Journal of Information Technology Management

Print ISSN: 2008-5893

Online ISSN: 2423-5059

A Mathematical Model for Multi-Region, Multi-Source, Multi-Period Generation Expansion Planning in Renewable Energy for Country-Wide Generation-Transmission Planning

Mohammadreza Taghizadeh-Yazdi

Associate Prof., Department of Industrial Management, Faculty of Management, University of Tehran, Tehran, Iran. E-mail: mrtaghizadeh@ut.ac.ir

Abdolkarim Mohammadi-Balani*

*Corresponding Author, PhD Candidate, Department of Industrial Management, Faculty of Management and Economics, Tarbiat Modares University, Tehran, Iran. E-mail: a_mohammadi@modares.ac.ir

Abstract

Environmental pollution and rapid depletion are among the chief concerns about fossil fuels such as oil, gas, and coal. Renewable energy sources do not suffer from such limitations and are considered the best choice to replace fossil fuels. The present study develops a mathematical model for optimal allocation of regional renewable energy to meet a country-wide demand and its other essential aspects. The ultimate purpose is to minimize the total cost by planning, including power plant construction and maintenance costs and transmission costs. Minimum-cost flow equations are embedded in the model to determine how regions can supply energy to other regions or rely on them to fulfill annual demand. In order to verify the applicability of the model, it is applied to a real-world case study of Iran to determine the optimal renewable energy generation-transmission decisions for the next decade. Results indicate that the hydroelectric and solar power plants should generate the majority of the generated renewable electricity within the country, according to the optimal solution. Moreover, regarding the significant population growth and waste generation in the country's large cities, biomass power plants can have the opportunity to satisfy a remarkable portion of electricity demand.

Keywords: Renewable energy, Generation expansion planning, Transmission, Mathematical programming, Iran.

DOI: 10.22059/jitm.2020.298258.2476

Introduction

The world has seen intense competition over energy resources, especially in current times, when supply and demand are experiencing huge fluctuations (Twidell & Weir, 2015). The inevitable depletion of fossil fuel resources such as oil, gas, and coal has put pressure on industrialized countries to develop plans to promote renewable energy sources against the fossil ones that are abundant in nature and result in no or little environmental pollution (Fizaine & Court, 2015; Szargut et al., 2002). Aside from environmental concerns, economic factors like the recent monotonous decline of oil prices and peak oil production have urged governments to establish rigorous regulation to encourage public and private sectors to shift to renewable sources(Mahmud & Zahedi, 2016).

Experts believe that the large-scale consumption of renewable energy sources like solar, wind, geothermal, hydropower, or biomass can help avoid a significant portion of the current carbon emission and other environmental problems. On the other hand, continuing the current trend of using fossil fuels for generating energy can indeed deplete the resources at an unprecedented rate. With that in mind, it has been several decades that the developed countries are shifting from fossil energy to renewable ones (Droege, 2008). For developing countries, the problem gets even worse if their investment issues are taken into account. The financial structure in the low-end developing countries cannot afford the costs associated with the renewable shift. Iran provides oil to its customers at competitive prices, contributing to the rapid depletion of its oil resources.

Developing an optimal renewable electricity generation expansion plan (REGEP) is a major challenge in shifting toward renewable sources, and making the current system compatible with future needs adds to the challenge (Schwerhoff & Sy, 2017). A considerable effort has been made in the global scientific community to address the issue. However, optimal plans with minimum costs and environmental impacts should be developed.

This study provides a mathematical model toward an optimized multi-period REGEP for renewable energy generation. The objective is to minimize costs concerning electricity generation using different renewable energy types, including wind, solar, geothermal, biomass, and hydroelectric. To make the model even more practical, real-world limitations and considerations are addressed in the model in the form of mathematical constraints.

Iran’s commitment to reduce the Earth’s greenhouse gas emissions, stated in the international environmental conference held in Paris, has made the country place the renewable energy generation in the agenda of the sixth development plan in the form of a bill (Office of Energy and Electricity Planning at Ministry of Energy, 2016). To show the applicability of the proposed mathematical model, it is implemented using Iran’s regional renewable energy generation potentials and for the next ten years.

The remaining parts of the present paper are organized as follows. Section 2 reviews the literature on renewable energy sources electricity generation planning. Section 3 explains the proposed mathematical model in detail. Section 4 provides the results of the implementation of the proposed model to the case study and presents the numerical results obtained. The paper concludes in Section 5.

Literature review

This section reviews the existing literature on the studies related to renewable energy generation in Iran. To keep discussions consistent, two phrases that are frequently used in this study are defined here.

The extent and the importance of renewable generation expansion planning have created an opportunity to apply a broad spectrum of quantitative and qualitative approaches. Such approaches include mathematical modeling, forecasting tools, multiple attribute decision-making, and statistical analysis. Dagoumas and Koltsaklis (2019) compared to the different approaches toward integrating renewable energy generation expansion planning and concluded that the combination of optimization models and perfect forecasting methods could help formulate useful models. Wang et al. (2019) reviewed the application of different deep learning methods as a forecasting module in REGEP and found that each of the five major categories of deep learning models can successfully predict electricity demand or other variables. Iqbal et al. (2014) discussed different components of the mathematical modeling approach for REGEP. The authors collected and compared a wide range of objective functions, constraints, and solution methods from the literature. Kumar and Saravanan (2017) reviewed the approaches of uncertainty modeling for renewable energy generation in microgrids. Multiple Attribute decision-making is another approach that can be used to develop REGEPs (Oree et al., 2017). Kumar et al. (2017) reviewed different MADM methods used in the literature for renewable energy planning. The authors also surveyed different MADM software, KPIs, attributes, and geographic locations, among others. Ecer et al. (2019) proposed a new MADM method to assess the REGEP and sustainability of OPEC members and determined the most sustainable country through sensitivity and comparison analysis. Ilbahar et al. (2019) reviewed and compared various MADM methods used in renewable energy decisions. The authors identified the MADM methods with the highest usage frequency, and renewable sources to be compared in future studies.

