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Optimization of Midterm Electricity Generation Mix Considering the Effects of Water, Cost, Land and Carbon Footprints

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Abstract

Electric energy plays a key role in the development of modern societies. Each of the electric power generation technologies (e.g., hydroelectric, wind, solar, thermal, etc.) has some advantages and disadvantages with respect to the fundamental resource indicators, including water footprint, land footprint, carbon footprint, as well as electricity generation costs. Due to the shortage and frequent crisis associated with the above resources, optimal selection of the mix of electricity generation technologies is very important and the share of each technology in the capacity expansion of the generation system must be carefully defined. Iran is in an arid and semi-arid region, with less than one third of the average world precipitation. Moreover, the available water resources are restricted due to the water crises in the Middle-East region. In this paper, we first estimated the peak power consumption of Iran in 2024, based on the time-series data from 2004 to 2014. Then, we formulated an optimization problem to find the share of each electric power generation technology to cover the required extra generation capacity for supplying the power consumption in the target year 2024, considering the effect of the four aforementioned performance indicators. The optimization problem is solved using Genetic Algorithm. Numerical results show that in the target year, 20 GW of electricity should be added to the generation capacity. The results also show that, solar thermal and solar photovoltaic are the best electric generation technologies regarding the available resources.

Key word: Sustainability, genetic algorithms, electricity generation mix, water footprint

1. Introduction

Efficient management of water resources is very important, especially in a country like Iran which is located in an arid and semi-arid region. Development of rural and urban societies depends on water resources availability. Therefore, the amount of water available for various sectors such as agriculture, industry, and electricity generation, is restricted.

Electric power generation technologies such as steam and gas fired power plants, nuclear power plant and combined cycle plants consumed lots of water in the process of electricity generation. Therefore, studying the optimal electricity generation mix regarding the water footprint along with other factors (cost, land and carbon footprint) is very important to ensure a sustainable development of the country with respect to restricted resources.

For hydrothermal systems, the limited energy storage capability of water reservoirs, along with the stochastic nature of their availability, make its solution a more difficult job than for purely thermal systems. The well-timed allocation of hydro energy resources is a complicated task that requires probabilistic analysis and long-term considerations, because if water is used in the present period, it will not be available in the future, increasing in this way the future operation costs (1).

Saeed Hadian & Kave Madani (2) considered four indicators consist of water, land, carbon and cost of electricity generation, to rate fifteen different generation technologies and proposed a method to find the best technologies. Results of this work showed that against of publicly accepted belief, hydro power plants are not highly rated in comparison with the other generation technologies. In another study, Mario T. L. Barros, and Frank T-C. Tsai (3) proposed a method for enhancing and managing the hydro power system of Brazil. The system is one of the largest power system in the world consisted of more than 75 hydro power plants with 96.925 GW capacity which stands for 65.3% of Brazil electricity generation capacity. This method was developed based on a Non-Linear Programming (NLP) model to tackle the nonlinearities in the input data as well as high dimension of the system. Then NLP model then transferred to a Linear Programming (LP) model to overcome computation difficulties.In this context, we proposed an optimization framework to formulated the problem of optimal selection of technologies for electricity generation mix, regarding not only the water footprint but also the cost, land and carbon footprints.

The rest of this paper is organized as follows. Sections 2, presents the input data set considered in this work. The applied and proposed methodologies are briefly presented in section 3. Then, preliminary results are discussed in section 4. Finally, a conclusion and further steps are presented in section 5.

2. Data

The first data set used in this work is the statistics of power consumption in Iran obtained from (4), (5), and (6). Figure 1, shows the peak power consumption of Iran from 2004 to 2014. The annual power consumption grow rate, is around 5% in this period.

