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A Two-Stage Chance-Constrained Stochastic Programming Model for Electricity Supply Chain Network Design: a Case Study

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Location;
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Chance-constrained programming.

ABSTRACT

Development of every society is dependent on the technological and economic effectiveness of energy sector. The electricity industry is growing and needs to have a better performance to cover the demand effectively. This industry is required to make a balance between cost and efficiency through careful design and planning. In this paper, a two-stage stochastic programming model is presented for the design of the electricity supply chain network. The proposed network consists of power stations, transmission lines, substations, and demand points. While minimizing costs and maximizing the grid effectiveness, this paper seeks to determine time and location of establishing new facilities as well as capacity planning for facilities. The chance-constrained optimization method is used to satisfy the uncertain demand with high probability. The proposed model is validated through a case study on Southern Khorasan Province's power grid network; the computational results show that the reliability rate is a crucial factor that greatly affects costs and demand coverage.

1. Introduction

Power grids are one of the largest and most complex infrastructures that form the basis of security and social/economic development [1]. The growth of demand for electricity is much faster than that for other forms of energy due to the rapidly commercializing process of technologies and devices that utilize electricity as their source of operation. The electricity power has a wide range of applications in generating heat and cold, lighting, and electrical devices [2].
The electricity supply chain is a network of facilities including power stations, transformers, substations, transmission lines, and distribution lines [3]. The generated electricity in power stations is delivered to distribution network via transmission facilities (i.e., substations and transmission lines). Distribution lines, then, deliver electricity to end-users. Design and planning of power grid require determining generation capacity, facility locating, choosing the best technology to generate power, and

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determining the best time to expand the network that aims to satisfy demand over a long period of time [2]. The rapid growth of demand for electricity has made the power grid expansion one of the main challenges in electric grid management [4]. Design and expansion of the power grid problem deal with optimal timing and amount of investment in order to fulfill the growing demand. Generation Expansion Planning (GEP) and Transmission Expansion Planning (TEP) are two main topics in this regard.

Generation Expansion Planning (GEP) is long-term planning that concerns the timing of investment and choosing of generation technology. The primary goal of the GEP is to satisfy the growing demand concerning economic criteria [5]. The problem has become more complicated by taking into account more real-world assumptions that affect the design and expansion of the network; two of these assumptions include uncertainty of some parameters and government regulations. These assumptions should be considered to obtain a more valid model.

Different technologies are used to generate electricity, each with different generation capacities, investment costs, and efficiency of power stations. Fossil fuel power stations, which include steam, gas, diesel, and combined cycle stations, play a significant role in providing the required electricity due to their high-generation capacity [6]. In steam power stations, for example, the heat generated by oil and natural gas is used to evaporate water, which is itself used to generate electricity. Combined-cycle power stations use both gas and steam turbines together; the heat generated by the gas turbine is used to evaporate water in the steam station. This process leads to a higher amount of electricity from the same amount of fuel, compared to traditional simple-cycle technology. Therefore, these power stations enjoy higher efficiency than gas and steam power stations, separately. Higher efficiency and lower cost per MWh are reasons that combined cycle power stations have a larger share than other technologies in generating electricity.

Transmission Expansion Planning (TEP) is to satisfy demand over time and deals with the optimization of timing and location of establishing new transmission lines [7]. Electricity companies need to increase their transmission capacity and, if the need arises, should expand their transmission services. However, establishing new lines is not always a feasible option; it may cause environmental issues, its magnetic and electric field may have a detrimental effect on surrounding areas, and it may cause surrounding properties to lose their values. These challenges, therefore, make it imperative to consider ways to increase transmission capacity by using existing lines to their full capacity. Constructing new lines is so costly and time consuming that expansion of line capacity (if possible) is a better option.

Mathematical formulation of transmission lines with Alternative Current (AC) leads to a non-linear model, which is time-consuming and difficult to solve even for small instances. Therefore, heuristic procedures are required. This is why most of the studies assumed Direct Current (DC) in formulating their models and used laws governing electric charge (first and second Kirchhoff laws) to state flow and voltage equations [8].

