

Research Article

An Integrated Decentralized Energy Planning Model considering Demand-Side Management and Environmental Measures

Seyed Mahmood Kazemi and Masoud Rabbani

Department of Industrial Engineering, College of Engineering, University of Tehran, P. O. Box 11155-4563, Tehran, Iran

Correspondence should be addressed to Seyed Mahmood Kazemi; kazemi_m_s@yahoo.com

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Decentralized energy planning (DEP) is looked upon as an indisputable opportunity for energy planning of villages, isolated islands, and far spots. Nonetheless, at this decentralized planning level, the value of demand-side resources is not fairly examined, despite enjoying great advantages. Therefore, the core task of this study is to integrate demand-side resources, as a competing solution against supply-side alternatives, with decentralized energy planning decisions and demonstrate the rewarding role it plays. Moreover, sustainability indicators (SIs) are incorporated into DEP attempts in order to attain sustainable development. It is emphasized that unless these indicators are considered at lower energy planning levels, they will be ignored at higher planning levels as well. Hence, to the best knowledge of the authors, this study for the first time takes into account greenhouse gas (GHG) emissions produced by utilization of renewable energies in DEP optimization models. To address the issues mentioned previously, multiobjective linear programming model along with a min-max goal programming approach is employed. Finally, using data taken from the literature, the model is solved, and the obtained results are discussed. The results show that DSM policies have remarkably contributed to significant improvements especially in terms of environmental indicators.

1. Introduction

Decentralized energy planning aims for efficient use of local resources to supply energy. DEP is an available option for satisfying energy needs of villages, isolated islands, and small-scale end users in a reliable, affordable, and environmentally sustainable way (Hiremath et al. [1]). To see some recent top researches conducted in the related area, the works of [2–7] are recommended. The DEP paramount feature is to provide an area-based DEP so that with the least economic and environmental costs develops alternate energy sources and satisfies energy requirements. References [8–11] are good example works done in the literature with focus on DEP modeling.

Energy demand management, also referred to as demand-side management (DSM), includes activities that modify end use energy demand; for example, the activities aim to reduce peak demand. It is worth mentioning that peak demand management does not necessarily lead to reduction in total energy consumption, but it defers the need for investments in

establishing new power plants. The most generally accepted definition of DSM is the one presented by Gellings in 1984 [12].

As discussed by Kreith and Goswami [12], DSM alternatives must be compared to supply-side alternatives. Thus, it entails considering and evaluating both supply-side and demand-side options in energy planning efforts. In the late 1980s, Ontario Hydro of Canada estimated that satisfying its customer peak demand via supply-side measures costs four times that of demand-side measures [13]. As a result, any energy planning model without simultaneously considering both sides is incomplete.

Although developing a model which considers a DEP with evaluating both supply-side and demand-side management measures is of great importance, it is not yet inclusive. The shortcoming is related to not taking SIs into account. To overcome this, we need to have such indicators quantified, which is of course a very challenging task [14] (see also [15, 16]). Evans et al. [17] ranked four renewable

energy technologies, namely, photovoltaic, wind, hydro and geothermal, against several SIs using data extracted from the literature. These indicators include electricity generation cost, GHG emissions, availability and limitations of each technology, efficiency of energy transformation, land use requirements, water consumption, and social impacts. Based on their findings, wind technology outranked the others followed by hydro, photovoltaic, and geothermal technologies, respectively. Nonetheless, it should be pointed out that the ranking was provided for the global international conditions, whereas each technology can be considerably geographically affected.

To cover the mentioned gaps in the literature, in this paper a multiobjective linear programming formulation for a DEP problem is proposed that not only takes both supply-side and demand-side alternatives into account but also considers a number of important SIs against which five energy resources, including DSM options, are evaluated. It is worth mentioning that using multi-objective formulations for energy planning is commonplace in the literature; see, for example, [10, 18–21].

In a nutshell, the contributions of this paper can be summarized as follows.

- (i) It is, to the best knowledge of the authors, for the first time that in DEP models supply-side and demand-side options are treated equally.
- (ii) It is, to the best knowledge of the authors, for the first time that in DEP models GHG emissions produced by renewable energy technologies during their life cycle are incorporated. It may be surprising that, for instance, for photovoltaic, the amount of produced GHG emissions is almost one quarter of natural gas emissions [22], while it had been a widespread supposition that GHG emissions of renewable energy technologies are insignificant.
- (iii) A variety of important sustainable indicators, namely water consumption, land use, cost of generation, employment, and GHG emissions, are considered.

