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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 $i = 1, \ldots, N$, 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 $(N+1) \times (N+1)$ matrix, called the *adjacency matrix A*. Each element a_{ij}, being $i, j = 1, \ldots, N+1$ 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

- if $a_{ij} = 0$ there is no link between node *i* and node *j*

No interactions occur between a node and itself; hence, the diagonal of the adjacency matrix *A* contains zeros.

Based on these assumptions, the defined energy network takes into account the energy status of each node *i*, evaluated through a surplus parameter S_i, which is defined as $S_i = G_i - D_i$. The value of the surplus parameter S_i defines three feasible conditions:

- a positive energy surplus means the node is able to distribute any energy exceed to its neighbors;
- a negative energy surplus means the node has partially satisfied its demand and, therefore, needs to receive energy either from its neighbors or from the central node;
- a nil energy surplus means the energy generation has matched the energy demand.

The sign of the energy surplus S_i, i.e. positive or negative, defines the direction of the energy flow. Obviously, all energy exchanges may occur only from a node with a positive energy surplus to a node with a negative energy surplus. The elements a_{ij} of the adjacency matrix are updated according to the sign of the energy surpluses and, precisely:

- $a_{ij} = 1$ if the energy exchange takes place from node *i* to node *j*;
- $a_{ij} = -1$ if the energy exchange takes place from node *j* to node *i*;
- $a_{ij} = 0$ if no energy exchange occurs.

The objective of the model is to find the optimal energy distribution among nodes by minimizing the energy output of the central node. Therefore, in order to determine the energy flow X_{ij} exchanged between node *i* and node *j*, the problem is formulated as a linear programming model. Each node *i* has to satisfy two constraints.

$$S_i = \sum_{j=1}^{N+1} a_{ij} X_{ij}, \forall i = 1, ..., (N+1), i \neq j \quad (1)$$

$$X_{ij} > 0 \quad (2)$$

Equation (1) represents the satisfaction of the energy balance at each node *i*. Equation (2) imposes that all energy flows are non-negative.

Hence, the objective function is expressed as

$$\min \sum_{a1j>0} a_{1j} X_{1j} \quad (3)$$

The topology of the obtained urban energy network may differ from the starting topology, for which all links were defined on the basis of a neighborhood criterion. In order to evaluate the percentage of the links effectively exploited for the energy distribution, a network index I_N is introduced in the analysis and is defined as follows

$$I_N = \frac{links_{exploited}}{links_{neighborhood}} \quad (4)$$

The numerator of Eq. (4) takes into account those links effectively exploited for the energy exchange, whilst the denominator regards all the links established through the neighborhood criterion.

The network index I_N may assume values within the interval $0 < I_N < 1$. More specifically, $I_N = 0$ means that none of the links of the starting topology are used for the exchange of energy and the central node satisfies all the energy demands of the nodes, whilst $I_N = 1$ means that all links were exploited. The larger I_N, the more exploited is the urban energy network.

3. Case study

The mathematical model presented in Section 2 is tested in an urban area. A neighborhood of 0.67 km^2 in the city of Catania, in southern Italy, has been chosen. This is characterized by 343 buildings with a given energy demand, considered as the electricity consumed for a year on the basis of a medium value per inhabitants [14]. The building stock is mostly constituted by residential multi-story concrete buildings. The energy generation is calculated as a percentage of the total energy demand of the network. Particularly, the energy generation has been varied for three different percentage values as reported in Table 1.

Table 1. Total energy demand and total energy generation of the modeled urban energy network

Configuration	Total Demand [MWh/y]	Total Generation [%Demand]
1	7332,03	2570,44
2	7332,03	3295,89
3	7332,03	3657,21

Particularly, configurations 1, 2 and 3 corresponds to a fixed percentage of energy generation that is respectively the 35, 45 and 50% of the total energy demand of the network. Each building has a generation capacity that depends on its roof's area. The modeled urban area is shown in Figure 1, where blue circles represents the nodes, in this specific case, the buildings.

