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Complex networks for the integration of distributed energy systems in urban areas

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HIGHLIGHTS

- Autonomous energy productions require models for the integration in the urban area.
- The proposed model is based on the complex network approach.
- The nodes are users with energy demand and energy production.
- The links represent the energy exchanges.
- The method optimizes the number of links distribution of the energy exchanges.

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ABSTRACT

Since cities are responsible for 67% of the world's energy demand and are the major contributors of CO_2 emissions, governments and researchers push towards energy policy initiatives aiming at increasing the sustainability of urban areas. In this context, the diffusion of autonomous energy production systems on territory has been recognized as a cost-effective solution. The integration of distributed energy systems in cities gives to consumers the possibility to exchange their own produced energy. In order to design the optimal energy distribution network among consumers and, at the same time, minimize the energy supply from traditional power plants, a comprehensive and focused approach is introduced and developed in this paper. The presented model encompasses the frameworks of complex networks theory and energy distribution issues, thus providing a suitable solution than current models. A real case study is then presented to validate the numerical results. Overall, the proposed model offers significant insights for the definition of proper urban action plans centered on the efficient usage of energy and favoring the exploitation of renewable energy, thus allowing urban planners to make reasoned investment decisions.

1. Introduction

According to the AR5, the Fifth Assessment Report of the International Panel on Climate Change (IPCC), urban areas are the major contributors of CO_2 emissions [1]. Indeed, the residential sector encompasses more than the 67% of the world's energy demand and produces more than the 70% of the global CO_2 emissions. Moreover, it is expected that the world population living in cities will increase from the actual percentage of 55% to the 66% in 2050, thus strengthening the impact of the problem. For these reasons, urban areas have a crucial role in tackling the climate change [2].

To reduce CO_2 emissions and achieve the energy efficiency of cities different solutions have been proposed for the building sector. These include structural interventions to reduce thermal losses (e.g. thermal insulation, double glazing) or applications of energy systems for the building's electricity and heat supply (e.g. photovoltaic systems, CHP systems, heat pumps). Although the building level has a great potential in reducing the emissions and increasing the energy efficiency in urban areas, these interventions consider edifices as "self-defined entities" [3]. In fact, they do not consider the feasibility of energy exchanges deriving from the installation of autonomous energy production systems. In this way, Distributed Energy Systems (DESs) based on renewable sources have gained particular attention [4], since they allow producing energy that is consumed in proximity to the points of production [5], thus reducing energy costs and carbon emissions [6]. Furthermore, installers of such systems gain twofold advantages; on one side to achieve the energy self-sufficiency and, on the other side, to distribute the excess of produced energy [5,7].

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As consequence, the integration of DESs on urban area shifts the attention from the building scale to the neighbor or municipal one in which energy exchanged are considered. At this level, the complexity of relationships between consumers and producers and the availability of different energy efficiency solutions require proper mathematical tools to address the decisional planning process towards the optimal insertion of distributed energy systems.

In literature numerous models for the optimal design of distributed energy systems are reported.

Various publications address the optimal design of a single technology, such as solar or photovoltaic energy systems [8–11] or combined cooling, heating and power systems [12,13]. Zhou et al. [14] propose a model for the design of DESs towards the optimal combination of a wide set of distributed energy technologies. The works in [15–18] focus on the same topic.

Other models consider the residential scale as optimization framework for the design and selection of DESs technologies. In this direction, Ren et al. [19] examines the optimal residential distributed technology for typical building complexes in China. Similar approaches are proposed in [20,21]. Contributions centered on the design of residential distributed energy systems are also developed in [22,23]. Yang et al. [24] present an advanced model for the optimal design and operation of DESs integrated with energy distribution networks. Similarly, but applying the energy hub concept, Orehounig et al. [25] optimize the insertion of DESs in a neighborhood and the resulting distribution of energy. The paper of Omu et al. [26] introduce the Distributed Energy Network Optimization (DENO) model to choose the optimal set of energy production technologies and evaluate the amount of energy distributed among buildings.

