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Review

A Review of Applications of Linear Programming and Mixed Integer Linear Programming in Energy Management: From Policy Makers/Producers to Consumers

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Abstract: Optimization methods in the field of energy efficiency and energy management is a popular research area. Applications of linear programming, mixed integer linear programming are important since they provide an efficiently-solvable model for these complex problems. This study focuses on those applications from the perspectives of policy makers/producers and consumers. Some of those applications are related to smart power distribution, renewables, energy efficient buildings, energy planning etc. As the demand for energy, new alternative energy sources and new technological developments will keep growing, use of optimization methods in general and linear programming in particular will find many different application areas.

Keywords: *Energy efficiency, Energy management, Linear programming, Mixed integer linear programming*

Enerji Yönetiminde Doğrusal Programlama ve Karma Tamsayılı Doğrusal Programlama Uygulamalarının Bir Derlemesi: Karar Vericiler/Üreticilerden Tüketicilere

Özet: Enerji verimliliği ve enerji yönetimi alanındaki optimizasyon yöntemleri popüler bir araştırma alanıdır. Doğrusal programlama, karma tamsayılı doğrusal programlama uygulamaları, karmaşık problemler için etkin çözülebilir bir model sağladıkları için önemlidir. Bu çalışma, karar vericiler/üreticiler ve tüketicilerin bakış açılarından bu uygulamalara odaklanmaktadır. Bu uygulamalardan bazıları, akıllı güç dağıtımı, yenilenebilir enerji kaynakları, enerji verimli binalar, enerji planlaması vb. ile ilgilidir. Enerji talebi, yeni alternatif enerji kaynakları ve yeni teknolojik gelişmeler büyümeye devam ettikçe, genel olarak optimizasyon yöntemlerinin kullanımı ve özel anlamda doğrusal programlama birçok farklı uygulama alanı bulacaktır.

Anahtar kelimeler: *Doğrusal programlama, Enerji verimliliği, Enerji yönetimi, Karma tamsayılı doğrusal programlama*

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1. Introduction

Today, to satisfy the fast growing energy demand of both corporations and societies, it is inevitable to efficiently use energy resources, have low-cost energy resources and achieve sustainability. As the costs of energy and equipment have rised, effective management of energy systems became an important subject. The growing importance of energy efficieny comes not only from the efficient use of resources for corporations and the value it adds to economies at the macro level but also from environmental perspective and sustainable development.

The problems studied in energy management can be listed as follows: Increasing energy efficiency, avoiding energy losses in the processes, choosing among alternative energy sources, planning energy projects, increasing energy performance of corporations, guiding energy policies and governmental planning and optimizing energy systems.

Therefore, there is a growing interest in optimization methods in the field of energy management as these problems have many constraints to be satisfied, sometimes different objectives to be optimized and become complex and hard to solve. In general, the objectives in these problems may range from minimizing cost of energy usage, efficient use of limited resources related to energy management for corporations, increasing efficiency of energy usage to increasing profit. One can refer to [14] for a review of the subject with a focus on the classification of the subject in terms of decision level, application area and energy type.

In this paper, we focus on the applications of Linear Programming (LP) and Mixed Integer Linear Programming (MILP) in energy management in relation to policy makers/producers and consumers. Such applications of LP, MILP are important because they provide an efficiently-solvable model for the aforementioned complex problems in energy management. In some of these applications, LP is used as a direct modeling tool whereas there are others proposing use of LP as an approximation scheme or as a part of a heuristic approach.

2. Materials and Method

In this study, researches using LP, MILP as a modeling tool in energy management and its applications are investigated. In LP models, a linear objective function is optimized satisfying some constraints, which can be linear equalities or inequalities [14].

Use of LP models to solve problems in energy management is a preferred research area. According to Bordin (2015), the most important problems that can be studied through LP and MILP in the energy sector are related to 'energy production' and 'energy dispatching'. The optimal generator plants management, scheduling and location and the optimal energy distrubition along optimized energy networks are key issues [5]. In [5], it is mentioned that to solve problems in areas such as thermal energy distrubution (district heating systems, district cooling systems), energy production, electrical energy distrubution (grid-connected systems, off-grid systems), LP, MILP in the deterministic sense can be used along with the other methods of optimization.