Considering uncertainty that is caused by systemic and environmental factors in the power grid allows flexibility and increases the efficiency of the proposed model in various settings. One of the most common approaches to handling uncertainty is to use hard capacity constraints [9]. The constraint guarantees that the installed capacity will satisfy demand under every scenario. Actually, it considers the worst-case scenario (highest demand), while the probability of the scenario can be very low. As a result, this paper uses another approach, service-level constraints, to defy uncertainty. These constraints ensure that the capacity of the network in each period will fulfill the demand with high probability. A chance-constrained model is proposed for an electricity supply chain network in a dynamic environment. The model decides over establishing new facilities and expanding existing ones with regard to problem constraints and cost considerations.

In summary, the contributions of this paper are as follows: 1) using chance constraint to deal with the uncertainty; 2) Incorporating a novel hybrid method for decisions about the grid capacity; 3) Considering substation; 4) Considering different technologies that are used to generate electricity; 5) Validating the proposed model via a real case study. The remainder of the paper is organized as follows: Section 2 reviews related studies. In Section 3, the chance constraint is explained, and a mathematical model is proposed. Section 4 provides details of the case study. Section 5 contains results of the model solution and sensitivity analysis. Finally, Section 6 concludes the paper and provides future directions.

2. Literature Review

Recent studies have focused on simultaneous optimization of generation and transmission expansion planning (GTEP) due to their mutual interaction effect on each other. Sharan and Balasubramanian [10], for example, proposed an integrated model for generation and transmission problem by considering fuel transportation limits to power stations. Thomé et al. [11] developed a model for GTEP and investigated possible methods to solve. Their model considers hydro-electric and steam technologies. Dawei et al.[12] presented a model with reliability considerations for power generation and transmission problem to provide electricity of oil fields.

There are two ways for increasing capacity in problems that deal with the design and expansion of power grids: 1) locating and establishing new facilities; 2) increasing the capacity of the existing facilities. In most studies, the grid expansion is achieved by the first method (see for example [6, 12, 13]). Although activating the potential capacity of existing facilities would achieve lower cost [14, 15], it may not suffice or even feasible approach in some cases. Therefore, the model is best-suited that allows both capacity expansion of existing facilities and adding new facilities; only a handful of papers consider these both options. More recently, Guerra et al. [2] proposed a model with both options for GTEP to expand the capacity of the network.

Although uncertainty is a crucial part of the power network design problems, most of the papers have not considered demand uncertainty and used deterministic parameters. Fuzzy programming and robust optimization are most the commonly used approaches in non-deterministic models. Torabi and Madadi [16] developed a fuzzy programming model for GTEP problem, which determines the location of new facilities and capacity of transmission lines in every period. Mansouri and Javadi [17] proposed a robust optimization framework for GTEP problem. They used Mulvey's robust paradigm to deal with the uncertainty of demand, fuel price, and generation level. Seddighi and Ahmadi-Javid [6] developed a multi-period model for GTEP problem under disruption assumption which takes into account the available capacity of facilities and transmission lines. They used stochastic programming to deal with uncertainty and used the grid network of North-Western Iran as their case study. Jabbarzadeh et al. [15] presented a robust optimization model for the design of the electricity supply chain network that uses the potential capacity of existing facilities to expand the network. They used Tehran grid network as a case study. Stochastic programming seems to be a good choice for GTEP problem as the historical data of electricity demand are available. Moreover, the chance constraint can be combined with scenario-based stochastic programming to obtain a more realistic model to capture uncertainty. The related papers are summarized in Table 1.

3. Model Formulation

First, the chance constraint paradigm and, then, electricity supply chain network design and expansion problem are explained and, then, a formulation will be proposed.

