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Design and Operation of a Multicarrier Energy System Based On Multi Objective Optimization Approach

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Abstract**—**Multi-energy systems will enhance the system reliability and power quality. This paper presents an integrated approach for the design and operation of distributed energy resources (DER) systems, based on energy hub modeling. A multi-objective optimization model is developed by considering an integrated view of electricity and natural gas network to analyze the optimal design and operating condition of DER systems, by considering two conflicting objectives, namely, minimization of total cost and the minimization of environmental impact which is assessed in terms of CO_2 emissions. The mathematical model considers energy demands of the site, local climate data, and utility tariff structure, as well as technical and financial characteristics of the candidate DER technologies. To provide energy demands, energy systems including photovoltaic, and co-generation systems, boiler, central power grid are considered. As an illustrative example, a hotel in Iran demonstrates potential applications of the proposed method. The results prove that increasing the satisfaction degree of environmental objective leads to increased total cost.

Keywords**—**Multi objective optimization, DER systems, Energy hub, Cost, CO_2 emission.

I. Introduction

On the one hand the population and energy consumption per capita has been growing very fast. On the other hand, the concerns about the depletion of fossil fuel resources and environmental pollution have also been increasing [1]. In this respect, policy makers admitted that transition to renewable energy sources is the path for consecutive success of human development [1], [2]. Iran enjoys valuable oil and natural gas resources. Due to the growing trends of energy consumption, the consumption of natural gas resources is highly increasing, while this can be supported by the fact that the rate of natural replenishment of fossil fuel resources is much smaller than the rate of energy demand in Iran [3]. Furthermore, statistics show that meeting the increased energy demand from fossil fuel would result in increased production of environmental pollutions. The CO_2 emission per capita is 6.6 ton in Iran in 2010, while the CO_2 emission per capita in the world is 4.4. In view of these two factors, it is clear that there is a necessity for systematic and progressive shift toward renewable energy systems in Iran [3], [4].

Distributed energy resources are small scale energy generation systems located close to end-users. In comparison with conventional energy supply systems, Distributed energy systems may employ a lot of energy conversion technologies such as: combined heat and power systems, wind turbines, photovoltaic, and those systems based on renewable energy resources [5], [6]. From the sustainable point of view, distributed energy systems are more reliable, efficient, and environmentally friendly [7].

Distributed energy systems are believed to enjoy a great potential for the reduction of environmental pollution for energy demand such as heating, electricity and, cooling, in Iran. Therefore, distributed energy systems represent a good alternative for a more sustainable development. However, designing an optimal distributed energy system that provide the energy demand of a district by considering environmental pollution (CO_2 emission) and costs, needs a new methodology. The development of which is the subject of this work.

Many references work on Distributed energy systems [6]-[8]. In spite of different benefits, the incorporation of DER technologies in the energy system is not an easy task. The optimal design of such a system requires selecting appropriate energy conversion system from numerous alternatives to match the energy demand. Besides, it is also required to determine the capacity of the assumed technologies and the operating conditions according to the fluctuation of energy demands.

In order to face with such a complicated and intricate subject, a systematic analysis and evaluation procedure is imperative. Some available models have been reviewed in literature [9]. Various literature [10]-[12] have surveyed about the available tools in this field. DER-CAM which has been developed by Lawrence Berkeley National Laboratory and HEATMAP and HOMER are the other beneficial tools for simulating of distributed energy systems. Hafez et al. [13] focuses on optimal design, planning, sizing, and operation of renewable energy systems by means of HOMER. The other research has developed a method for optimal sizing of DER in micro grid by considering the reliability and cost [14]. Furthermore, a mathematical model is a presented by Handschin et al. [15] to increase the economic efficiency of DER systems while considering the uncertainties.

Ren et al. [16] developed a mathematical model of distributed energy systems operation which evaluates the economic and environmental effects of the DER technologies.

Each of the aforementioned research, dealing with distributed energy system modeling, has its own characteristics. It can be concluded that an integrated approach for the design and operation of distributed energy systems while considering the renewable and non-renewable energy

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resources, based on energy hub modeling has rarely been mentioned.

The outline of the paper is as follows: first, the energy hub concept has been described. Next, the problem is stated. Then the modeling part is presented. As the result, the developed model is applied to the case of study. At the end, conclusions are given.

II. Energy Hub Modeling

Recently, due to environmental advantages, integrated energy systems have received much more attention against conventional energy systems based on fossil fuels [17].