While several approaches have been used for REGEP, mathematical modeling optimization remains among the powerful yet popular approaches. Mathematical modeling is suitable for large-scale optimization of the country-level and regional REGEP, while numerical methods are best for deriving insights from the optimization results (Theo et al., 2017). Ajithapriyadarsini et al. (2019) proposed a system for automatic control of renewable energy sources using a differential evolution algorithm based on adaptive fuzzy logic. Results showed that the control system could stabilize the energy generation and transmission of a system with two regions that can transmit renewable energy between them. Zaibi et al. (2018) proposed a sizing methodology for producing freshwater and electricity in remote areas from multiple renewable energy sources. Keles et al. (2017) proposed a Particle Swarm Optimization algorithm for finding the optimal energy mix rates in multi-pulse width modulation energy mixer units in an area with multiple regions that can transmit electricity between them. Djebbri et al. (2018) developed a transmission control system for a multi-region multi-source electricity generation system using the fractional-order model reference adaptive control. Abdelkafi et al. (2018) developed an assisted management control system for a standalone power system that relies on the electricity generated by multiple renewable sources and a supercapacitator storage system. The authors showed that this system could create a reliable balance between electricity generation and consumption. Melamed et al. (2018) proposed a robust optimization methodology to address multi-period multi-source unit commitment planning. The authors developed a hybrid uncertainty measure to maximize the total profit of an electricity generation unit in a deregulated region. San Cristóbal (2012) proposed a goal programming model to optimize the mix of different renewable energy power plants in the northern areas of Spain. The model, whose objective is to minimize deviations from predefined goals, locates five places for the renewable power plants in a multi-source multi-sink network.

Different geographical locations possess different potentials for generating renewable electricity. In regional REGEPs, where each region can generate electricity from various sources and have the option to transmit excess electricity supply, the REGEP should encompass the transmission plan in addition to the electricity generation capacity plan. Chassin et al. (2018) proposed a dispatching policy based on pricing signals from different regions. The policy is applied to a real-world case from North America and showed that it could cut costs by a quarter. Nazir et al. (2020) provided an algorithm for obtaining the optimal transmission plan for an unbalanced deterministic feeder with has high penetration rates of solar photovoltaic. The authors proposed an initial non-convex mathematical program and then reformulated it into a convex second-order cone program (SOCP) one.

Naval et al. (2020) proposed a virtual power plant framework for potential investors in the energy sector to hedge against the severe volatilities and fluctuations of the renewable energy market. The authors embedded two hierarchical levels within the power plant to model the processes in two different scopes. De la Nieta et al. (2018) developed a mixed-integer linear programming model the economic dispatch of renewable electricity generated in a multi-region system. The model considers various aspects of the system, including cost, flexibility, and supply-demand balance. Li et al. (2016) developed a data-driven real-time approach for a power dispatch system that seeks to maximize variable renewable generation.

The authors developed a mixed-integer linear programming model in conjunction with a sampling scheme for the system to learn from historical data on how to regulate the dispatching module and parameters to optimize it. Wei et al. (2015) proposed a mixed-integer linear programming model for robust dispatch decisions for energy generation and reservation. The authors separated the dispatch decision into pre-dispatch and re-dispatch decisions, where the energy is re-dispatched according to the realized energy generation in case the pre-dispatching is insufficient.

Iran is located in the Northern hemisphere, west of the Asian continent, and east of the Middle East. As an oil-rich country, Iran currently fulfills 99 percent of its annual demand through non-renewable fossil fuels (Asrari et al., 2012). In line with global trends, Iran has aimed to decarbonize the electricity generation process. As a result, several plans are established for different sectors to replace the fossil fuels with renewable ones. Due to high climate and geographic diversity, the country can produce electricity from almost all of the renewable sources (Hosseini et al., 2013). Therefore, developing single- and multi-source REGEP has attracted many researchers to study the feasibility of such plans.

Mollahosseini et al. (2017) reviewed the current state of renewable and fossil energy generation in Iran and discussed various considerations on renewable energy potentials and possible plans for renewable sources to replace fossil fuels. They concluded that although Iran possesses the potential to generate renewable electricity from renewable sources, the country lacks legislative support. Aghahosseini et al. (2018) formulated an hourly resolution mathematical model for Iran to reach pure renewable energy by 2050. The authors considered two scenarios for demand and optimized the mathematical model for each of the scenarios, proving the feasibility of the targeted pure renewables sources within the planning horizon. Ghorbani et al. (2020) explored the feasibility of a 100% renewable strategy for Iran. The authors obtained levelized cost of the system in each scenario.

Khojasteh et al. (2018) argued that despite Iran’s high potential for marine renewable energy generation, it had been largely neglected. The authors reviewed and assessed Iran’s renewable potentials while dedicating the focus to the wind and tidal energy in the water bodies in the northern and southern parts of the country. Afsharzade et al. (2016) explored the possibilities of promotion and extension of renewable energy in the rural areas of Iran and concluded that an innovative policy and aggressive implementation could increase the renewable energy penetration in rural areas.

The next section presents the details of the proposed mathematical model for renewable electricity generation expansion planning.

Research methodology

This section presents the details of the proposed mathematical model for multi-period multi-source regional renewable electricity generation. The model follows the notation presented in the nomenclature in Table 1. The designed model is a nonlinear programming model that consists of a two-objective function with seven constraints.

