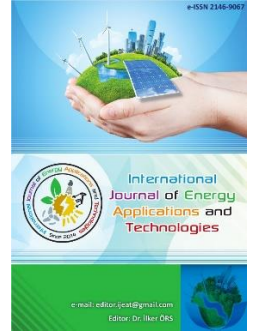




e-ISSN: 2548-060X

International Journal of Energy Applications and Technologies

journal homepage: www.dergipark.gov.tr/ijeat

Original Research Article

Optimization of a grid connected hybrid energy system

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ARTICLE INFO

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Accepted April 23, 2020Published by Editorial Board
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doi: 10.31593/ijeat.680639

ABSTRACT

Nowadays, energy policy makers in Turkey are discussing about transition to regional energy pricing policy due to the illegal usage rates in some regions in the country. A possible transition to regional pricing policy needs a detailed analysis on development of regional energy networks. By developing such networks, outer-dependency of energy can be reduced in regions and energy costs can reduce by using energy generation potential from renewable resources within regional networks. Moreover, the existing energy grid can be considered as a backup option to satisfy shortened demand after generation from renewable resources. In other words, grid-connected hybrid energy systems can be a promising solution to satisfy energy demand at a lower cost. Hybrid energy systems are discovered as a beneficial way to provide sustainable energy supply in regions with renewable energy potential. On the other hand, these kind of energy systems requires an analytic investigation in terms of design and operation, because of the existence of different energy resources. So, optimization of system design and operation decisions are extremely important. In this paper, optimization of a hybrid energy network is considered and a linear programming model to optimize operation decisions in a hybrid energy network for a town is proposed. The proposed model is solved on a numerical example with 10 demand points and 2 generation plants. An operation strategy for the numerical example is obtained after solution with a commercial LP solver. This model can be used a decision support tool for policy makers in development of energy policies.

Keywords: Grid connected hybrid energy system; Energy network design; Linear programming; Optimization

1. Introduction

Energy is an important part of human life. Due to the rapid growth of technology and increase of world population, the world needs more energy every passing day. Renewable resources are considered to be a good way to supply energy in a clean and sustainable manner. Besides the positive aspects of renewables on energy supply, they are mostly dependent on climate conditions and provide energy at variable amounts. Moreover, some other problems about energy supply from renewables are energy fluctuations, supply shortages, and low quality of energy. For these reasons, renewables are commonly not useful for energy

supply in large areas. These disadvantages lead to the concept of hybrid energy systems. Hybrid energy systems are energy systems that combines renewable and/or conventional energy sources, and they are useful for sustainable energy supply from renewable resources.

In order to utilize the benefits of hybrid energy systems completely, optimization of system activities is required. But, there are too many decision variables and parameters should be taken into account and the existence of these elements makes the optimization job as a computationally hard job. Furthermore, optimization activity has to be done by considering different climate conditions that vary in seasonal and daily periods. So, this kind of energy systems has to be

optimized at least at hourly detail level and for a planning period of one year.

In this study, determination of the best operation strategy for a hybrid energy system was considered. In order to determine the best operation strategy, a linear programming model is proposed for hybrid energy systems. Supply and demand characteristics of a grid-connected hybrid energy network with renewable energy resources was modelled. A numerical example was presented to demonstrate that the model can be solved by using a commercial optimization software.

The rest of the paper is as follows: second part consists of the descriptive information for the problem and the mathematical formulation of the proposed model. The data and solution results for the numerical example was given in the Third Part. Final conclusions, future research directions and limitations of the study was presented in the Fourth part.

2. Literature Review

Some researchers studied on optimization of hybrid energy systems so far. Sizing of system components and determination of operation strategy of system are the most common decision problems. Evaluation of systems made both by considering single criterion and combination of multiple criteria related to economic, environmental and technical aspects of solutions. Some of these studies are explained shortly as follows:

One of the first papers on this subject in 1997 was analysed grid connected and stand-alone cases for design and control problem of a solar-wind hybrid energy system for a 24-hour period by using a linear programming model [1]. A study was conducted in Japan in 2006 to determine the best component sizing of a grid connected solar, wind and storage unit which satisfy demand of a house at minimum cost [2]. Another study was conducted in 2011 by using Multi-Objective Honey Bee Mating Algorithm to obtain the optimum solution for operational decisions in a solar, wind, fuel cell system with grid connection by considering active electricity power losses, voltage deviation, total electricity energy cost and emission of renewable systems and transformers objectives four-week period data of January and July are used to represent all year's demand and supply characteristics [3]. A conference paper presented in 2012 considered a rural area, in which grid cannot supply electricity at all times and system components of a biomass, wind and solar system with grid connection were determined by considering net present value of investment cost [4]. Grid-connected hybrid system returns a smaller objective function value than the stand-alone hybrid system and grid-connected hybrid system reduces gas emissions 80% in comparison to only grid-connected case. Hourly generation and storage amounts for a one-year planning period were determined in a grid connected solar and storage unit hybrid system by considering levelized cost energy by Bortolini et al. in 2014 [5]. Gonzalez et al. studied

on the optimization of the life cycle cost of a hybrid solar, wind, biomass system with grid connection by using a genetic algorithm and component sizes were determined [6]. Another study on a grid connected hybrid energy system with solar and wind renewable resources used Particle Swarm Optimization algorithm to determine the optimum sizes of system components that satisfy electricity demand [7].

