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Optimum Investment Planning for Development and Operation of Electricity Network in Presence of Renewable Units

S. M. Seyed Hoseini[1], A. Mohammadzadeh[2]*, M. Seighli[2], F. Rezaei[3]

[1] Department of Industrial Management, Qazvin Branch, Islamic Azad University, Qazvin, Iran
[2] Department of Financial Management, Qazvin Branch, Islamic Azad University, Qazvin, Iran
[3] Department of Accounting, Qazvin Branch, Islamic Azad University, Qazvin, Iran

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A B S T R A C T

With the increase in world population and limited energy resources, countries have faced the high demand of energy and energy consumption problem. The crisis that threaten countries and human societies are the limited resources of non-renewable (fossil) energy and the increase in environmental pollution caused by excessive consumption of fossil fuels and global warming. These factors have motivated researchers and investors in the energy sector to control and supply energy from renewable sources. The uncertainty caused by these generations can have many effects on the costs imposed on the network and the operation of the electricity networks, such as an increase in power outages and unsupplied energy. Network development planning is one of the important issues in the power system to meet the growth of electricity demand in the coming years due to urban development, increasing social welfare, energy security, and job creation. The final objective of this model is to minimize energy losses, investment and operating costs, unsupplied energy, and environmental pollutants. The proposed methods have been implemented by MATLAB software on the Garver electricity network and the IEEE 33-bus distribution network and solved by PSO algorithms. The final model can be effectively used for planning the supply chain of the conventional electricity network with the penetration of renewable energy-based generations in various economic, environmental, and social dimensions.

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INTRODUCTION

Today, electricity plays a key role in people's lives and is used in various fields such as home consumption, production, various industries, transportation, etc. For this reason, a power outage in the network can have serious consequences [1]. Currently, the main source of electricity production worldwide (with more than 67%) is fossil fuels [2], which, due to an increasing trend of electricity consumption and the demand for more production, its destructive environmental effects due to the emission of pollutants such as carbon dioxide have caused many concerns [3]. Due to these negative effects, laws, and agreements have been established at the national and international levels to reduce various pollutants and minimize the global crisis [1, 4].

Environmental and global warming problems are one of the biggest concerns of societies. Using renewable energy-based production technologies such as solar and wind power plants is one of the most important ways to solve these problems. So, these products' influence on the power grid has increased greatly in recent years and is still expanding at a high rate. In addition to all the benefits of renewable products, their presence in the power grid has posed serious challenges [5]. Increasing the presence of renewable resources in distribution systems must be managed, and the optimal installation location should be considered according to the intended goals and grids [6].

*Corresponding Author Email: *a.mohammadzadeh@qiau.ac.ir*
(A. Mohammadzadeh)

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Increasing awareness of the concept of sustainability around the world has caused many industries, such as the electricity industry, to be pressured by people, governmental and non-governmental institutions, the media, and various stakeholders and try to achieve sustainability goals [1, 7].

The challenge facing the design of a sustainable supply chain is to find optimal solutions because the purpose of designing a supply chain in the first place is the economic aspect (reducing costs), and this is while paying attention to the environmental and social dimensions will increase the costs [1].

The variable of the output power of renewable energy-based resources because of their dependence on climatic conditions is one of the main concerns of power grid planners and beneficiaries. The uncertainty caused by these products can greatly affect the power outages and costs imposed on the operation and development of power grids [5]. In planning power grids, there are many factors, such as the type of initial grid structure, the limitations of the power grid, and the uncertainties, each of which requires a case study [8].

Electric energy grids are one of the most complex man-made devices in the last few decades. This complexity has led to extensive and precise studies for the planning of these grids at different generation, transmission, and distribution levels. Due to the long life and wide geographical area of electric energy grids and the very high costs related to their construction and operation, it is necessary to plan these grids in a completely optimal way to avoid additional costs [9].

LITERATURE REVIEW

Renewable energy is a type of energy that, unlike non-renewable energy, can return to nature. These energies include wind, solar, geothermal, biomass, and hydroelectric power. The potential of renewable energy sources to meet the energy demand in the world is very high. These energies are one of the clean effects compared to fossil fuels; they are attractive options for economic growth, meeting energy needs, creating jobs, and creating manufacturing and service industries, especially in developing countries.

Renewable energies play an important role in the economic, social, environmental, and security activities of any country because, with the exhaustion of fossil fuels on the one hand and the increase in the environmental pollution on the other hand, the importance of using these types of energy is increasing day by day. It has become an incentive for researchers and investors in the energy sector to be attracted to supply energy from renewable sources.

Energy is very important in the economic development of any country. Without energy, economic development in a developed and under developing country seems impossible. Studies show that in the current situation, obtaining enough energy to meet human needs and achieve minimum economic growth, solving issues related to the environment and increasing energy efficiency, and providing the necessary investment in the energy sector are among the important issues in the energy sector that have attracted the attention of different countries.

The importance of renewable energy in sustainable development, reducing greenhouse gases and increasing energy security on the one hand, and the need for renewable energy projects for financial resources and large investments on the other hand, doubles the role and importance of financial development in renewable energy.

Rapid economic growth in developing countries and continuous growth in industrialized countries have increased the energy demand. The diversity of existing technologies, along with technical and economic limitations, has made the technical-economical planning of electricity generation particularly important.

But the perspective of receptive energies is completely different from the current capacity. In 2021, about 84% of the capacity added to the world's power grid was from energy plants. More than half of this variable capacity is related to solar technologies, 30% is related to wind technologies and the rest is related to other renewable technologies (electricity, biomass, geothermal and others). It is predicted that by 2050, more than 85% of the world's electricity will be supplied through energy sources led by solar technologies.

Energy storage is one of the areas that have been highly considered for the development of clean energy in recent years. In 2022, about 337 billion dollars have been invested directly in the field of energy storage.

China is the most active country in the world in the field of renewable energy development. With a production capacity of more than 1000 GWh per year, this country is more than 3 times the production capacity of the second country, the United States (with a capacity of 325 GWh per year), and ranks first in the world by a margin.