3-1. Chance-constrained programming

In some cases, we can assume a penalty cost for inaccurate decisions and impose this cost when a constraint is violated. However, compensation cost is too subjective or even impossible to measure. For instance, it is impossible to assume a price for security, human lives, and health condition of individuals and try to compensate any of them. In these situations, it is crucial to make feasible decisions as possible. Chance constraints in stochastic programming models ensure that most of the scenario realizations will not violate constraints. The overall structure of chance constraint is [18]:

$$\min_{x\in X} f(x) \quad s.t. \qquad \Pr\left\{G(x,\xi)\le 0\right\}\ge 1-\varepsilon \qquad (1)$$

where ξ denotes stochastic parameter, $G(x,\xi)$ is the mathematical formula of the constraint, and ε is the probability of constraint violation. Therefore, objective function $f(x)$ is minimized, while constraint $G(x,\xi)\le 0$ is satisfied with at least $1-\varepsilon$ probability.

Tab. 1. related works

References	Power grid network			Decisions					Modelling approach	
				Capacity expansion						
	Power Station	Transmission	Sub-Stations	New Facility	Existing Facility	Hybrid	Generation	Circuit Laws	deterministic	uncertain
Torabi and Madadi [16]	*	*		*	*				*	Fuzzy
Sharan and Balasubramanian [10]	*	*		*				*	*	
Thomé et al. [11]	*	*				*	*	*		
Romero et al. [14]	*	*	*		*			*		TSS
Seddighi and Ahmadi-Javid [6]	*	*		*		*		*	*	MSS
Kim et al.[8]	*	*		*				*	*	
Guerra et al. [2]	*	*					*	*		
Moreira et al.[13]	*	*		*				*	*	RO
Dawei et al. [12]	*	*		*				*		
Mansouri and Javadi [17]	*	*		*				*		RO
Jabbarzadeh et al. [15]	*	*	*		*	*				RO
This work	*	*	*			*	*	*		TSCC

TSS: Two-Stage Stochastic programming, MSS: Multi-Stage Stochastic programming, RO: Robust Optimization, TSCC: Two-Stage Chance-Constrained programming.

3-2. Problem statement

In the proposed model, a grid network is considered that consists of existing facilities as well as candidate locations to establish new facilities. Generation capacity is increased by establishing new facilities or expanding the capacity of the existing power stations. Similarly, establishing new transmission lines or increasing capacity of the existing lines are options to expand transmission network. The voltage of the electricity generated in the power stations needs to be increased. This is done through substations where they can be located in any of the nodes. Figure 1 shows the schematic view of our model. The model includes power stations, transmission network, substations, and demand points.

The decisions made in the problem are strategic-level decisions; thus, we need to consider parameters' change over a long period of time. As a result, this paper designs the network in a dynamic fashion where it deals with location, assignment, and capacity planning decisions. Each of the existing facility has an initial capacity that can be increased even in the first period. Operational capacity of facilities is restricted to maximum and minimum possible capacity (i.e., nominal capacity).

Investment costs of generation and transmission are considered as fixed costs, which include the cost of property and facility acquisition to establish power plants, the cost of transmission lines, and the cost of other facilities. Utilization costs are proportional to the capacity of facilities. Therefore, only variable cost changes if the capacity of a facility is increased.

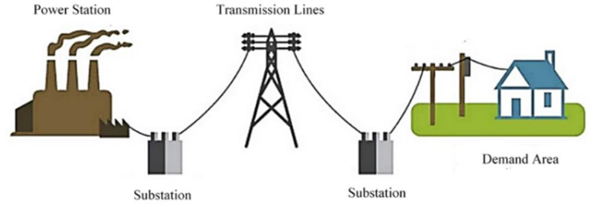

Fig. 1. Power grid network

Operation and maintenance of power plants are usually very costly and are dependent on the hourly generation rate. On the other hand, these costs for transmission lines are negligible, which is why we only incorporate maintenance cost for power plants in the objective function.

3-3. Mathematical model

Let us first introduce the notations used in the formulation.

