Applied Energy 191 (2017) 1–9

Contents lists available at ScienceDirect

Applied Energy

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

GIS-based urban energy systems models and tools: Introducing a model for the optimisation of flexibilisation technologies in urban areas

Alaa Alhamwi *, Wided Medjroubi, Thomas Vogt, Carsten Agert

NEXT ENERGY - EWE Research Centre for Energy Technology at the University of Oldenburg, Carl-von-Ossietzky-Str.15, 26129 Oldenburg, Germany

HIGHLIGHTS

- Overview of the current state of practise of GIS-based urban energy systems models.
- A growing research interests in modelling urban energy systems using GIS.
- GIS plays a significant role for planning sustainable energy systems in cities.
- Using open source data and models can effectively replicate urban energy features.
- Open GIS-based platform for the optimisation of flexibilisation technologies in cities.

ARTICLE INFO

Article history:
Received 2 November 2016
Received in revised form 31 December 2016
Accepted 15 January 2017
Available online 27 January 2017

Keywords:
Geographic information systems
Urban energy systems
Flexibilisation options
Open source data
OpenStreetMap
Cities

ABSTRACT

Planning of sustainable *Urban Energy Systems* is a challenging task for the many involved stakeholders which requires optimal use of available knowledge for decision support. Therefore, systematic approaches integrating energy models and interactively linking them to real-world data are highly required. In this regard, Geographic Information Systems (called GIS) offer as a platform many advantages and can play a significant role in integrating renewable energy sources at the urban scale. The optimal integration and placement of different possible flexibilisation technologies such as storage can profit from the possibilities offered by GIS tools. In addition, GIS facilitate policy making, allowing for a realistic and multilayer representation of urban energy systems. This contribution first draws an overview of GIS-based models for urban energy systems by investigating the current state of modelling. It introduces in a second step, an outline of a transferable GIS-based platform for the optimisation of storage and other flexibilisation technologies in urban areas. The model is composed of three main components and deals with the optimal integration of flexibilisation technologies. The fields of applications of the model are, but not restricted to, analysis of the emergence of sustainable cities, self-consumption at the urban levels, autarky measures, capacity demand and economic efficiency, and the integration of flexibility options. The method developed by the authors and presented here deals with the first component of the proposed model which is setting up the spatial framework. The framework relies mainly on spatial features of urban objects extracted from the open source OpenStreetMap database. The different steps involved in the spatial framework set-up are extraction and filtering of the data sets and their algorithmic steps which will be introduced here in details. A central finding of this contribution illustrates the feasibility and effectiveness of using open source data and tools to replicate urban energy features.

1. Introduction

Since 2007, our world is experiencing the highest rates of global urbanisation in history. More than half of world's population are living in cities, a number expected to increase to more than 5 billion representing about 60% of the population by 2030 Pfeier et al. [1]; Fund [2]. Consequently, cities infrastructures will face significant challenges to satisfy the growing demand on energy services, which without the integration of renewable energies will cause higher emissions of greenhouse gases and pollutants. However, cities can play a central role for achieving the transition towards sustainable energy systems. The Paris agreement recognises the global role of cities and urban authorities in addressing climate change and in achieving global reductions in CO_2 emissions Commission [3].

* Corresponding author.
E-mail address: alaa.alhamwi@next-energy.de (A. Alhamwi).

http://dx.doi.org/10.1016/j.apenergy.2017.01.048

The energy revolution towards sustainable urban energy systems (UES) begins in cities where city districts represents an optimal scale for integrating local renewable energy sources to balance the localised energy demand Manfren et al. [4]. Therefore, there is a need for setting the best techno-economical framework conditions for planning future UES as highlighted by the German Advisory Council on Global Change (WBGU) Kraas et al. [5] introducing a guiding concept of "decentralised concentration", recommending that urban spaces should be structured in a decentralised way with a view to develop poly-centric spatial, balanced and settlement structures. Hence, the structural transition towards a sustainable energy system will be based on the expansion of renewable energies involving all actors and achieving a supportive mechanism through energy incentives Schellnhuber et al. [6].

In Germany, incentive mechanisms have been introduced to promote e-mobility and to facilitate the integration of Photovoltaic (PV) self-consumed energy in buildings making it commercially attractive to locally consume self-generated PV-power Lang and Lang [7]; Baum et al. [8]. In this context, the Association for Electrical, Electronic and Information Technologies (VDE) introduced *the cellular approach* as a concept to investigate future scenarios for energy transition and the integration of renewable energy technologies in urban environment VDE [9]. The concept is based on balancing demand and supply at the smallest local scale, in which self-consumption and autarky degree play an important role for planning future UES and smart cities.