BENEFITS OF RENEWABLE RESOURCES

1. No need for large investment and attraction of public participation with medium capital, 2. Short-term investment return and high security of investment in the guaranteed purchase of long-term electricity, 3. Reducing greenhouse gas generation and environmental pollutants, 4. Reducing losses and increasing reliability, 5. Reducing installation and launch time compared to centralized power plants, 6. High efficiency and effectiveness, 7. Ensuring energy stability and security, 8. Creating jobs and strengthening resilience to maintain people's health, well-being, etc.

PROBLEM STATEMENT

The supply chain is defined as a grid of facilities consisting of suppliers, producers, distribution centers, etc., which include a set of operations, including raw material supply, transmission to the manufacturer, final product production, and ultimately distribution [4].

The supply chain in the field of the electricity industry and electricity production has been posed in three main areas of production, transmission, and distribution in the electricity network as the main decision-making units in the optimization of the supply chain. In the electricity industry, these three areas consist of three layers, including power plants, electricity transmission posts, and low-voltage electricity posts or distribution posts [1].

In various research, supply chain research includes five essential components: production, transmission, distribution, metering and retailing, and dispatching.

The production sector is dedicated to the electricity production stage. Typically, power plants with different technologies are involved in this sector. System operators do the management of power transmission or grid transmission systems. There are various possible configurations for system operators, specifically regarding grid ownership and planning and implementation of expansion programs and grid updates. Transmission expansion planning (TEP) is used to meet demand over time and optimize the time and location of new transmission lines. Electricity companies need to increase their transmission capacity and expand their services if needed. Power distribution is the electricity transmission from sub-posts to end consumers, performed at moderate and low voltage by distribution system operators (DSO). The basic responsibility of DSOs is the quality control of the supply. In the power industry, the quality of supply or electricity refers to the voltage control, frequency, and shape of the waves (voltage and current) to preserve them in a predefined range. The retailers are electrical sales activity to end users. Dispatching means optimal selection of power plants and loads under transmission and operating limitations.

The complexity of activities, given the sustainability considerations at the national and international levels, has forced researchers not to pay attention to these units separately but to analyze the entire chain seamlessly [2].

Despite the differences in the components of the supply chain in different sectors and industries, however, the common challenge in designing a sustainable supply chain is balancing short-term economic benefits on the one hand, minimizing long-term environmental effects, and meeting social expectations on the other hand, because these goals are usually in conflict with each other. If sustained supply, with real and practical goals, is designed, it will have a positive effect on the functions of supply chain management, that is, planning, implementation, cooperation, and participation, and it will help companies to adopt appropriate strategies and committed to environmental goals and fulfill their social responsibilities [10].

Sustainability consists of three environmental, social development, and economic performance components, and the interface between these three dimensions leads to activities in companies that not only have a positive effect on the natural environment and society but also it will bring economic benefit in the long term [11-15].

The concept of sustainability in the supply chain goes beyond the economic dimension and requires attention to all the environmental, social, and economic dimensions. Also, identifying and evaluating social dimensions such as sustainable development, healthy business methods, reducing corruption, and corporate social responsibility (CSR) is essential to improve sustainability in the electricity network [11].

In some cases, the negative environmental effects caused by the generation of electric energy are so significant that they have caused problems in the sustainable development of societies and have caused problems in the social dimension, among which social justice, equality, and sustainable economic development can be mentioned [12].

This is while the growth of demand and the expansion of the production and distribution network and the uncertainty in forecasting the demand for electricity consumption and the amount of production of renewable wind and solar resources on the one hand, and the pressure on companies from society and governments to consider different economic, social and environmental dimensions in the electricity supply chain, on the other hand, have caused the design and planning of power systems in the electrical industry to be difficult and challenging [13].

The challenge facing the design of a sustainable supply chain is to find optimal solutions because the purpose of designing a supply chain in the first place is the economic aspect (reducing costs), and this is while paying attention to the environmental and social dimensions will increase the costs [1].

In some cases, the negative environmental effects caused by the generation of electric energy are so significant that they have caused problems in the sustainable development of societies and have caused problems in the social dimension, among which social justice, equality, and sustainable economic development can be mentioned [14].

The planning problem TEL existing power grid (conventional or traditional power supply chain) is designed without regard for large renewable energy farms, regardless of Dispersed Generations (DGs) resources. As a result, using them can create the probability of undesirable conditions such as overloading of lines, unwanted power outages, increased costs, increased carbon emissions, etc.

The necessity of providing a sustainable supply chain development plan (ESCND) in the electrical industry for the expansion of the conventional supply chain (with large and focused products), considering uncertainties, is one of the major concerns of power grid beneficiaries in this study. Also, an optimized investment model for developing a multiobjective sustainable supply chain in TEI is proposed with renewable farms and considers economic, environmental, social, and energy security goals in the critical conditions.

The difference between the present study and the previous domestic and foreign studies and the existing scientific theory about the research subject

The application of the presented model in the electricity industry

Among the applications of this model in the electricity industry, the following can be mentioned. Table 1 summarized the differences between the present work with previous studied in terms of research objectives. 1. Providing an optimal model for the development of the supply chain of the common electricity industry and examining the benefits of changing the approach from large and centralized productions and moving towards distributed and small productions in the supply chain of the electricity network with the approach of reducing losses, increasing reliability, reducing costs and environmental pollutants. 2. The optimal multi-objective economic, environmental, social, and security investment model in the supply chain of the TEL electricity network. 3. Examining the effect of the presence of renewable resources in the form of small distributed generation in the sustainable supply chain. 4. Reducing investment costs in the field of power transmission and network modeling in the probabilistic space. 5. Providing the investment model and determining the capacity and optimal installation location of renewable and non-renewable distributed generations in the common supply chain 6. Reducing loss of energy and unsupplied energy and thus increasing the reliability of energy supply in the common electricity supply chain.

