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Stochastic multi-stage multi-objective expansion of renewable resources in distribution systems with considering storage units, crypto-currency miners and responsive loads

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Abstract

Due to global warming and greenhouse gasses emission, heavy penalties should be paid by pollution producers. These problems can be solved by different proceedings such as renewable energies utilization and loads participation in energy management. This paper investigates the expansion of renewable resources and electrical energy storage units in distribution systems to reduce investment costs, environmental pollutions, and achieve a zero energy structure. Since the expansion of components is not possible in a single-stage due to the limitation of staff and funds, a multi-stage programming is utilized to consider the effect of various restrictions. According to the rapid growth of crypto-currency miners in recent years, the impact of such loads is also evaluated. Furthermore, to analyze the role of the responsive loads and simulate realistic conditions, an incentive-based demand response program is implemented and the uncertainty of renewable resources is modeled by a scenario generation/reduction approach. The results show that a zero energy structure with minimum investment cost is achievable by the expansion of renewable resources and energy storage systems, the drawbacks of miner loads can be mitigated by responsive loads and considering uncertainty improves the system robustness.

Keywords: Crypto-currency miners; electrical storage systems; multi-stage expansion; renewable resources; zero energy structure, uncertainty management.

Nomenclature

Parameters	**Definitions**	**Variables**	**Definitions**
B	Line susceptance (Ω^{-1})	b	Binary
C	Cost ($/MWh or $/kg)	L	Load (MW)
EF	Emission factor (kg/MWh)	N	Number
IC	Investment cost ($)	SoC	State of charge (MWh)
L	Line limit (MW)	TC	Total cost ($)
OC	Operation cost ($/MWh)	TEM	Total emission (kg)
PL	Power of line (MW)	x	Variable
Prob	Probability	P	Power (MW)
TL	Total load (MW)	δ	Voltage angle (rad)
β	Coefficient of curtailable load	**Abbreviations**	**Definitions**
γ	Coefficient of miner load	B	Base
η	Constant coefficient	C	Curtailable
θ	Time interval	ch and dch	Charge and discharge
λ	Coefficient of flexible load	DRP	Demand response program
μ	Time coefficient	DG	Distributed generation
ρ	Multi-stage index	EES	Electrical energy storage
ω	Season coefficient	EP	Emission penalty
Indices	**Definitions**	EXV	Expected value
i	Bus i	F	Flexible
j	Bus j	IEA	International energy agency
se	Season	MG	Main grid
s	Scenario	PV	Photovoltaic
t	Time (h)	RES	Renewable energy source
y	Year	WT	Wind turbine

1. Introduction

1.1. Motivation

Environmental pollution has become a critical subject in power systems. According to the target of "40-27-27" agreement, by 2030, the greenhouse gases emission should decrease by 40% and the growth of renewable energy sources (RESs) and energy efficiency should improve by 27% [1]. Due to clean energy generation and the maturity of power generators such as wind turbines (WTs) and photovoltaics (PVs), they can be a great choice to achieve the mentioned goals [2-4]. In this regard, their expansion in distribution grids as the interface part of power systems is evaluated in recent years [5, 6]. In return, the uncertainty of RESs should be considered as the main drawback and solved by proper solutions such as utilizing storage systems.

1.2. Literature review

In recent years, the expansion planning of electrical energy systems is investigated from various perspectives. Reference [7] presents a new multi-stage distribution expansion planning that specifies the optimal location, connection and time of construction. A stochastic expansion planning of an integrated network with WT and hydrogen storage is proposed to achieve the optimal location and size of components [8]. Reference [9] proposes a similar research based on a multi-objective model including cost and risk minimization. An expansion planning with considering the viewpoint of private investors and uncertainty of renewable resources is formulated to obtain a probabilistic solution for the load flow problem by using Hong's two-point estimate method [10]. A bi-level optimization algorithm for expansion planning of an integrated network with cooling, heating, and electricity systems is modeled in [11]. Minimizing cost and maximizing electricity export and reliability under uncertain environment are the main goals of the mentioned study. Reference [12] presents a novel uncertain approach to model the expansion planning of distribution networks with the aim of emission and cost minimization. Since the problem contains many variables and constraints, a harmony search algorithm is used to find the optimal solution. A hierarchical model for expansion planning of a combined heat and power system is presented and a three-stage iterative heuristic algorithm is utilized to deliberate different uncertainties [13]. An epsilon-constraint multi-objective multi-stage distribution expansion planning is proposed to deal with wind and solar power penetration and minimize the total cost [14]. Reference [15] suggests an expansion planning framework in the presence of wind energy high penetration to find optimal allocation and minimize wind energy curtailment. A multi-objective non-linear expansion planning is presented for integrated power system and electric vehicles (EVs) that attempts to minimize the investment costs and maximize exploitation of allocated charging stations [16]. Reference [17] considers multiple network management schemes for expansion planning of distribution network which minimizes investment costs and determine the optimal type, location, and size of infrastructures. A multi-objective stochastic expansion planning based on chance constraints for regionally integrated energy systems is suggested by [18]. This study considers cross-correlation and auto-correlation to minimize investment costs and energy risk. A novel mixed-integer non-linear expansion planning of distribution network is proposed to find the optimal generation expansion and minimize total costs [19]. Reference [20] designs several strategies for motivating distribution companies to develop the flexibility of their systems by considering the installation of conventional distributed generations (DGs), electrical energy storage (EES) systems and demand response programs (DRPs). Reference [21] presents a distribution network expansion planning incorporating renewable resources, energy storage, and charging stations based on adaptive robust optimization which models the uncertainty in the short-term and long-term intervals. An expansion planning of distribution network composed of electricity and heat components is formulated to enhance the supply capacity and decrease pollution [22]. Reference [23] compares distribution network expansion by utilizing new lines and electrolyzers where the results show that new lines are more cost-effective. A probabilistic expansion planning of a combined distribution network with natural gas and energy hub is modeled to minimize total cost and allocate optimal location, size, and type of infrastructures [24]. A two-stage robust expansion planning is presented to specify the optimal location, type, and size of components in [25]. Reference [26] introduces an innovative stochastic expansion planning with high penetration of renewable resources to determine the location, type, and size of sources. A multi-stage convex expansion planning for distribution network with the goal of minimizing power system pollution by a financial method and sizing and siting of renewable resources [27].

As mentioned earlier, achieving a zero energy structure should be one of the main goals of the energy systems expansion due to global warming and environmental issues [28]. Reference [29] presents a two-stage stochastic integer expansion model to manage the carbon dioxide and optimize the operation cost incorporating load and wind uncertainties. A linearized AC power flow is formulated to specify the optimal capacity, operation, cost and emission [30]. Reference [31] considers renewable resources uncertainty and proposes a linear expansion planning for coordinated generation and transmission networks. This model reduces carbon emission by utilizing several policies and analyzing their effects. Similarly, reference [32] proposes a linear expansion planning for coordinated generation and transmission networks to reduce carbon emission by using renewable resources. A novel transmission expansion planning based on a new emission index is introduced to demonstrate the reaction and relation between transmission expansion planning and carbon emission [33]. A mixed-integer non-linear expansion planning is presented to minimize operation cost, emission penalty, and unreliability cost [34]. In this study, different scenarios are designed to evaluate the efficiency as well as decision analysis is used to tackle market uncertainties. Furthermore, a coordinated method is proposed to consider interactions between building and energy system design and obtain a zero energy structure [35].

1.3. Paper contribution

The expansion planning of electrical energy systems has been investigated from different points of view. However, there are still various problems that are not considered comprehensively, as explained below:

- Many researchers only have focused on fuel-based generators and transmission line expansion and the environmental pollution problem is neglected.
- In several studies, renewable resources are used to expand the system, however, they usually consider one type of resources and their uncertainty is not modeled accurately.
- The effect of EES system expansion in the presence of renewable resources high penetration is not analyzed.
- The simultaneous impact of crypto-currency miners and responsive loads is not evaluated in the previous studies.
- Most of the expansion planning problems have a single-stage process that is not acceptable due limitation of staff and yearly funds.

Hence, this paper aims to expand RES and EES units in distribution systems based on a multi-stage process to achieve a zero energy structure with the minimum investment cost. The main novelties and contributions of this research can be summarized as follows:

- Expansion planning of RES and EES systems in distribution grids based on zero energy concept.
- Proposing a multi-stage multi-objective linear programming composed of investment cost and environmental pollution functions.
- Considering the impact of crypto-currency miners and implementing an incentive-based DRP.

- Modeling the uncertainty of renewable resources by a scenario generation/reduction approach.

The paper structure is divided into several subsections as follows: Mathematical formulation of expansion planning is presented in Section 2. Section 3 is assigned to the modeling of crypto-currency miners and Sections 4 and 5 are dedicated to the DRP and multi-stage programming. The uncertainty of renewable resources is modeled in Section 6 and the test system introduction and primary data is introduced in Section 7. Eventually, simulation results and conclusions are proposed in Sections 8 and 9, respectively.

2. Problem formulation

2.1. Objective functions

To model the presented multi-objective expansion planning, the cost (1) and pollution (2) are considered as objective functions. The first and second terms of (1) are the transferred power from/to the main grid and the next three terms indicate the investment and operation costs of WT, PV and EES, respectively. The investment cost due to installing new power lines is determined by the sixth term and eventually, the amount of obtained revenue by responsive loads is specified by the last term. Moreover, the produced pollution by the main grid caused by exporting power to the distribution system is formulated in (2).

$$F_1(s) = TC_{Buy}(s) - TC_{Sell}(s) + TC_{WT}(s) + TC_{PV}(s) + TC_{EES}(s) + TC_{Line}(s) + TC_{DRP}(s) \qquad (1)$$

$$F_2(s) = TEM_{MG}(s) \qquad (2)$$

Since the solving process of a multi-objective programming is time-consumed, the cost and pollution functions can be integrated into a single-objective function. In this regard, the multi-objective problem is converted to a single-objective type by inserting (2) in (1) as the environmental pollution penalty cost (3).

$$\begin{aligned} F_1(s) = {} & TC_{Buy}(s) - TC_{Sell}(s) + TC_{WT}(s) + \\ & TC_{PV}(s) + TC_{EES}(s) + TC_{Line}(s) + TC_{DRP}(s) + TC_{EP}(s) \end{aligned} \tag{3}$$

The cost of buying and selling power is modeled by (4) and (5) and the operation and investment costs of WT, PV and EES are determined by the first and second terms of (6)-(8), respectively. The investment cost of new power lines can be also calculated by (9) and the pollution penalty cost is specified by (10).