3. Applications

3.1. Policy Makers/Producers

Damyant and David (1990) developed an LP model to calculate the least cost configuration of the energy system in the province of Ontario in Canada for the year 2021. Both non-renewable and renewable sources were considered to meet the energy demands of residental, industrial and transportation sectors [10].

Fujii (2002) used an LP energy system model to investigate the possible future configuration of energy and CO_2related infrastructure in Asia and Eurasia which minimizes inter-temporally the sum of the discounted total energy system costs until the year 2050 [15].

An LP process was used in [8] to support the energy flow optimisation model for the analysis of the entire energy system of the Apulia region of Italy.

Iniyan and Sumathy (2003) developed an optimal renewable energy mathematical model with LP method to evaluate renewable energy sources in India. The model was developed with the objective of minimizing cost/efficiency ratio based on social acceptance, reliability, demand and potential constraints. The potential for biomass, bio gas, firewood and ethanol were varied in the model and different renewable energy distribution patterns were obtained. They proposed an LP model to optimize the use of renewable energy technologies for 6 different end-uses (lighting, cooking, pumping, heating, cooling and transportation) in rural areas in India [20].

Önüt and Soner (2006) proposed a model for measuring energy efficiency. Data Envelopment Analysis that is a special LP model was used. The methodology was evaluated in 32 five-stars hotels in Antalya, Turkey. Ideal energy consumptions (electricity, water, liquefied petroluem gas consumptions) were evaluated with the proposed methodology [29].

Dicorato et al. (2008) used an LP model on energy flow optimisation for evaluating the contribution of distributed-genaration production and energy-efficiency actions. The proposed methodology was applied to a realistic energy system [12].

DEA (Data Envelopment Analysis)-type LP models were proposed in [49] to measure the energy efficiency performances of 21 OECD countries.

An MILP model was constructed by Tan et al. (2010) to address the uncertainties in the boundary constraints and objection functions concerning waste management in a local energy system [37].

Huneke et al. (2012) developed an LP model for optimal configuration of the electrical power supply system following characteristic restrictions as well as hourly weather and demand data. From the model, the optimal mix of solar and wind based power generators combined with storage devices and a diesel generator set is formed. Model was tested in two real off-grid energy systems: a cluster of villages in India and Titumate in Colombia [19].

Lopez-Pena et al. (2012) studied a cost minimization model on energy efficiency for reducing CO_2 emissions in Spanish energy sector. An LP model was used and different sectors such as transportation and buildings were compared according to their research results [25].

Manfren (2012) proposed an LP approach for dynamic energy management management. Dynamic energy management models are a part of this 'systems thinking' vision that aims to create a new field of applications that is at the intersection of computing sicence and energy technology [26] .

Rizzo and Savino (2012) used an LP model for the optimal selection on Sustainable Energy Action Plans has. The model allows to allocate in optimal way the economic resources among different actions to achieve a given level of CO_2 emissions reduction, considering resource constraints [33].

Song et al. (2012) used an MILP model to minimize the total cost of regional energy systems. The model was developed to support sustainable waste treatment with greenhouse gases mitigation, addressing the possibility for development towards a regional fossil fuel-free society between 2011 and 2030. A case study in Sweden was performed to demonstrate the applicability of the developed MILP model in five distinct scenarios [36].

Xydis and Koroneos (2012) used an LP model to optimize the way to meet the country's energy needs using renewable energy sources and at the same time to define the remaining available space for energy recovery units from municipal solid waste in each region to participate in the energy system. The model was studied for the Hellenic energy system for all different regions [47].

He et al. (2015) developed a new approach on the energy resilience of an economy using an MILP model and economic input-output analysis. An energy import resilience index has been improved by examining the maximum level on energy import reduction. China input-output data was used under different power generation portfolio assumptions to determine the energy import resilience index for an economy. The developed methodology focused on the relationship between energy imports, industrial production technologies and capacities [17].