There are several concepts from holistic view of distributed energy systems. One of which is hybrid energy hub. The concept of energy hub first has been introduced by Giedl et al. [18], [19]. Energy hubs can be defined as interconnected energy systems which include energy generation, conversion, and storage systems. They are interfaces between different energy generation and loads.

Increased Reliability, load flexibility, and system performance are some of motivations and advantages of this concept over the other energy supply systems [20], [21]. Fig. 1 illustrates an example of the energy hub.

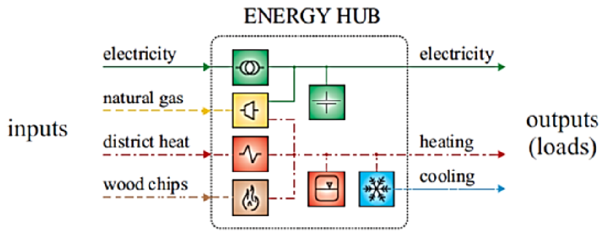

Fig. 1 Example of energy hub [18]

The energy hub concept has been formulated by Giedl et al, in which the input flows (energy resources) have been related to the output flows (energy demand) by introducing Matrix C. This kind of formulation may be so useful for the optimization due to the integrated view to all the flows. Many references developed and also implemented this concept [18], [21]-[23], but it is still in infancy.

$$L=CP \tag{1}$$

As it can be seen in (1), L is vector of output energy from the hub which can be the energy demand. P is the vector of the input flow to the energy hub. Moreover, C is the coupling matrix related to energy conversion systems characteristics. In fact, output flow can be connected to input flow by means of matrix C [21].

III. Nomenclature

Z	Total objective
Z_1	Total annual cost($/yr)
Z_2	CO_2 emission(ton/yr)
C_{Op}	Operational cost of every technologies($/yr)
C_{fuel}	cost of input energy flows($/yr)
C_{Invest}	Capital cost of technologies($/yr)
$Income$	energy transfer Revenue with the grid($/yr)
CRF	Capital recovery factor
CI_j	CO_2 emission of every technology(kg/kwh)
$P_{j,h,m}$	Input flow of each energy carrier in every hour at each month
$tech_j^{max}$	The capacity of DER technologies for every energy input flow
c_j^{invest}	Unit cost of investment for every energy flow
$tech_{(i,j,h,m)}$	Output energy flow of every technologies in each hour of each month
c_j^{op}	Unit cost of operation for every input energy flow($/kWh)
C_{fuel}	Total energy flow input cost($/yr)
$P_{(j,h,m)}$	Input energy flow at each hour of each month
c_j^f	Unit cost of energy flow input($/m^3)or ($/kWh)
c_i^{sell}	Unit cost of energy output sold to the grid($/kWh)
$C_{i,j}$	The converting matrix between the energy flow input and output
$tech_{i,j,h,m}^{self}$	Energy flow converting from j to i in each hour of each month for supplying the demand
$irad_{h,m}$	Solar irradiation in each hour of each month
A	Area(m^2)
i	Output energy carrier
j	Input energy carrier
h	hour
m	month

IV. Problem Definition

It was developed a model for the optimal design of an energy hub by considering different energy conversion technologies such as combined heat and power systems, photovoltaic, and boiler. By assuming the energy demand of a determined district, the optimal combination and optimal capacity of the energy conversion technologies will be determined. Moreover, the operating condition of selected technologies can be discovered. As an example, a typical hotel in Tehran is considered as a case study. An illustrative example of model is presented in Fig. 2.

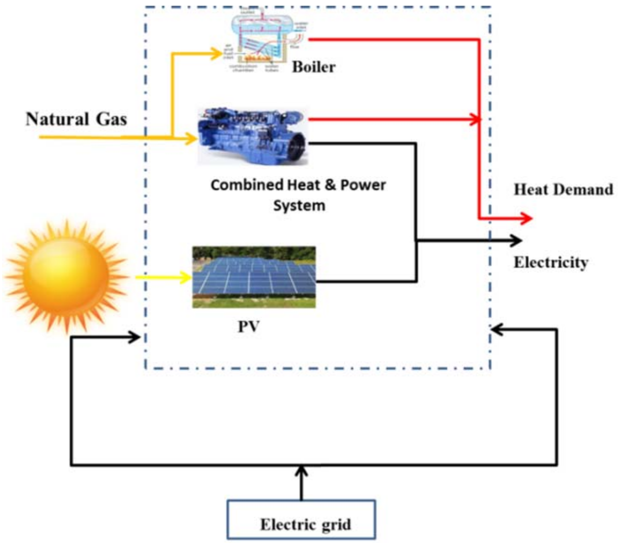

Fig. 2 Example of energy hub model for typical hotel

To provide the electrical energy demand of the hotel, there is an option between combined heat and power systems and photovoltaic and also electricity grid. Besides, Boiler and CHP considered for providing the heat demand. The surplus electricity is delivered to the grid while the generated electricity by DER exceeds the electricity demand; the Electric grid provides the deficit electricity.