Table 1. Nomenclature

Sets	
R	Set of all electricity generation regions, indexed by r
P	Set of all types of renewable energy sources, indexed by p
T	Set of all available planning periods, indexed by t
Parameters	
$uc^{\mathrm{c}}_{r,p}$	Unit construction cost for power plant of renewable source p in region r in ($/MW)
$uc^{\mathrm{op}}_{r,p}$	Unit operation and maintenance cost for power plant of renewable source $p$in region r in ($/MWh)
uc^{d}	Unit transmission cost ($/km)
ct_p	Construction time for a power plant of renewable energy source p (periods)
d_t	Total electricity demand in period t (MWh)
$p^{\max}_{r,p}$	Maximum electricity generation capacity of source p in region r
$d^{\min}_t$	Minimum percentage of electricity demand to be satisfied in period t (%)
b^{mo}_t	Country-level monetary budget for construction and maintenance of renewable sources for period t ($)
s_r	Regional share of total country-level monetary budget and demand (%)
$dis_{r,r'}$	Distance required to transfer electricity between regions r and r'
$u^{\min}$	Minimum utilization share of total regional energy of all types throughout the planning horizon (%)
$ps^{\max}$	Maximum possible share of a renewable source in the total energy mix
$ps^{\min}$	Minimum possible share of a renewable source in the total energy mix
Decision variables	
$X_{r,p,t}$	Electricity generation capacity for renewable energy source p in region r at period t (MW)
Y_t	Electricity generated from fossil fuels in period t (MWh)
$\theta_{r,r'}$	Net electricity dispatched from region r to region r' (MWh)
$C^{\mathrm{c}}_{r,p,t}$	Construction cost for power plant p in region r in period t($)
$C^{\mathrm{op}}_{r,p,t}$	Operations and maintenance cost for power plant p in region r in period t($)
C^{d}	Transmission cost for dispatched electricity ofregion r($)

The proposed model of this work is presented in Equation (1) to Equation (13).

$$\text{Minimize } TC = \sum_{p\in P}\sum_{r\in R}\sum_{t\in T}\left[C^{\mathrm{c}}_{prt} + C^{\mathrm{op}}_{prt}\right] + C^{\mathrm{d}} \tag{1}$$

Subject to:

$$C^{\mathrm{c}}_{r,p,t} = \frac{uc^{\mathrm{c}}_{r,p,t}}{ct_p} X_{r,p,t} \qquad \forall p \in P, \forall r \in R, \forall t \in T \tag{2}$$

$$C^{\mathrm{op}}_{r,p,t} = 8760 \times uc^{\mathrm{op}}_{r,p,t} \times X_{r,p,t} \qquad \forall p \in P, \forall r \in R, \forall t \in T \tag{3}$$

$$X_{r,p,t} \le p^{\max}_{rp} \qquad \forall p \in P, \forall r \in R, \forall t \in T \tag{4}$$

$$8760 \sum_{r\in R}\sum_{p\in P} X_{r,p,t} \ge d_t \times d^{\min}_t \qquad \forall t \in T \tag{5}$$

$$8760 \sum_{r\in R}\sum_{p\in P} X_{r,p,t} + Y_t = d_t \qquad \forall t \in T \tag{6}$$

$$\sum_{r\in R}\sum_{p\in P}\left(C^{\mathrm{c}}_{r,p,t} + C^{\mathrm{op}}_{r,p,t}\right) + C^{\mathrm{d}} \le b^{\mathrm{mo}}_t \qquad \forall t \in T \tag{7}$$

$$\sum_{p\in P}\left(C^{\mathrm{c}}_{r,p,t} + C^{\mathrm{op}}_{r,p,t}\right) \le s_r \times b^{\mathrm{mo}}_t \qquad \forall r \in R, \forall t \in T \tag{8}$$

$$\sum_{p\in P}\sum_{t\in T} X_{r,p,t} \ge u^{\min} \times \sum_{p\in P} p^{\max}_{r,p} \qquad \forall r \in R \tag{9}$$

$$\sum_{r\in R} X_{r,p,t} \le ps^{\max} \times \sum_{r\in R}\sum_{p\in P} X_{r,p,t} \qquad \forall p \in P, \forall t \in T \tag{10}$$

$$\sum_{r\in R} X_{r,p,t} \ge ps^{\min} \times \sum_{r\in R}\sum_{p\in P} X_{r,p,t} \qquad \forall p \in P, \forall t \in T \tag{11}$$

$$C^{\mathrm{d}} = uc^{\mathrm{d}} \times \sum_{r\in R}\sum_{\substack{r'\in R\\ r\ne r'}} dis_{r,r'} \times \theta_{r,r'} \tag{12}$$

$$\sum_{r'\in R}\theta_{r,r'} - \sum_{r'\in R}\theta_{r',r} = 8760\sum_{p\in P}\sum_{t\in T} X_{r,p,t} - s_r \times \sum_{t\in T} d_t \qquad \forall r \in R \tag{13}$$

The model optimizes energy generation and energy transmission decisions. Equation (2) to (11) consider the energy generation aspect of the model, while Equation (12) and (13)reflect the transmission decisions.

Equation (1) states that the objective is to minimize the total cost (TC), where TC equals the sum of construction, operations, and maintenance costs over the planning horizon, plus the transmission costs. Equation (2) and Equation (3) define the construction cost and operations and maintenance cost, respectively. Equation (4) determines the upper bound of variable $X_{r,p,t}$. Equation (5) states that the electricity generation plan must satisfy a certain percentage of the total electricity demand in each year. Equation (6) defines the balance between renewable electricity and fossil electricity. The sum of the two electricity sources must be equal to the total electricity demand in each year. Equation (7) shows that the total cost in each year must not exceed that year's monetary budget for renewable electricity. Equation (8) determines the electricity consumption of each year in each region proportional to the predefined rates. Equation (9) states that each region should utilize at least a certain percentage of its total renewable potentials. Equation (10) and Equation (11)state that the electricity generation from each of the renewable sources in each year should be within certain bounds. This constraint helps the optimal plan not deviate too much from a balanced energy mix.