SOLUTION APPROACH(S)

This study presents an effective and efficient method for security and probably planning of the TEI supply chain development, considering the uncertainty of renewable resources production and consumed peak load uncertainty. In the proposed method, the effect of existing uncertainties and high-limit changes of load curtailment on the cost of the supply chain investment have been evaluated. Given that the output of the TEI planning problem is the decision to build new lines, this problem can be mathematically modeled as an optimization problem, which includes two parts: objective function and constraints. Due to the research nature of the proposal, it is necessary to use authentic domestic and foreign

Table 1. Difference between the present study and previous studies

No.	Authors	Mathematical modeling	Providing multi-objective function	Problem-solving techniques	Reducing energy loss	Reliability	Uncertainty	Objective function
1	Yun et al. [15]	✓						Control system, business and reducing greenhouse gas emissions
2	Bayatloo and Bozorgi-Amiri [13]	✓				✓	The power station and transmission lines of consumption points	Objectives include cost, network effectiveness, facility location, reliability, and capacity planning.
3	Jabbarzadeh et al. [2]	✓	✓					There is a conflict between economic and environmental objectives.
4	Gbadamosi and Nwulu [16]	✓						The study of the reliability indicators in the development of the electricity supply chain is stated, along with the studies of the uncertainty of the subscriber's load.
5	The present research model	✓	✓	Weighing	✓	✓	Demand and production of renewable resources	This research aims to present the optimal investment model for developing two supply chains of the traditional and modern electricity industry with the approach of solving economic, environmental, social, and security problems.

scientific resources, consult with specialists, and use library resources and recent articles for information education and data collection tools. Data analysis is done using computer simulation with MATLAB or GAMS software. A genetic algorithm and PSO introduce the TEI model. This algorithm is taken from the behavior of nature and living creatures.

TEI SUPPLY CHAIN MATHEMATICAL MODEL

The TEI supply chain planning is done to develop the power grid at the lowest cost so that it also meets all the technical constraints of the grid. By doing this, the installation location and the number of lines required between different areas of the grid will be identified to transfer the electrical energy generated by centralized power plant units with acceptable reliability to the end consumer. Environmental problems caused by greenhouse gases and the topic of global warming have caused the influence of renewable energy-based products in the TEI supply chain. The influence of these resources, despite the uncertainty of their output power, has faced power grid supply chain planning with serious challenges.

The main variables of decision-making in the supply chain design (SCND) models are binary variables related to location, size decision-making, selection of appropriate technology levels, and selection of transportation modes between installations. Since the product flows are generally modeled along the supply chain in general with continuous constraints, SCND models are often mixed integer relations that can be linear or non-linear. Some random models are also found that allow uncertainty, such as demand level. In general, a wide range of modeling techniques have been used to address sustainable SCND problems, the most used technique being mixed integer programming (MIP) for linear or non-linear problems. Some models consider a single goal that combines economic and environmental or sometimes social factors. However, most models explicitly consider two or three different goals or sometimes more [13, 17, 18].

This study presents an effective and efficient method for security and probably planning of the TEI supply chain development, considering the uncertainty of the consumed peak load and the uncertainty of renewable resources production. In the proposed method, this sector is considered a high limit for the permissible load curtailment. The effect of existing uncertainties and high-limit changes of load curtailment on the cost of supply chain investment is evaluated. A genetic algorithm and PSO will solve the final optimization problem.

Indicators and variables

According to Figure 1, each power network consists of a set of areas and lines. These areas are called nodes. The lines between the nodes are called the route, and the consumers of each node are called the load, and the transmitted power between the two nodes is the total power passing through all routes between these two nodes.

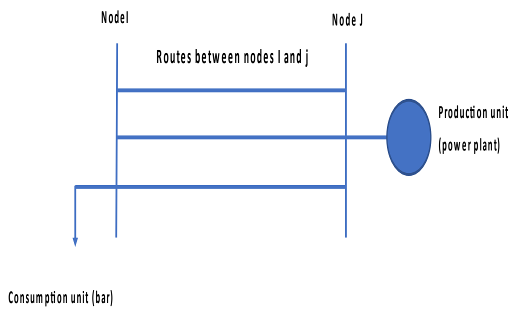

Figure 1. The schematic of a power network

Indicators and variables

Each node intersects different routes that can or do not have a production and consumption unit. Production units are renewable. The meaning of the node's production power or the node or the consumption power of the node is actually the total power produced or consumed by the sum of the production and consumption units in each node. The power transferred between two nodes means the total power passing through all routes between these two nodes. Table 2 summarized the indicators and variables of the mathematical model. The variables and indicators of the TEI supply chain mathematical model are used as follows:

Table 2. Indicators and variables of a mathematical model

Indicator of nodes	i, j, n, m, k
Non-renewable and renewable production units (wind) indicator	g and w
The total set of nodes (β), load nodes (δ), non-renewable production units (G), and renewable production units (WG)	WG, G, Δ, B
The number of newly added transmission lines between nodes i and j (the main variable of decision)	n_{ij}
Power passing through the transmission line between nodes i and j (MW)	L_{ij}
Load power lost in node k (MW)	f_k
Production power of non-renewable unit g in node i (MW)	$P_{i,g}$
Production power of renewable (wind) unit w in node i (MW)	$P_{i,w}$
Power passing from the transmission line between nodes I and J by assuming the line interruption between nodes m and n (MW)	$L_{i,j}^{m,n}$

Indicator of nodes	i, j, n, m, k
Production power of unit g in node i with the assumption of line interruption between nodes m and n (MW)	$P_{i,g}^{mn}$
Power is lost in the node k if the line exits the nodes between m and n (MW)	f_k^{mn}
The number of grid lines at the beginning of the planning horizon between nodes i and j	n_{ij}^0
The maximum number of new lines allowed to be built between nodes i and j	$\bar{n}_{ij}$
Maximum production of unit g in node i (MW)	$\bar{P}_{i,g}$
Maximum demand at node i (MW)	d_i
Maximum transmission line capacity between nodes i and j (MW)	$\bar{L}_{ij}$
Maximum load curtailment power in node k ($/MW)	$\bar{f}_k$
Lost load penalty ($/MW)	τ
The cost of adding a new route between nodes i and j ($/MW)	π_{ij}
Scale equality coefficient of each component of the final objective function	ω_1 ،ω_2 ، ω_3 and ω_4
Total CO_2, NO_X, and SO_2 pollutants (in kg) produced for the production of each 1mW energy per production unit g in node i (Kg/MW)	$\alpha_{i,g}$

Objective functions

This study aimed to provide a multi-objectives sustainable supply chain optimization model in TEI and focuses on the four objectives of economic, environmental, social, and energy supply security in critical conditions. The four main objectives in the TEI supply chain are considered. These four objectives are stated as follows:

