Energy and Buildings 49 (2012) 200–208

Contents lists available at SciVerse ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

A linear programming approach to household energy conservation: Efficient allocation of budget

Fehmi Görkem Üçtuğ*, Ergün Yükseltan

Bahcesehir University, Department of Energy Systems Engineering, 34353 Besiktas, Istanbul, Turkey

ARTICLE INFO

Article history:
Received 20 July 2011
Received in revised form
20 December 2011
Accepted 5 February 2012

Keywords:
Energy conservation
Household energy consumption
Linear programming
Optimization
Building energy efficiency
Turkey
Insulation
Photovoltaic cells
Energy labels

ABSTRACT

Linear programming method was used to optimize the allocation of budget in order to maximize the energy savings of a hypothetical household in Turkey. The energy conservation methods involved in this study 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 household appliances with A-Energy Class ones. The costs of these different energy conservation methods were obtained from the manufacturers' or distributors' websites. The annual energy savings of these methods were either obtained from available sources or calculated when necessary. The results showed that installing double-glazed windows and purchasing compact fluorescent light bulbs are the proper choices for low budgets. When budget increased, solar panel installation emerged as the feasible choice. The findings indicated that replacing household appliances should be considered only when a budget greater than €20,000 is available. Payback periods were found to be less than one and a half years, even at the highest budget. A budget decision of €800 was found to be the optimum decision for short term investments, whereas a budget decision of €24,000 was found to be the optimum decision for long term investments.

1. Introduction

Efficient use of energy is a very important concept, not only because it favors a more stable economy, but it also helps prevent environmental pollution, and the combination of these two facts is essential for sustainable development. Buildings are responsible for the consumption of approximately 40% of all commercial energy supplied as processed fuels or electricity in developed countries [1,2]. For thousands of years, mankind has tried to improve the energy efficiency of buildings via simple methods such as choosing the ideal geographic location or by using appropriate building and insulating materials depending on the climate. As the technology developed, the measures to minimize energy loss have become more complex. However, it was the 1973 global energy crisis that triggered a worldwide pursuit in designing buildings with less energy consumption, by incorporating energy efficiency and renewable energy resources [3]. Since then, many countries adopted laws and regulations on how to use energy more efficiently and energy efficiency in residential and commercial buildings have become a common area of interest [4–8]. Above-mentioned laws and regulations impose certain targets and deadlines regarding both residential and commercial buildings with the aim of reaching specified energy consumption limits. For instance, in Turkey the Energy Efficiency Law came into effect in May 2007, aiming to minimize the high level of energy intensity so as to achieve productive and effective use in every field of energy, prevention of wasteful expenditure and protection of the environment. This law, which was revised recently in February 2011, comprises the principals and procedures in order to increase the energy efficiency in industrial, building and transport sectors. With this law, Turkey aims to accomplish an energy saving of 30% in the next decade [9]. In order to achieve this goal, home-owners or tenants must take suitable actions to reduce their energy consumption without having to compensate from their quality of living. Therefore, the solution must satisfy energy-related, environmental and financial aspects of the problem. When the great number of possible actions that can reduce the energy consumption of a building is concerned, using a sophisticated method to determine the optimum choice(s) is inevitable. Before proceeding with linear programming, which is our choice of method, we would like to briefly review similar studies in the field.

Abbreviations: CFL, compact fluorescent light; DSW, dishwasher; LED, light-emitting diode; RFG, refrigerator; TRY, Turkish Lira; WMC, washing machine.

* Corresponding author at: Bahcesehir University, Department of Energy Systems Engineering, Ciragan Caddesi, 34353 Besiktas, Istanbul, Turkey.
Tel.: +90 0 212 381 5691; fax: +90 0 212 381 0550.
E-mail address: gorkem.uctug@bahcesehir.edu.tr (F.G. Üçtuğ).

0378-7788/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
doi:10.1016/j.enbuild.2012.02.020

1.1. Review of computer-aided techniques for building energy efficiency improvement

Several decision analysis methods have been put forward in the field of energy, and building energy efficiency in particular, recently. In his study, Al-Homoud reviewed a significant variety of computer-aided building energy analysis methods, ranging from simple steady-state methods to detailed hourly analysis techniques [10]. He concluded that "available energy simulation models are useful and powerful tools for the evaluation of the thermal performance of buildings and they can provide extensive performance information on the selected building considering the dynamic behavior of the system, as well as part load behavior". He also stated that "optimization techniques can also be useful in providing designers and decision makers with prescriptive information that cannot be easily achieved using simulation models alone". In a more recent study, Kolokotsa et al. analyzed various decision support methods for energy management in buildings [11]. They concluded that several constraints such as environmental, social, financial and energy-related aspects must be taken into account in order to make an optimum choice.