Equation (12) defines the total transmission cost as a function of the total amount of electricity distributed between regions and the unit transmission cost. Equation (13) maintains the balance between the total electricity distributed in the national grid and the net consumption of the regions. The regional net consumption is calculated by subtracting the each region' consumption share from its total electricity generation. It is noteworthy that Equation (12) and (13), together with the second term of the objective function, form a minimum-cost flow problem.

Case study and Numerical results

This section presents the results of applying the proposed model to the real-world data obtained in Iran. The country's national grid is divided into 16 electricity generation regions, as displayed in Table 2 ($R = \{1, \dots, 16\}$). The planning horizon was set to $T = \{1, \dots, 10\}$,and five renewable energy sources of solar, wind, hydropower, geothermal, and biomass are considered ($P = \{1,2,3,4,5\}$).

The model was programmed and solved in GAMS. According to the reports, the model consists of 13 blocks of equations, 2375 single equations, seven blocks of variables, 2241 single variables, and 18782 non-zero elements.

Table 2. Iran's electricity generation regions (Iran Ministry of Energy, 2020)

Region	Name	Region	Name
1	Azarbaijan	9	Sistan
2	Esfahan	10	Gharb
3	Bakhtar	11	Fars
4	Tehran	12	Kerman
5	Khorasan	13	Guilan
6	Khuzestan	14	Mazandaran
7	Zanjan	15	Hormozgan
8	Semnan	16	Yazd

The proposed mathematical model should be verified before being solved. The authors consulted with two experts from relevant fields, and they verified the model. The model is then solved with the data for the last four years of renewable electricity generation in Iran. The results are presented in Figure 1.

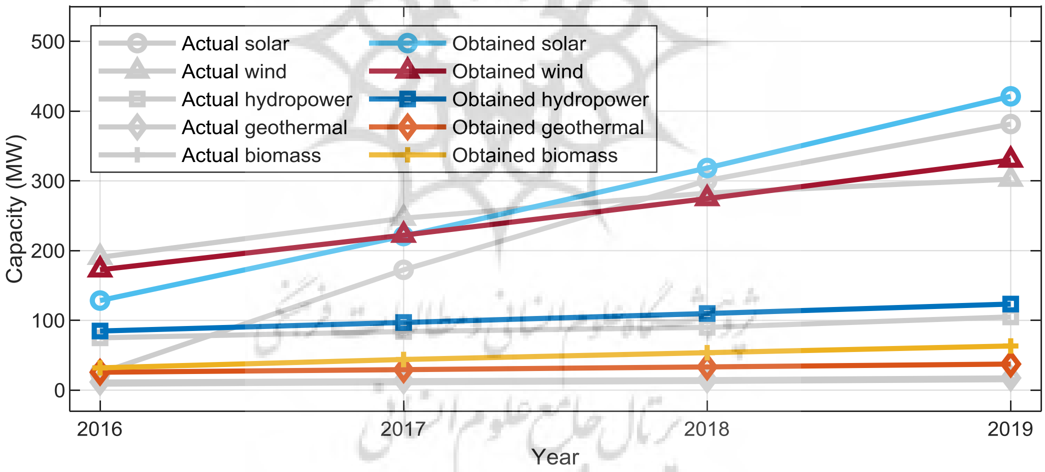

Figure 1. Renewable energy capacity obtained from model vs. historical data

It can be observed that the obtained results for the past four years show similar trends in comparison to real-world data. Wilcoxon's signed rank test is used to determine whether or not the results obtained from the proposed model for each energy source match that of the historical data. The null hypothesis of this test states that the differences between the actual and the optimal obtained capacity come from a continuous distribution with a median equal to zero. In other words, the null hypothesis states that the obtained data conform to the actual data. The alternative hypothesis states the opposite. The exact statistic is used for all of the tests.Table 3 displays the results of the test. The *p*-value of the test for all of the energy sources is greater than $\alpha = 0.05$; therefore, null hypotheses are not rejected and the obtained data from the model conforms to the actual data. This means that the model can produce reliable results for upcoming years, too.

Table 3. Results of Wilcoxon's signed rank test

Source	Statistic	p-value	Retain H_0?
Solar	0	0.125	✓
Wind	6	0.875	✓
Hydropower	0	0.125	✓
Geothermal	0	0.125	✓
Biomass	0	0.125	✓

The model is solved to determine the detailed renewable electricity plan for the next ten years in Iran. Table 4shows how much electricity generation capacity should be built in the next ten years.

Table 4. Renewable energy capacity planning to be built throughout the planning horizon

Year	Solar	Wind	Hydropower	Geothermal	Biomass
2020	529.11	387.82	137.65	41.71	64.83
2021	642.12	448.54	152.57	46.23	78.83
2022	760.27	512.03	168.16	50.96	84.37
2023	883.56	578.28	184.44	55.89	90.36
2024	1011.99	647.28	201.39	61.03	96.92
2025	1145.55	719.05	219.02	66.37	103.93
2026	1284.25	793.58	237.33	71.92	115.68
2027	1428.08	870.87	256.32	77.67	127.17
2028	1577.05	950.91	275.98	83.63	133.65
2029	1731.16	1033.72	296.32	89.79	149.13

Figure 2 visualizes the results of Table 4. It is observed that solar energy is the dominant source for generating renewable electricity. This is in line with the fact that the central, southern, and southeastern areas in Iran are areas with high sunshine hours and solar potential. According to SATBA statistics, solar electricity generation is gaining momentum in Iran. As evident in Figure 1, solar energy generation surpassed wind energy in about the year

2018. Wind energy was the dominant renewable energy source until then and should be the second important renewable electricity source for Iran in the upcoming decade.