Research related to integrated energy planning in spatial frameworks has drawn significant interest among scientists, engineers and policy makers to meet the increasing share of renewable energy sources (RESs) and decreasing carbon emissions targets. Geographic Information Systems (GIS)-based models facilitate decision-making in this field Camargo et al. [10] and contribute to the development of the *smart city* settings. This concept was introduced to handle the transformation towards clean and green cities enabling a better use of renewable energy technologies. GIS-based models have been commonly used for regional and national planning. Integrating environmental and energy models in city planning is recommended for future cities development Manfren et al. [4]; Roche [11]. In this context, GIS can play a key role for the deployment of renewable energy Manfren et al. [4] and for implementing so called *power flexibilisation options* such as storage, demand-side management (DSM) and backup-power plants de Sisternes et al. [12].

In general, modelling energy systems is essential to appropriately analyse and gain insights into future energy supply systems Pfenninger et al. [13]; Keirstead et al. [14]; Connolly et al. [15]. In Pfenninger et al. [13], the authors reviewed several energy system models with respect to their focus and simulation techniques. This review study concluded that, the existing models are not always capable in adequately addressing the challenges like transparency, complexity, human dimension and uncertainty which are faced by future energy systems. In the case of UES, models are widely used by city planners, engineers and policy makers Keirstead et al. [14]; Pfenninger et al. [13]; Kumar [16]. In his review Goodchild [17], Goodchild stated that modelling UES using GIS highlights many important issues related to the transition toward sustainable energy systems, including the importance of scale and resolution as well as the validation of energy models. To date, integrating energy system planning in GIS modelling environment is still under development and in its very early stages Mentis et al. [18]. On the other hand, GIS tools can help decision-makers and urban planners by offering the opportunity to visualise the spatio-temporal parameters as well as to perform qualitative and quantitative analysis of the results and different scenarios for the deployment of smart city technologies.

GIS-based models can be used to build strategies, investigate future scenarios and answer different questions about the transition towards sustainable UES Sahoo et al. [19]; Ma and Cheng [20]. Nowadays, most of the available models are black boxes as they are transparent and not freely or publicly available Wiese et al. [21]. The same situation applies for the energy system data necessary for energy system modelling Wiese et al. [21]. In order to increase public awareness engagement and acceptance, energy models should be transparent, open and publicly available which also applied to GIS-based models Pfenninger et al. [22].

Many Tools for the integration of RESs into energy systems have been developed. A review article done by Connolly et al. [15], analyses 37 tools that are used for the integration of RESs into energy systems. The optimisation of decision making process in UES planning requires the integration of the spatial characteristics of energy resources Mentis et al. [18]. Manfren et al. [4] argues that, advanced planning practice of future cities needs an appropriate platform for communication and participation, hence the opinion that, GIS applications will play an increasingly important role in the coming years.

The present contribution draws an overview of GIS-based models for UES and proposes a definition for such models. The current state of modelling is highlighted and different research fields are categorised and summarised. As a result of the overview conducted by the authors, it was found that GIS-based models dealing with the integration of flexibilisation options and strategies were not covered by the identified literature. Following up on this gap in the literature, the authors introduce the outline of a proposed *GIS-based platform for the optimisation of flexibility options in cities* (called *FlexiGIS*). The aim of the platform is to systematically investigate different scenarios of self-consumption as well as to analyse the characteristics and roles of different flexibilisation technologies such as storage in promoting higher autarky levels in cities. As a contribution towards transparency in models and data, the model proposed in this article is intended to be open and will be made freely available.

This paper is organised as follows, first, the methodology used in the literature overview of GIS-based UES models is introduced and the current state of practice is categorised in Section 2. In Section 3, the proposed model, FlexiGIS, is introduced and the setting of the spatial framework is presented in details. Section 4 contains the conclusions and presents an outlook for future work. Finally, this contribution provides in Appendix A supplementary material including real OpenStreetMap (OSM) data and results of the spatial framework.

2. Overview of GIS-based UES models

In order to draw a comprehensive overview of GIS-based UES modelling which appropriately addresses its main characteristics, a precise definition of GIS-based UES modelling should be specified. The term *modelling urban energy systems* is used in several contexts, therefore, it is worthy to clarify its meaning in the context of this publication. As done in Keirstead et al. [14], first we start by adopting Jaccards definition of energy systems as "*the combined processes of acquiring and using energy in a given society or economy*" Jaccard [23]. Then, the task is to specify this adopted definition to cover UES. In urban areas, all kinds of activities and procedures related to energy services in industrial, commercial, and residential sectors are occurring within the city geopolitical boundaries. The definition of the physical borders of energy systems in cities is however still problematic. In Ramaswami et al. [24], three different approaches are suggested to define the term *urban*. The *geographic-plus* definition in Ramaswami et al. [24] fits best the present review for two reasons. First, it includes, in addi-