Krishan and Suhag used HOMER (Hybrid Optimization Model for Electric Renewable) software to analyse the hybrid energy system of a poor rural community [8] by considering the combination of wind, photovoltaic and battery options. A study conducted for a wind farm in Iran focused on the reliability concern for energy supply and a solution by hybridization wind power with biomass energy was investigated [9]. Techno-economic evaluation of system was made by using meteorological data. A simulation model was developed for the energy management of a hybrid railway power substation system in 2019 and simulation results of the system for one-year horizon with hourly time steps was evaluated [10]. Power balance and economics of the system was optimized by using a linear formulation. A study on the technical comparison of a hybrid solar water heater and electric storage tank water heater was presented in Hohne et al.'s study [11]. A life cycle cost analysis was also presented in their study with break-even point calculation for the hybrid solar water heating system. Bento et al. [12] proposed an optimized control strategy for hybrid energy systems which contains photovoltaics, pumped-storage hydropower, and wind power under different scenarios. A hybrid energy system with grid-connection in Mali was optimized using HOMER software [13]. Integration of photovoltaics into energy system made emission decrease of carbon dioxide emitted by thermal plants. A study conducted for Sierra Leone by Konneh et al. [14] considered determination of sizing decisions of a hybrid energy system including solar, wind and biomass energy options in Sierra Leone by using used multi-objective particle swarm optimization approach and takes four objective functions into account.

A short representation of the studies can be seen in Table 1 as follows.

Differ from the aforementioned studies, the best operation strategy for a hybrid energy system was considered in this study. To do so, a linear programming model is proposed. A grid-connected hybrid energy network with renewable energy resources was modelled within the model by considering supply and demand constraints.

3. Problem Description

An energy network of a town with different class of demand points like residential areas, community buildings (school, hospital, etc.), commercial buildings like shopping malls and industry region is considered in this study.

Table 1. Summary of the literature review

Study	Year	Authors	Method	Application Area
[1]	1997	Chedid and Rahman	Linear programming	Lebanon
[2]	2006	Senjyu et al.	Genetic algorithm	Japan
[3]	2011	Niknam et al.	Modified honey bee mating optimization	Iran
[4]	2012	Kumaravel et al.	Mathematical modelling	India
[5]	2014	Bortolini et al.	Analytic model	Italy
[6]	2015	González et al.	Optimization approach	Spain
[7]	2017	Mohamed et al.	Particle swarm optimization	Saudi Arabia
[8]	2019	Krishan and Suhag	HOMER	India
[9]	2019	Tajeddin and Roohi	Analytic model	Iran
[10]	2019	Yang et al.	Simulation	France
[11]	2019	Hohne et al.	Mixed-integer non-linear programming	South Africa
[12]	2019	Bento et al.	Simulation	Czech Republic
[13]	2019	Touré et al.	HOMER	Mali
[14]	2019	Konneh et al.	Particle swarm optimization	Sierra Leone

Solar energy is considered as the first option to satisfy electricity demand in this network. Grid-connection is the backup option for energy shortages. Assumptions for the mathematical model of this network is given as follows:

- Viewpoint in the optimization study is the perspective of the investor. Aim of the investors is to obtain the maximum profit from the network activities. The difference of revenue obtained by selling generated energy and the total cost expressed as the sum of generation and transmission costs and operation and maintenance costs.
- The energy network represents the energy system of a town.
- Optimization study is made for determination of the hourly generation and transmission decisions over one-year planning period. Seasonal and hourly changes of demand and supply characteristics can be analysed with this model.
- Generation and transmission decisions to satisfy demand of the town will be optimized. Grid-connection will be used only when generated energy from solar plants are inadequate.
- Solar energy is the only economically and technically feasible renewable resource in the town. Energy generation plants are assumed to be installed and ready-to-use.