The economic objective function is seeking to minimize the cost of establishing and expanding the TEI supply chain lines in order to respond to the demand for peal load of the subscribers with minimal investment in the planning horizon, and it is modeled as follows:

$$ECOF = \sum_{(i,j)\in \mathrm{B}} \pi_{ij}\, n_{ij} \tag{1}$$

The social objective function minimizes the lost load and the unsupplied energy of subscribers in the planning horizon. In this objective function, according to the following relation, for any unsupplied load, the penalties are considered to move the general objective function of the system to maximize load supply.

$$ROF = \tau \sum_{k\in\Delta} f_k \tag{2}$$

The N-1 criterion is used in the security objective function. According to this criterion, the model is planned so that, for any reason, one of the lines (routes) is removed from the circuit; the system is designed to continue its performance and not interfere with the TEI supply chain. This objective function is defined as the amount of energy unsupplied in node K if the k is left out of the route between the nodes m and n.

$$SOF = \tau \sum_{(m,n)\in\Psi,\mathrm{k}\in\Delta} f_k^{mn} \tag{3}$$

The environmental objective function includes the penalty for the release of pollutants produced by non-renewable producers:

$$EOF = \sum_{g\in G} P_{i,g}\,.\,\alpha_{i,g} \tag{4}$$

The general objective function mathematical model of the TEI supply chain is stated in the following relation:

$$OF\text{: } \min[\,\omega_1\{ECOF\} + \omega_2\{SOF\} + \omega_3\{EOF\} + \omega_4\{ROF\}] \tag{5}$$

$$OF\text{: } \min\left\{\begin{array}{c} \omega_1\left(\sum_{(i,j)\in\mathrm{B}} \pi_{ij}\, n_{ij}\right) + \\ \omega_2\left(\tau \sum_{k\in\Delta} f_k\right) + \\ \omega_3\left(\tau \sum_{(m,n)\in\Psi,\mathrm{k}\in\Delta} f_k^{mn}\right) + \\ \omega_4\left(\sum_{g\in G} P_{i,g}\,.\,\alpha_{i,g}\right) \end{array}\right\} \tag{6}$$

ω_1, ω_2, ω_3, and ω_4 are the weighting coefficient to equalize the scale of each component of the objective function. In other words, these coefficients make it possible to equalize objective functions.

In order to equal the scale changes in each objective function, their final value normalizes between the minimum and maximum value based on the following relations. Suppose the minimum and maximum value of each component of the objective function is specified with the Min and MAX indices. In that case, the weighting coefficients are obtained from the following relations. To calculate the minimum and maximum values for each objective function, the problem is solved as a single objective, and the values of the worst and best scenarios are included.

$$\frac{\omega_1}{\omega_2} = \frac{ECOF^{max} - ECOF^{min}}{SOF^{max} - SOF^{min}} \tag{7}$$

$$\frac{\omega_1}{\omega_3} = \frac{ECOF^{max} - ECOF^{min}}{EOF^{max} - EOF^{min}} \tag{8}$$

$$\frac{\omega_1}{\omega_4} = \frac{ECOF^{max} - ECOF^{min}}{ROF^{max} - ROF^{min}} \tag{9}$$

Probabilistic math model

In this section, stochastic and probabilistic modeling is intended to minimize the predictive error rate based on the Monte Carlo [16] simulation. In the proposed model of the TEI supply chain development, the following are considered stochastic and uncertainty:

- Producing renewable resources according to the weather conditions
- The value of a load of subscribers
- Availability of any of the lines (routes)

Given that the renewable source used in this part of the research is the type of wind farms, in order to model the output power changes of wind turbines, information received from wind blow records and its velocity (V) is used to model the probability density function (PDF) of wind turbine production. Rayleigh PDF is used to model wind velocity. This function can be calculated from the following relation for changes in the wind velocity

$$PDF(v) = \left(\frac{v}{sf^2}\right).exp\left[-(\frac{v^2}{2sf^2})\right] \tag{10}$$

In this relation, v and sf are the average wind velocity and the scale factor, respectively. The relation between the production power of wind farms and the wind velocity is further stated:

$$P_w(v(t)) = \begin{cases} 0 & , \; v(t) < v_{ci} \\ \frac{v(t)-v_{ci}}{v_r - v_{ci}} * P_r, & v_{ci} < v(t) < v_r \\ P_r & , \; v_r < v(t) < v_{co} \\ 0 & , \; v(t) > v_{co} \end{cases} \tag{11}$$

where v_{ci}, P_r, v_{co}, and P_{wtg} are internal cut-in velocity, external power, external cut-in velocity, and the output power of the wind turbine, respectively.

In addition, the uncertainty of the load is also considered a random variable whose forecasting errors are modeled using a normal PDF.

The renewable source used in this study is the type of wind farms; in addition, the uncertainty of the load is also considered a stochastic variable, whose predictive errors are modeled using a density function of the normal probability.

Each route has a specific failure rate based on life and geographical location. The normal probability density function is also used to examine the failure and lack of availability of lines. It should be noted that demand, wind speed, and availability of transmission lines are assumed independent variables.

The problem-solving steps in the probabilistic space are as follows:

1. The mandatory exit rate is considered for each of the routes.
2. The demand on the planning horizon determines the parameters of the probabilistic density function.
3. Getting mean ($V_{W,Mean}$) and standard deviation values (σ_w) of wind speed according to the information obtained from the Rayleigh density function indicating the wind speed at the wind turbine.installation
4. Producing many probabilistic density functions of exit rate and comparison with the exit rate of each line as specified in step 1. This number is compared with the lack of availability to each line. If this value is less than the lack of availability, the line will be removed; otherwise, the line will remain in the circuit.
5. Producing many probabilistic density functions of demand specified in step 2 and calculating the amount of demand for each node
6. Producing a number of the probabilistic density function of the wind speed specified in step 3.
7. After going through steps 3 to 6, respectively, the grid configuration (according to the removed route or routes), the value of the load, and the amount of production of wind units are randomly obtained.
8. The obtained information solves the useful optimization problem and saves the output information.

