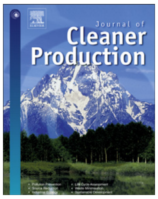
Journal of Cleaner Production xxx (2015) 1–16

Contents lists available at ScienceDirect

Journal of Cleaner Production

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



An integrated supply-demand model for the optimization of energy flow in the urban system

Hooman Farzaneh [a], [b], [*], Christopher N.H. Doll [a], Jose A. Puppim de Oliveira [a], [c]

[a] United Nations University, Institute for the Advanced Study of Sustainability, Tokyo, Japan
[b] National Institute for Environmental Studies, Tsukuba, Japan
[c] Brazilian School of Public and Business Administration, Getulio Vargas Foundation (FGV/EBAPE), Brazil

ARTICLE INFO

Article history:
Received 3 September 2014
Received in revised form
26 April 2015
Accepted 25 May 2015
Available online xxx

Keywords:
Urban energy system
Optimization modeling
Cost-effective
Electricity deficiency
Co-benefits
Delhi

ABSTRACT

This research aims to develop a bottom-up integrated supply-demand model to assess the optimal performance of urban energy systems. To this end, an optimization model founded on the principles of microeconomics was developed and deployed using mathematical programming. In this model, the urban energy system is treated as an economic actor in the market seeking to establish an effective energy system to improve its overall resource efficiency with minimum total cost of the system. The model leads the system to achieve supply and demand energy commitments which include alternative energy and energy efficiency targets. In this paper, we apply the model to address the electricity deficiency in Delhi, India, as a case study. The results suggest that the saving at the end-user level could reach about 220 GWh per annum in the near future through improving energy end-use efficiency in the domestic sector. Besides this, the installation of about 40 MW from waste-to-electricity plants and generating approximately 210 GWh electricity from the rooftop solar PV by 2030 could enable a sufficient surplus for the power supply sector to meet the city's electricity demand in the near future. Even though the system has some inherent limitations stemming from the assumptions of microeconomics and challenges related to data needs, the model can help the local actors, from governments to property owners, to find the best solutions for their energy needs. Such a modeling framework could address an organization's sustainable performance at the urban level through the resource use optimization, minimization of waste, cleaner technologies and pollution limits which are used in achieving co-benefits and a broad range of Eco-Industrial Development (EID) goals.

1. Introduction

One of the biggest challenges in moving towards Eco-Industrial Development (EID) is to address the escalating demand for energy in urbanizing areas. Cities are being increasingly recognized as major contributors to climate change, consuming two thirds of global primary energy and generating about 71% of energy-related CO_2 emissions which is expected to rise to 76% by 2030 (IEA, 2008). The main challenges for urban energy transitions include: 1) increased urbanization in developing countries; 2) changing infrastructure in developed countries; 3) climate change-energy security imperatives; and 4) new technologies at local and grid levels (Keirstead and Shah, 2013). These challenges highlight the need for cities to reconsider how new urban investments should be prioritized in order to reduce resource consumption and emissions, as well as to achieve local and national development goals using a co-benefits approach (Puppim de Oliveira, 2013). Thus, a framework that helps to plan this energy transition is an important field of research in urban energy systems in order to pursue low-carbon energy development and to propose more energy efficiency pathways for our cities.

An urban energy system can be defined as the combined processes of producing and using different forms of energy to satisfy the service demand of a given urban area (Keirstead et al., 2012). While, many of the energy conversion steps and processes (i.e. electricity generation, refining, storage, etc.) are not taking place in the cities, they should be considered in the overall system, particularly, if they are being used to service urban energy demands. Moreover, even though cities might be seen as the net consumers of

---

[*] Corresponding author. United Nations University, Institute for the Advanced Study of Sustainability, 5-53-70, Jingumae, Shibuya-ku, Tokyo, Japan. Tel.: +81 090 96971354.

E-mail address: farzaneh@unu.edu (H. Farzaneh).

http://dx.doi.org/10.1016/j.jclepro.2015.05.098

Please cite this article in press as: Farzaneh, H., et al., An integrated supply-demand model for the optimization of energy flow in the urban system, Journal of Cleaner Production (2015), http://dx.doi.org/10.1016/j.jclepro.2015.05.098

energy supplied from external resources, there are significant opportunities for local energy generation in cities. Thus, both supply and demand sides should be taken into account in the definition of the urban energy system. There is a myriad of technology options and control strategies on both the supply and demand side that can be considered in future urban energy systems. In order to achieve the imperative of low-carbon urban systems, planning has to consider both the high penetration of alternative energy sources on the supply side and highly efficient energy consumption strategies on the demand side. Furthermore, the urban energy system should be viewed as a socio-technical system which means that society, the market, government institutions and other organizations also need to be taken into account in this context (McGranahan and Marcotullio, 2005). Notwithstanding the inherent limitations of all models, having a good model of the urban energy system, decision makers can better plan how to influence future energy demand and supply decisions, as well as enhance its integration into other areas of planning, management and control.