$$TC_{Buy}(s) = \sum_{y,se,t} P_{Buy}(s,y,se,t) \times C_{Buy}(s,y,se,t) \times \theta \tag{4}$$

$$TC_{Sell}(s) = \sum_{y,se,t} P_{Sell}(s,y,se,t) \times C_{Sell}(s,y,se,t) \times \theta \tag{5}$$

$$TC_{WT}(s) = \sum_{i,y,se,t} P_{WT}(s,i,y,se,t) \times OC_{WT} \times \theta + \sum_{i} N_{WT}(s,i) \times IC_{WT} \tag{6}$$

$$TC_{PV}(s) = \sum_{i,y,se,t} P_{PV}(s,i,y,se,t) \times OC_{PV} \times \theta + \sum_{i} N_{PV}(s,i) \times IC_{PV} \tag{7}$$

$$TC_{EES}(s) = \sum_{i,y,s,t} (P_{dch}(s,i,y,s,t) + P_{ch}(s,i,y,se,t)) \times OC_{EES} \times \theta + \sum_{i} N_{EES}(s,i) \times IC_{EES} \tag{8}$$

$$TC_{Line}(s) = \sum_{i} N_{Line}(s,i) \times IC_{Line} \tag{9}$$

$$TC_{EP}(s) = \sum_{y,se,t} P_{Buy}(s,y,se,t) \times EF_{MG} \times C_{EP}(y) \times \theta \tag{10}$$

Furthermore, the revenue of flexible and curtailable loads due to participating in DRP is stated by (11).

$$TC_{DRP}(s) = \sum_{i,y,se,t} \left[L_C(s,i,y,se,t) \times C_C + L_F(s,i,y,se,t) \times C_F \right] \tag{11}$$

2.2. Operation of components

2.2.1. Wind turbine and photovoltaic units

As the power of WT and PV depends on climate changes such as variation of wind speed and solar radiation, their operation is restricted by time and season coefficients to achieve real conditions, as modeled by (12) and (13) [36].

$$0 \le P_{WT}(s,i,y,se,t) \le P_{WT}^{n}(s,i,y,se,t) \times \omega_{WT}(se) \times \mu_{WT}(t) \tag{12}$$

$$0 \le P_{PV}(s,i,y,se,t) \le P_{PV}^{n}(s,i,y,se,t) \times \omega_{PV}(se) \times \mu_{PV}(t) \tag{13}$$

2.2.2. Electrical energy storage system

The energy storage units can enhance the flexibility of system especially in the presence of renewable resources. The operation of such components is modeled through (14)-(19). In this regard, the storage state of charge (SoC) is determined in (14) and its final value is limited by (15) to increase the storage lifetime. The limitations of SoC and charging/discharging power are specified by (16)-(18), respectively. Furthermore, (19) confirms that the storage can only be in charge or discharge state [3].

$$\mathrm{SoC}(s,i,y,se,t) = \mathrm{SoC}(s,i,y,se,t-1) + (P_{ch}(s,i,y,se,t) \times \eta^{ch} - P_{dch}(s,i,y,se,t) / \eta^{dch}) \tag{14}$$

$$\mathrm{SoC}(s,i,y,se,t_n) = \mathrm{SoC}(s,i,y,se,1) \tag{15}$$

$$\mathrm{SoC}(s,i,y,se,1) \le \mathrm{SoC}(s,i,y,se,t) \le \alpha \times \mathrm{SoC}^{max} \tag{16}$$

$$P_{ch}^{min} \times b_{ch}(s,i,y,se,t) \le P_{ch}(s,i,y,se,t) \le P_{ch}^{max} \times b_{ch}(s,i,y,se,t) \tag{17}$$

$$P_{dch}^{min} \times b_{dch}(s,i,y,se,t) \le P_{dch}(s,i,y,se,t) \le P_{dch}^{max} \times b_{dch}(s,i,y,se,t) \tag{18}$$

$$b_{dch}(s,i,y,se,t) + b_{ch}(s,i,y,se,t) \le 1 \tag{19}$$

2.3. Problem constraints

To achieve an optimal solution, technical and economical constraints should be considered. Hence, (20)-(23) specify the power balance, power flow, angle of buses and injected power into the lines, respectively [8].

$$\begin{aligned} &\mathrm{TL}(s,i,y,se,t)+P_{ch}(s,i,y,se,t)+\sum_{j}P(s,i,j,y,se,t)= \\ &\qquad P_{Buy}(s,y,se,t)+P_{Sell}(s,y,se,t)+P_{WT}(s,i,y,se,t)+P_{PV}(s,i,y,se,t)+P_{dch}(s,i,y,se,t) \end{aligned} \tag{20}$$

$$P(s,i,j,y,se,t)=B(i,j)\times\left[\delta(s,i,y,se,t)-\delta(s,j,y,se,t)\right] \tag{21}$$

$$\delta^{\min}\le\delta(s,i,y,se,t)\le\delta^{\max} \tag{22}$$

$$PL^{\min}\le P(s,i,j,y,se,t)\le PL^{\max} \tag{23}$$

The limitation of imported and exported power from/to the main grid is determined by (24) and (25) as well as (26) confirms that the local system can only buy or sell power in each time interval.

$$0\le P_{Buy}(s,i,y,se,t)\le b_{Buy}(s,i,y,se,t)\times {P_{Buy}}^{\max} \tag{24}$$

$$0\le P_{Sell}(s,i,y,se,t)\le b_{Sell}(s,i,y,se,t)\times {P_{Sell}}^{\max} \tag{25}$$

$$b_{Sell}(s,i,y,se,t)+b_{Buy}(s,i,y,se,t)\le 1 \tag{26}$$

The constraints (27)-(32) indicate the limitation of each bus for new components and the maximum number of WT, PV and EES, respectively.

$$N_{WT}(i)\le N_{WT-i}^{\max} \tag{27}$$

$$\sum_{i}N_{WT}(i)\le N_{WT}^{\max} \tag{28}$$

$$N_{PV}(i)\le N_{PV-i}^{\max} \tag{29}$$

$$\sum_{i}N_{PV}(i)\le N_{PV}^{\max} \tag{30}$$

$$N_{EES}(i) \le N_{EES-i}^{max} \tag{31}$$

$$\sum_{i} N_{EES}(i) \le N_{EES}^{max} \tag{32}$$

The limitation of new lines between two buses and the maximum number of installed lines are determined by (33) and (34).

$$N_{Line}(i,j) \le N_{Line-ij}^{max} \tag{33}$$

$$\sum_{i,j} N_{Line}(i,j) \le N_{Line}^{max} \tag{34}$$

3. Crypto-currency miners

The crypto-currency miners are a new type of electrical load that can affect the normal operation of the system. The report of international energy agency (IEA) shows the rapid penetration of miners in distribution systems. In this regard, the consumption of bitcoin miners as a special miner load is about 2% of total grid demand [37, 38]. Since miner loads have a constant consumption during whole planning time, it is possible to model the consumption of miners as a percentage of base load. In this regard, crypto-currency miners are modeled by (35).

$$L_M(s,i,y,se,t) = \gamma(i) \times L_B(s,i,y,se,t) \tag{35}$$

4. Demand response program

In this paper, an incentive-based DRP is implemented to enhance operation flexibility. In such modeling, the total load can be divided into three sections including base, flexible and curtailable loads (36). The flexible load refers to a load that can be transferred from one time to another time such that the summation of total shifted and added loads should remain constant (37). The limitation of shifted and added loads is presented in (38) and (39), respectively. As well, the curtailable load refers to a load that can be curtailed directly with a limitation (40).

$$\mathrm{TL}(s,i,y,se,t)=\mathrm{L_B}(s,i,y,se,t)+\mathrm{L_F}(s,i,y,se,t)+\mathrm{L_C}(s,i,y,se,t) \tag{36}$$

$$\sum_{i,y,se}\left[\mathrm{L_{F+}}(s,i,y,se,t)+\mathrm{L_{F-}}(s,i,y,se,t)\right]=0 \tag{37}$$

$$-\lambda\times\mathrm{TL}(s,i,y,se,t)\le\mathrm{L_{F-}}(s,i,y,se,t)\le 0 \tag{38}$$

$$0\le\mathrm{L_{F+}}(s,i,y,se,t)\le\lambda\times\mathrm{TL}(s,i,y,se,t) \tag{39}$$

$$-\beta\times\sum_{i,y,se}\mathrm{TL}(s,i,y,se,t)\le\sum_{i,y,se}\mathrm{L_C}(s,i,y,se,t)\le 0 \tag{40}$$

5. Multi-stage scheduling

Due to the unavailability of the funds at the start of long-term expansion planning and according to the limitation of staff and equipment, a single-stage optimization is not acceptable for long-term scheduling. In this regard, a multi-stage approach can be used to simulate a realistic condition with considering various limitations. Such a process is illustrated in Fig. 1 and explained as follows:

- First of all, the number of stages is determined which is equal to the number of years. Then, the number of installed components in each stage is limited by (41) and (42).

$$\rho_{\mathrm{Stage}}=\frac{1}{\mathrm{N_{Stage}}} \tag{41}$$

$$\mathrm{N_{Stage}^{max}}=\rho_{\mathrm{Stage}}\times\mathrm{N^{max}} \tag{42}$$

- The objective functions are optimized and the allocation of components is stored for the first stage.

- In the second stage, the optimization is restricted by the results of the previous step. Indeed, the specified location and sizing of components in the previous stage should remain constant in the new stage.
- Such a process continues until the last stage of planning.

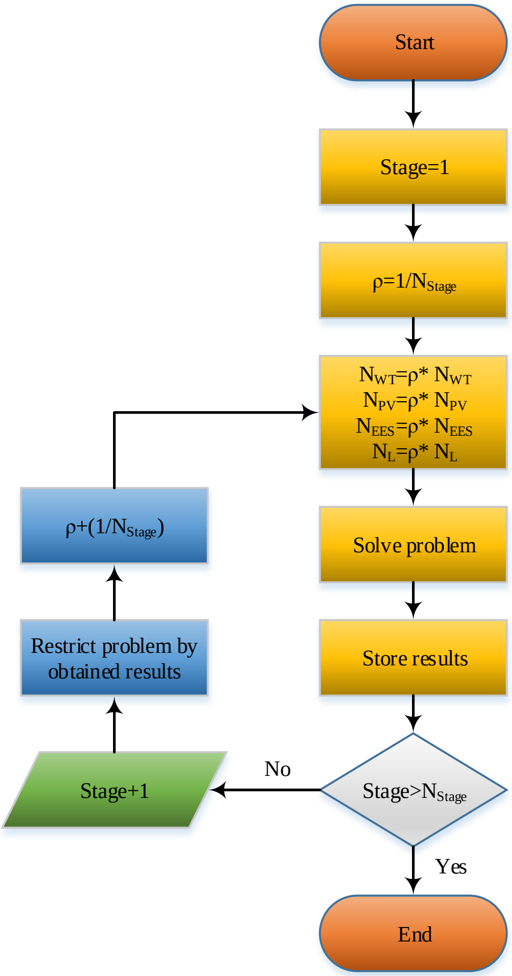

Fig. 1. The process of implementing multi-stage long-term planning.