4. Mathematical Model

Based on the given assumptions, a linear programming model is proposed with the following notations and mathematical formulation:

Sets:

i : energy generation plants

j : demand points

t : planning periods

Parameters:

spe_i : unit selling price of energy generated at plant i

ce_{ij} : unit transition cost of energy from plant i to point j

A_i : fixed cost of energy generation at plant i

ED_{jt} : electricity demand of point j in period t

cap_{it} : energy generation capacity of plant i in period t

Decision Variables:

XE_{ijt} : amount of energy transmitted from plant i to point j in period t

XSE_{jt} : amount of energy purchased from grid to satisfy energy shortage at point j in period t

$Y_{it} = \begin{cases} 1, & \text{if plant } i \text{ is used for energy generation in period } t \\ 0, & \text{otherwise} \end{cases}$

$fe_{jt} = \begin{cases} 1, & \text{if demand of point } j \text{ is satisfied by renewable resources in period } t \\ 0, & \text{otherwise} \end{cases}$

$Q_i = \begin{cases} 1, & \text{if energy generated at plant } i \text{ during planning period} \\ 0, & \text{otherwise} \end{cases}$

$$\max TP = \sum_t \sum_i \sum_j spe_i XE_{ijt} \tag{1}$$

$$- \left(\sum_i \sum_j \sum_t ce_{ij} XE_{ijt} + \sum_i A_i Q_i \right)$$

$$\sum_i XE_{ijt} + XSE_{jt} \geq ED_{jt} \quad \forall j, t \tag{2}$$

$$\sum_i XE_{ijt} \geq ED_{jt} * fe_{jt} \quad \forall j, t \tag{3}$$

$$XSE_{jt} \leq M * (1 - fe_{jt}) \quad \forall j, t \tag{4}$$

$$\sum_j XE_{ijt} \leq \text{cape}_{it} \times Y_{it} \quad \forall i,t \quad (5)$$

$$\sum_t Y_{it} \leq M \times Q_i \quad \forall i \quad (6)$$

$$XE_{ijt} \geq 0 \quad \forall i,j,t \quad (7)$$

$$XSE_{jt} \geq 0 \quad \forall j,t \quad (8)$$

$$Y_{it} \in \{0,1\} \quad \forall i,t \quad (9)$$

$$Q_i \in \{0,1\} \quad \forall i \quad (10)$$

$$f_{e_{jt}} \in \{0,1\} \quad \forall j,t \quad (11)$$

Profit function of energy network is expressed by Equation (1). Investor’s profit is calculated by subtraction of total of transmission cost of generated energy and operation and maintenance cost of plants from obtained revenue by energy sale. The goal is to find the maximum of this value.

Electricity demand is satisfied by generation and grid connection. Grid-connection is only considered when the generated energy is not enough to satisfy demand. This consideration is formulated by Equation (2), Equation (3) and Equation (4). Capacity limitations for generation plants are expressed by Equation (5). Operation and maintenance costs are activated for used plants and fixed costs are linked with plant utilization in Equation (6). Sign restrictions of decision variables are given by Equation (7-11).

5. Numerical Example

A numerical example is presented to demonstrate that the LP

model returns an optimal solution. In this example, an energy network with 10 demand points and 2 solar energy plants is configured. Optimization study is made by considering a planning horizon of 672 hours, which represent seasonal and hourly variation of supply and demand characteristics. 672 hours shows one-week data for each season and this consideration is proposed in several studies [2]. Parameter values of the model are taken from several studies in the literature and capacity and demand values are exported from HOMER software. Generation and transmission costs are assumed to be $ce_{ij} = 0.0632 + 0.0001 * d_{ij}$, where d_{ij} denotes the randomly generated distance between generation and demand points. Cost values are assumed to be $A_i = \$ 18000$, and $spe_i = 13.3$ cent / kWh. Supply characteristics for generation plants are presented in Figure 1 and hourly demand for different type of demand points are presented in Figure 2. There are no restrictions for grid-connection amounts.