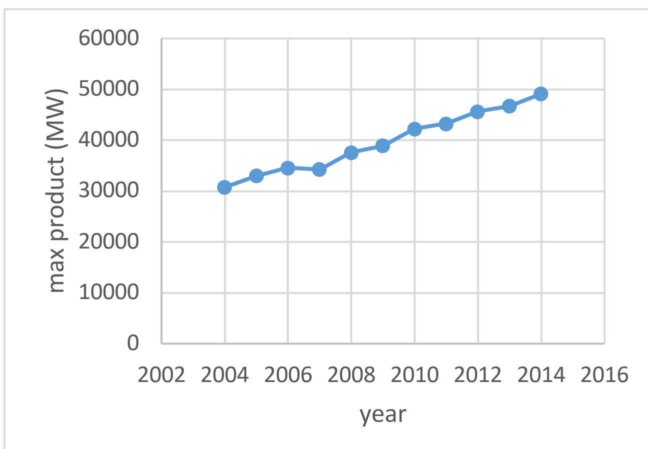

Figure 1: Maximum product per year

The second input data set is the performance of 15 different generation technologies with respect to four performance indicators, namely, water, carbon, land footprints, and cost (2). For each technology, the minimum and maximum performance value is presented in Table 1. The authors conducted a survey among experts and consultants to estimate the value of maximum potential capacity of each technology in Iran.

Technology	Carbon footprint (gCO2/kWh)		Water footprint(m3/GJ)		Land footprint (m2/GWh)		Cost (cents/kWh)		Maximum potential capacity in Iran (MW)
	Min	Max	Min	Max	Min	Max	Min	Max	
Ethanol fromcorn	81	85	78	78	10667	12500	2	4	0
Ethanol fromsugarcane	19	19	99	99	9520	9520	2	4	10000
Biomass: wood-chip	25	25	42	42	14433	21800	4	10	10000
Biomass: miscanthus	93	93	37	37	14433	21800	4	10	0
Solar thermal	8.5	11.3	0.037	0.78	340	680	4	10	unlimited
Solar photovoltaic	12.5	104	42	42	704	1760	10.9	23.4	unlimited
Wind: onshore	6.9	14.5	0.001	0.001	2168	2640	4.16	5.72	2400
Wind: offshore	9.1	22	0.001	0.001	2168	2640	3.64	8.71	2400
Wave andtidal	14	119	0.001	0.001	33	463	5	15	10
Hydropower	2	48	22	22	538	3068	3.25	12.35	16200
Coal	834	1026	0.15	0.58	83	567	3.77	5.87	unlimited
Oil	657	866	4.29	8.6	1490	1490	8	10	unlimited
Natural gas	398	499	0.1	0.1	623	623	5.46	11.96	unlimited
Nuclear	9	70	0.42	0.76	63	93	4.55	5.46	13500
Geothermal	15	55	0.005	0.005	33	463	1	8	55

Table 1:: Performance indicators for 15 different electricity generation technologies

3. Methodology

3.1 Regression

In this work, we applied the linear regression technique in order to estimate the peak power consumption in the target year (i.e., 2024), based on available time-series of peak power consumption from 2004 to 2014. In linear regression, the relationships are modelled using linear predictor functions whose unknown model parameters are estimated from the data. Here, the linear regression represents the relationship between the response parameter (power consumption at year y – denoted as P_y), and the independent parameter (year y).

$$\boldsymbol{P_y = my + b} \quad (1)$$

Note that, the linear relationship should be such that the sum of the distances between the available data (y, P_y) and the line is minimum.

3.2 Genetic algorithm

Genetic algoritms are a type of optimization algorithm, meaning they are used to find the optimal solution(s) to a given computational problem that maximizes or minimizes a particular function. Genetic algorithms represent one branch of the field of study called evolutionary computation, in that they imitate the biological processes of reproduction and natural selection to solve for the 'fittest' solutions (7). Like in evolution, many of a genetic algorithm's processes are random, however this optimization technique allows one to set the level of randomization and the level of control. These algorithms are far more powerful and efficient than random search and exhaustive search algorithms yet require no extra information about the given problem (7). This feature allows them to find solutions to problems that other optimization methods cannot handle due to a lack of continuity, derivatives, linearity, or other features.

4. Proposed Model

The proposed optimization model composed by an objective function and a set of constraints. Here, the decision variable (x_i) is the capacity of each generation technology (i) that is required to be installed to cover the power consumption in the target year. The objective function is as equation (2).

$$\min_{x_i}\left(\sum_i (c_i + WF_i + LF_i + CF_i)x_i\right) \tag{2}$$

Where c_i, WF_i, LF_i, and CF_i are the per unit coefficients represent the cost, water footprint, land footprint, and carbon foot print associated with technology I, respectively. Note that the per unit values are computed based on the available data presented in Table 1, such that all the coefficients varies between 0 and 1 for various technologies.