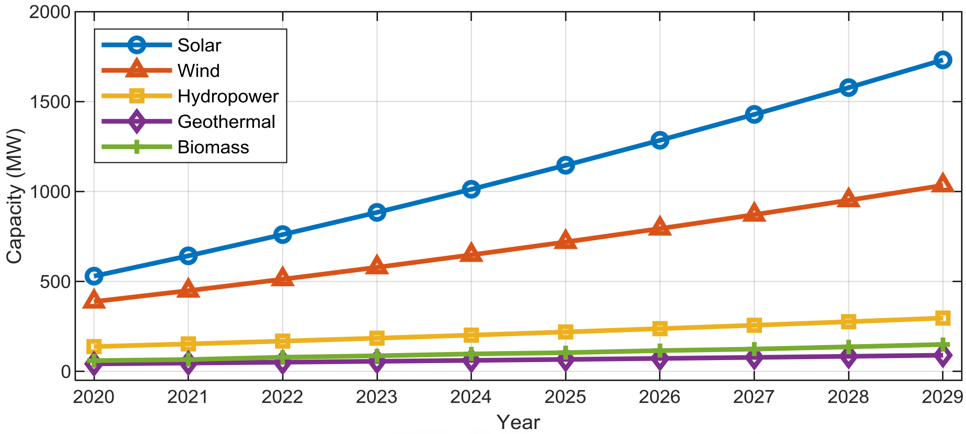

Figure 2. Optimal renewable electricity generation plan

To better understand the details of the optimal solution obtained, the results are portrayed for regions and energy sources. Figure 3shows that regions can be divided into two packs, according to the optimal renewable energy generation plan. It is observed that regions with lower energy generation are the ones that consist of only one province.

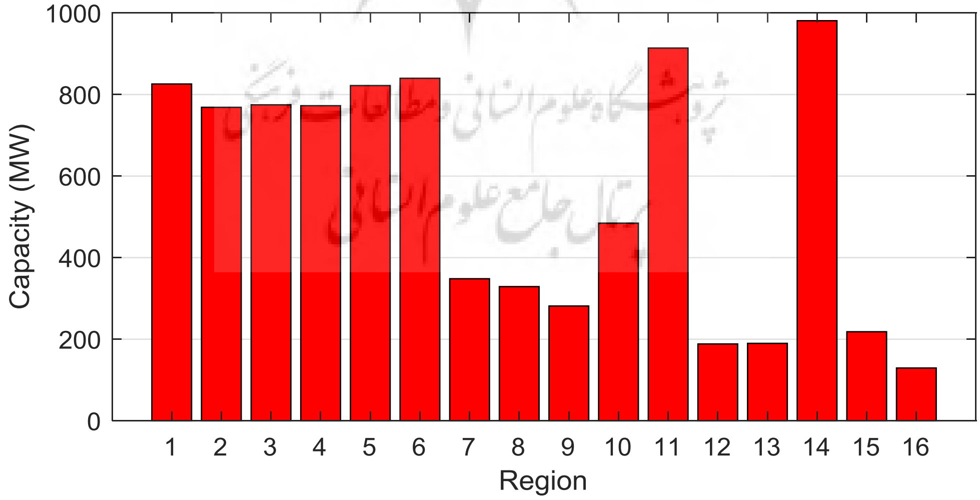

Figure 3. Renewable energy capacity planning by region

Figure 4 shows how much of each renewable energy source should be generated according to the optimal energy mix. Solar energy is, by far, the primary energy source. Solar and wind should produce a significant portion of the country's electricity.

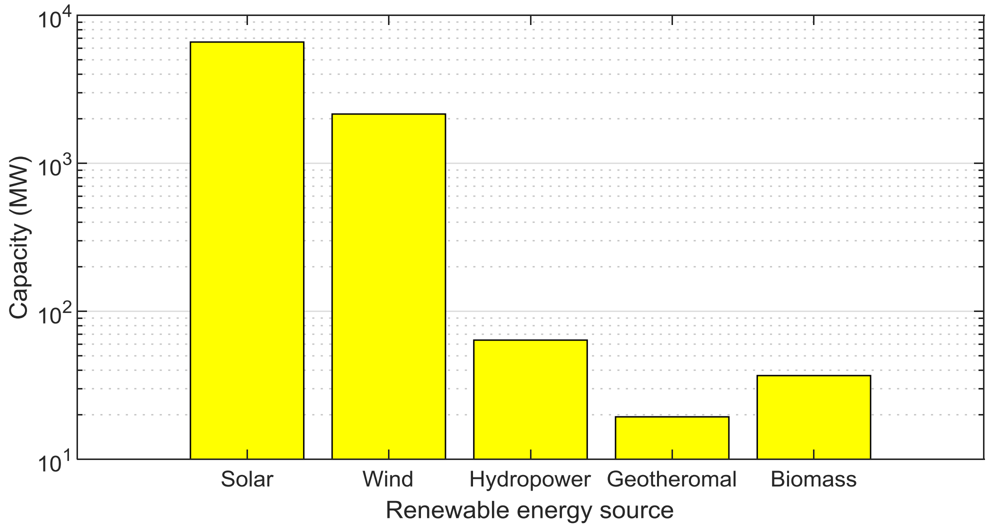

Figure 4. Renewable energy capacity planning by energy source

Figure 5shows how different renewable sources contribute to the total energy mix in the optimal plan obtained by solving the model.