The given data for the optimization are the electricity and heat demand for each month of the year for a typical hotel in Tehran. DER technologies cost and their technical information, feed in tariff of electricity, gas price, price of selling excess electricity, hourly solar irradiance profile for each month of the year are the required information of the energy hub modeling.

What to be determined by the modeling and optimization are the allocations and capacities of DER systems, hourly electricity and heat profiles, transfer of electricity between grid and the proposed Energy hub.

V. Objective Function

In order to achieve optimum design of en energy hub, decision variables should be determined using an optimization model. The optimization model is composed of objective function, decision variables as well as physical constraints. In the present research, two objective functions are considered to form the Pareto curve that represents the tradeoffs between conflicting objectives. Solution to a multi objective optimization is a concept rather than a definition, notwithstanding single objective optimization method.

One of the most common general methods for multi objective optimization is the weighted global criterion method in which all objectives are gathered in a single function. One of the most general functions is presented in the weighted exponential sum (2).

$$U = \sum_{i=1}^{k} w_i [F_i(x)]^p, \forall i F_i(x) > 0 \qquad (2)$$

where k is the number of the objective functions and wi is the weighted factor that should follow as (3).

$$\sum_{i=1}^{k} w_i = 1 \qquad (3)$$

In this paper, multi objective optimization is performed by considering two objectives namely, minimization of total annual cost ($/yr) versus minimization of CO_2 emission (ton/yr). (4)

$$MIN(Z) = w(\text{annual total cost}) - (1-w)(CO2\ emmison) \qquad (4)$$

Since the multi objective optimization methodology is very sensitive to the objective function scaling, it is recommended that the objectives can be normalized into a dimensionless scale. (5) [24]

$$F_i^{trans} = \frac{F_i(x)}{|F_i^{max}|} \qquad (5)$$

The first objective is related to the minimization of total energy cost. It includes cost of fuel and operational cost of every technologies as well as the investment cost of DER systems. Moreover, the energy transfer income with the grid is also considered in the objective which can be heat or electrical.

To get the annual investment cost, the Capital recovery factor (CRF) of every technology is also considered in which r is the interest rate and n is the lifetime of every technology.

$$CRF = \frac{r.(1+r)^n}{(1+r)^n - 1}$$

The other objective is the minimization of CO_2 emission. According to the energy hub modeling, all the parameters and all the variables are considered as a matrix.

The objective function is presented in (6) and (7).

$$Z = Z_1 \times w + Z_2 \times (1-w) \qquad (6)$$
$$Z_1 = C_{Op} + C_{fuel} + C_{Invest} \times CRF - Income$$
$$Z_2 = \sum_{j,h,m} CI_j \times P_{j,h,m}$$

$$C_{Invest} = \sum_{j} tech_j^{max} \times c_j^{invest}$$
$$C_{op} = \sum_{i,j,h,m} tech_{(i,j,h,m)} \times c_j^{op} \qquad (7)$$
$$C_{fuel} = \sum_{j,h,m} P_{(j,h,m)} \times c_j^{f}$$
$$Income = \sum_{i,j,h,m} tech_{i,j,h,m}^{sell} \times c_i^{sell}$$

VI. Constraints

The first constraint is related to the balance of supply and demand (input flow and output flow) and also flow transfer with the grid. The excess energy flow produced by DER technologies can be bought to the grid in a form of electricity or heat. Therefore, the output energy flow of every technology has two parts, one is related to the energy flow consumed by energy hub's end users and the remaining part is transferred to the grid (8).

$$L_{i,h,m} = \sum_j (C_{i,j} \times P_{j,h,m} - tech^{sell}_{i,j,h,m})$$
$$tech_{i,j,h,m} = C_{i,j} \times P_{j,h,m}$$
$$tech_{i,j,h,m} = tech^{sell}_{i,j,h,m} + tech^{self}_{i,j,h,m}$$
$$tech_{i,j,h,m} \le tech^{\max}_{j} \quad (8)$$