Fig. 1. Modeled urban area

The urban area is studied by varying the distance d of connections. In this work, the urban energy network is studied for distances within the interval $25\ m < d < 200\ m$, at steps of $25\ m$. For convenience of representation, the urban energy network for a distance respectively of $50, 100, 150$ and $200\ m$ are shown in Figure 2.

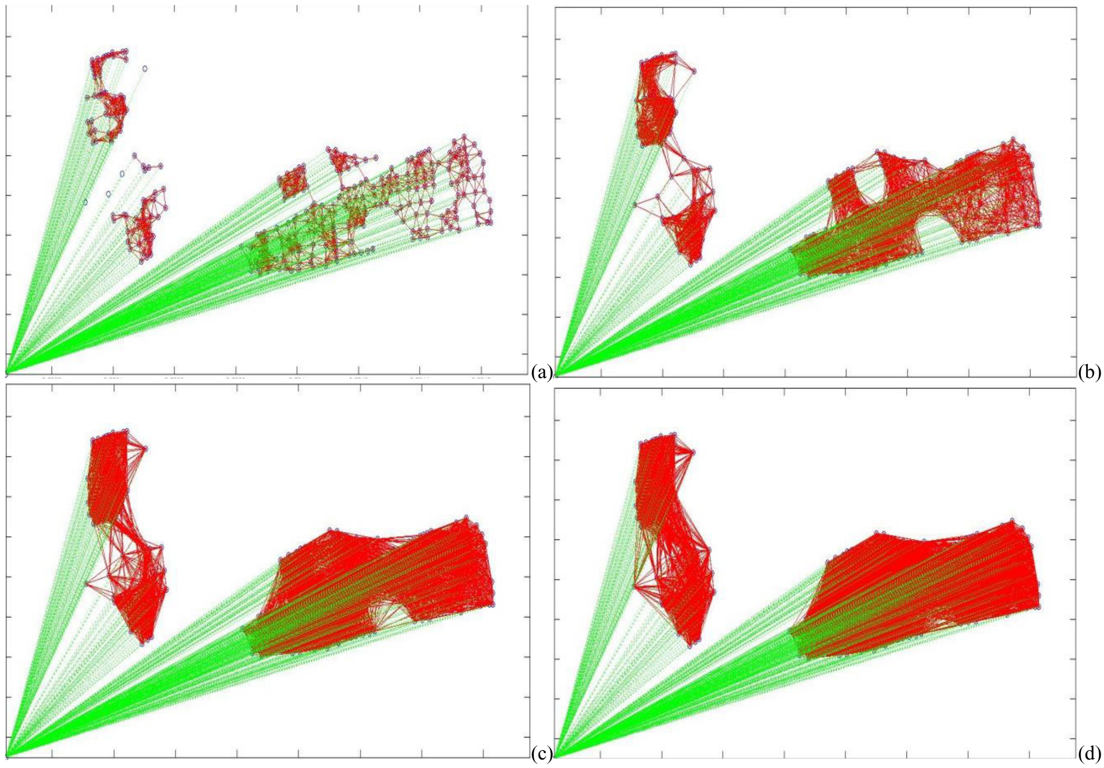

Fig. 2. (a) Urban energy network with a distance of connection equal to d = 50 m; (b) Urban energy network with a distance of connection equal to d = 100 m; (c) Urban energy network with a distance of connection equal to d = 150 m; (d) Urban energy network with a distance of connection equal to d = 200 m

In Figure 2, red links stand for the connections among nodes, whilst green links symbolize the connection of each node with the central node, placed in the bottom left of the figure. Obviously, the number of red links increases by increasing the distance *d* of connection. Instead, the number of green links is unvaried, because of the imposed condition that every node is connected to the central node in the starting topology.

The aim of the optimization is to minimize the energy flows exiting from the central node. Once the network is solved, the model maintains only those links effectively characterized by an energy flow. In order to evaluate the percentage of the links involved in the energy exchange, the network index I_N is taken into account.

The effects of the distance *d* of connection are illustrated in Figure 3, where the three configurations of Table 1 are compared.