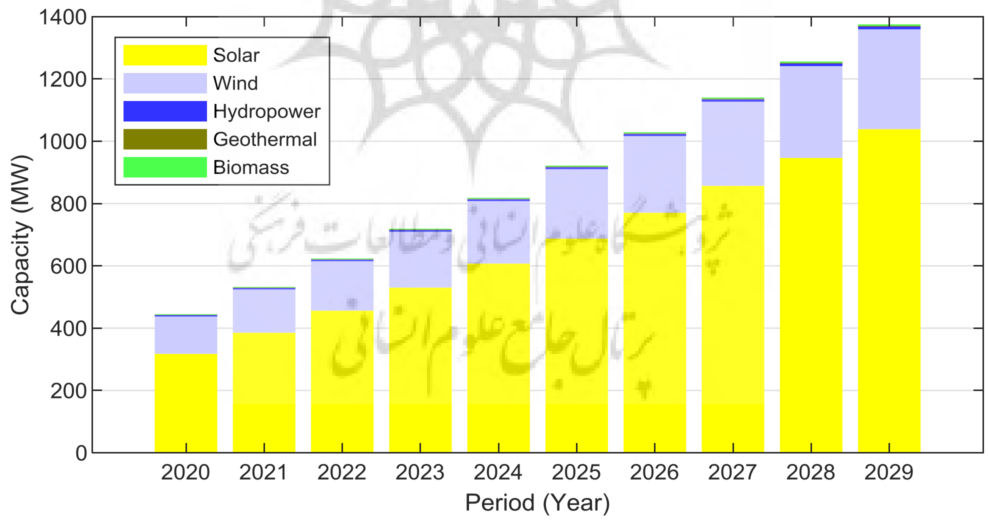

Figure 5. Renewable energy capacity planning stacked by source and year

In addition to the optimal generation capacity, the proposed model can determine the optimal electricity transmission pattern. Figure 6displays the optimal transmission pattern obtained from the results. Values of $\theta_{r,r'}$ are shown above the baseline, while values of $\theta_{r',r}$ are displayed below the baseline. A $\theta_{r,r'} > 0$ for region r means that it generates more electricity than its consumption from any source; therefore, it dispatches the excess electricity to the neighboring regions. In the case of $\theta_{r',r} > 0$, the region r'sdemand exceeds its electricity generation, and receives electricity from neighboring regions. If $\theta_{r,r'} > 0$ and $\theta_{r',r} > 0$, then it is considered a transmission hub. Transmission hubs transfer electricity between two regions that are not contiguous. If $\theta_{r,r'} > \theta_{r',r}$ then region r receives some electricity and adds to it before dispatching to the destination region. Otheriwise, if $\theta_{r,r'} > \theta_{r',r}$, then region r consumes some of the electricity received. In the case of $\theta_{r,r'} \approx \theta_{r',r} \approx 0$, region r is a self-sufficient region, meaning that it produces as much as it needs electricity and that it neither relies on other regions, nor other regions rely on it.

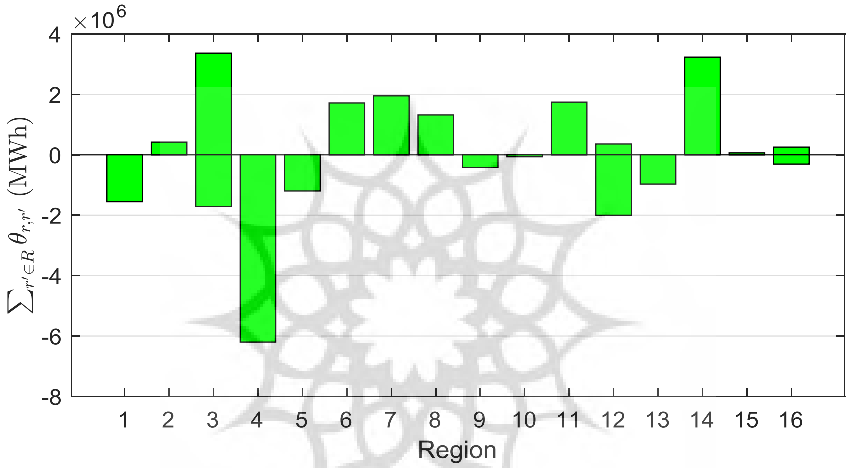

Figure 6. Transmission status of regions

Conclusion

The world is currently phasing out fossil fuels and replacing renewable sources as the primary source for generating electricity. Renewable sources have no environmental pollution and are regenerated by nature, without any intervention by humans. However, the shift toward renewable sources does not take place overnight and needs precise plans, sometimes for decades. A crucial characteristic of such plans would be considering various energy sources and the balance between generating electricity from each source during the planning horizon.

This paper proposes a mathematical programming model for optimizing the renewable energy generation and transmission portfolio. The optimal solution of the model is a multi-period multi-source plan for renewable electricity generation for different regions within a country. The objective is to minimize the total construction, maintenance, and transmission cost throughout the planning horizon. Various constraints are included in the model to make its results feasible for implementing real-world projects. Each region has different potentials for each renewable source, and the generation plan must fulfill at least a certain percentage of the total electricity demand in each year. The building blocks of the model are electricity generation regions, which may consist of several provinces. Differences in the regions' characteristics may lead to conditions where a region generates more energy than its demand and transfers this excess electricity to other regions with insufficient or uneconomic renewable sources.

The proposed model is applied to a real-world case of Iran to obtain the optimal regional renewable electricity generation expansion plan. Both historical data and expert opinions were used to collect the required data. To verify the model, it was first applied to the data for the last four years. Results showed that the model was able to obtain logical results that significantly match real-world statistics. Next, the model was solved to optimize the ten-year renewable electricity generation and transmission expansion plan. The results were discussed from different aspects, including separate aggregate plans by region, energy source, and year. Also, the optimal transmission plan obtained from the solution was also discussed. It was revealed that Iran should mostly rely on solar and wind energy in its long-term plan. This is in line with the geographic properties of the country, which is located near the Equator, and the southern and southeastern regions of the country benefit from high annual sunshine hours.