6. Renewable resources uncertainty

According to the system structure, renewable resources uncertainty have a high impact on the operation. In this regard, a scenario generation/reduction method is applied to model the uncertainties of RES. In the first step, 1000 scenarios are randomly created with a probability distribution function (PDF) and standard deviation between 0%-20%, as illustrated in Fig. 1. Since scenarios with critical conditions such as reducing power generation are more important for the operator, all scenarios are sorted from the mentioned point of view. Then, a random matrix is generated with the summation equal to 100% and sorted from the higher probability to the lower one and eventually, twenty upper scenarios are selected and the expected value is specified for each variable (43).

$$\mathrm{EXV}(x) = \sum_{s} \Pr ob(s) \times x(s) \tag{43}$$

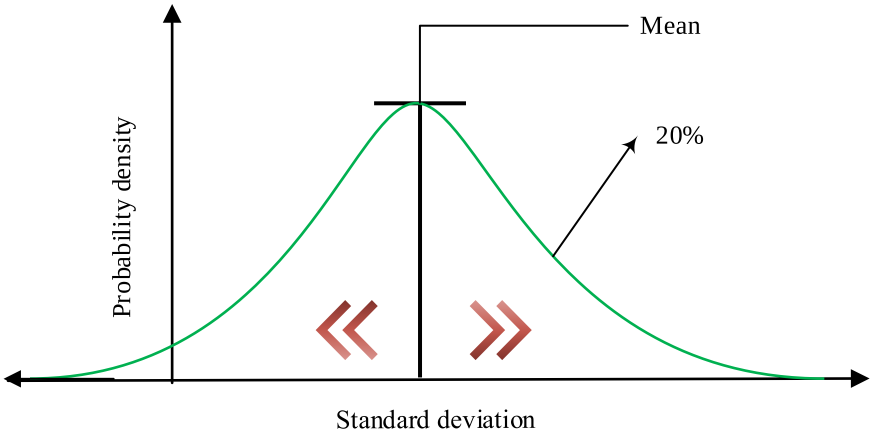

Fig. 2. Probability distribution function for wind and solar powers.

7. Test system introduction and primary data

To analyze the presented method, simulations are implemented on the IEEE 33-bus distribution system, as illustrated in Fig. 3. The data for the mentioned grid such as load consumption and line specifications are deduced from [39, 40]. Moreover, the availability of PVs and WTs in each season and hour is depicted in Fig. 4. As well, the base value of energy cost and the amount of pollution penalty cost are illustrated in Fig. 5, the growth indices for load, pollution penalty and energy cost are presented in Table 1, and the investment costs and components specifications are proposed in Table 2. The emission factor of the main grid is

724 kg/MWh, penetration of crypto-currency miners is 20%, the indices of flexible and curtailable loads are equal to 20% and 10% and their obtained revenue for participating in DRP is equal to 10% and 50% of energy buying cost from the main grid, respectively. Due to the limitation of area, the maximum possible rating of each component to be installed on each bus is equal to 4 MW. Furthermore, only five new lines can be installed between two buses after the final stage. The expansion planning is considered for ten years that is divided into four seasons and a sample day is selected to determine the system operation.

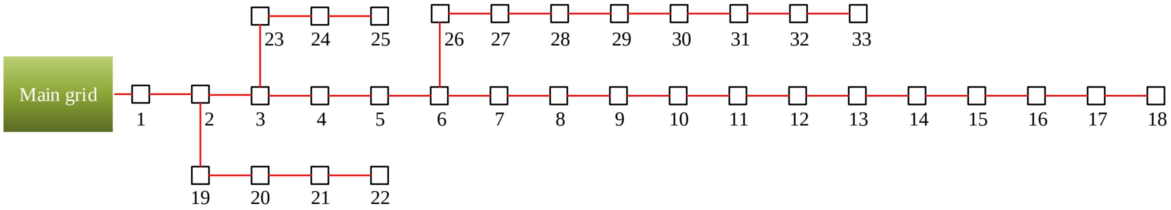

Fig. 3. The structure of under study test system for the long-term planning.

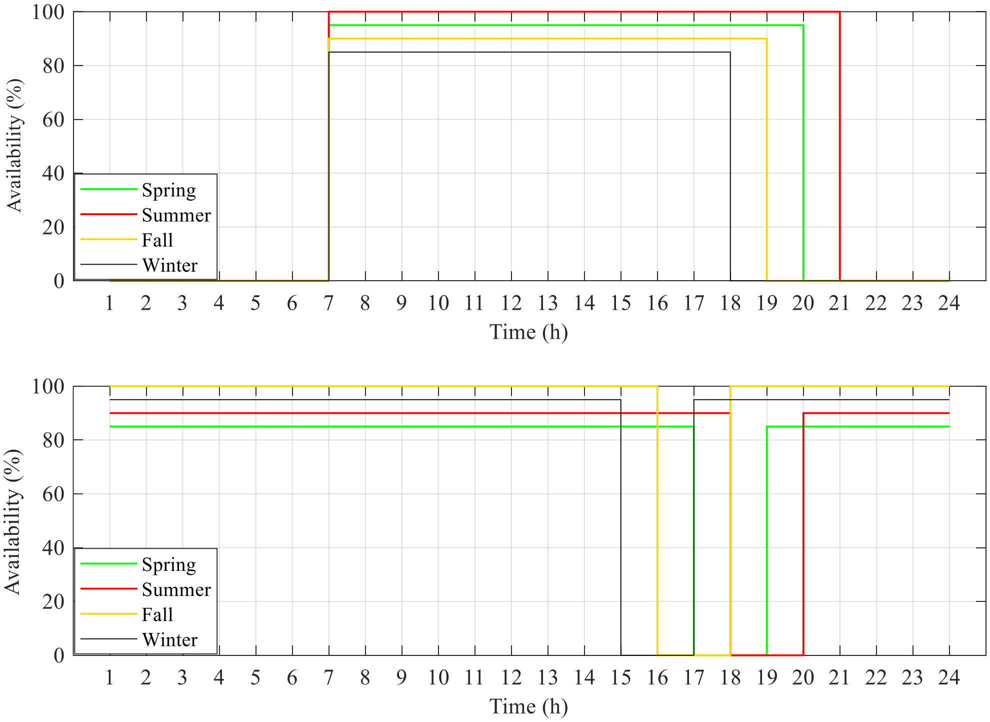

Fig. 4. Availability of PVs and WTs in each season and hour.

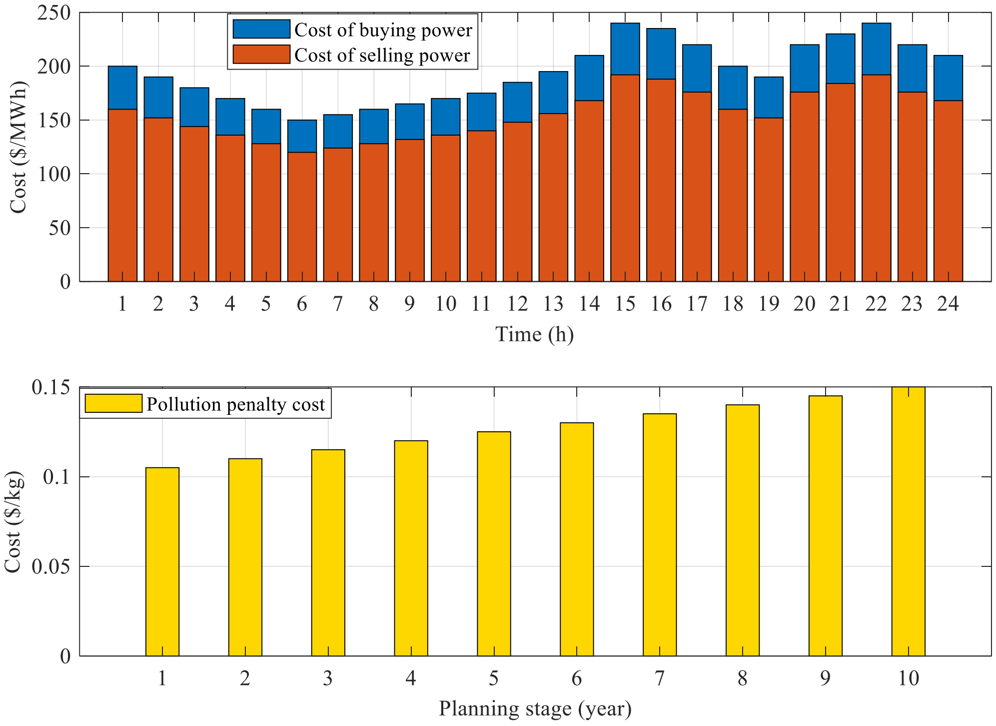

Fig. 5. The base value of energy cost for 24-hour and amount of pollution penalty cost [41, 42].

Table 1. Different growth indices for load, pollution penalty and energy cost.

Parameter	Year	Season			
		Spring	Summer	Fall	Winter
Load growth index	20%	1	1.1	1.05	0.95
Pollution penalty growth index	5%	-	-	-	-
Energy cost growth index	1%	1	1.1	1.05	0.95

Table 2. Amount of investment cost and components specifications [3, 8, 43]

Parameter	Value	Parameter	Value
Base power (MW)	100	PV investment cost ($/kW)	500
Line investment cost ($/km)	40000	WT investment cost ($/kW)	500
EES investment cost ($/kW)	100	Charge efficiency	0.95
Max rating of ESS (MW)	20	Discharge efficiency	0.9
Max rating of PV (MW)	20	Max rating of WT (MW)	20
EES operation cost ($/MWh)	1	PV operation cost ($/MWh)	3
WT operation cost ($/MWh)	5	Min possible rating (MW)	0.1

8. Simulation results

The simulation results are analyzed in three scenarios. In the first scenario, the expansion of renewable resources and storage systems is performed. Afterward, the impact of crypto-currency miners and responsive loads are evaluated. In the final scenario, the influence of renewable resources uncertainty is investigated.