The rest of the paper is organized as follows. In the next section, materials and methods used are elaborated. In Section 3, results and discussions are provided. Finally, conclusion remarks are drawn in Section 4.

2. Materials and Methods

2.1. Materials. The data used in this paper are collected from the literature and are based on the global international conditions. To solve the model for a numerical example, Lingo 8.0 software was employed.

2.2. Mathematical Formulation. As stated before, five SIs are taken into account. These SIs are regarded as distinct objective functions. The notations used in this model along with the proposed integrated multi-objective formulation are presented below.

Notations. Sets are as follows:

I : set of renewable energy technologies;

J : set of end uses.

Parameters and variables as follows:

w_{ci} : water consumption of i th resource option (kg/kWh);

GHG_i : greenhouse gas emissions of the i th resource option (g CO_{2-e}/kWh);

lu_i : land use characteristic of i th resource option (m²/kWh);

c_{ij} : electricity generation cost of resource i for j th end use (US\$/kWh);

$CDSM_j$: electricity saving cost using the implemented DSM program in the j th end use (US\$/kWh);

w_j : employment generation of i th resource option (jobs/kWh);

D_j : total energy demand for j th end use (kWh);

η_{ij} : conversion efficiency for the i th resource option for j th end use;

S_i : availability of the i th resource option for j th end use (kWh);

P_j : the maximum possible saving using the DSM program in the j th end use (kWh);

$SOBJ_j$: the required saving that is, to be achieved by the DSM program (kWh).

Decision variables:

x_{ij} : optimal amount of i th resource option for j th end use (kWh);

$SDSM_j$: optimal saving in j th end use using the implemented DSM program (kWh).

$$\begin{aligned} \text{Minimize total cost} &= \sum_i \sum_j c_{ij} \times x_{ij} \\ &+ \sum_j SDSM_j \times CDSM_j, \end{aligned} \quad (1)$$

$$\text{Maximize total jobs created} = \sum_i \sum_j x_{ij} \times w_i, \quad (2)$$

$$\text{Minimize total water consumption} = \sum_i \sum_j x_{ij} \times w_{ci}, \quad (3)$$

$$\begin{aligned} \text{Minimize total greenhouse gas emissions} \\ &= \sum_i \sum_j x_{ij} \times GHG_i, \end{aligned} \quad (4)$$

$$\text{Minimize total land used} = \sum_i \sum_j x_{ij} \times lu_i. \quad (5)$$

Which are subjected to the following:

$$\sum_i x_{ij} + \text{SDSM}_j \geq D_j, \quad \forall j \in J, \quad (6)$$

$$\sum_j \frac{x_{ij}}{\eta_{ij}} \leq S_i, \quad \forall i \in I, \quad (7)$$

$$\text{SDSM}_j \leq P_j, \quad \forall j \in J, \quad (8)$$

$$\text{SDSM}_j \geq \text{SOBJ}_j, \quad \forall j \in J, \quad (9)$$

$$x_{ij} \geq 0, \quad \text{SDSM}_j \geq 0. \quad (10)$$

The objective function given in (1) minimizes the total electricity generation costs. As can be seen, costs associated with implementing the DSM program are also considered in the first objective function, and it is treated just like other energy resources. It means that saving a unit of electricity by implementing DSM can be treated like producing a unit of electricity by a power plant, provided that the data for the associated costs are available. Equation (2) maximizes total number of jobs created due to electrifying the area. It should be noted that since the data for the number of jobs created by implementing the DSM program were not found, assumed to be negligible in this paper. The objective function given in (3), (4), and (5) minimize total water consumption, greenhouse gas emissions, and total land used, respectively. Constraints (6) and (7) are demand and resource availability constraints, respectively. Constraint (8) denotes that the maximum expected saving that could be achieved by executing the DSM program is limited to a realistic upper bound. Constraint (9) forces energy planners to implement DSM programs and meet some predetermined energy efficiency goals [23]. Constraint (10) indicates that decision variables are nonnegative real numbers.