Future studies can develop the model of this work in various ways. A large number of parameters are estimations based on specific measurements. For example, regional potentials for each renewable source is subject to variations to different degrees. It is recommended to embed approaches in the model that enhance the sensitivity of the results to variations in the numeric parameters, including fuzzy and interval numbers. Mathematical modeling approaches for uncertainty, such as stochastic programming and robust programming, can also be utilized in future studies.

References

Abdelkafi, A., Masmoudi, A., & Krichen, L. (2018). Assisted power management of a stand-alone renewable multi-source system. *Energy*, *145*, 195–205. https://doi.org/10.1016/j.energy.2017.12.133

Afsharzade, N., Papzan, A., Ashjaee, M., Delangizan, S., Van Passel, S., & Azadi, H. (2016). Renewable energy development in rural areas of Iran. *Renewable and Sustainable Energy Reviews*, *65*, 743–755. https://doi.org/10.1016/j.rser.2016.07.042

Aghahosseini, A., Bogdanov, D., Ghorbani, N., & Breyer, C. (2018). Analysis of 100% renewable energy for Iran in 2030: Integrating solar PV, wind energy and storage. *International Journal of Environmental Science and Technology*, *15*(1), 17–36. https://doi.org/10.1007/s13762-017-1373-4

Ajithapriyadarsini, S., Mary, P. M., & Iruthayarajan, M. W. (2019). Automatic generation control of a multi-area power system with renewable energy source under deregulated environment:

Adaptive fuzzy logic-based differential evolution (DE) algorithm. *Soft Computing*, *23*(22), 12087–12101. https://doi.org/10.1007/s00500-019-03765-2

Asrari, A., Ghasemi, A., & Javidi, M. H. (2012). Economic evaluation of hybrid renewable energy systems for rural electrification in Iran—A case study. *Renewable and Sustainable Energy Reviews*, *16*(5), 3123–3130. https://doi.org/10.1016/j.rser.2012.02.052

Chassin, D. P., Behboodi, S., & Djilali, N. (2018). Optimal subhourly electricity resource dispatch under multiple price signals with high renewable generation availability. *Applied Energy*, *213*, 262–271. https://doi.org/10.1016/j.apenergy.2018.01.041

Dagoumas, A. S., & Koltsaklis, N. E. (2019). Review of models for integrating renewable energy in the generation expansion planning. *Applied Energy*, *242*, 1573–1587. https://doi.org/10.1016/j.apenergy.2019.03.194

de la Nieta, A. A. S., Gibescu, M., Wang, X., Song, M., Jensen, E., Saleem, A., Bremdal, B., & Ilieva, I. (2018). Local Economic Dispatch with Local Renewable Generation and Flexible Load Management. *2018 International Conference on Smart Energy Systems and Technologies (SEST)*, 1–6. https://doi.org/10.1109/SEST.2018.8495823

Djebbri, S., Ladaci, S., Metatla, A., & Balaska, H. (2018). Robust MRAC Supervision of a Multi-source Renewable Energy System Using Fractional-Order Integrals. *2018 International Conference on Electrical Sciences and Technologies in Maghreb (CISTEM)*, 1–6. https://doi.org/10.1109/CISTEM.2018.8613425

Droege, P. (Ed.). (2008). *Urban energy transition: From fossil fuels to renewable power* (1st ed). Elsevier.

Ecer, F., Pamucar, D., Hashemkhani Zolfani, S., & Keshavarz Eshkalag, M. (2019). Sustainability assessment of OPEC countries: Application of a multiple attribute decision making tool. *Journal of Cleaner Production*, *241*, 118324. https://doi.org/10.1016/j.jclepro.2019.118324

Fizaine, F., & Court, V. (2015). Renewable electricity producing technologies and metal depletion: A sensitivity analysis using the EROI. *Ecological Economics*, *110*, 106–118. https://doi.org/10.1016/j.ecolecon.2014.12.001

Ghorbani, N., Aghahosseini, A., & Breyer, C. (2020). Assessment of a cost-optimal power system fully based on renewable energy for Iran by 2050 – Achieving zero greenhouse gas emissions and overcoming the water crisis. *Renewable Energy*, *146*, 125–148. https://doi.org/10.1016/j.renene.2019.06.079

Hosseini, S. E., Andwari, A. M., Wahid, M. A., & Bagheri, G. (2013). A review on green energy potentials in Iran. *Renewable and Sustainable Energy Reviews*, *27*, 533–545. https://doi.org/10.1016/j.rser.2013.07.015

Ilbahar, E., Cebi, S., & Kahraman, C. (2019). A state-of-the-art review on multi-attribute renewable energy decision making. *Energy Strategy Reviews*, *25*, 18–33. https://doi.org/10.1016/j.esr.2019.04.014

Iqbal, M., Azam, M., Naeem, M., Khwaja, A. S., & Anpalagan, A. (2014). Optimization classification, algorithms and tools for renewable energy: A review. *Renewable and Sustainable Energy Reviews*, *39*, 640–654. https://doi.org/10.1016/j.rser.2014.07.120

Iran Ministry of Energy. (2020, August 16). *List of Iran's regional power companies*. List of Regional Power Companies. http://moe.gov.ir/Sites-of-Water-Electricity/Regional-power-companies

Keles, C., Alagoz, B. B., & Kaygusuz, A. (2017). Multi-source energy mixing for renewable energy microgrids by particle swarm optimization. *2017 International Artificial Intelligence and Data Processing Symposium (IDAP)*, 1–5. https://doi.org/10.1109/IDAP.2017.8090163