8.1. Expansion of renewable resources and storage systems

In this section, the results for the long-term planning of renewable resources and storage systems are analyzed. Thereupon, three scenarios are designed including base system long-term planning, renewable resources expansion, and storage expansion. In the first scenario, it is assumed that all the required power is imported from the main grid and only the transfer lines can be expanded. As illustrated in Figs. 6 and 7, the cost of system is increased significantly during the last intervals due to the load growth and a huge amount of pollution penalty is imposed to the local system. Hence, the total planning cost for ten years of base system is equal to 2.2E+8 $ where about 6.74E+7 $ and 1.52E+8 $ are paid as the pollution penalty and the cost of imported power from the main grid. According to Table 3, two lines with the total cost equal to 80000 $ are also required to be installed in the 5th and 6th years between buses 1-2 and 2-3, respectively. In the second scenario, the expansion of renewable resources is done without storage systems. As seen, despite installing renewable resources in the first three years, about 1.11E+7 $ is paid by the operator due to insufficient capacity of renewable resources. In the mentioned years, the imported and exported powers are equal to about 322 MW and 283 MW, respectively. In the fourth year, the amount of renewable resources rating is increased sufficiently where the amount of total cost is reduced notably and even a revenue about 2.47E+6 is achieved. The amount of revenue from fifth year is increased and the imported power and penalty cost are reduced to zero. In fact, after the fourth year, the system operates independently from the main grid such that the revenue grows in the tenth year and achieves to 1.91E+7 $. It is noteworthy that two lines between buses 1-2 and 2-3 and one line between buses 1-2 should be installed in the 1st and 8th years, respectively. In the final scenario, the electrical storage systems are also added to evaluate their application. The results in Tables 4 and 5 show the location and rating of new installed components with considering the multi-stage process for the last scenario. As evident, the rating of components is increased in each stage and achieved to its maximum capacity until the last interval. The highest rating of WTs, PVs and EESs is installed on buses 1 and 2 where the main reason of this case is the higher capacity of the network primary lines. In order to support power transferring, two lines are installed between buses 1-2 and 2-3 in the 1st year and two lines are located between buses 1-2 in the 8th and 9th years, respectively. According to Figs. 6 and 7, the amount of imported power in the presence of storage systems is reduced to zero in the fourth year and a revenue equal to about 1.92E+7 $ is obtained in the last year. However, the exported power is reduced slightly due to charging and discharging of electrical storages, as illustrated in Fig. 8. It should be noted that the whole power generation of renewable resources for the second and third scenarios is constant and depicted in Fig. 9 for different conditions.

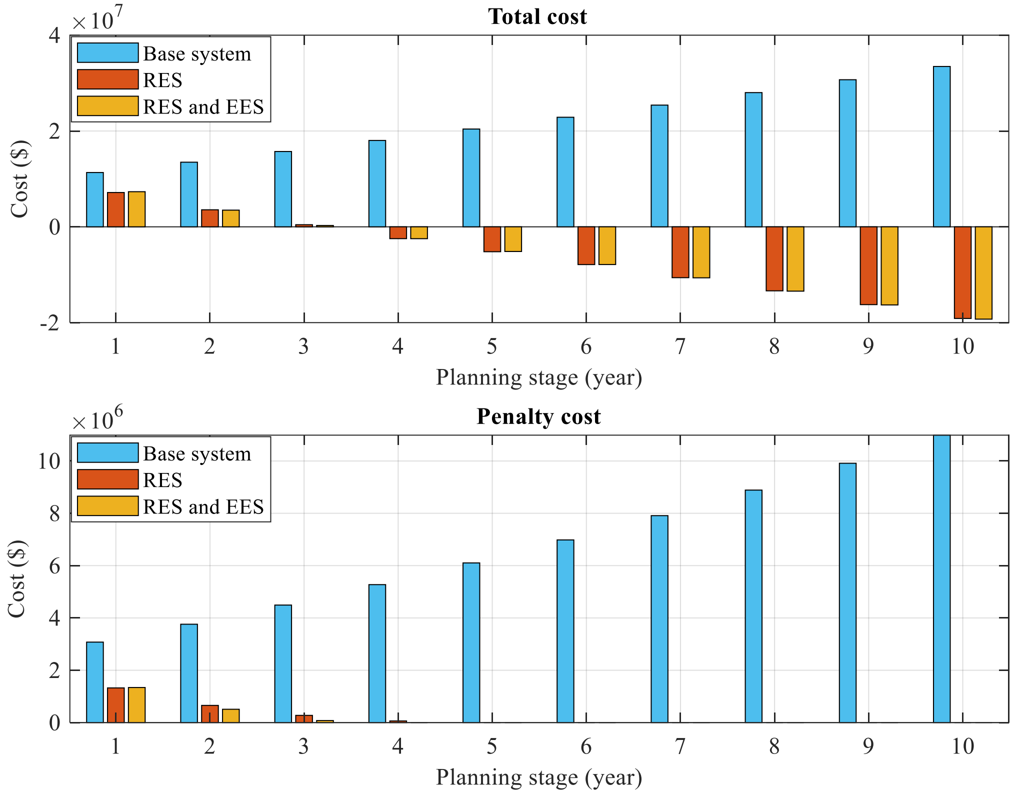

Fig. 6. Total cost and amount of pollution penalty for different scenarios.

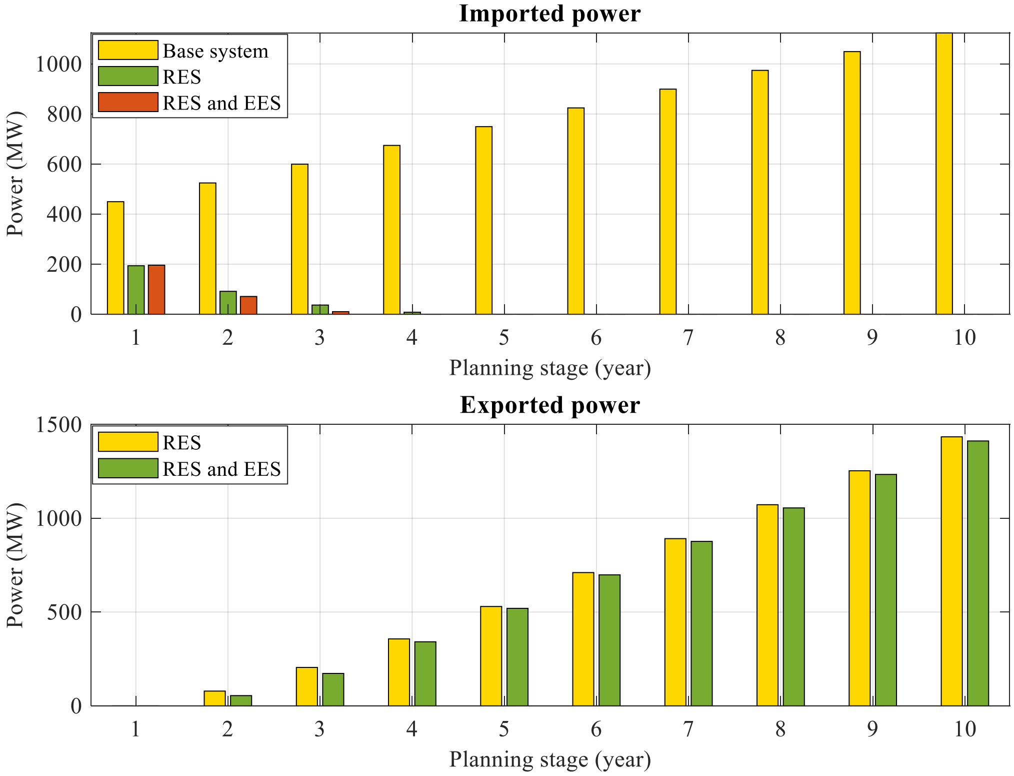

Fig. 7. Amount of imported and exported power for different scenarios.

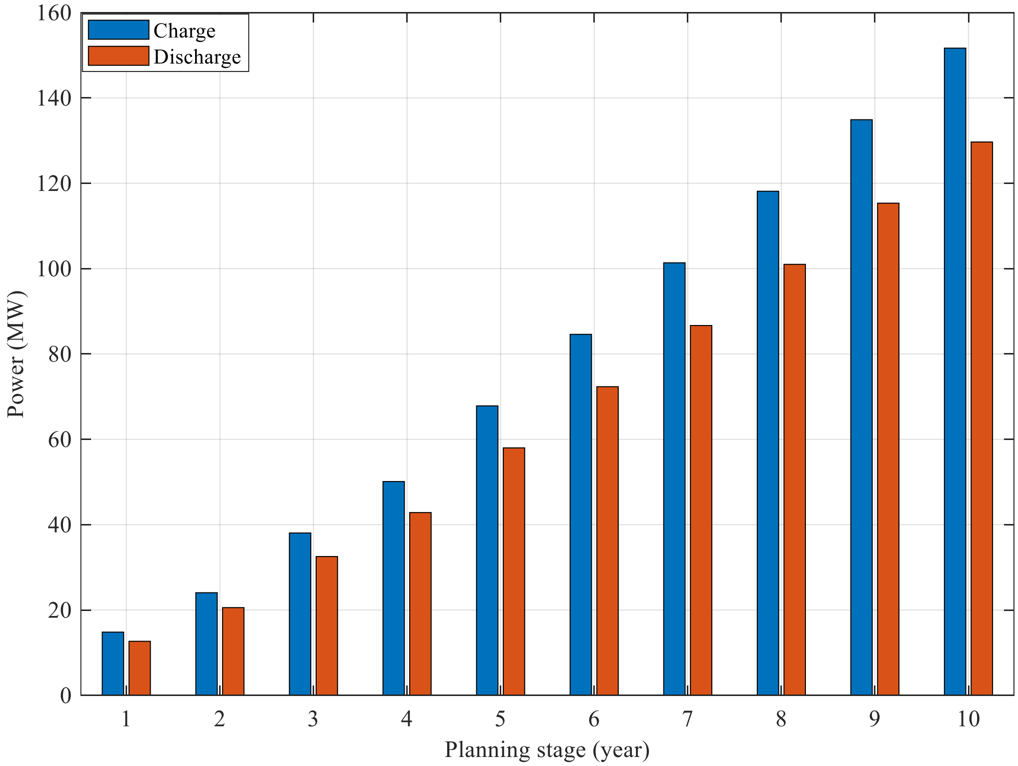

Fig. 8. Charging and discharging of electrical energy storage during long-term expansion.