Sets & indices

R	Set of all nodes indexed by $i, j \in R$
TE	Set of generating technologies indexed by $v \in TE$
PW	Set of existing and candidate power station with technology *v* indexed by $(i,v) \in PW$
OLT	Set of existing and candidate transmission lines indexed by $i < j, (i,j) \in OLT$
T	Set of time periods indexed by $t \in T$
Ω	Set of scenarios indexed by $s \in \Omega$

Parameters

ρ_{iv}	1 if there is a power station with technology *v* at site *i*, 0 otherwise $(i,v) \in PW$
ρ'_{iv}	1 if it is possible to establish power station with technology *v* at site *i*, 0 otherwise $(i,v) \in PW$
ϑ_i	1 if there is a substation at site $i \in R$, 0 otherwise
χ_{ij}	1 if there is a transmission line between *i* and *j*, 0 otherwise $(i,j) \in OLT$
χ'_{ij}	1 if it is possible to establish a transmission line between *i* and *j*, 0 otherwise $(i,j) \in OLT$
ct_{ij}^{min}, ct_{ij}^{max}	Minimum and maximum capacity of transmission between *i* and *j* $(i,j) \in OLT$ (MW)
cr_{iv}^{min}, cr_{iv}^{max}	Minimum and maximum capacity of power station type *v* at site *i* $(i,v) \in PW$ (MW)
ec_{iv}	Initial capacity of the existing power station *i* with technology *v*. $(i,v) \in PW$ (MW)
ecl_{ij}	Initial capacity of the existing transmission line *i-j* $(i,j) \in OLT$ (MW)
β_t	available budget for network construction and expansion in period *t* (\$)
fr_{iv}	fixed cost of opening a power station type *v* at site *i* $(i,v) \in PW$ (\$)
fr'_{iv}	unit variable cost of installation and expansion of power station *i* type *v* $(i,v) \in PW$ (\$)
fp	fixed cost of opening a substation (\$)
f_{TR}	fixed cost of establishing a transmission line (\$)
f'_{TR}	unit variable cost of establishment and expansion of transmission line $(\$/MW.km)$
om_{iv}^t	Unit operation & maintenance cost of power station type *v* at node *i* in time period $t \in T$, $(i,v) \in PW$ $(\$/MWh)$
d_{it}^s	Load demand at node *i* at time period $t \in T$ under scenario $s \in \Omega$, $i \in R$ (MW)
dis_{ij}	Distance between node *i* and node *j*, $(i,j) \in OLT$ (km)
α_{ij}	Susceptance of line *i-j* $(i,j) \in OLT$
Δt	Duration of the period $t \in T$ (hour)
q	Interest rate
P_s	The probability of occurrence of scenario $s \in \Omega$

variables

RI_{iv}^t	A binary variable that is equal to one if a new electricity plant of technology type *v* is installed at node *i*, in period $t \in T$, $(i,v) \in PW$
ST_{it}	A binary variable that is equal to one if a new substation is installed at node $i \in R$ in a period $t \in T$
LT_{ij}^t	A binary variable that is equal to one if a new transmission line is installed at arc (*i,j*) in period $t \in T$, $(i,j) \in OLT$

UR_{iv}^{t}	Generation capacity of electricity plant type v at node i in time period $t \in T$, $(i,v) \in PW$ (MW)
UT_{ij}^{t}	capacity of transmission line installed at arc (i,j) in period $t \in T$, $(i,j) \in OLT$ (MW)
EG_{iv}^{ts}	The electricity generated at electricity plant type v at node i in time period $t \in T$ under scenario $s \in \Omega$, $(i,v) \in PW$ (MW)
EF_{ij}^{ts}	The electricity flow from node i to node j at time period $t \in T$ under scenario $s \in \Omega$, $(i,j) \in OLT$ (MW)
V_{it}^{s}	The voltage angle at node $i \in R$ at time period $t \in T$ under scenario $s \in \Omega$ (radian)

$$\psi = min \sum_{t \in T} \left(\frac{1}{1+q}\right)^{t-1} \Bigg[\sum_{i \in R} fp(ST_{it} - ST_{it-1}) + \tag{2}$$