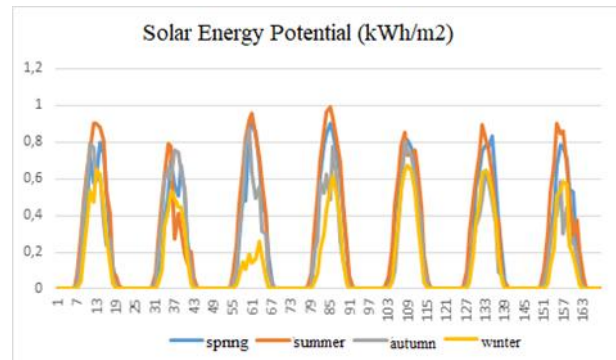


Fig. 1. Solar energy potential

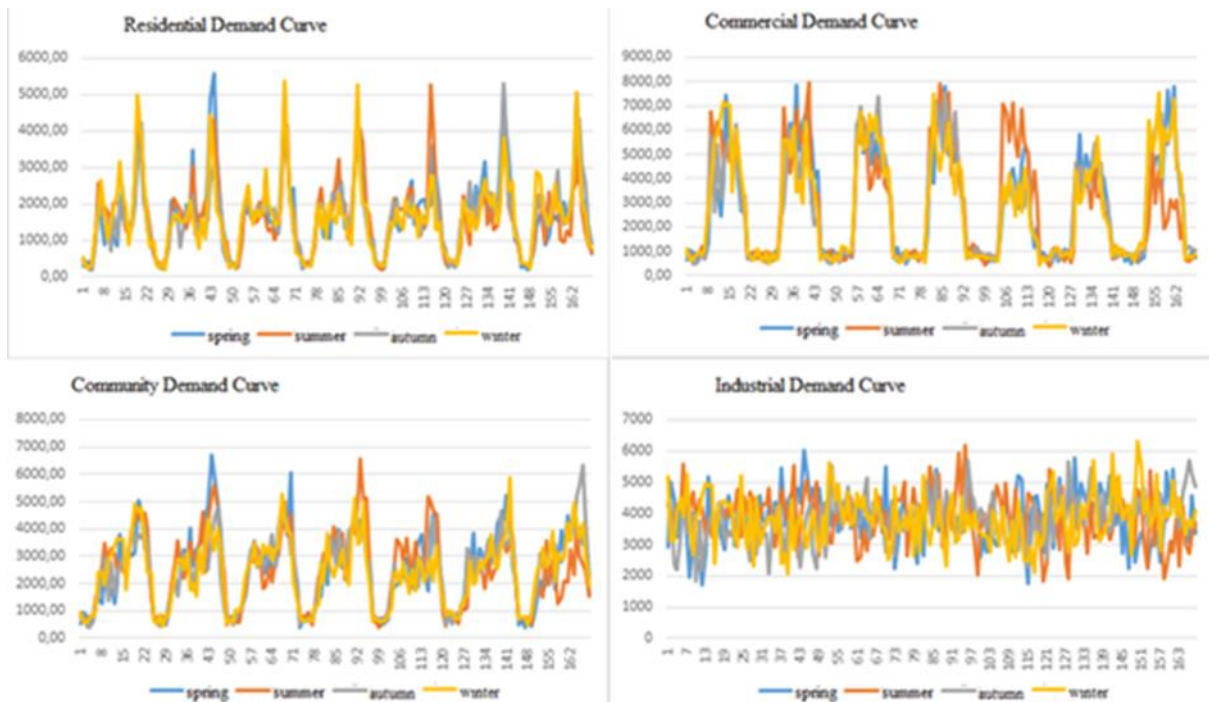


Fig. 2. Demand characteristics of demand points

CPLEX solver of GAMS software is used to obtain the optimal solution to the problem. GAMS software is run on a PC with Intel® Core™ i5-6500T processor and 8 GB RAM and optimal solution is obtained. Solution results are presented in Table 2 as follows:

Table 2. Solution results

Objective Function Value	158618.30
Solution Time	0.172 seconds
Iteration Numbers	1
GAP Interval	0.00%

According to the obtained solution, profit value for the problem is equal to 158618.30 \$. Solution results indicate that the demand is mostly satisfied by grid connection, which means the capacity of renewables are generally inadequate to satisfy demand. Number of generation plants must be increased in the network in order to obtain a solution with more contribution of renewables.

6. Conclusions

Energy demand increases in the world and conventional resources to generate energy are expected to be depleted in near future. To provide sustainable energy supply, hybrid energy systems, which are combination of different energy resources, are considered as a promising solution.

In this study, a linear programming model is proposed to overcome operational difficulties in management of hybrid energy systems. Optimal solution to operation strategy of energy network is thought to be obtained by using this model. According to our literature review, researchers are generally analyzing these systems simulation models or heuristic approaches. The main contribution of the paper is taking the problem into account from the optimization perspective. A numerical example with 10 demand points and 2 solar energy plants is solved with a commercial solver software and grid-connection is considered to cover energy shortages of generation plants.

It is demonstrated by obtaining the optimal solution to the proposed model that mathematical models can be considered as a useful decision support tool in hybrid energy systems for operational decisions.

This study can be solved for greater number of demand and supply points. Storage units and different renewable energy resources can be inserted into the model. Several supply and demand satisfaction mechanisms can be analyzed. In addition to the aforementioned extensions, multiple objective optimization of hybrid energy networks can be considered instead of single objective optimization.

Acknowledgments

A simple version of this study was presented by Mehmet Kabak in 8th International Conference on Advanced Technologies and Gazi University Scientific and Research Project Fund (06/2019-10) provided him financial support for attendance to the conference. Ahmet Aktas was a visiting researcher at University of Coimbra during a part of this study with the support of the Scientific and Technological Research Council of Turkey (TUBITAK-2214-A program). The authors acknowledge support of TUBITAK and Gazi University on this study.

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