As far as multiobjective methodological approach is concerned, the following studies attracted our attention: Wright et al. investigated that application of a multi-criterion genetic algorithm in the search for a non-dominated set of solutions to pay-off between energy cost and occupant discomfort [12]. Their results showed that multi-criterion genetic algorithm was able to identify the pay-off characteristic between daily energy cost and zone thermal discomfort. Alanne et al. proposed a multi-criteria "knapsack" model to determine the most feasible renovation actions in the conceptual phase of a renovation project [13]. Amongst the 27 different options, radiator network adjustment via the installation of thermostatic valves emerged as the most feasible action. Chen et al. used an energy-time consumption index in order to maximize energy utilization efficiency in intelligent buildings, via an approach called analytic network process, which is a multicriterion decision method [14]. The distinctive feature of this study is the allocation of priority values to each criterion by taking the opinions of property owners, property managers, occupants and visitors. Verbeeck and Hens developed a global methodology to optimize concepts for extremely low energy dwellings, taking into account energy use, environmental impact, and financial costs over the life cycle of the buildings [15]. They used a software called TRNSYS to execute their energy simulations. The ecological impact was evaluated through a life cycle inventory of the whole building, whereas costs were evaluated through a cost–benefit analysis. Verbeeck and Hens reached two important conclusions regarding the economic implications of energy efficiency improvement in buildings. Firstly, they concluded that without financial support or incentives, building energy efficiency improvement will be limited to a small number of consumers with a high environmental consciousness that are willing to invest large budgets. However, they also stated that the energy payback time is extremely low for energy efficient dwellings and is, in most cases, less than two years. Diakaki et al. suggested a considerable number of energy efficiency improvement options to choose from, such as door and window types, insulation thickness and type of heating system [16]. Their model calculated not only the energy consumption but also the CO_2 emission of the building. And for the last but not the least, Magnier and Haghighat described an optimization methodology based on a combination of an artificial neural network and a multiobjective evolutionary algorithm, by using Latin Hypercube sampling and GenOpt automation engine in order to create the database of cases [17]. Their study produced the energy impact of the thermal comfort choice made by the user as the output.

1.2. Justification of the method

In this study, linear programming method was used to optimize the allocation of budget in order to maximize the energy savings of a hypothetical household in Turkey. Linear programming is a mathematical method for determining a way to achieve the best outcome (such as maximum profit or lowest cost) in a given mathematical model for a list of requirements represented as linear relationships [18]. A linear programming model simply contains an objective function (to be maximized or minimized) and a constraint function. Linear programming method is a very convenient tool that it is used extensively to solve and optimize various types of economical and industrial problems.

Our model, whose details will be presented in the following Section 3.3, accepts energy savings (W) as the objective function and the budget as the constraint function. There are various actions that result in energy savings in a house, each with a specified unit cost. The aim of the algorithm is to allocate the budget to these actions in order to obtain the maximum energy savings. Different budget values were used as constraint to get energy saving values as a function of budget.

While developing the method, our main idea was to analyze the issue of building energy efficiency from the household consumer's point of view. We wanted to create a simple, yet effective algorithm. Our algorithm was designed to answer the question of "how much energy would be saved if certain amount of money was spent". After obtaining the maximum possible energy savings values for each different budget, we calculated payback periods and profitability values to convert the output into a more understandable form for the consumer.

A further strength of this study is the realization of a detailed market research in order to get approximate cost values for each particular energy-saving measure. The readers can simply check the references listed at the end to get the actual cost values for any given item or method.

2. Energy conservation methods in buildings

The materials and techniques employed in order to improve the energy efficiency in buildings vary greatly. Jaber and Ajib [19] listed the main steps to achieve energy conservation in residential buildings as follows:

i. Passive design by considering climate effects so as to decrease heating, cooling, dehumidification, lighting, equipment and hot water loads.
ii. Improving the efficiency of the mechanical and electrical equipment used in the building.
iii. Replacing fossil fuels with renewable sources for the supply of primary energy

Heating and cooling systems make up for a significant portion of the total expenditure of households. Heating systems like boilers, heat pumps and cooling systems like air conditioners are expensive to install and operate; consequently the entire energy requirement of a building cannot solely be met by using such equipment as far as energy efficiency is concerned. Therefore, using insulation materials to minimize heat loss (or gain) is essential to achieve meaningful energy conservation. Windows lose energy more readily than walls or a floor, therefore using insulation materials in windows is the most straightforward approach to minimize heat loss. The most common technique applied for insulating windows is double glazing, in which double or triple glass window panes separated by an air-(or other gas)-filled space are used to reduce heat transfer across a part of the building envelope. Double glazing is not only an