The TEI supply chain constraints are as follows:

$$\begin{aligned} & L_{i,j}^{mn} + P_{g,i}^{mn} + P_{w,i} + f_i^{mn} = d_i \\ & (i,j) \in \mathrm{B}, (m.n) \in \Delta, \mathrm{g} \in \mathrm{G}, \mathrm{w} \in \mathrm{WG} \\ & |L_{ij}| \leq (n_{ij}^0 + n_{ij})\bar{L}_{ij} \quad , \; (i,j) \in \mathrm{B} \\ & 0 \leq P_{i,g} \leq \overline{P_{i,g}} \quad , \quad g \in G \\ & 0 \leq f_k \leq \bar{f}_k \quad , \quad (m.n) \in \Delta \\ & 0 \leq n_{i,j} \leq \bar{n}_{i,j} \quad , \quad (i.j) \in \mathrm{B} \end{aligned} \tag{12}$$

Production modeling of small wind units

Rayleigh PDF is used to model the wind velocity behavior appropriately in each forecasting period. Rayleigh PDF is a particular type of Weibull PDF.

$$f_w(v) = \left(\frac{2v}{c^2}\right) exp\left[-\left(\frac{v}{c}\right)^2\right] \tag{13}$$

where fw(v), c, and v are the Rayleigh PDF, the scale factor, and the wind velocity, respectively, if the wind mean velocity (VM) for one area is specified, then the scale factor c can be calculated as shown in the following relations.

$$\begin{aligned} v_m &= \int_0^\infty v f_w(v) dv = \int_0^\infty \left(\frac{2v^2}{c^2}\right) exp\left[-\left(\frac{v}{c}\right)^2\right] dv \\ &= \frac{\sqrt{\pi}}{2} c \\ c &\cong 1.128 v_m \end{aligned} \tag{14}$$

The power produced by the turbine is calculated as the following relation.

$$P_g^{DG}(v) = \begin{cases} 0, 0 \leq v_{aw} \leq v_{ci} \\ P_g^{rated} \times \frac{(v_{aw} - v_{ci})}{(v_r - v_{ci})}, P_{rated} v_r \leq v_{aw} \leq v_{co}, v_{ci} \leq v_{aw} \leq v_r \\ 0, v_{co} \leq v_{aw} \end{cases} \tag{15}$$

where vci, vr, and $P_g^{DG}(v)$vco are cut-in velocity, nominal velocity and cut-off velocity of the wind turbine in the area, and output power of the g[th] distributed generation unit of wind type for v wind velocity.

Solar power production modeling

The output power of the photovoltaic unit depends on the radiation intensity. The clock distribution of radiation in a particular situation usually follows a two-peak distribution, which is a linear combination of two single-peak distribution functions. For each single-peak function, a PDF of the beta is used below.

$$f_b(si) = \begin{cases} \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)} \times si^{(\alpha-1)} \times (1-si)^{(\beta-1)}, for 0 \le si \le 1, \alpha \ge 0, \beta \ge 0 \\ 0, otherwise \end{cases} \quad (16)$$

where Si indicates the sun's radiation (kW/m^2), to calculate the parameters of the beta distribution function (α, β), the mean and standard deviation of the random variables are calculated as follows.

$$\beta = (1-\mu) \times \left(\frac{\mu \times (1+\mu)}{\sigma^2} - 1\right) \quad (17)$$

$$\alpha = \frac{\mu \times \beta}{1-\mu} \quad (18)$$

With the distribution of radiation and the transformation function of radiation to power, the distribution of solar power is obtained. The transformation function of radiation to the power used in the study is as follows.

$$P_g^{DG}(si) = \eta_g{}^{DG} \times S_i \times si_i \quad (19)$$

where, $P_g^{DG}(si)$, η^{pv}, and Spv are the output power of the gth distributed generation unit of photovoltaic type for Si radiation (in kW), productivity, and total surface area of the region equipped with photovoltaics in the ith area, respectively.

RESULTS

Initially, the problem of the development of the TEI supply chain is examined definitively, regardless of the uncertainties introduced. The TEI problem is then resolved by considering the three uncertainties, including the uncertainty of the subscriber's electrical energy consumption, the uncertainty of the maximum electrical load curtailment, and the uncertainty of renewable energy-based features, and the results are evaluated.

The exit rate of routes is intended to equal 1% for evaluating the system's security margin. In addition, the amount of penalty lost for the definitive supply chain τ is considered equal to $10^6 \,^{\$}/_{MW}$. It should be noted that the maximum $\bar{n}_{ij} = 4$ can be added between two nodes. The economic, social, security and environmental effects on the final objective function are considered equal.

Test grid

The TEI proposed method is applied to the test grid with six areas. According to development planning, a new unit will be built on the grid to increase the load consumption on the grid. Figure 2 shows the Schematic of ESC with new production units and loads.

The proposed development plan is used to build new lines to supply the added loads optimally. Information on the capacity of the production units and load consumption of subscribers in each area, and the capacity and cost of installing lines in the grid are specified in the related Tables 3 and 4.

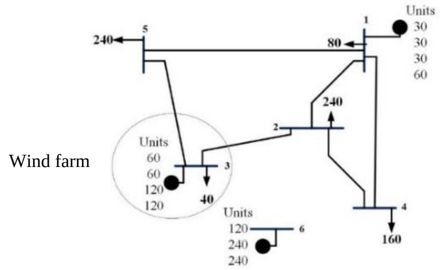

Figure 2. Schematic of ESC with new production units and loads

Table 3. Information on production units and consumption of subscribers (Garver, 1970)

Area No.	Maximum production (MW)	Emission (kg/MWh)	Value of load (MW)
1	150	723	80
2	0	0	240
3	360	310	40
4	0	0	160
5	0	0	240
6	600	610	0

Table 4. Line information (Garver, 1970)

The number of the two areas at the beginning and end of the line	The initial number of lines	Line capacity (MW)	Line installation cost ($k)
1-2	1	100	40
1-3	0	100	38
1-4	1	80	60
1-5	1	100	20
1-6	0	70	68
2-3	1	100	20
2-4	1	100	40
2-5	0	100	31
2-6	0	100	30
3-4	0	82	59
3-5	1	100	20
3-6	0	100	48
4-5	0	75	63
4-6	0	100	30
5-6	0	78	61

Development of definitive TEI supply chain with fixed production values for production units

A) Without considering the security objective function

By solving the objective function by both algorithms to fulfill the system constraints and adequacy of the problem regardless of uncertainties and security objective function, adding three new lines between areas 4 and 6 ($n_{46} = 3$), one new line between areas 3 and 5 ($n_{35} = 1$) and 1 line between areas 2 and 3 ($n_{23} = 1$) are needed. The total investment cost without any lost electrical energy is \$ 130,000. Table 5 summarized definitive TEI regardless of security constraints.