In the context of smart energy systems [2] proposed an LP framework to model distribution network characteristics in the presence of variable renewable energy. This LP was basically used as an approximation to the nonlinear load flow distribution market clearing and relevant in the regional integrated energy models. A case study from Europe was also provided.

As mentioned in [6], in the popular area of off-grid power systems, cost of renewables integration, is an important component and from this perspective, especially battery degradation. Bordin et al. (2016), defining battery degradation costs, used LP models to include these processes inside the optimization models [6].

Umetani et al. (2016) proposed an LP based heuristic to smart charge and discharge scheduling of electric vehicles problem with an emphasis on vehicle-to-grid power [40].

He et al. (2017) looked at energy-economic recovery resilience problem and developed a model which leads to MILP models. This can especially be helpful in planning and allocation of recovery resources in the economy [18] .

A smart power plant composed of wind turbines coupled with Lithium Ion storage devices was considered in [7], where heuristic and LP methods were compared in energy management optimization.

Kaldemeyer et al. (2018) developed an MILP model for a generic formulation of compressed air energy storage with a focus on unit commitment of specific technical concepts in arbitrary market environments [21].

To optimize sizing of solar-wind renewable energy systems, Lamedica et al. (2018) used an MILP methodology. The methodology considered the followings: Load requirements, physical and geometric constraints for the renewable plants installation, operating and maintenance costs both wind and solar power plants, and the electric energy absorbed by the public network [22].

In [34], the design and operation of integrated urban energy system was considered and a general MILP model was proposed. For representing integrated networks of resources and technologies, it used a fleaxible value web framework. A case study in central England was provided.

Urbanucci (2018) discussed limits and potentials of MILP for optimization of polygeneration energy systems. It is mentioned that to increase energy efficiency and facilitate the development of distributed energy systems, the simultaneous production of different energy vectors from hybrid polygeneration plants is a promising approach [41].

Wang et al. (2018) studied energy optimization for waste heat recovery in distributed energy systems, especially in a district-scale microgrid and developed an MILP model. The model distinguished waste heat quality for planning and operation optimization of distributed energy systems [44].

3.2. Consumers

3.2.1. Regional Energy Management/Industry/Machines/ Equipment

Delarue and D'haeseleer (2008) proposed an MILP approach to solve a unit commitment problem to meet electricity demand at lowest cost [11].

Dragicevic and Bojic (2009) used an LP methodology for optimizing an industrial steam-condensing system. The methodology was used to minimize the operating costs in steam-condensing systems that consisted of the boiler, the desuperheater, the turbine with steam extraction and the heat pump [13].

In [30], an LP model was developed to optimize temperature changes in using borehole heat exchangers on energy extraction of closed shallow geothermal systems. The optimization objective was to minimize the ground temperature changes and therefore maximize heat pump perfpormance, comply with regulative theresholds for induced temperature changes and mitigate environmental impacts.

Torres et al. (2014) proposed an optimization model using LP method for the scheduling problem where conventional and photovoltaic sources of energy were scheduled to be delivered to satisfy energy demand [39].

Wakui et al. (2014) used MILP models on a residental energy supply network using multiple cogeneration systems. In the first MILP model, energy loss characteristics of connecting pipes between storage tanks was investigated by considering the influence of hot water retention. In the second MILP model, a hot water demand calculation model considering energy loss from networked pipe was developed [43].

Tenfen and Finardi (2015) studied a mathematical model for the energy management problem of a microgrid by means of an MILP approach. The objective of the problem was to determine a generation and a controllable load demand policy. In the study, a detail modelling for microturbines and fuel cells was proposed [38].

Gupta et al. (2016) proposed a two-step LP formulation to determine the timetables in metro railway networks to minimize total energy consumed and maximize the utilization of regenerative energy produced. An application for Shanghai Metro was provided [16].

As mentioned in [46], energy efficiency optimization of crude oil refinery is an important problem as oil transportation consumes a large portion of energy. Wu et al. (2017) suggested an LP approach to this non-linear-in-nature problem to efficiently solve it. In this work, a real-world industrial case study was also provided [46].