$$\sum_{(i,v) \in PW} fr_{iv}(RI_{iv}^{t} - RI_{iv}^{t-1}) +$$

$$\sum_{(i,v) \in PW} fr'_{iv}(UR_{iv}^{t} - UR_{iv}^{t-1} - ec_{iv}) +$$

$$\sum_{(i,j) \in OLT} f_{TR}(LT_{ij}^{t} - LT_{ij}^{t-1}) +$$

$$\sum_{(i,j) \in OLT} f'_{TR} dis_{ij}(UT_{ij}^{t} - UT_{ij}^{t-1} - ecl_{ij}) +$$

$$\sum_{s \in \Omega} P_s \left(\sum_{(i,v) \in PW} om_{iv}^{t} \Delta t EG_{iv}^{ts} \right) \Bigg]$$

$$cr_{iv}^{min}(RI_{iv}^{t} + \rho_{iv}) \le UR_{iv}^{t} \le cr_{iv}^{max}(RI_{iv}^{t} + \rho_{iv}) \quad \forall (i,v) \in PW, t \in T \tag{3}$$

$$RI_{iv}^{t} \le \rho'_{iv} \quad \forall i \in R, v \in TE, t \in T \tag{4}$$

$$RI_{iv}^{t-1} \le RI_{iv}^{t} \quad \forall (i,v) \in PW, t \in T \tag{5}$$

$$ec_{iv} \le UR_{iv}^{t} \quad \forall (i,v) \in PW, t = 1 \tag{6}$$

$$UR_{iv}^{t-1} \le UR_{iv}^{t} \quad \forall (i,v) \in PW, t > 1 \tag{7}$$

$$EG_{iv}^{ts} \le UR_{iv}^{t} \quad \forall (i,v) \in PW, t \in T, s \in \Omega \tag{8}$$

$$ST_{it-1} \le ST_{it} \quad \forall i \in R, t \in T \tag{9}$$

$$ct_{ij}^{min}(LT_{ij}^{t} + \chi_{ij}) \le UT_{ij}^{t} \le ct_{ij}^{max}(LT_{ij}^{t} + \chi_{ij}) \quad \forall (i,j) \in OLT, t \in T \tag{10}$$

$$LT_{ij}^{t} \le \chi'_{ij} \quad \forall i,j \in R, t \in T \tag{11}$$

$$LT_{ij}^{t-1} \le LT_{ij}^{t} \quad \forall (i,j) \in OLT, t \in T \tag{12}$$

$$ecl_{ij} \le UT_{ij}^{t} \quad \forall (i,j) \in OLT, t = 1 \tag{13}$$

$$UT_{ij}^{t-1} \le UT_{ij}^{t} \quad \forall (i,j) \in OLT, t > 1 \tag{14}$$

$$LT_{ij}^{t} \leq \sum_{v \in TE} (RI_{iv}^{t} + \rho_{iv}) + ST_{it} + \vartheta_{i} \quad \forall (i,j) \in OLT, t \in T \tag{15}$$

$$LT_{ij}^{t} \leq \sum_{v \in TE} (RI_{jv}^{t} + \rho_{jv}) + ST_{jt} + \vartheta_{j} \quad \forall (i,j) \in OLT, t \in T \tag{16}$$

$$\chi_{ij}\left(EF_{ij}^{ts} - \alpha_{ij}\left(V_{it}^{s} - V_{jt}^{s}\right)\right) = 0 \quad \forall (i,j) \in OLT, t \in T, s \in \Omega \tag{17}$$

$$-M\left(1 - LT_{ij}^{t}\right) \leq EF_{ij}^{ts} - \alpha_{ij}\left(V_{it}^{s} - V_{jt}^{s}\right) \leq M\left(1 - LT_{ij}^{t}\right) \quad \forall (i,j) \in OLT, t \in T, s \in \Omega \tag{18}$$

$$-UT_{ij}^{t} \leq EF_{ij}^{ts} \leq UT_{ij}^{t} \quad \forall (i,j) \in OLT, t \in T, s \in \Omega \tag{19}$$

$$Pr\left(\begin{array}{l} \sum_{v|(i,v) \in PW} EG_{iv}^{ts} + \sum_{j|\forall (j,i) \in OLT} EF_{ji}^{ts} - \\ \sum_{j|\forall (i,j) \in OLT} EF_{ij}^{ts} \geq d_{it}^{s} \end{array} \right) \geq 1 - \alpha \tag{20}$$