B) With considering the security objective function

By solving the TEI and considering the general objective functions, the results of both algorithms indicate the supply chain needs to add seven new lines, according to the related table. Also, the total investment cost without lost load and with the security criteria of the N-1 in this case of \$ 180,000. This test is performed with three different priorities between the objective functions. Table 6, the test results are calculated when the weight of all objectives is equal. In Table 7, the weight of the environmental objective function has increased. As can be seen, with the increasing weight of the environmental objective function, the model has moved towards fewer pollution products. For this reason, the amount of pollution has decreased by 4200 kg. However, the investment cost has increased by \$ 40,000 due to less attention to the economic objective than the previous one.

On the other hand, in Table 8, the weight of the economic objective function has increased more than others. According to the results of this table, the investment cost is \$ 30,000 less than Table 6 and \$ 70,000 less than Table 7. However, due to less attention to the environmental objective function, the number of emissions increased by 1440 kg more than in Table 6 and 5650 kg more than in Table 7.

Definitive TEL with changeable and adjustable production values between production units

This test has been performed to examine the effect of adjustment point changes on the production units on the TEI supply chain development plan. In this test, the total production power is considered 760 MW. This amount of power is unevenly divided between the three grid production units. The effect of changes in the adjustment points of production units on TEI is evaluated.

Suppose the amount of production of units located in areas 1, 3, and 6 is adjusted in accordance with Table 9. In that case, new lines and investment costs will be

Table 5. Definitive TEI regardless of security constraints

Added lines		
$n_{46} = 3$	$n_{35} = 1$	$n_{23} = 1$
	Production power	
$P_{1,1} =$ 149 (MW)	$P_{3,2} =$ 312.8(MW)	$P_{6,3} =$ 298.2 (MW)
	Investment cost	
	130,000 \$	
	Lost load	
	0	
	Greenhouse gas emissions (kg)	
	386600	

Table 6. Definitive TEI balanced between all objective functions with considering N-1 security criteria

Added lines			
$n_{46} = 3$	$n_{26} = 1$	$n_{35} = 2$	$n_{23} = 1$
	Production power		
$P_{1,1}$ $= 131\ (MW)$	$P_{3,2} = 357.7(MW)$		$P_{6,3}$ $= 271.3\ (MW)$
	Investment cost		
	180,000 \$		
	Lost load		
	0		
	Greenhouse gas emissions (kg)		
	371100		

Table 7. Definitive TEI with the priority of environmental objective function with considering N-1 security criteria

Added lines			
$n_{46} = 2$	$n_{26} = 2$	$n_{35} = 3$	$n_{23} = 2$
	Production power		
$P_{1,1} =$ 100 (MW)	$P_{3,2} = 360(MW)$		$P_{6,3} =$ 300 (MW)
	Investment cost		
	220,000 \$		
	Lost load		
	0		
	Greenhouse gas emissions (kg)		
	366900		

Table 8. Definitive TEI with the priority of economic objective function with considering N-1 security criteria

Added lines			
$n_{46} = 2$	$n_{26} = 1$	$n_{35} = 2$	$n_{23} = 1$
	Production power		
$P_{1,1} =$ 150 (MW)	$P_{3,2} = 360(MW)$		$P_{6,3} =$ 250 (MW)
	Investment cost		
	150,000 \$		
	Lost load		
	0		
	Greenhouse gas emissions (kg)		
	372550		

calculated according to the table by solving the TEI security development planning problem. Table 10 stated the definitive TEI considering N-1 security criteria in the event of production according to the table above.

But suppose the production value of the units located in areas 1, 3, and 6 is adjusted following Table 11. In that case, the new lines will be calculated in Table 12, and the investment cost will be 318 k$ by solving the TEI security development planning problem.

Finally, by adjusting the production points following Table 13, the combination of new lines is obtained in Table 14.

According to the results of the previous test, the effect of adjustment points changes between production units to the constant power production of the units, as well as the effect of security constraints along with the system adequacy on the configuration and investment cost of the TEI supply chain, is quite tangible. In operating the power system, the share of production of each unit of the total power required by the grid is determined by the price offers from units and the market settlement point. In the test grid, the investment and system expansion plan is heavily dependent on the unit production of area 3 because this area is located near the large consumption loads of the system, i.e., areas 2 and 3.

Table 9. The amount of power distributed between production units

$P_{1,1}$ (MW)	$P_{3,2}$ (MW)	$P_{6,3}$ (MW)
50	165	545

Table 10. Definitive TEI considering N-1 security criteria in the event of production according to the table above

Added lines			
$n_{46}=3$	$n_{26}=4$	$n_{35}=2$	$n_{36}=1$
Investment cost			
298,000 $			
Lost load			
0			

Table 11. The amount of power distributed between production units

$P_{1,1}$ (MW)	$P_{3,2}$ (MW)	$P_{6,3}$ (MW)
130	85	545

Table 12. Definitive TEI with considering N-1 security criteria in the event of production according to the table above

Added lines				
$n_{46}=3$	$n_{26}=4$	$n_{35}=2$	$n_{36}=1$	$n_{15}=1$
Investment cost				
318,000 $				
Lost load				
0				

Table 13. The amount of power distributed between production units

$P_{1,1}$ (MW)	$P_{3,2}$ (MW)	$P_{6,3}$ (MW)
50	265	445

Table 14. Definitive TEI with considering N-1 security criteria in the event of production according to the table above

Added lines		
$n_{26}=4$	$n_{46}=3$	$n_{35}=3$
Investment cost		
270,000 $		
Lost load		
0		

Probabilistic TEI

A) Probabilistic TEI without considering renewable energy-based units

In this section's first three series of simulations, no renewable energy-based production is considered. The standard deviation of loads PDF in each area is considered equal to (0%, 10%, and 5%), respectively, to examine the effect of peak load uncertainty on TEI. For each peak load standard deviation, three values of the maximum load curtailment (0%, 10%, 5%) are considered. These values are expressed as a percentage of the maximum load consumption of the system. The results of each simulation are stated in the following tables. Table 17 summarized the probabilistic TEI considering N-1 security criterion and 10% peak load uncertainty.