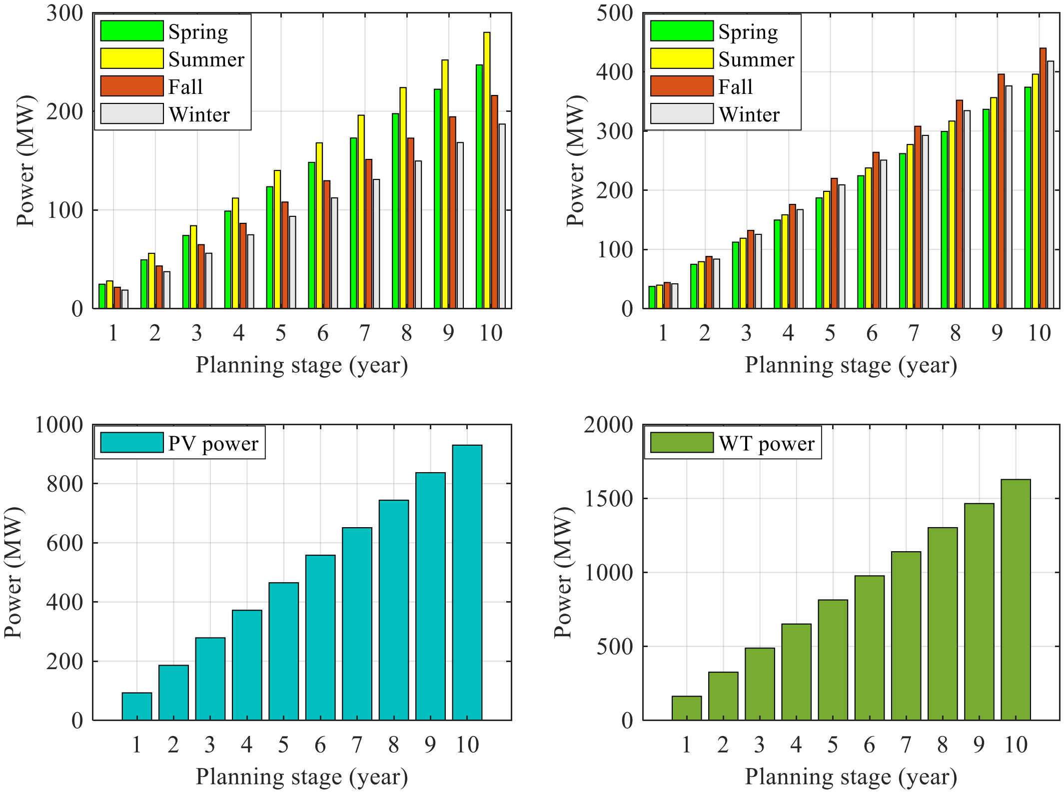

Fig. 9. Total power generation of renewable resources in each season and year.

Table 3. Line expansion during long-term planning with considering different scenarios.

Scenario	Line	Number	Stage	Investment cost ($)
Base system	1-2	1	5	40000
	2-3	1	6	40000
Considering RES expansion	1-2	1	1	80000
	2-3	1		
	1-2	1	8	40000
Considering RES and EES expansion	1-2	1	1	80000
	2-3	1		
	1-2	1	8	40000
	1-2	1	9	40000

Table 4. Location and rating of WTs and PVs with considering storage systems.

Stage	Location (bus) and rating (MW)																	
	1		2		3		4	9	10	11	18		19		23		33	
	WT	PV	WT	PV	WT	PV	PV	PV	WT	PV	WT	PV	WT	PV	WT	PV	WT	PV
1	0	0	0	0	0	0	0	1.8	0	0	1.2	0	0	0	0	0	0.8	0.2
2	0	0	0	0	0	0	0	3.4	1.8	0	1.2	0	0	0	0	0	1	0.6
3	0	0	0	0	2	0	0	3.4	1.8	0	1.2	0	0	2	0	0	1	0.6
4	0	2	0	0	4	0	0	3.4	1.8	0	1.2	0	0	2	0	0	1	0.6
5	0	2.1	2	0	4	0.1	0	3.4	1.8	0	1.2	0	0	3.6	0	0.2	1	0.6
6	2	3.9	2	0	4	0.1	0	3.4	1.8	0.1	1.2	0	0	3.6	0	0.2	1	0.7
7	4	4	2	0	4	0.5	1.3	3.4	1.8	0.1	1.2	0.1	0	3.7	0	0.2	1	0.7
8	4	4	2.2	0	4	0.5	1.3	3.4	1.8	0.1	1.2	0.1	0	3.7	1.8	2.2	1	0.7
9	4	4	4	2	4	0.5	1.3	3.4	1.8	0.1	1.2	0.1	0	3.7	2	2.2	1	0.7
10	4	4	4	4	4	0.5	1.3	3.4	1.8	0.1	1.3	0.1	0.2	3.7	3.6	2.2	1.1	0.7

Table 5. Location and rating of EESs with considering renewable resources.

Stage	Location (bus) and rating (MW)												
	1	2	3	4	9	11	14	18	20	22	23	25	31
1	0	0	0	0	1.8	0	0.1	0	0	0	0	0.1	0
2	0	0	0	2	1.8	0	0.1	0	0	0	0	0.1	0
3	0.1	0.1	0	2	1.8	0	0.1	0.1	0	0	0.1	0.1	1.6
4	0.1	0.1	0	2	1.8	0	0.1	0.3	0	1.8	0.1	0.1	1.6
5	1.8	0.2	0.1	2	1.8	0	0.1	0.3	0.1	1.8	0.1	0.1	1.6
6	3.8	0.2	0.1	2	1.8	0	0.1	0.3	0.1	1.8	0.1	0.1	1.6
7	3.9	0.2	0.1	2	1.8	0	0.1	1.2	0.1	2.8	0.1	0.1	1.6
8	4	2.1	0.1	2	1.8	0	0.1	1.2	0.1	2.8	0.1	0.1	1.6
9	4	2.5	0.1	2	1.8	0	0.1	1.2	0.1	2.8	0.1	1.7	1.6
10	4	3.9	0.6	2	1.8	0.1	0.1	1.2	0.1	2.8	0.1	1.7	1.6

6.2. Impact of miner loads and DRP

The advent of miner loads has changed the system operation due to a significant increase in electrical demand. On the other side, responsive loads can mitigate the impact of miner loads and achieve an acceptable objective function. In this section, the expansion planning of renewable resources and storage systems is optimized with considering miner loads and DRP. Tables 6-8 present the expansion of renewable resources and energy storage systems where buses 1-3 have the highest rating. The results in Fig. 10 show the objective function for various conditions. As evident, due to increasing the required power by the miner loads, the total cost of system and the penalty cost are increased. According to Fig. 11, the imported power in the first three years has a notable growth as well as the exported power is decreased simultaneously. In return, responsive loads have improved the system performance even with considering miner loads. In this regard, the presented DRP decreases the total cost and pollution penalty compared to the previous scenarios and the total revenue is increased, too. The main reasons of such a case are reducing the imported power in the first three years and increasing the exported power from the second year. Fig. 12 shows that the load profile has changed with considering DRP where a huge amount of load in the 1st, 14th-24th intervals is moved to other times to improve the system flexibility. Thereupon, a revenue is paid to the flexible and curtailable loads due to participating in DRP, as depicted in Fig. 13. As illustrated in Fig. 14, in most of time intervals, the storage systems are charged less than other scenarios in the presence of miner loads. However, the storage expansion is started from the second year considering the DRP where such results approve that the investment of energy storage system is delayed. The results in Table 6 validate that three lines are required to be installed between buses 1-2 and 2-3 with considering miner loads, in return, implementing DRP beside miner loads needs six new lines.

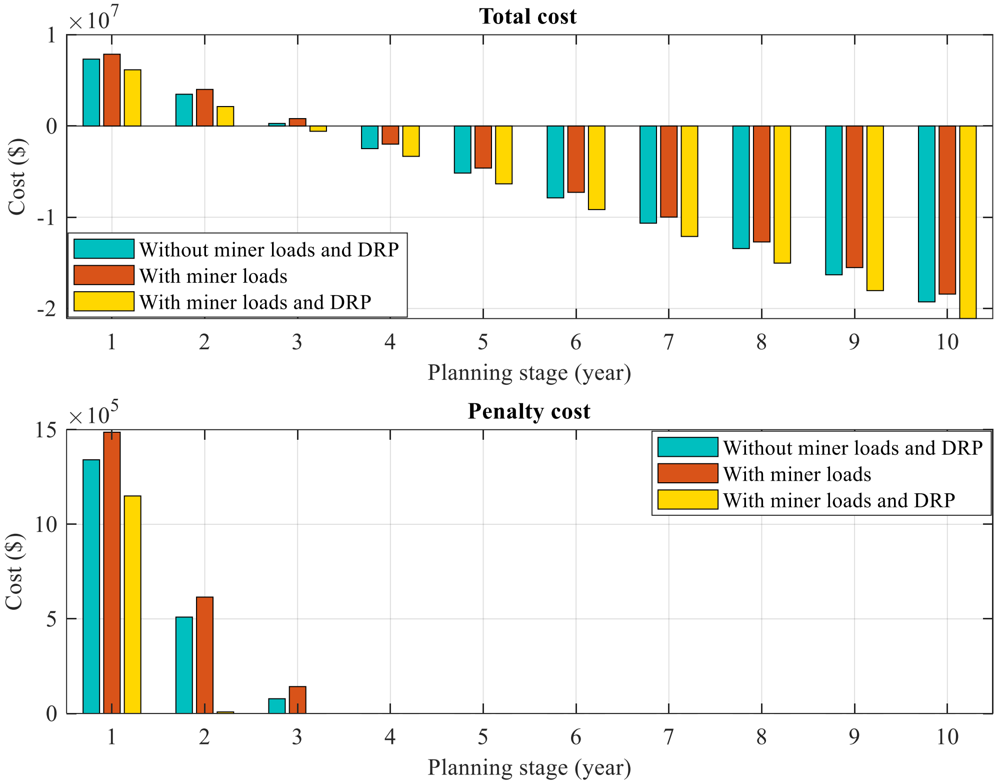

Fig. 10. Total cost and amount of pollution penalty with considering miner loads and DRP.

