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Designing sustainable energy regions using genetic algorithms and location-allocation approach

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A B S T R A C T

Geographical areas have diverse green energy resources and different levels of energy consumptions. An important challenge to satisfy the energy demand using green energy resources is to balance energy supply and demand. Territory design deals with the problem of grouping geographic areas into larger geographic clusters called territories in such a way that the grouping is acceptable according to a planning criterion. The aim of this study is to group geographic areas so that energy requirement in a geographic cluster matches the available green energy potential in the same cluster. In this way, investments may be supported through region specific policies. The problem is formulated as a mixed-integer linear programming model. A location-allocation approach is employed to solve the model. The location and allocation problems are solved iteratively. In order to solve the initial location problem, a Genetic Algorithm is developed to find the results of the p-median problem. Then, the allocation problem is solved optimally using the ILOG Cplex solver. The territory design problem is solved for Turkey and the results of various numbers of territories are compared. Among those trials, 10 territories result in the best balance of demand and supply.

1. Introduction

Energy supply system is defined as the chain of systems and activities required to ensure supply of energy and include supply sector, energy transforming sector and energy consuming sector [9]. The supply involves production, imports or exports of fuel and changes in stock levels, transformation converts different forms of energies for ease of use by consumers, and finally the end users utilize various forms of energies to meet their daily needs. The balance between supply and consumption is a very important issue since an imbalance may cause vital problems for users. Maintaining the balance has been a hot topic for energy planners.

From the perspectives of planners and policy makers, another important issue is to plan the type of energy to be used. IEA [30] states that without the heat and electricity from fuel combustion, economic activity would be limited. Despite their important role, fossil fuels, such as oil, coal and natural gas, are not unlimited resources, and also their extensive use has caused some major human health and human welfare problems. Due these drawbacks of the fossil fuels, new energy descriptions such as green energy and renewable energy have gained importance. Renewable energy is defined as energy that comes from resources which are naturally replenished sunlight, wind, rain, tides, waves and geothermal heat. On the other hand green energy is defined as an energy type that is produced in such a way as to minimize its negative impact on the environment. Recently, GE (green energy) sources have gained tremendous attention and have become the key factor in sustainable development. According to Midilli et al. [47] the reasons for green energy to be the key factor is because: Green Energy (i) provide a more environment-friendly and more sustainable future, (ii) increase energy security, (iii) facilitate or necessitate the development of new and clean technologies, (iv) reduce air, water and soil pollution and the loss of forests, (v) reduce energy-related illnesses and deaths, (vi) reduce or stop conflicts among countries regarding energy reserves.

The investment in green energy technologies has steadily increased and reached approximately 12.9% of global primary energy supply [32]. Solar and wind energy have recently showed a significant growth but they still cover a small fraction of global energy supply. The investments in clean energy have also increased in the recent years, while the investments were about 54 billion dollars in 2004 it reached to 260 billion in 2011 from with a constant increase [10]. The structure of the investments has also changed, a decade ago governments were leading the GE investments, but today the largest source of the capital for new

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projects belongs to private investments. Wüstenhagen and Menichetti [67] state that there are two main factors for this change, first private sector investments are encouraged by the new energy policies and as a second factor, technology improvement has led to increased reliability and declining costs. Wind and solar energy are the two examples that one can realize the effects of declining costs. Average project cost for wind energy has decreased from 3500$/kW in 1985 to $900–$1300/kW range in 2014 [66] and the average price of grid connected solar PV (photovoltaic) systems has decreased around 30% just in the year of 2009 [31]. As a result, wind and solar energy together constitutes 90% of new investments in 2013 [24].

Energy planning has widely been examined in energy literature. The mostly used approaches can be given as optimization models, multicriteria decision making models and forecasting models. Optimization models try to find the best solution given a set of constraints. Energy flow optimization, energy source optimization models can be given as examples. Multi criteria decision making techniques are used to select the best alternative among the predefined set of alternatives, in the energy literature these methods are generally used for selection policies or energy sources. Forecasting models are used to get insight about future demand and supply levels. The forecasting problems have been modeled for different time periods and geographical areas. The findings of these studies can be used for future energy planning. The focus of the studies may also be different; for example integrated energy planning aims to optimize overall energy system using both commercial and renewable energy sources. On the other hand DEP (decentralized energy planning) considers various available resources and demand in the appropriate planning level such as villages, blocks or districts.