Table 15. Probabilistic TEI considering N-1 security criterion and 0% peak load uncertainty

The standard deviation of the loads' PDF									
0%									
Maximum load curtailment									
0%				5%			10%		
Added new lines									
n_{46}	n_{35}	n_{23}	n_{26}	n_{46}	n_{35}	n_{23}	n_{46}	n_{35}	n_{23}
3	2	1	1	3	2	1	3	1	1
investment cost									
180,000 $				150,000 $			130,000 $		
Greenhouse gas emissions (kg)									
371100				347920			324740		

Table 16. Probabilistic TEI considering N-1 security criterion and 5% peak load uncertainty

The standard deviation of the loads' PDF										
5%										
Maximum load curtailment										
0%				5%				10%		
Added new lines										
n_{46}	n_{35}	n_{23}	n_{26}	n_{46}	n_{35}	n_{23}	n_{26}	n_{46}	n_{35}	n_{23}
3	2	2	1	3	2	1	1	3	2	1
investment cost										
200,000 $				180,000 $				150,000 $		
Greenhouse gas emissions (kg)										
394280				371100				347920		

Table 17. Probabilistic TEI considering N-1 security criterion and 10% peak load uncertainty

The standard deviation of the loads' PDF											
10%											
Maximum load curtailment											
0%				5%				10%			
Added new lines											
n_{46}	n_{35}	n_{23}	n_{26}	n_{46}	n_{35}	n_{23}	n_{26}	n_{46}	n_{35}	n_{23}	n_{26}
3	2	1	2	3	2	2	1	3	2	1	1
investment cost											
210,000 $				200,000 $				180,000 $			
Greenhouse gas emissions (kg)											
417460				394280				371100			

According to the results of these tables, the final planning plan to expand the TEI supply chain is significantly affected by peak load uncertainty and maximum load curtailment. As expected, for the same amount of maximum load curtailment, the investment cost increases with an increase in peak load uncertainty. On the other hand, the configuration is chosen when the amount of the load curtailment increases, which has less investment cost. It is noteworthy that for the uncertainty of peak load equal to zero and load curtailment equal to zero, the result is similar to the previous test in TEI conditions with security constraints.

B) Probabilistic TEL with considering the renewable energy-based units

In order to simulate wind uncertainty as a renewable energy-based production unit and its effect on the TEI problem, a wind unit with 120 MW nominal capacity is installed in area 3, and parameters $V_{ci} = 3.5\ {}^{m}/_{S}$, $V_{co} = 25\ {}^{m}/_{S}$, and $V_r = 11.9\ {}^{m}/_{S}$ are obtained. The mean wind speed equals $V_{W,Mean} = 7\ {}^{m}/_{S}$ m⁄s, and its standard deviation equals $\sigma_W = 2.5\ {}^{m}/_{S}$. Considering the 10% standard deviation to model the uncertainty of the peak load and the different values of the maximum load curtailment, the TEI solution results are obtained according to Table 18.

In Table 19, the probability of load curtailment (P_R) is also evaluated for configuration with the lowest investment cost in different wind features.

According to the development investment plan stated in Table 19, adding only one new line (n_{26}) compared to the solution obtained in the definitive TEI (the previous test), the probability of load curtailment and restricting loads can be maintained at a satisfactory level. However,

Table 18. Probabilistic TEL considering the renewable energy productions and N-1 security criteria and 10% peak load uncertainty

The standard deviation of the loads' PDF													
10%													
Maximum load curtailment													
0%					5%					10%			
Added new lines													
n_{46}	n_{35}	n_{26}	n_{23}	n_{15}	n_{46}	n_{35}	n_{26}	n_{23}	n_{15}	n_{46}	n_{35}	n_{26}	n_{23}
3	2	3	1	1	3	2	2	1	1	3	2	2	1
investment cost													
260,000 $					230,000 $					210,000 $			
Greenhouse gas emissions (kg)													
387460					364280					341100			

Table 19. Probabilistic TEL with considering the renewable energy productions and N-1 security criteria and 10% peak load uncertainty in wind parameters conditions in fixed investment costs

The standard deviation of the loads' PDF											
10%											
Mean wind speed equal to $V_{W,Mean}$ and standard deviation σ_W											
$V_{W,Mean} = 5.5\ {}^{m}/_{S}$ $\sigma_W = 2\ {}^{m}/_{S}$				$V_{W,Mean} = 7\ {}^{m}/_{S}$ $\sigma_W = 2.5\ {}^{m}/_{S}$				$V_{W,Mean} = 10\ {}^{m}/_{S}$ $\sigma_W = 3.5\ {}^{m}/_{S}$			
Added new lines											
n_{46}	n_{35}	n_{23}	n_{26}	n_{46}	n_{35}	n_{23}	n_{26}	n_{46}	n_{35}	n_{23}	n_{26}
3	2	1	2	3	2	1	2	3	2	1	2
investment cost											
210,000 $				210,000 $				210,000 $			
Greenhouse gas emissions (kg)											
342600				341100				338100			
The probability of load curtailment with considering the fixed investment cost and changing wind parameters (PR)											
0.112				0.059				0.031			

part of the conventional load capacity is provided by the unit in node 3.

Uncertainty of wind unit production increases the risk of planning and thus increases the investment cost to achieve a configuration with similar results in the system adequacy and security standards. When the wind speed is low, the probability of load curtailment increases, but it reduces environmental pollutants.

Different scenarios to evaluate simulation

A) Scenario 1

The purpose of this scenario is to study the status of the supply chain before updating and installing DG units and applying the proposed method. Given that electrical energy is provided by different fuel-based large power plants, in this case, the pollution rate produced to provide each MWh of electrical energy is considered to be 810 kg. The results of the first scenario are stated in Table 20.

One of the biggest problems with the conventional supply chain is the low reliability of the energy supply. Given the one-sided and radialness of this chain, if one of the routes of the grid is damaged, the total energy of the downstream subscribers is disconnected, causing many economic and social damages.

B) Scenario 2

In this scenario, a state of installing DGs is suggested that the costs and energy losses are minimal; that is, only economic and social objectives are considered. Given that there is no limit to the production of environmental pollutants in this scenario, the model uses DGs with the lowest cost. For this reason, all DGs are selected from the diesel generator. The results of the second scenario is stated in Table 21.