1.1. *Classification of urban energy system models*

Models of the urban energy systems serve as analytical tools for understanding and managing the demand for resources in cities. Over the last decades, many analytical tools and models with different approaches have been developed and implemented to assess the efficiency of the urban energy systems over wide temporal and spatial scales. Nakata et al. (2011) presented a review of the energy system models with a special focus on the low carbon society, considering the utilization of waste for energy, the penetration of clean coal technologies and transportation sector models as an example of sectoral approaches. Keirstead et al. (2012) presented six areas of practice in the review of urban energy system models: technology design; building design; urban climate; systems design; policy assessment; and transport and land use. With respect to the main aim of this research, we begin with a brief review of urban energy system models classified into three main groups: 1) demand-side models, 2) supply-side models and 3) integrated models. Applying this classification of models enables us to find an applicable analytical framework through focusing on major conceptual instruments of EID such as resource efficiency, cleaner production and using renewable energy in both energy and material use.

1.1.1. *Demand-side models*

Demand-side models consist of a broad range of methodologies which focus on determining the final energy consumption at the city's end-user level: buildings (residential, industrial and commercial), industrial energy use and the urban transportation system. In these models, industrial activities are usually merged into the commercial sector. Building energy models cover a range of spatial scales from a single building to the whole city and can rely on bottom-up simulation techniques and Geographical Information System (GIS)-based tools. Bottom-up simulation models have been widely used to estimate energy demand in buildings (De Lieto Vollaro et al., 2015; Verbai et al., 2014; Kavgic et al., 2013; Eom et al., 2012) and to study their design and renovation (Aksoezen et al., 2015; Chantrelle et al., 2011) or the way they are affected by the urban climate (Berger et al., 2014; Hong et al., 2013; Liu and Sweeney, 2012). Development of simulation models have been also pursued by scholars for analyzing energy efficiency metrics in residential buildings with a special focus on managing heating and cooling loads and introducing demand side management programs (Mardookhy et al., 2014; Ma et al., 2014; Jiang et al., 2013; Tulsyan et al., 2013). Such programs require the estimation of load demand profiles, which can be difficult due to the uncertainty of domestic consumption. Zúñiga et al. (2014) utilized fuzzy logic to model human behavior related to the activation of appliances and lighting at home and showed that the residential consumption sector contributes the most to the formation of the curve peaks and valleys. Further models built on this premise have examined the energy demand management strategy of the commercial buildings through the thermal storage system (Zhang et al., 2012) and estimation of the daylight luminance and its distribution in an office (Kazanasmaz, 2013). The energy consumption of urban buildings is also affected by the surrounding microclimate which can decrease sunlight and wind potentials for internal solar gains and passive cooling. The microclimate in urban areas differs significantly from the climate in rural areas. The importance of accounting for the urban microclimate for the prediction of the energy demand of buildings is addressed by simulation models with hourly temporal resolution (Malys et al., 2014; Yi and Peng, 2104; Allegrini et al., 2012).

At the city level, bottom-up statistical methodologies combined with the GIS techniques have been used to show how the impacts of behavioral and technical changes in the building stock can be assessed and visualized in the residential sector in cities (Mattinen et al., 2014) and to prioritize the implementation of energy retrofit measures for the residential stock of cities (Mastrucci et al., 2014).

Urban transportation plays a pivotal role in end-use energy consumption, largely due to the strong reliance on fossil fuels and a significant growth in mobility demand. Technology-based measures to reduce energy consumption in the passenger vehicles and public transport system are the basis of a lot of applications of models based on different analytical approaches and methodologies. These applications focus on the feasibility of improvements in multiple aspects of the design of the urban transportation system such as the introduction of more efficient vehicles (i.e. electric and hybrid) and utilization of alternative fuels like CNG, biodiesel, ethanol and hydrogen. Control-oriented simulation models have been developed and applied to estimate the logic relationship between the design of the power train and the fuel economy of the vehicles (Wu et al., 2015; Schwickart et al., 2014; Yun et al., 2014). Tank-to-wheel analysis models have been proposed for the simulation of fuel consumption and emissions of road vehicles equipped with internal combustion engines, using conventional or alternative fuels (Raykin et al., 2012). Optimization modeling frameworks for energy management within small electric energy systems (SEES) including vehicle-to-grid (V2G) systems which are expressed through linear programming algorithm, allow for assessment of the effect of V2G as a contribution to the management of energy resources of a SEES (Guille and Gross, 2009). The impact of driving strategy “Ecodriving” on the tank-to-wheel energy use of vehicles in different traffic conditions has been also studied through the development of the optimal-control models (Saboohi and Farzaneh, 2009) and a micro traffic-fuel consumption simulation model (Orfila, 2012).

Overall the methodological focus of this cluster of urban energy system models considers the demand side endogenously and supply-side issues were not considered at all.

1.1.2. *Supply-side models*

Supply-side models have mostly focused on energy supply technologies, particularly, solar energy systems, urban wind turbines, heating and cooling technologies and waste-to-electricity systems. Models are characterized by a limited spatial scale, generally considering a single piece of technology using a simulation technique or experimental work to perform the analysis including the design and performance of the system. The models may therefore be characterized as calculating supply-side parameters related to technology design or, in some cases, its

Please cite this article in press as: Farzaneh, H., et al., An integrated supply-demand model for the optimization of energy flow in the urban system, Journal of Cleaner Production (2015), http://dx.doi.org/10.1016/j.jclepro.2015.05.098