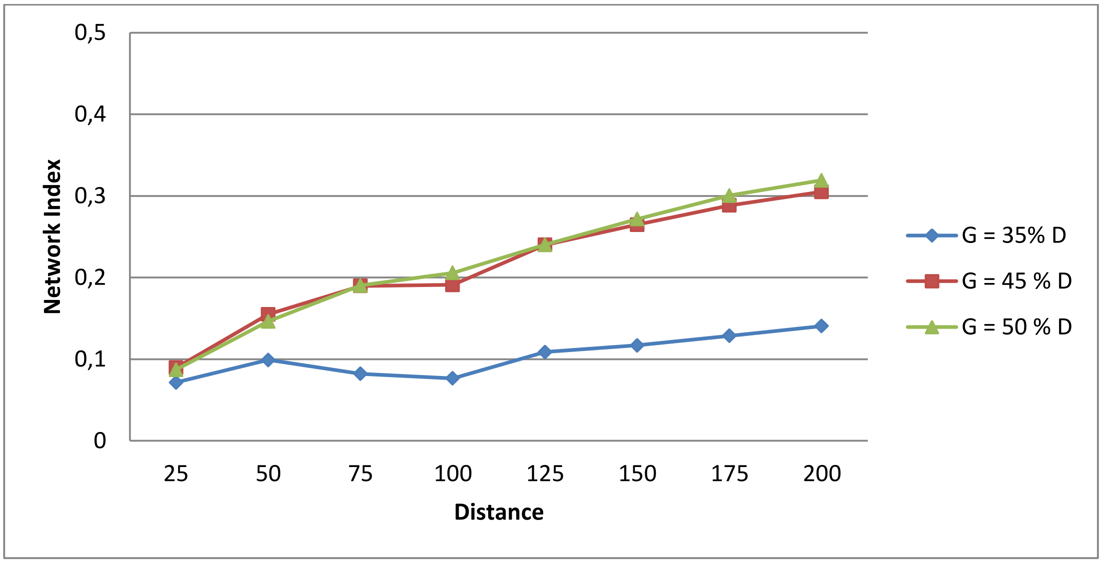

Fig. 3. Network Index by varying the distance *d* of connection for different percentage of energy generation

The results show that the increase of the distance *d* yields an increase of the network index. On the strength of this result, nodes distribute their energy surpluses to a major number of neighbors.

Regarding the trend of the network index I_N in relation to the percentage of energy generation, it can be clearly seen that further installations of decentralized energy systems with a total energy generation capacity that is beyond the 45% of the total energy demand of the network does not bring benefits for the distribution of energy. This is evident in the fact that, as shown in Figure 3, the number of effectively used links for the energy exchange does not increase even if the energy generation capacity, and consequently the energy distribution, increases.

4. Conclusions

In this work a mathematical model based on the complex network theory for the analysis of the energy distribution in urban areas is presented. Due to the installation of decentralized energy systems, consumers have the potential not only to consume, but also to produce energy. In comparison to the existing literature, the main contribution of this work is the comprehensive evaluation of the energy interactions that may occur among consumers. In fact, each consumer uses the produced energy primarily for the satisfaction of its own energy needs and, subsequently, for the distribution to other consumers. The opportunity for each consumer to distribute the own produced energy to its neighbors require the definition of a proper mathematical model in order to analyze how the energy distribution occurs. The model presented in this paper is constructed as a linear programming model, with the aim to maximize the energy exchanges among consumers that have installed decentralized energy systems. The model has been tested to an urban neighborhood within the city of Catania.

The study aims to determine the effective exploitation of the obtained urban energy network by varying the distance *d* of connections among neighbors for different percentages of energy generation. The results permit to conclude that the distance of connections is a discriminating factor for the distribution of the energy surpluses among consumers. However, the energy generation capacity cannot be increased indiscriminately, since beyond the 45% of energy generation, the urban energy network does not activate further links and the distribution is not guaranteed.

Further studies will take into account an enlargement of the urban area and consequently of the number of buildings.

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