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Application of the complex network theory in urban environments. A case study in Catania

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Abstract

Cities are responsible for the 70% of the world's energy demand and represent the largest source of GHG emissions. The constant growth of cities encourages towards the configuration of urban energy plans in order to make urban areas more sustainable places. In this direction, Decentralized Energy Systems (DES) play an important role in order to improve the efficiency in urban energy consumptions. However, the decentralization of urban energy systems requires a comprehensive evaluation of the energy interactions that can occur among consumers. To this aim, proper mathematical models need to be defined in order to take into account how those interactions occur. In this paper, a mathematical procedure based on the complex network theory is introduced and tested to a neighborhood within the city of Catania.

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Keywords: Decentralized Energy Systems; Complex networks; City; Energy consumptions

1. Introduction

The United Nations Department of Economic and Social Affairs predicts that by 2050 over the 66% of the world's population will live in urban areas [1]. Since cities are responsible for the 70% of the world's energy

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demand [2] and represent the largest source of greenhouse gases emissions [3], urban planning should include energy issues and urban energy plans have to be configured in order to make urban areas more sustainable places.

As the accessibility of renewable energy sources increases, urban areas become able not only to consume, but also to produce energy. In this direction, Decentralized Energy Systems (DES) based on renewable sources may play an important role in order to improve the efficiency in urban energy consumptions and, consequently, decrease GHG emissions. Hence, the decentralization of energy systems reduce the dependence on fossil sources, by allowing the on-site production of energy.

For all the above reasons, the integration of DES in urban areas has been promoted by the city governments through several action plans [4, 5, 6]. Particularly for the case of Italy, a national energy policy initiative regulates the local generation and distribution of energy [7]. Obviously, the adoption of such energy systems requires the definition of proper methodologies able to account for the generation and distribution of energy.

In literature, the spread of sustainable decentralized energy systems is broadly treated. In the work of Webb et al. an empirical overview of UK energy plans directed to the diffusion of DES is presented [8]. On the same topic, Chmielewski et al. analyze the installation of decentralized energy systems in Poland [9]. Moreover, several works focus on the optimization of DES. Villatoro Flores et al. [10] select the generation technologies for optimal decentralized energy systems. In Chauhan et al. [11] the installation of optimal DES is treated for rural areas in India. In the meantime, Katsoulakos and Kaliampakos [12] present a linear optimization model for the improvement of decentralized energy systems in mountainous areas.

However, the decentralization of urban energy systems requires a comprehensive evaluation of the energy interactions that can occur among several consumers, identified as buildings, neighborhoods or municipalities, because the installation of decentralized energy systems encourages the consumers to exchange their own produced energy. Hence, proper mathematical models need to be defined in order to take into account how those exchanges occur. To this aim, a procedure based on the complex network theory is applied to the study of the energy interactions within cities. By virtue of the ability to highlight the interactions among components, networks seem suitable to account for the optimization of energy flows that can be exchanged among consumers. Nodes and links typically used for the study of the network [13] are here intended respectively as consumers and energy flows. The obtained network is hereinafter called urban energy network.

Therefore, in this work, a purpose-built mathematical procedure for the optimization of energy flows among consumers and its application to an urban neighborhood is presented. The paper is structured as follows. Section 2 introduces the mathematical model based on the complex network theory; Section 3 presents the application of the model to a real case study and Section 4 discloses the conclusions.

2. The mathematical model

The chance to install autonomous energy generation systems allows the consumers to satisfy their own energy demand and, eventually, to distribute the excess of the produced energy. The energy distribution that derives from those energy systems is evaluated within the framework of the complex network theory. To the purpose, consumers are treated as nodes and their energy interactions as links.

To model an urban area, N nodes are distributed on a two-dimensional space. Each node i, for $i = 1, ..., N$, is characterized by an energy demand D_i and an energy generation G_i, whereas links are responsible for the transmission of the energy flows. Nodes use the generated energy primarily for the satisfaction of their energy demand, and only the eventual energy exceed is then distributed to other nodes. The distribution of the energy exceed occurs according to a neighborhood criterion, for which two nodes are connected through a link if their distance d is under a given threshold. In addition to these connections with all feasible neighbors, each node is connected to the power station, hereinafter called central node. The central node has nil energy demand, whilst its energy generation corresponds to the remaining energy demand that is not covered by the decentralized energy production.

The interactions among nodes are described in a $(N+1)$ x $(N+1)$ matrix, called the *adjacency matrix A*. Each element a_{ij}, being $i, j = 1, ..., N+1$ with $i \neq j$, of the adjacency matrix may assume different values:

- if $a_{ij} = 1$ there is a link between node i and node j