There are a set of constraint pertaining to the limitation of the DER technologies. For example, PV is assumed to produce electricity in proportion to the installed capacity and the amount of solar irradiation. Furthermore, the set of constraint is inserted to ban the energy hub from buying and selling energy simultaneously with the gird (9).

$$P_{sun,h,m} = irad_{h,m} \times A$$
$$A \le 100 \quad (9)$$
$$P_{elec,h,m} \times \sum_j tech^{sell}_{i,j,h,m} = 0$$

VII. Case Study

In this research, the developed model has been applied to a typical hotel as an energy hub [25].

Mostly hotels consume more electricity and they have also considerable heat demand. [26] In this case study, a 5000 m2 hotel as an energy hub is considered. Energy load profile of the typical hotel in Tehran is presented in Figs. 3 and 4. The typical electricity and heat profiles for the representative days of each month of the year are also depicted in these figures. Moreover, the heat demand also includes hot water consumption needs.

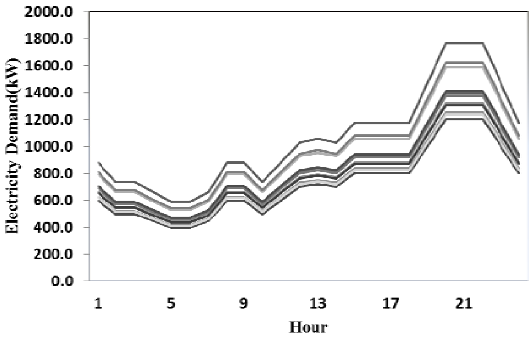

Fig. 3 Hourly electricity demand of hotel in different months

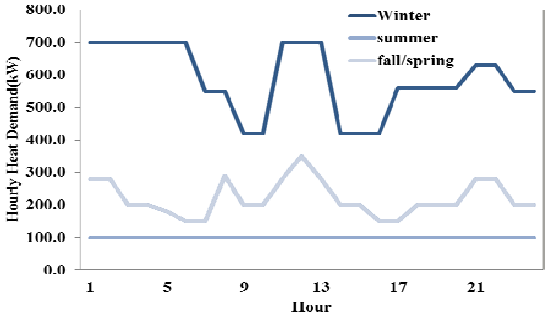

Fig. 4 Hourly heat demand for a typical hotel

The feed in tariff of input Energy carries (gas and electricity) is also presented in Table I.

TABLE I
THE FEED IN TARIFF OF ENERGY CARRIES [3]

Grid electricity price($/kWh)	.055
Natural gas price($/m^3)	.06
Selling price of electricity to the central power grid($/kWh)	.055
Selling price of heat to the heat grid($/kWh)	0

The CO_2 emission factor for natural gas and electricity grid is shown in Table II.

TABLE II
CO_2 EMISSION (KG/KWH)[5]

CO_2 emission from grid electricity	.781
CO_2 emission from natural gas	.184

Table III presents the information of the DER technologies, which includes electrical and thermal efficiencies of DER technologies as well as their capital and operational cost. The limitation of available areas for the PV systems is 100 m^2. The efficiencies of different technologies are supposed to be fixed. This assumption is so useful in systematic modeling of energy hub and can be acceptable according to the related literature. [27]

The interest rate is considered 15% and the life time of every technology is assumed 20 years [3], [5].

TABLE III
THE INFORMATION OF DER TECHNOLOGIES

	CHP	PV	Boiler
Capital Cost($/kW)	900	2000	700
Operational Cost ($/kWh)	.027[5]	0	.027[5]
Efficiency	Electricity (35%), Heat (50%)	14%	85%

The hourly solar irradiations on the 35 degree tilted plan in the location of Tehran in every month are also depicted in Fig. 5.