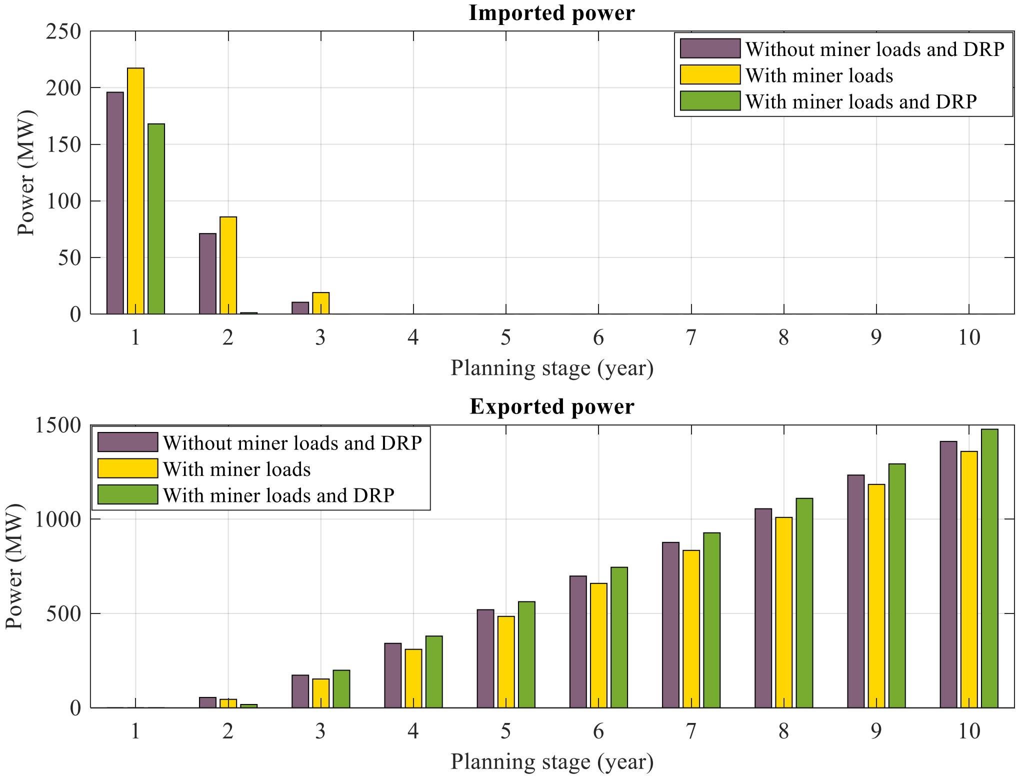

Fig. 11. Amount of imported and exported power with considering miner loads and DRP.

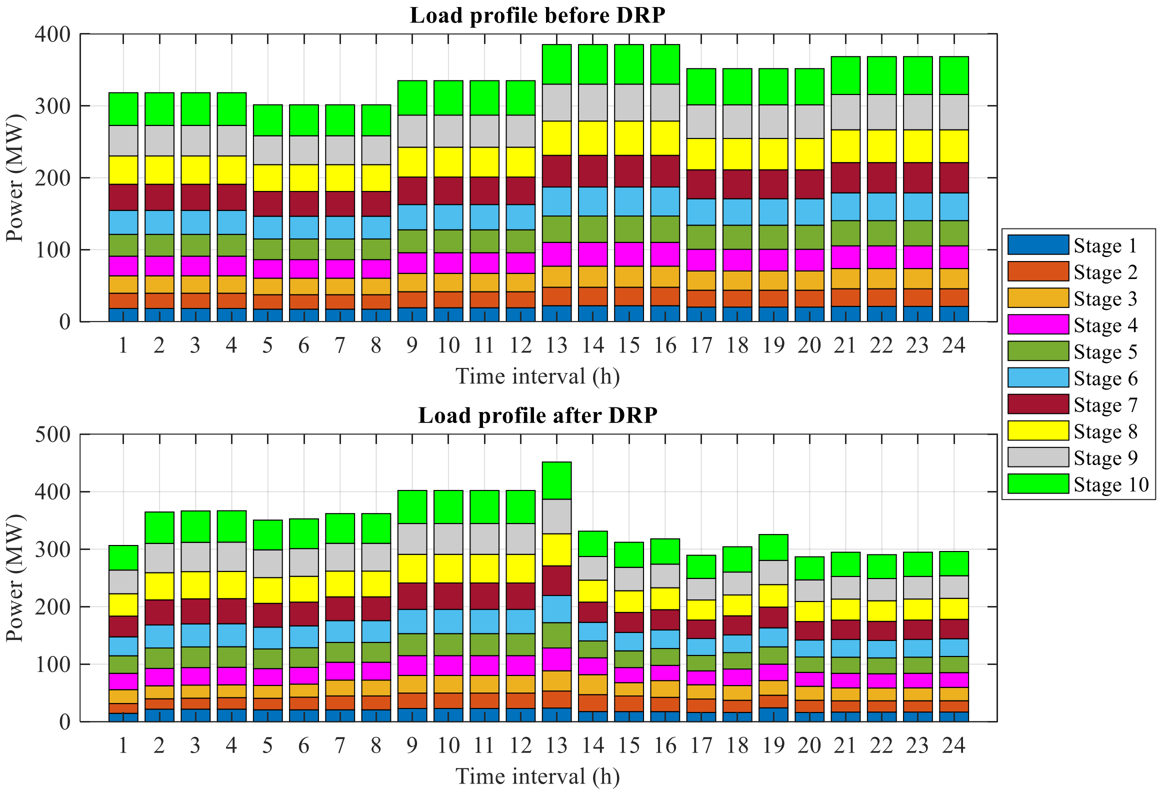

Fig. 12. Variation of load profile with considering miner loads and DRP.

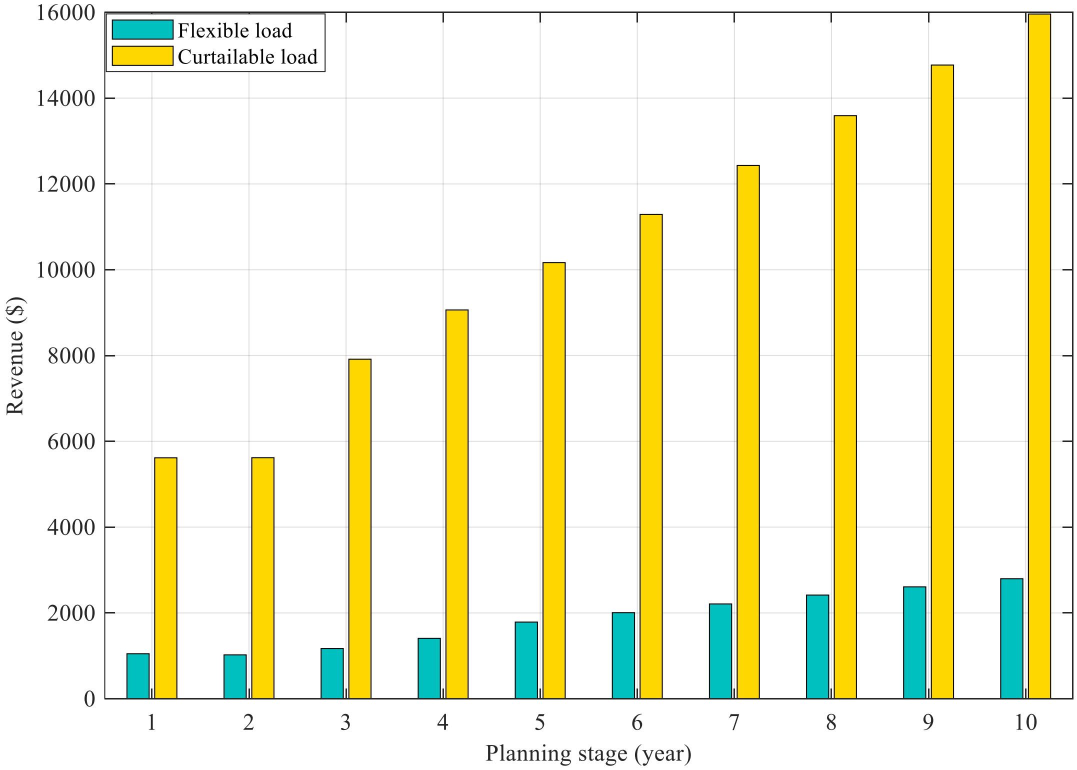

Fig. 13. Amount of obtained revenue by responsive loads due to participating in DRP.

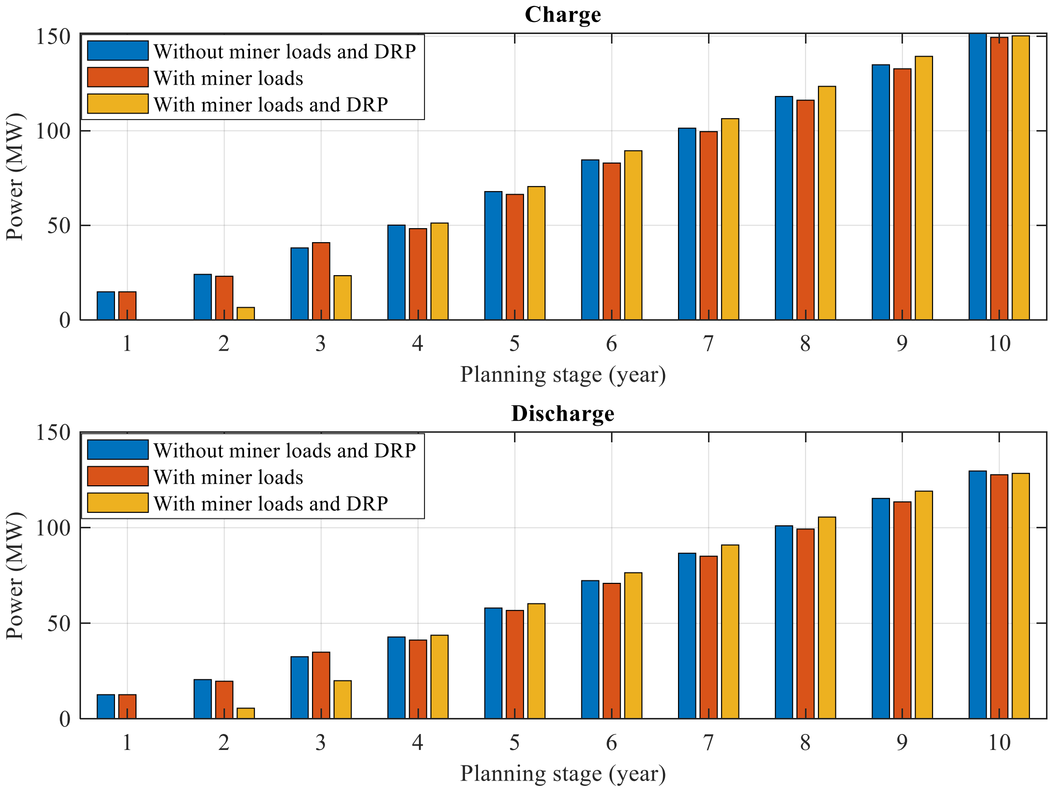

Fig. 14. Charging and discharging of electrical energy storage with considering miner loads and DRP.

Table 6. Line expansion with considering renewable resources, storage systems, miner loads and DRP.