$$\begin{aligned} &\sum_{i \in R} fp(ST_{it} - ST_{it-1}) + \sum_{(i,v) \in PW} fr_{iv}(RI_{iv}^{t} - RI_{iv}^{t-1}) + \\ &\sum_{(i,v) \in PW} fr'_{iv}(UR_{iv}^{t} - UR_{iv}^{t-1} - ec_{iv}) + \\ &\sum_{(i,j) \in OLT} f_{TR}(LT_{ij}^{t} - LT_{ij}^{t-1}) + \\ &\sum_{(i,j) \in OLT} f'_{TR} dis_{ij}(UT_{ij}^{t} - UT_{ij}^{t-1} - ecl_{ij}) \leq \beta_{t} \qquad \forall t \end{aligned} \tag{21}$$

$$RI_{iv}^{t}, ST_{it}, LT_{ij}^{t} \in \{0,1\} \tag{22}$$

$$UR_{iv}^{t}, UT_{ij}^{t}, EG_{iv}^{ts} \geq 0 \tag{23}$$

$$EF_{ij}^{ts}, V_{it}^{s} \in \mathbb{R} \tag{24}$$

The objective function minimizes costs of design and network expansion to satisfy demand. The function includes the cost of investment, cost of utilization of power plant and new transmission lines, the fixed cost of establishing substations, cost of increasing the capacity, and the average cost of maintenance. Constraint (3) restricts the operational capacity of the new and existing power plants at their upper and lower bounds.
Constraint (4) determines candidate locations to establish new power plants.
Constraint (5) ensures that if a power plant is established in a period, it will operate until the end of the planning horizon. Constraint (6) states the initial capacity of the existing power stations in the first period. Constraint (7) guarantees that the capacity of power plants does not decrease over time. The maximum generation capacity of power plants is stated in constraint (8).
Constraint (9) ensures that every substation will remain active after being established. Upper and lower bounds of the operational capacity of the transmission lines are imposed in constraint (10). Constraint (11) identifies candidate arcs to establish new transmission lines. Constraint (12) guarantees that transmission lines would sustain until the end of the planning horizon if they were established in a period. Constraint (13) states the initial capacity of the existing transmission lines in the first period. Constraint (14) does not allow the transmission capacity to decrease over time. Constraints (15) and (16) state the relation

between facilities: every transmission line should be connected to a substation or power station.
Constraints (17) and (18) impose Ohm's law on existing and new transmission lines, respectively. Ohm's law states that the current of a conductor is equal to the multiplication of the voltage and susceptance of the circuit. Constraint (19) limits the current of the network to its allowance levels which is the operational capacity of the transmission lines. Note that the lower bound is considered since the value of the currents can also be negative. Constraint (20) is the chance constraint, and ensures that the demand of the network is satisfied with a probability of at least $1-\alpha$ in every period. Constraint (21) states the available budget to establish and expand facilities. Constraints (22) to (24) define the decision variables.
Two-stage chance-constrained stochastic programming is challenging to solve because its feasibility region is typically non-convex and needs multi-dimensional integration. The suggested solution is to replace the actual distribution of the random parameter by an empirical distribution. Monte Carlo simulation can be used to generate a large number of demand scenarios with equal probability [19]. Therefore, constraint (20) can be reformulated as follows:

$$1/N\sum_{s=1}^{N}\psi\left(\begin{array}{l}\sum_{v|(i,v)\in PW} EG_{iv}^{ts}+\sum_{j|\forall(j,i)\in OLT} EF_{ji}^{ts}-\\ \sum_{j|\forall(i,j)\in OLT} EF_{ij}^{ts}\geq d_{it}^{s}\end{array}\right)\geq 1-\alpha \tag{25}$$

where ψ (.) is an indicator function which is equal to one when . is true and zero otherwise. Constraint (25) is still non-convex. Therefore, we linearize the chance constraint by constraints (26) and (27). Binary variable G_s is zero when the demand of scenario *s* is satisfied [20].