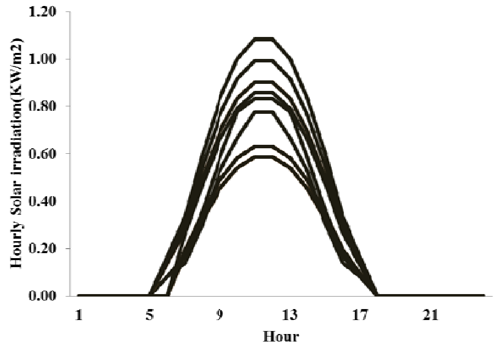

Fig. 5 The hourly solar irradiance in different months of year [28]

VIII. Results and Discussion

A. Multi-Objective Approach Results

In proposed study, two competing objectives are assumed for multi objective optimization. First, minimization of annual total cost ($/yr) versus minimization of CO_2 emission (g/yr); The Multi objective optimization for the optimal design of the energy hub creates a Pareto curve, as shown in Fig. 6.

In the Pareto curve, point A, (w=1) corresponds the minimum total annual cost of 430993 $/yr at 4712 ton/yr$CO_2$ emission production. By decreasing weighting factor (w) or increasing importance of the environmental issues, production of less CO_2 emission may be possible at the higher amount of cost. In the other side, point C (w=0) is related to the minimum CO_2 emission of 3873 ton/yr for total annual cost of 598432 $/yr. multi objective optimization outcomes are so useful for decision makers to determine the optimal design of the energy hub. They can estimate the minimum CO_2 emission production by considering the desired total annual cost via the pareto curve.

As it can be understood in the upper part of the Pareto curve (Fig. 6), an increase of 0.9% on the total annual cost between points A and B leads to 13%reduction of CO_2 emission which is favorable. On the other hand, in the lower part of the Pareto curve, increasing the total annual cost is less appealing, since in the lower part of the Pareto curve (between points B and C), a decrease of only 5% in the CO_2 emission, leads to 27% total annual cost increase. It can be seen that this considerable increase in cost is due to the entrance of the renewable systems such as photovoltaic to the optimal mix of DER technologies in the energy hub.

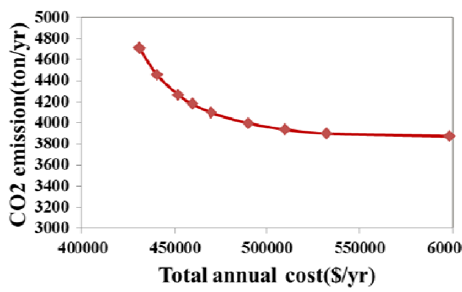

Fig. 6 Pareto curve of total annual cost verses CO_2emission production

Moreover, optimal allocation and capacity of each technology for different weighting factors are illustrated in Fig. 7.

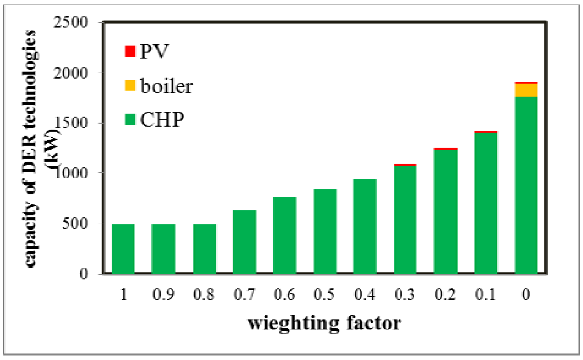

Fig. 7 Optimal allocation and capacity of each DER technology at different weighting factor

IX. Conclusion

This research work presents a holistic view for the design and operation of distributed energy resources (DER) systems, based on energy hub modeling.

A multi-objective optimization approach is assumed to consider two conflicting objectives, namely, minimization of total cost and the minimization of CO_2 emissions. According to the energy hub concept, the mathematical model is developed which considers energy demands of the site, local climate data, and utility tariff structure, as well as technical and financial characteristics of the candidate DER technologies. To provide energy demands, energy systems including photovoltaic, and co-generation systems, boiler, central power grid are considered. The model is implemented for the demand of typical hotel in Tehran. The main conclusions of the present research are as follows:

- A Multi objective optimization model based on energy hub concept is developed for the design and the operation of distributed energy systems which is rarely done by literature
- In comparison with single objective economic optimization, the consideration of CO_2 emission as an objective leads an increase in the share of DER technologies and consequently, a reduction in CO_2 emissions. However, the total cost is increased
- Multi objective optimization of PV/EL system predicts the minimum total annual cost of 430993 $/yr at 4712 ton/yr$CO_2$ emission production and minimum CO_2 emission production of 3873 ton/yr for total cost of 598432 $/yr.
- It can be seen that the entrance of photovoltaic system to the optimal mix of DER technologies in the energy hub results in a considerable increase in total cost. On the other side, the CO_2 emission is reduced.

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