Scenario	Line	Number	Stage	Investment cost ($)
Considering miner loads	1-2	1	1	80000
	2-3	1		
	1-2	1	8	40000
Considering miner loads and DRP	1-2	1	1	80000
	2-3	1		
	1-2	1	6	40000
	1-2	1	8	40000
	2-3	1	9	40000
	1-2	1	10	40000

Table 7. Location and rating of WTs and PVs with considering storage systems, miner loads and DRP.

Stage	Location (bus) and rating (MW)																			
	1		2		3		4	15	16	17	18	20	21	22		23		30	33	
	WT	PV	WT	PV	WT	PV	PV	WT	WT	P V	PV	PV	WT	WT	PV	WT	PV	WT	WT	PV
1	0	0	0	0	0	0	0	1.3	0	1.1	0	0	0	0	0	0	0.1	0	0.7	0.8
2	0	0	0	2	0	0	0	1.3	0.3	1.1	0	0	0	0	0	0	0.1	1.7	0.7	0.8
3	0	0	0	4	0	0	0	1.3	0.6	1.1	0	0	0	0	0	0	0.1	3.4	0.7	0.8
4	0	0	0	4	2	0	0	1.3	0.6	1.1	0	0	0	0	0	0	2.1	3.4	0.7	0.8
5	2	2	0	4	2	0	0	1.3	0.6	1.1	0	0	0	0	0	0	2.1	3.4	0.7	0.8
6	4	4	0	4	2	0	0	1.3	0.6	1.1	0	0	0	0	0	0	2.1	3.4	0.7	0.8
7	4	4	1.8	4	2	2	0	1.3	0.6	1.1	0	0	0.2	0	0	0	2.1	3.4	0.7	0.8
8	4	4	3.8	4	2	4	0	1.3	0.6	1.1	0	0	0.2	0	0	0	2.1	3.4	0.7	0.8
9	4	4	3.8	4	3.3	4	0	1.3	0.6	1.1	0	1.3	0.2	0.6	0	0.1	2.8	3.4	0.7	0.8
10	4	4	3.9	4	4	4	0.5	1.3	0.6	1.1	0.2	1.3	0.2	0.7	0.2	1.2	3.9	3.4	0.7	0.8

Table 8. Location and rating of EESs with considering renewable resources, miner loads and DRP.

Stage	Location (bus) and rating (MW)											
	1	2	3	7	9	16	19	22	25	27	32	33
1	0	0	0	0	0	0	0	0	0	0	0	0
2	1.1	0	0	0.1	0	0	0	0	0	0	0	0
3	3.6	0	0.1	0.1	0	0.1	0	0	0.1	0	0	0.1
4	3.6	0	0.1	0.1	0.1	0.1	3.8	0	0.1	0	0	0.1
5	4	0	0.1	0.1	1	0.1	3.9	0.6	0.1	0	0	0.1
6	4	0	0.1	0.1	1	0.1	3.9	0.6	2.1	0	0	0.1
7	4	1.9	0.1	0.1	1	0.1	3.9	0.6	2.1	0	0.1	0.1
8	4	3.9	0.1	0.1	1	0.1	3.9	0.6	2.1	0	0.1	0.1
9	4	4	2	0.1	1	0.1	3.9	0.6	2.1	0	0.1	0.1
10	4	4	3.9	0.1	1	0.1	3.9	0.6	2.1	0.1	0.1	0.1

6.3. Impact of renewable resources uncertainty

The high penetration of renewable resources increases the uncertainty of power systems and can affect the grid operation. In this regard, it is assumed that the availability of WTs and PVs is not constant during planning. As illustrated in Fig. 15, different scenarios are considered based on risk-averse strategy to model the uncertainty of renewable resources and enhance the robustness. In the presented risk-averse strategy, only scenarios that model the critical conditions (i.e., reducing availability) are used. The optimal location and rating of components are presented in Tables 9 and 10 where buses 1-3 for renewable resources and buses 1, 2 and 25 for electrical storage have the highest capacity. As well, the line expansion is similar to the deterministic state in the previous section. According to Fig. 16, the total generated power of renewable resources is reduced compared to the deterministic state. Such results approve that that the uncertainty increases the total cost and pollution penalty and reduces the revenue, however, the amounts of the mentioned variations are low due to positive effect of responsive loads, as depicted in Fig. 17. Moreover, Figs. 18 and 19 show that the transferred power is changed and energy storage charging state is reduced due to the uncertainty. It is worth mentioning that although the total cost of system is increased with considering uncertainty, the system robustness is increased about 7% against fluctuations of wind and solar power.

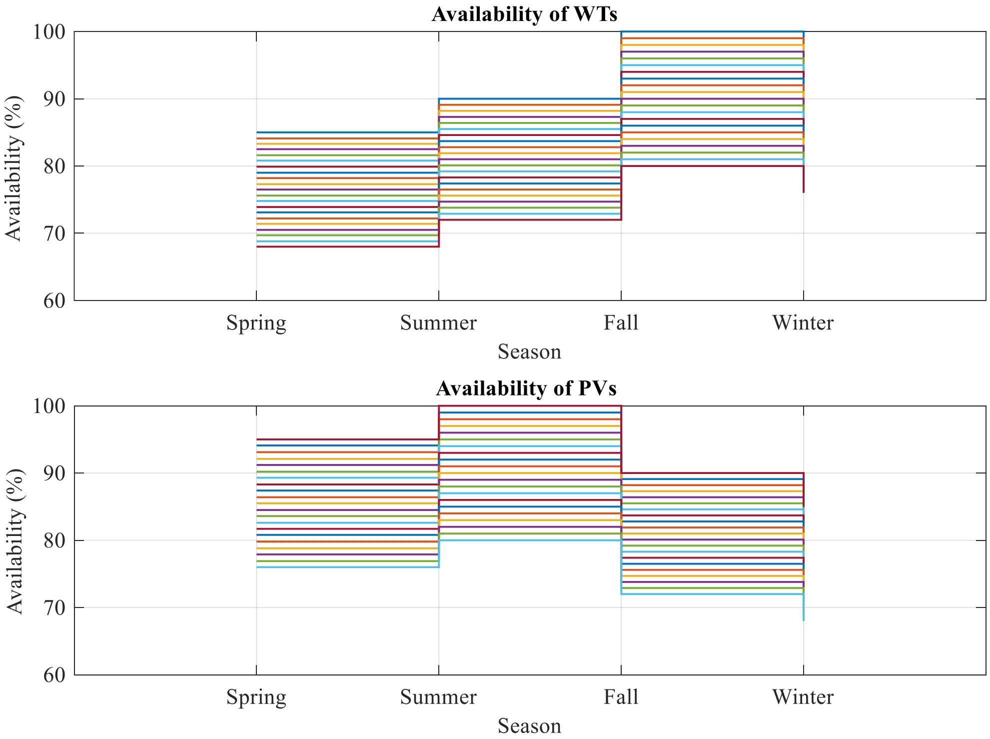

Fig. 15. The availability of WTs and PVs with considering their uncertainty.

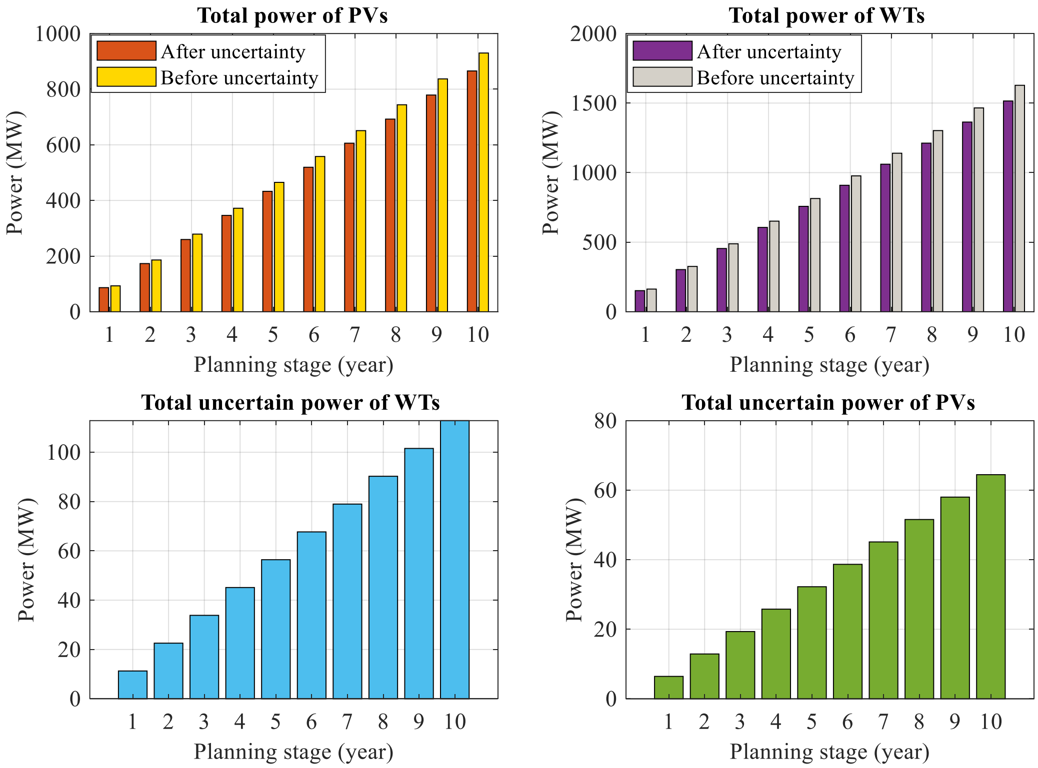

Fig. 16. Total power generation of renewable resources with considering uncertainty.