Yin et al. (2017) is another work related to metro train scheduling and energy-efficieny. Here, in addition to minimizing energy, passenger waiting time was also minimized. For the formulation trying to achieve these two objectives simultaneously, an integer LP was achieved and for the formulation utilizing also the regenerative braking energy an MILP was achieved. A case study from Beijing metro was provided [48].

Bohlayer and Zöttl (2018) focused on an energy supply system of a manufacturing company to energy optimize its synthesis, design and operation [4].

Bertrand et al. (2019) provided an MILP mixed formulation, for energy servise companies, for regional waste heat valorization. The proposed approach was applied in a region in Luxembourg [3].

3.2.2. Household

Privitera et al. (2011) proposed an LP optimisation process to optimize the installed costs of renewable energy technologies for use in buildings to meet CO_2 emissions reduction targets [32].

Üçtuğ and Yükseltan (2012) used an LP method to optimize the allocation of budget in order to maximize the energy savings of a hypothetical household in Turkey. In that study, the energy conservation methods were installing photovoltaic solar cells, replacing regular windows with double-glazed ones, replacing incandescent bulbs with compact fluorescent light bulbs and replacing C-energy class househould appliances with A-energy class ones [42].

Omu et al. (2013) proposed an MILP model to design (technology selection, unit sizing, unit location and distrubution network structure) a distrubuted energy system that meets the electricity and heating demands of a cluster of commercial and residental buildings while minimising annual investment and operating cost [27].

Somma et al. (2015) developed an MILP model to determine the quality level of the energy sources (like high quality fossil fuels) used to satisfy the basic energy needs of a building depending on the the level of energy demand (low, high etc.) The study focused on an optimization model of a distributed energy system [35].

In terms of residential energy systems, Lauinger et al. (2016) used LP to combine energy conversion units with energy storage devises trying to decrease total yearly energy costs and CO2 emissions [23].

For energy system design of Zero Energy Buildings, Lindberg et al. (2016) proposed an MILP model to minimize cost. A case study of a Norwegian school building was provided [24].

Omu et al. (2016) proposed an iterative MILP approach instead of a conventional MILP formulation to optimize the design of a solar domestic hot water system providing a case study of an apartment building in Switzerland [28].

Pilla et al. (2016) proposed an optimization methodology for the evaluation of retrofit incentives by using the data collection of ENEA (Italian National Agency for New Technologies, Energy and Sustainable Economic Development). Two LP models were used to improve the distribution of energy building incentives. The first model maximizes energy savings and second one minimizes retrofit costs. The proposed methodology can be used for setting future incentive distribution plans and energy-financial plans [31].

In [1], in the context of residential energy management system, a linear optimization algorithm was developed along with a pricing scheme. More specifically, power scheduling of electric devices was considered and the system is applied in a smart home community.

For managing building clusters with a shared electrical energy storage, Dai and Charkhgard (2018) proposed a bi-objective MILP formulation. These collaborative building clusters bring an opportunity to minimize operational costs. This study assumed demand was deterministic and that the storage is shared between two buildings and introduced three energy storage sharing strategies [9].

Wang et al. (2018) developed an MILP model to determine the optimal generation, conversion and delivery of electricity, heat, cooling and other services for a comunity level multiple energy systems. A case study for a subsidiary administrative center in Beijing, China was provided [45].

4. Results and Discussion

As the importance of energy management increased, the use of optimization methods became a popular area of research. As such, from efiicient solvabality perspective, we see many different LP/MILP-related studies. In this work, we looked at those studies, which were presented from the perspectives of policy makers/producers and consumers. For example, some of those applications are related to smart power distribution, renewables, energy efficient buildings, energy planning etc. As the demand for energy, new alternative energy sources and new technological developments will keep growing, use of optimization methods in general and linear programming in particular will find many different application areas. Although some of these problems are complex in nature and hard to solve, new numerical techniques are going to be needed. Finally, it looks like new studies and applications of other optimization methods in energy efficiency and energy management will be of great need.

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