$$\sum_{v|(i,v)\in PW} EG_{iv}^{ts}+\sum_{j|\forall(j,i)\in OLT} EF_{ji}^{ts}- \sum_{j|\forall(i,j)\in OLT} EF_{ij}^{ts}\geq d_{it}^{s}-G_s.M \quad \forall i\in R, s\in\Omega, t\in T \tag{26}$$

$$\sum_{s\in\Omega} P_s G_s \leq \alpha \tag{27}$$

4. Case Study

Southern Khorasan power grid is part of the Khorasan Regional Electric Company and owns several diesel and gas power plants, transmission lines, and substations. Population and agriculture growth along with new industrial parks has dramatically increased demand for electricity in recent years. The company needs to expand its generation and transmission capacity in order to cover the demand. In this regard, one of their main strategies is to expand gas power plants and to equip them with steam technology to make them combined-cycle power plants. Figure 2 illustrates the grid network of the Khorasan region. The network has 8 nodes, each representing a populous city or a developing one. As shown, the existing facilities include power plants (diesel and gas), substations, high- and low-voltage transmission lines, and candidate arcs and nodes to establish new facilities. Details of the network, including the geographical coordinates of nodes, and capacity of facilities are presented in Tables 2 and 3.

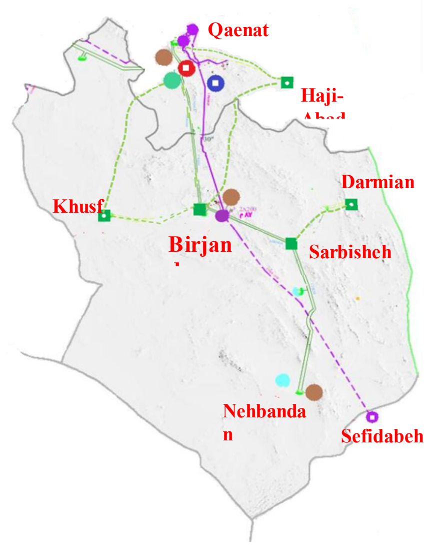

Fig. 2. Southern Khorasan power grid

Tab. 2. Geographical coordinates of cities

Number	City	Latitude [º]	Longitude [º]
1	Birjand	32.86	59.22
2	Darmian	33.03	60.11
3	Haji-Abad	33.59	59.99
4	Sarbisheh	32.50	59.65
5	Qaenat	33.75	59.46
6	Nehbandan	31.51	59.65
7	Khusf	32.86	58.62
8	Sefidabeh	30.97	60.52

The distance of the nodes from each other (dis_{ij}) is calculated by Equation (27), which uses the geographical coordinates of the nodes.

$$dis_{ij} = 6371.1 \times \arccos[\sin(LAT_i) \times \sin(LAT_j) + \cos(LAT_i) \times \cos(LAT_j) \times \cos(LONG_j - LONG_i)] \quad (27)$$

where $(LAT_i, LONG_i)$ and $(LAT_j, LONG_j)$ denote geographical coordinates of nodes i and j, respectively.

5. Results & Sensitivity Analysis

The proposed model is implemented in the commercial solver GAMS 24.1.2 with CPLEX solver by a Core i7 computer 8GB Intel RAM. With a service level of 95%, we analyzed the sensitivity of the model to specific parameters.
Increasing the number of combined-cycle power plants is a priority for the Regional Electric Companies, because of their lower maintenance cost, higher generation capacity, and higher efficiency. The model solution identifies Qaen combined-cycle power plant to be established. Substations are set up at Khusf, Darmian, and Haji-Abad due to their increasing demand, and transmission lines from Birjand to Khusf, from Sarbisheh to Darmian, and from Qaenat to Haji-Abad are set up to serve this purpose. Furthermore, the transmission capacity has been increased by 4574 MW in the first, 405 MW in the second, and 26 MW in the third periods.