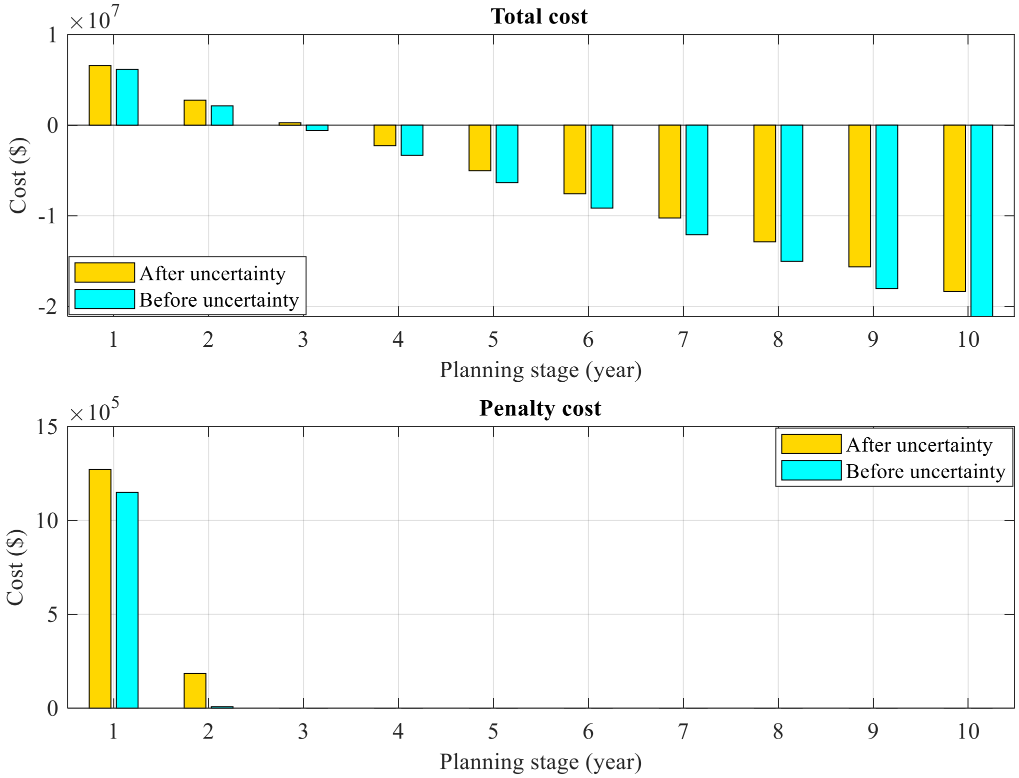

Fig. 17. Total cost and amount of pollution penalty with considering uncertainty.

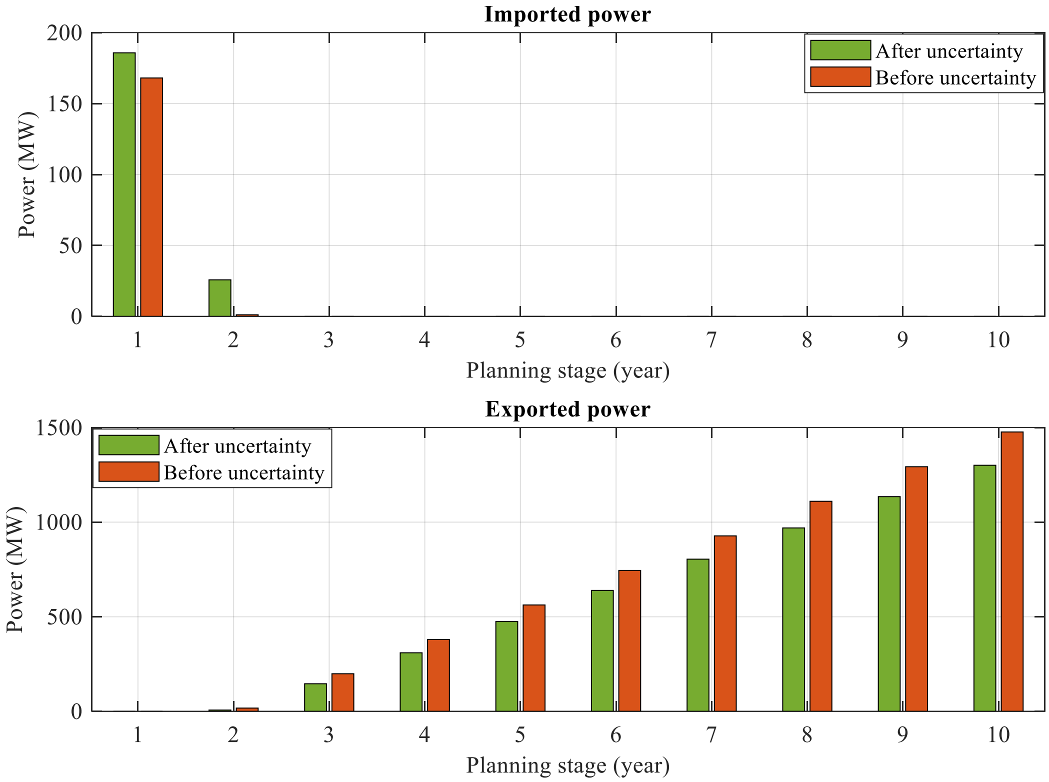

Fig. 18. Amount of imported and exported power with considering uncertainty.

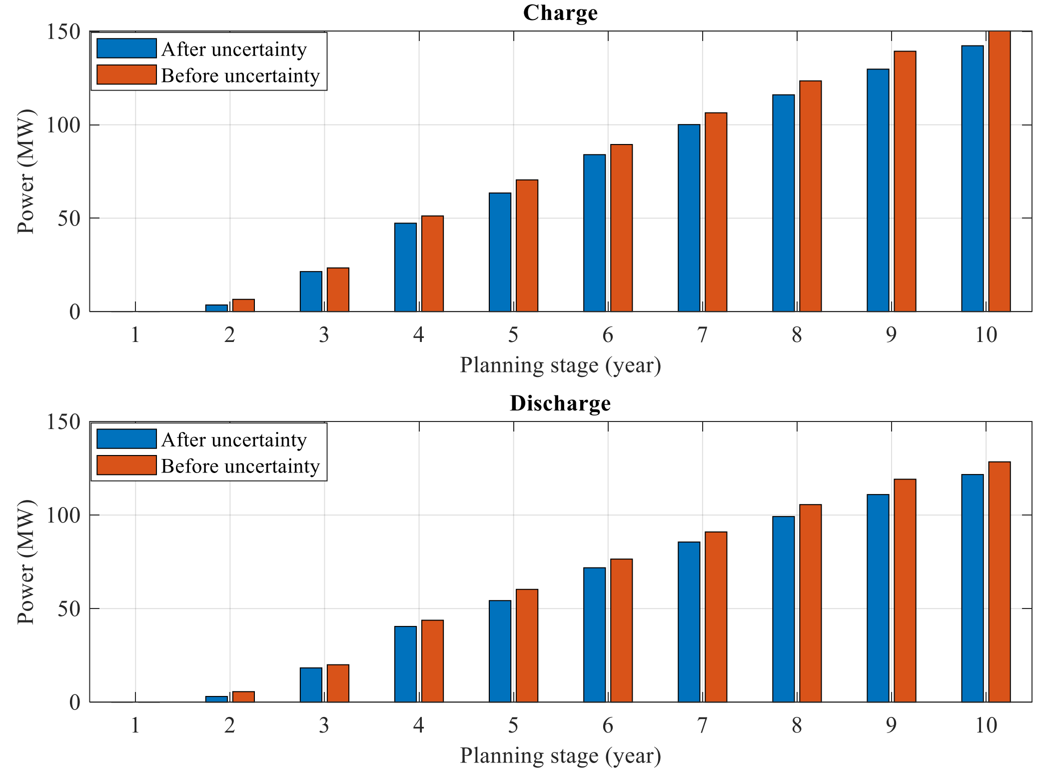

Fig. 19. Charging and discharging of electrical energy storage with considering uncertainty.

Table 9. Location and rating of WTs and PVs with considering uncertainty.

Stage	Location (bus) and rating (MW)																	
	1		2		3		4	15	17		20	21		23		31	33	
	WT	PV	WT	PV	WT	PV	PV	WT	WT	P V	WT	WT	PV	WT	PV	WT	WT	PV
1	0	0	0	0	0	0	0	1.5	0	0.8	0	0	0	0	0	0	0.5	1.2
2	0	0	0	0	0	0	1.2	1.5	0.4	1.6	0	0	0	0	0	1.6	0.5	1.2
3	0	0	0	0	2	1.7	1.5	1.5	0.4	1.6	0	0	0	0	0	1.6	0.5	1.2
4	0.8	0	0	0	3.2	3.7	1.5	1.5	0.4	1.6	0	0	0	0	0	1.6	0.5	1.2
5	2.8	1.7	0	0	3.2	3.7	1.5	1.5	0.4	1.6	0	0	0	0	0.3	1.6	0.5	1.2
6	3.9	3.7	0	0	3.2	3.7	1.5	1.5	0.4	1.6	0.3	0	0	0.6	0.3	1.6	0.5	1.2
7	3.9	4	0	0	3.2	3.7	1.5	1.5	0.4	1.6	2	0.3	1.7	0.6	0.3	1.6	0.5	1.2
8	4	4	1.9	1.7	3.2	3.7	1.5	1.5	0.4	1.6	2	0.3	2	0.6	0.3	1.6	0.5	1.2
9	4	4	3.9	3.7	3.2	3.7	1.5	1.5	0.4	1.6	2	0.3	2	0.6	0.3	1.6	0.5	1.2
10	4	4	3.9	4	4	4	1.5	1.5	0.4	1.6	2.6	0.3	2	1.2	1.7	1.6	0.5	1.2

Table 10. Location and rating of EESs with considering uncertainty.

Stage	Location (bus) and rating (MW)									
	1	2	3	9	19	20	21	22	25	32
1	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0.1	0	0.1	0	0.6
3	0	0	0.1	1.5	0.1	0.1	0.1	0.1	0.1	1.9
4	0	0.4	0.1	1.5	0.1	0.1	0.1	0.1	3.7	1.9
5	2	0.4	0.1	1.5	0.1	0.1	0.1	0.1	3.7	1.9
6	4	0.4	0.1	1.5	0.1	0.1	0.1	0.1	3.7	1.9
7	4	0.5	0.1	1.5	0.1	0.1	2	0.1	3.7	1.9
8	4	2.5	0.1	1.5	0.1	0.1	2	0.1	3.7	1.9
9	4	3.9	0.6	1.5	0.2	0.1	2	0.1	3.7	1.9
10	4	4	2.5	1.5	0.2	0.1	2	0.1	3.7	1.9

9. Conclusion

In this paper, the expansion planning of renewable resources and energy storage systems has been investigated with considering crypto-currency miners and responsive loads. The presented scheduling is structured based on multi-objective functions to achieve the minimum of cost and pollution. As well, to simulate a realistic condition and consider the limitation of staff and equipment, stochastic multi-stage programming is utilized for the mentioned goals. The simulation results show that the expansion of renewable resources besides storage systems can be a great solution to reduce environmental pollution and decrease the dependency of local systems on the main grid. Moreover, the drawbacks of miner loads can be mitigated by responsive loads and implementing incentive-based programs. Furthermore, the uncertainty of renewable resources is a critical problem, especially in renewable-based structures. The simulations validate that considering their uncertainty increases the total cost, however, the system robustness improves against fluctuations of renewable energies. As future work, several suggestions can be presented as follows: Expansion planning of integrated distribution systems such as electrical, gas, heating and cooling networks to increase reliability, modeling the uncertainty of other components, and utilizing different methods such as robust optimization to handle the uncertainties.

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