Khojasteh, D., Khojasteh, D., Kamali, R., Beyene, A., & Iglesias, G. (2018). Assessment of renewable energy resources in Iran; with a focus on wave and tidal energy. *Renewable and Sustainable Energy Reviews*, *81*, 2992–3005. https://doi.org/10.1016/j.rser.2017.06.110

Kumar, A., Sah, B., Singh, A. R., Deng, Y., He, X., Kumar, P., & Bansal, R. C. (2017). A review of multi criteria decision making (MCDM) towards sustainable renewable energy development. *Renewable and Sustainable Energy Reviews*, *69*, 596–609. https://doi.org/10.1016/j.rser.2016.11.191

Kumar, K. P., & Saravanan, B. (2017). Recent techniques to model uncertainties in power generation from renewable energy sources and loads in microgrids – A review. *Renewable and Sustainable Energy Reviews*, *71*, 348–358. https://doi.org/10.1016/j.rser.2016.12.063

Li, Z., Qiu, F., & Wang, J. (2016). Data-driven real-time power dispatch for maximizing variable renewable generation. *Applied Energy*, *170*, 304–313. https://doi.org/10.1016/j.apenergy.2016.02.125

Mahmud, N., & Zahedi, A. (2016). Review of control strategies for voltage regulation of the smart distribution network with high penetration of renewable distributed generation. *Renewable and Sustainable Energy Reviews*, *64*, 582–595. https://doi.org/10.1016/j.rser.2016.06.030

Melamed, M., Ben-Tal, A., & Golany, B. (2018). A multi-period unit commitment problem under a new hybrid uncertainty set for a renewable energy source. *Renewable Energy*, *118*, 909–917. https://doi.org/10.1016/j.renene.2016.05.095

Mollahosseini, A., Hosseini, S. A., Jabbari, M., Figoli, A., & Rahimpour, A. (2017). Renewable energy management and market in Iran: A holistic review on current state and future demands. *Renewable and Sustainable Energy Reviews*, *80*, 774–788. https://doi.org/10.1016/j.rser.2017.05.236

Naval, N., Sánchez, R., & Yusta, J. M. (2020). A virtual power plant optimal dispatch model with large and small-scale distributed renewable generation. *Renewable Energy*, *151*, 57–69. https://doi.org/10.1016/j.renene.2019.10.144

Nazir, N., Racherla, P., & Almassalkhi, M. (2020). Optimal Multi-Period Dispatch of Distributed Energy Resources in Unbalanced Distribution Feeders. *IEEE Transactions on Power Systems*, *35*(4), 2683–2692. https://doi.org/10.1109/TPWRS.2019.2963249

Office of Energy and Electricity Planning at Ministry of Energy. (2016). *Iran Energy Balance Sheet 2016*.

Oree, V., Sayed Hassen, S. Z., & Fleming, P. J. (2017). Generation expansion planning optimisation with renewable energy integration: A review. *Renewable and Sustainable Energy Reviews*, *69*, 790–803. https://doi.org/10.1016/j.rser.2016.11.120

Quaschning, V. (2016). *Understanding renewable energy systems* (Revised edition). Routledge, Taylor & Francis Group, Earthscan from Routledge.

Radovanović, M., Filipović, S., & Pavlović, D. (2017). Energy security measurement – A sustainable approach. *Renewable and Sustainable Energy Reviews*, *68*, 1020–1032. https://doi.org/10.1016/j.rser.2016.02.010

San Cristóbal, J. R. (2012). A goal programming model for the optimal mix and location of renewable energy plants in the north of Spain. *Renewable and Sustainable Energy Reviews*, *16*(7), 4461–4464. https://doi.org/10.1016/j.rser.2012.04.039

Schwerhoff, G., & Sy, M. (2017). Financing renewable energy in Africa – Key challenge of the sustainable development goals. *Renewable and Sustainable Energy Reviews*, *75*, 393–401. https://doi.org/10.1016/j.rser.2016.11.004

Szargut, J., Ziębik, A., & Stanek, W. (2002). Depletion of the non-renewable natural exergy resources as a measure of the ecological cost. *Energy Conversion and Management*, *43*(9–12), 1149–1163. https://doi.org/10.1016/S0196-8904(02)00005-5

Theo, W. L., Lim, J. S., Ho, W. S., Hashim, H., & Lee, C. T. (2017). Review of distributed generation (DG) system planning and optimisation techniques: Comparison of numerical and mathematical modelling methods. *Renewable and Sustainable Energy Reviews*, *67*, 531–573. https://doi.org/10.1016/j.rser.2016.09.063

Twidell, J., & Weir, T. (2015). *Renewable energy resources* (Third edition). Routledge, Taylor & Francis Group.

Wang, H., Lei, Z., Zhang, X., Zhou, B., & Peng, J. (2019). A review of deep learning for renewable energy forecasting. *Energy Conversion and Management*, *198*, 111799. https://doi.org/10.1016/j.enconman.2019.111799

Wei, W., Liu, F., Mei, S., & Hou, Y. (2015). Robust Energy and Reserve Dispatch Under Variable Renewable Generation. *IEEE Transactions on Smart Grid*, *6*(1), 369–380. https://doi.org/10.1109/TSG.2014.2317744

Zaibi, M., Cherif, H., Champenois, G., Sareni, B., Roboam, X., & Belhadj, J. (2018). Sizing methodology based on design of experiments for freshwater and electricity production from multi-source renewable energy systems. *Desalination*, *446*, 94–103. https://doi.org/10.1016/j.desal.2018.08.008

Bibliographic information of this paper for citing:

Taghizadeh-Yazdi, Mohammadreza & Mohammadi-Balani, Abdolkarim (2020 A Mathematical Model for Multi-Region, Multi-Source, Multi-Period Generation Expansion Planning in Renewable Energy for Country-Wide Generation-Transmission Planning. *Journal of Information Technology Management*, 12(4), 215-231.