2.3. Methods. Before we can solve the model by Lingo 8.0 software, we must find a way to cope with the multi-objective nature of the proposed formulation. To do so, a min-max goal programming approach was applied to obtain the best mix of renewable energy sources. For further study about goal programming (GP) approaches, the respected reader is referred to [24]. Now, using GP approach the model presented in the previous subsection can be easily reformulated as a single-objective linear programming formulation as presented in the following:

$$\text{Minimize max deviation} = d,$$

$$\text{Subject to } \alpha_j p_j + \beta_j n_j \leq d, \quad j = 1, 2, \dots, 5,$$

$$\sum_i \sum_j c_{ij} \times x_{ij} + \sum_j \text{SDSM}_j \times \text{CDSM}_j$$

$$- p_1 + n_1 = t_1,$$

$$\sum_i \sum_j x_{ij} \times w_i - p_2 + n_2 = t_2,$$

$$\sum_i \sum_j x_{ij} \times wc_i - p_3 + n_3 = t_3,$$

TABLE 1: Parameter values for renewable energy technologies.

	PV	Wind	Hydro	Geothermal
w_i (10^{-4} number of jobs produced/kWh)	0.27549	0.27549	1.466	0.4 ^a
wc_i	10	1	36	100
lu_i	0.046	0.072	0.411	0.05 ^a
GHG_i	90	25	41	170
S_i	8000000	327000	555000	100000 ^a
c_{ij} ($\forall j$)	0.398	0.02	0.039	0.03 ^a
η_{ij} ($\forall j$)	0.13	0.39	0.9	0.15

^aThe value has been assumed by the authors.

$$\sum_i \sum_j x_{ij} \times \text{GHG}_i - p_4 + n_4 = t_4,$$

$$\sum_i \sum_j x_{ij} \times lu_i - p_5 + n_5 = t_5,$$

$$\sum_i x_{ij} + \text{SDSM}_j \geq D_j \quad \forall j \in J,$$

$$\sum_j \frac{x_{ij}}{\eta_{ij}} \leq S_i, \quad \forall i \in I,$$

$$\text{SDSM}_j \leq P_j, \quad \forall j \in J,$$

$$\text{SDSM}_j \geq \text{SOBJ}_j, \quad \forall j \in J,$$

$$x_{ij} \geq 0, \quad \text{SDSM}_j \geq 0, \quad n_j \geq 0, \quad p_j \geq 0.$$

(11)

As shown above, parameter d denotes maximum deviation from every target (t_j). The parameter values α_j and β_j are set by decision maker. In some sense, this method is similar to the weighted Tchebycheff approach except that here the optimum z^* is replaced by target value.

3. Results and Discussion

In this section, in order to demonstrate the applicability of the model to real case problems, a numerical example based on the data obtained from the literature is developed. It should be pointed out that for the unavailable data, assumed values are considered. Tables 1 and 2 show the parameter values of the model that are either taken from [10–12, 17] or assumed by the authors.

The values of parameter CDSM_j in Table 2 are taken from [12]. For example, it is stated that a successful DSM program (2002 Massachusetts Electric-Residential Lighting Program) cost was \$3.3 million while it resulted in 18037 MWh energy saving. Therefore, the unit cost of energy saving using the implemented DSM program in the domestic sector is calculated as follows:

$$\text{CDSM}_{\text{domestic}} = \frac{3.3 \times 10^6 \$}{18037 \times 10^3 \text{ kWh}} = 0.183 \text{ (US$/kWh)}. \quad (12)$$

TABLE 2: Parameter values for different end uses.

	Domestic	Agriculture	Community	Industry
CDSM _j	0.183	0.238	0.917	0.055
D _j (the demand that is to be satisfied)	258267	278915	5276	18815
Already supplied demand (ASD)	116220 ^a	125512 ^a	2374 ^a	8467 ^a
P _j (0.15 × ASD) ^a	17433	18827	356	1270
SOBJ _j (0.05 × ASD) ^a	5811	6276	119	423

^aThe value has been assumed by the authors.

TABLE 3: Goal programming optimum solutions.

	Domestic (kWh)	Agriculture (kWh)	Community (kWh)	Industry (kWh)
DSM	17433	18827	119	1270
PV	100007.6	0	0	0
Wind	127530	0	0	0
Hydro	13296.4	245088	5157	17545
Geothermal	0	15000	0	0

The way of calculating the other values are the same. In this example, a rural area is assumed that is partly electrified, but the most parts are not yet provided with electricity. An energy saving target ranging from 5 to 15 percent in the already electrified parts of the area is considered.

