The results indicate that the electric vehicle charging station reduces the planning cost about 28%. The microgrid without vehicle to grid technology needs about 74 MW (127%) larger micro turbine. It is also verified that the uncertainty in the parameters like wind and solar energy increases the planning cost by about 58%.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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