The constraints of the optimization model include the availability of each of the fundamental resources (i.e., water, land and carbon). For instance, let us define W^{max} as the total water limit for electricity generation, in per unit. Therefore, the constraint for water resource limit is as equation (3).

$$\sum_i WF_i x_i \leq W^{max} \tag{3}$$

Moreover, the capacity of each technology is limited due to technical limitation as presented in equation (4).

$$0 \leq x_i \leq X_i^{max} \tag{4}$$

A complete set of the constraints of the optimization model will be presented in the full version of the paper.

5. Analysis and Results

Figure 2, shows the results of linear regression model. As it can be seen in this figure, the linear model well fits the available data (blue points). The R-square of the fitting is 0.9930 and the linear relationship parameters (see equation (2)), are m = 1.8405e+03, and b = -2.5168e+06.

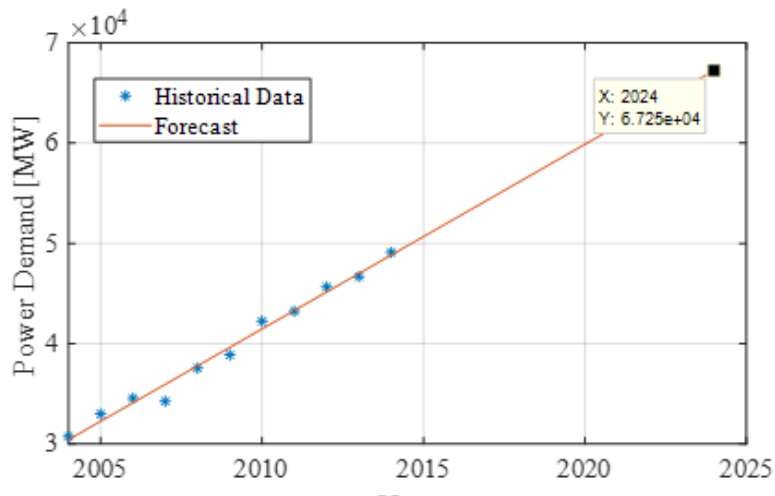

Figure 2: results of linear regression model

The results of the optimization problem, assuming that the maximum capacity of each technology is limited according to the data provided in Table 1. The optimal amount of capacity of each technology solution as the solution of the optimization problem is depicted in Figure 3.

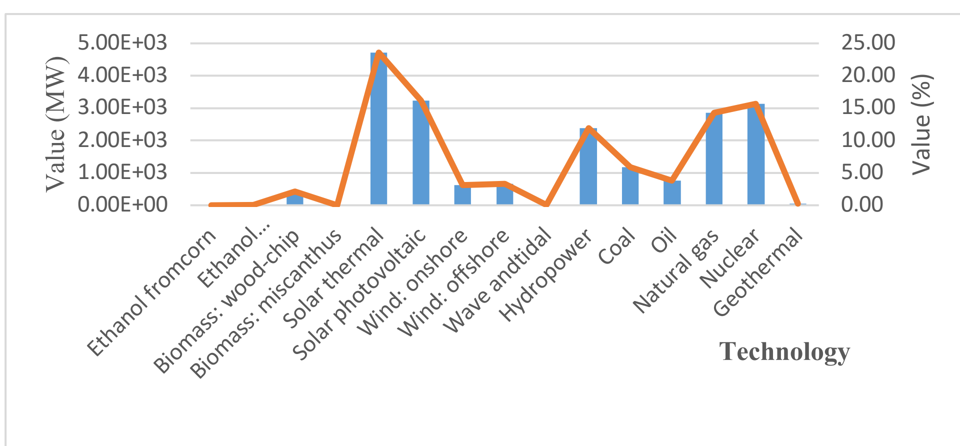

Figure 3: results of the optimization problem

6. Conclusion

Regarding the numerical results of the optimization model proposed in this paper, five technologies of Solar thermal, Solar photovoltaic, Natural gas, Nuclear, and Hydropower, are the best options for electricity generation mix in Iran. This result highlights that further attention to these technologies is very important to ensure sustainable supply of electricity in Iran, regarding the fact that 80% of the current generation mix is composed by thermal power plants.

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