To solve the goal programming model proposed in Section 2.3, all α_j and β_j values are set to be 0.5. The objective functions are also considered as presented below.

The first objective function:

$$\frac{(\sum_i \sum_j c_{ij} \times x_{ij} + \sum_j \text{SDSM}_j \times \text{CDSM}_j - 21528.53)}{21528.53} \quad (13)$$

The second objective function:

$$\frac{(105.9338 - \sum_i \sum_j x_{ij} \times w_i)}{105.9338} \quad (14)$$

The third objective function:

$$\frac{(\sum_i \sum_j x_{ij} \times wc_i - 4086100)}{4086100} \quad (15)$$

The fourth objective function:

$$\frac{(\sum_i \sum_j x_{ij} \times \text{GHG}_i - 19418390)}{19418390} \quad (16)$$

The fifth objective function:

$$\frac{(\sum_i \sum_j x_{ij} \times lu_i - 24075.8)}{24075.8} \quad (17)$$

As a decision maker, the following target values are assigned to the five objective functions mentioned above, respectively.

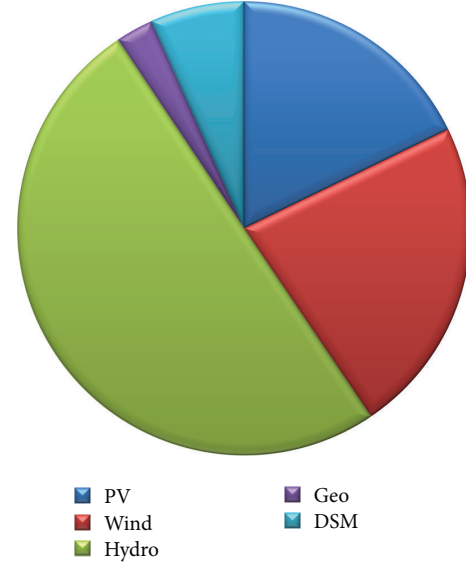


FIGURE 1: The role of each renewable energy source in electrifying the area under study.

The first objective function: 0.16.

The second objective function: 0.7.

The third objective function: 1.2.

The fourth objective function: 0.3.

The fifth objective function: 2.7.

Table 3 shows the outputs of Lingo 8.0 software for this numerical example.

Figure 1 shows the degree to which renewable energy sources have contributed to electrifying the area under study.

Using the solution given in Table 3, one can calculate the value of each individual objective function separately (Case 1). Also, by solving the original model presented in Section 2.2 once for each objective function (as a single-objective model) independently, the optimum value of each individual objective function is obtained (Case 2). Comparing the objective function values obtained in Case 1 with those obtained in Case 2 the following conclusions can be drawn.

- (1) Goal programming results are more practical to implement.
- (2) If the main limitations are water and land use requirements, minimizing GHG emissions and generation

costs or maximizing employment will not be an attractive goal to attain.

- (3) If financial resources are scarce, minimizing water consumption and land used will not be an attractive goal to attain.
- (4) If maximizing employment is of the highest importance, similar to the previous, minimizing water consumption and land used will not be an attractive goal to attain.

From the results pointed out above, it can be summarized that provided that target values are determined carefully, the model could be useful under various geographical conditions.

4. Conclusions

In this study, an integrated multi-objective linear programming formulation was developed for decentralized energy planning such that demand-side management and environmental measures were also taken into account. Moreover, a number of important sustainability indicators were utilized upon which four renewable energy technologies were compared. Using goal programming approach, the proposed model was solved by Lingo 8.0 software. The findings indicate that fine choices of sustainability indicators for doing the decision-making process are extremely affected by the limitations the policy makers encounter. For example, poor countries suffer from scarce funding resources. Thus, when planning for their energy supplies, it is not so sensible to consider minimizing the land occupied by the supply technologies as an important criterion to pursue. Also, the obtained numerical results show that in the optimum solution hydro outranked the other renewable energy technologies followed by wind, photovoltaic, DSM resources, and geothermal, respectively. It is worth pointing out that DSM alternatives have greatly contributed together with the other energy supply technologies.

Conflict of Interests

The authors declare that they have no conflict of interests.

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