Territory design is the problem of grouping small geographic areas such as counties, zip codes or company trading areas, into larger geographic clusters called territories according to relevant planning criteria. The planning criteria can be in economic terms such as average sales potentials, workload or number of customers; or demographical such as number of inhabitants, voting population. In territorial design problems, spatial restrictions such as contiguity and compactness can be demanded [33]. In the field of energy planning, identifying the geographical areas that will be the focus of decentralized planning efforts can be obtained by territorial design. To that end, the planning criteria should be related to energy planning issues, such as energy production capacity and consumption.

In this study, a case study is presented for using territorial design approach to a new green energy planning problem. The aim of the model is to determine the green energy planning territories in Turkey in order to make the energy consumption and the GE potential equal for each territory. To the best of our knowledge, this is the first application of territorial design in green energy planning area.

In this manner, the chapter is organized as follows: In Section 2 energy planning literature about energy planning and territory design is provided. Section 3 describes territorial design and provides a brief literature review about previous studies. Section 4 contains a territorial design application for the case of Turkey and computational experiments. Finally further steps are discussed in conclusion.

2. Literature review

2.1. Energy planning

Energy planning focus on meeting the excess energy demand in an optimal way, and to this end it deals with the supply side and demand side management activities. In the literature, energy planning studies are carried out both in centralized and decentralized level. While the first one focuses on conventional energy sources, the former focus on efficient utilization of the regional sources and thus it is in close contact with this paper. Another group of studies which are directly related with the scope of this study are the papers that focus on energy planning using renewable energy sources. In order to present the state of the art, this section focus on both depersonalized energy planning and renewable energy integrated planning studies.

One of the research areas in DEP focuses on optimization and planning. Some of the studies in this group can be listed as: Soares et al. [61] focus on optimization of the time allocation of domestic loads within a planning period of 36 h in a smart grid context. The authors utilize a multi-objective genetic algorithm to solve the problem of minimizing the electricity bill and the end-user's dissatisfaction. Merkel et al. [46] discuss the implementation of decentralized residential heat supply in optimizing energy system models. The authors use mixed integer programming to accurately model the capacity planning of residential heat supply systems. The results show that the proposed approach produce results that comply with the realistic capacity planning of heat supply systems in a shortened computation time. Ravindra and Iyer [55]; suggest that locally installed micro grids to provide appropriate decentralized options to augment the centralized grid based systems. The authors propose a framework to identify the proper decentralized energy options for demand–supply matching within a community. After defining the options, the authors then determine appropriate solution that can suitably plug the existing demand–supply gap at varying levels of grid unavailability. Malik and Bouzguenda [39] present a methodology to evaluate the long-term load management benefits of smart grid in terms of avoided cost of generation, transmission and distribution. The transmission and distribution capacity cost is calculated indirectly and the savings in transmission and distribution losses and environmental benefits are included into the study. The results of a case study in Oman show that the long-term load management benefits of smart grid could outweigh the cost of upgrading the grid to make it smarter. Mallikarjun and Lewis [40] present a two-stage multi-objective decision model for optimal energy technology allocation for distributed energy resources. The objectives of the proposed study contain economic, technical, and environmental objectives. In the first stage of the study, a production frontier estimation model for each end-use to evaluate the performance of each energy technology based on the three objectives is utilized. And in the second stage of the framework the bottleneck multi-criteria decision model which provide pareto-optimal energy resource allocation is constructed consisting of efficiencies determined in the first stage, capacity limitations, dispatchability, and renewable penetration for each technology, and demand for each end-use. The authors also propose a case study using a dataset of a typical commercial building located in the Northeastern United States. Zhu et al. [68]; propose interval-parameter full-infinite joint-probabilistic mixed-integer programming method for electric power systems optimization under uncertainties. The proposed method is capable of reflecting the risk of violating system constraints under joint probability and can deal with other uncertainties such as crisp interval values and functional intervals. The authors develop a model for planning electronic power systems considering air pollution in the municipality level. Bang Moller et al. [6] investigate options for increasing the efficiency of decentralized combined heat and power plants fueled with biomass compared to conventional technology. The authors focus on the performance of an alternative plant design based on thermal biomass gasification and solid oxide fuel cells. The results indicate that design of a decentralized combined heat and power