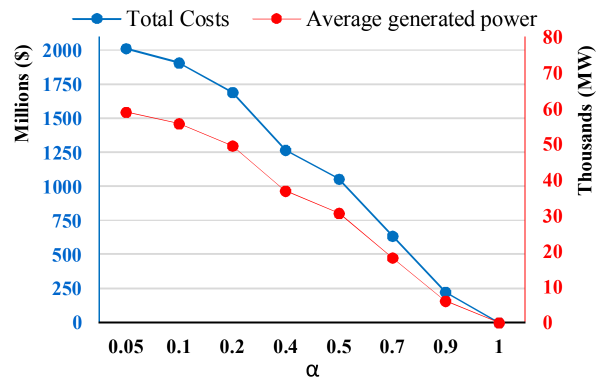

Fig. 3. The impact of α on the total cost and average generation

shows the flexibility of the chance constraint; as it decreases, the demand is covered with higher probability. We investigate the effect of α on the average generation of power plants and objective function.
Results are shown in Figure 3. The chance constraint is violated more often when α increases. In other words, service level (1-α) decreases and a large amount of the demand is unmet demand. This leads to the lower generation and, thus, lower objective value. In addition, an increase in service level requires paying for capacity expansion in power plant as well as transmission lines.

Tab. 3. Characteristics of power stations

Power plant	Technology	Status	maximum generation capacity (MW)	Existing capacity (MW)	minimum generation capacity (MW)
Qaen	diesel	available	24	2.4	-
Qaen	gas	available	75	50	-
Kaveh (Qaen)	CCP	the power station is running on natural gas and combined cycle under construction.	636	477	-
Birjand	diesel	available	17	14.1	-
Nehbandan	diesel	available	4.5	2.8	-
Kaveh (Qaen)	steam	candidate	320	-	159

Kaveh (Qaen) combined-cycle power plant is only operable by the gas turbine, and its steam turbines have not been set up yet.

Figure 4 presents results of the demand variations on the objective function under various α values. As illustrated, increasing the demand results in increasing the objective function. Besides, the rate of these changes is higher under α=0.05 service level.

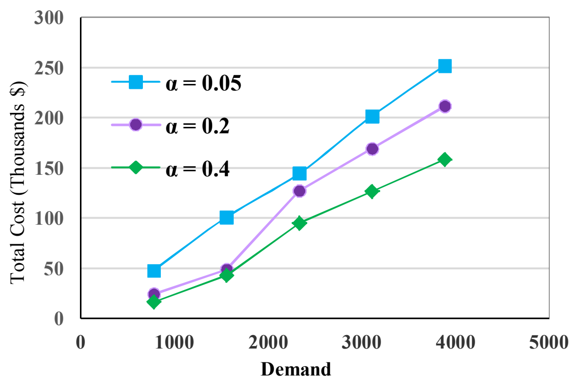

Fig. 4. Demand variations versus Total cost under different service level

Fig. 5. The objective function versus the number of scenarios

Although increasing scenarios may increase the accuracy of the solution, it also increases the model complexity and solving time. Figure 5 shows that the lower number of scenarios obtain erratic solutions, while, in a higher number of scenarios, solutions asymptotically converge to a specific value and the solution accuracy increases (about 90%); however, this also increases the solving time from 3 seconds to 19.6 minutes.

6. Concluding Remarks

Design of power grids is one of the main challenges in electric grid management due to the growing demand for electricity in various sectors. Considering this fact, a stochastic programming model was proposed to design a power grid. For a long period of time, the model optimizes location, capacity, and timing of establishing new facilities, increases capacity of the existing facilities, and chooses the best technology for new facilities. The chance constraint was utilized to defy demand uncertainty and to fulfill the demand with higher reliability level. Eventually, the model was validated on the Southern Khorasan power grid. As results suggested, the combined-cycle power plant was selected among other types. The reliability rate $1-\alpha$ is a crucial factor that greatly effects costs and demand coverage. In the reliability rate of 95%, for example, only one scenario does not cover its demand. In order to develop this study, one can incorporate disruption in the model. Electricity pricing, as well as the uncertainty of fossil fuel resources, can be other future directions.

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