C) Scenario 3

In this scenario, all the objectives stated earlier are considered. In other words, it is suggested that the installation of DGs is suggested to minimize the number of energy losses and pollution produced in the grid in addition to the loss of costs and energy. Given that the amount of pollutants is also one of the objective functions in this scenario, it uses DGs to lower pollution and cost as much as possible. For this reason, the microturbine has been selected among the non-renewable DGs. In addition, the solar panel has been preferred to the wind turbine among renewable units due to lower costs. The results of the third scenario are stated in Table 22.

Table 20. The results of the first scenario

Energy loss (kWh)	Unsupplied energy (kWh)	Pollution rate (kg/kWh)
320	200	3094.2

Table 21. The results of the second scenario

Scenario No	Pollution rate (kg/kWh)	Unsupplied energy (kWh)	Energy loss (kWh)
Scenario 1	3094.2	200	320
Scenario 2	3597.2	0	210

Table 22. The results of the third scenario

Scenario No.	Pollution rate (kg/kWh)	Unsupplied energy (kWh)	Energy loss (kWh)
Scenario 1	309.2	200	320
Scenario 2	3597.2	0	210
Scenario 3	1076	0	90

CONCLUSION

According to the results of the large and centralized supply chain due to the million dollar investment cost, the cost of electricity transmission due to the distance from the place of generation to consumption, environmental pollution due to the use of fossil fuels, lower reliability, social issues, unemployment problems, national production, and energy waste due to the disconnection of transmission network lines, non-participation of the private sector due to the huge cost show the necessity and importance of this issue.

Due to the rapid increase in population followed by the increase in energy demand on the one hand and the limitation of energy resources on the other hand, it is predicted that the world will face a crisis in the not-too-distant future, so one of the basic measures is to reform the energy structure. Energy is considered not only an important component in the development of societies but also a fundamental pillar to achieving the economic development and prosperity of a country in such a way that energy is one of the most important and vital data in people's lives and almost all production and consumption activities in various economic sectors. This has caused the developed countries of the OECD because a large part of the world's GDP and production is in their hands; in recent years, with energy management methods moved towards optimization topics, the use of distributed generations, the consumer side of small power plants with less generation capacity and subsequently to less investment. Due to the use of renewable energies (wind, solar, biomass) can create higher reliability (social, employment, national production issues), lower energy loss, less environmental pollution, and higher energy security.

This study presented an efficient method for supply chain development planning in the power industry with influential renewable production. Along with price factors, the model considers the N-1 security criterion, energy supply reliability as a social objective, and the topic of the emission reduction of environmental pollutants. The supply chain probabilistic model also considered the uncertainty of the production of renewable resources, the peak load consumed, and the uncertainty of the availability of grid routes. The results showed that the types of uncertainties increased the investment cost of the supply chain.

The following showed the necessity of moving the electricity supply chain from a one-way mode with centralized and large generations to a modern supply chain with distributed and small generations. In this regard, the appropriate strategy for determining the optimal location, type, and capacity of these generations in the supply chain of the modern electricity industry was proposed as a useful optimization problem with four objectives minimizing costs, unsupplied energy, generated pollutants, and energy losses.

All kinds of uncertainties increase the investment cost of the supply chain. On the other hand, this cost decreases with the increase of the allowable load that can be interrupted. The effect of wind speed probability parameters that lead to changes in the output power of the wind unit was also evaluated on the supply chain.

Adding the issue of security to the system increases the cost of planning. This increase is the cost that the operator must bear to increase reliability. On the other hand, by changing the adjustment points between the generation units, it is concluded that the closer the large power plants are to the load centers, the line development will be done at a lower cost.

Therefore, according to the results obtained from the research, the political recommendation is to prioritize investment in solar energy in Iran to increase electricity generation from all types of renewable energy sources. The government should support the production of this type of energy in such a way that for solar energy investors, facilities with lower interest rates, more tax exemptions, and if they need imported goods or devices, discounts will be made on their customs tariff. In addition, since today all governments are involved in environmental issues, solar energy can be one of the options to reduce this type of pollution and give different privileges and certificates to those who consume more solar energy.

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Persian Abstract

چکیده

با افزایش جمعیت جهان و محدود بودن منابع انرژی، کشورها با مشکل مصرف انرژی مواجه شده‌اند. بحران‌هایی که کشورها و جوامع بشری را تهدید می‌کند، محدود بودن منابع انرژی‌های تجدیدناپذیر (فسیلی) و نیز افزایش آلودگی‌های زیست محیطی ناشی از مصرف بیش از اندازه سوخت‌های فسیلی و گرمایش کره زمین است. این عوامل محرکی شده است که محققان و سرمایه‌گذاران در بخش انرژی، به سمت مهار و تامین انرژی از منابع تجدیدپذیر شوند. عدم قطعیت ناشی از این تولیدات می‌تواند در هزینه‌های تحمیلی بـه شبکه و بهره‌برداری از شبکه‌های برق، تاثیرات زیادی مانند افزایش قطعی برق و انرژی تامین نشده داشته باشد. برنامه‌ریزی توسعه شبکه یکی از مسائل مهم در سیستم قدرت برای برآوردن رشد تقاضای برق در سال‌های آینده با توجه به توسعه شهری، افزایش رفاه اجتماعی، امنیت انرژی و ایجاد شغل است. هدف‌گذاری نهایی این مدل، کمینه‌سازی تلفات انرژی، هزینه‌های سرمایه‌گذاری و بهره‌برداری، انرژی تأمین نشده و آلاینده‌های زیست‌محیطی است. روش‌های پیشنهادی توسط نرم افزار MATLAB بر روی شبکه برق Garver و شبکه توزیع ۳۳ ناحیه‌ای IEEE پیاده‌سازی و توسط الگوریتم‌های ژنتیک، PSO حل شده‌اند. مدل نهایی را می‌توان به طور موثر برای برنامه‌ریزی زنجیره تامین شبکه برق مرسوم با نفوذ تولیدات مبتنی بر انرژی‌های تجدیدپذیر در ابعاد مختلف اقتصادی، زیست محیطی و اجتماعی بکار گرفت.