The aforementioned models are technology driven, i.e. the design and the optimization of the DES mainly regard the choice of the technology considering both economic and environmental perspective. They are very useful for the design of DESs, but due to the high level of detail of the models, they have a high computational complexity, which grows with the increase in the number of technologies involved in the optimization process and the number of buildings considered in the exchange. As consequence, the previous models are not able to highlight optimal distributed configurations when a large amount of consumers and producers are considered, such those characterizing the neighbor or municipal level.

On the other hand, well-defined urban plans aiming at integrate DESs in urban area should focus, in the first instance, on two important aspects: the optimal energy capacity to be installed by each producer and the role assumed by each energy exchange for the optimal design of the energy distribution system, i.e. the useful connections among consumers and producers of energy, for the achievement of sustainable and energy efficiency targets.

To this purpose, models able to focus on the neighbor or municipality level and to define optimal configurations of distributed energy systems, without inferring conclusions on technological details, are necessary.

This paper concerns this issue and amounts to be a useful tool for urban planners, since it provides a purpose-built model for the definition of the optimal energy distribution network of DESs determining the power installed by producers and the interactions among consumers and producers that occur on territory. Indeed, the study of the energy distribution network implies the analysis of which energy interactions occur on territory.

For this aim, the framework of complex networks [27,28] may fit the purpose. In fact, although in many scientific fields, as for example, in technology and social sciences, the network paradigm has been used for its ability to unveil the fundamental role of the interactions among the elements of the system, models to analyze the way in which the interactions characterize the energy use in an urban area are barely emerged [29]. Being networks characterized by nodes and links [30], the matching to the energy problem is possible by considering nodes as the building, districts, municipalities and links as the energy interactions for the energy exchange among citizens [31].

Thus, in this paper a model based on complex networks is proposed to analyze scenarios deriving from the energy interactions among autonomous producers in order to define proper energy planning strategies focused on the insertion of DESs for the achievement of the energy efficiency targets in cities.

2. Problem formulation

The insertion of autonomous energy production systems on territory calls for models able to design the optimal energy distribution network in terms of the energy exchanges occurring among installers for the reduction of the emissions and the achievement of energy efficiency targets of cities. To the purpose, the urban area is described as a complex network where nodes stand for consumers and potential energy producers, whilst links represent the connections along which the energy exchange is feasible.

To model an energy distribution network, nodes are distributed on a two-dimensional space. The number of nodes varies depending on the level of detail taken into account in the analysis. Specifically, at different scales, nodes can be identified as buildings, neighborhoods or municipalities. Links are established according to a neighborhood criterion for which two nodes are connected if their reciprocal spatial distance respects a chosen threshold value. The connected neighboring nodes constitute the starting topology of the energy distribution network. Each node, beyond the connections with neighbors, is also connected to a further node, hereinafter called *central node*, representative of the power station.

First of all, the data related to the nodes are:

- $N + 1$ is the set of nodes that constitute the energy distribution network; for convention the central node corresponds to $i = 1$;
- E_{di} is the energy demand of the i-th node, with $i = 1, \ldots, N + 1$; the central node has a nil energy demand, i.e. $E_{d1} = 0$;
- E_{gi} is the energy production of the i-th node, with $i = 1, \ldots, N + 1$.

As before stated, each node that has installed autonomous energy production systems uses the produced energy primarily for the satisfaction of its own energy demand and only the eventual exceeding energy is distributed to other nodes. The central node satisfies the energy demands of the nodes if there is no energy production or the energy production does not fully satisfy the demands.

To determine whether a node has exceeding energy to distribute or not, the surplus parameter S_i defined as $S_i = E_{gi} - E_{di}$ is introduced. In particular,

- If $S_i > 0$, the node i is able to distribute the exceeding energy to other nodes;
- If $S_i < 0$, the node i has no exceeding energy to distribute and, on the contrary, needs energy from other nodes or, as last instance, from the central node to satisfy its residual demand;
- If $S_i = 0$, the node has neither exceeding energy to distribute nor residual demand to satisfy.

In the specific case of the central node, the energy surplus is not-negative, i.e. $S_1 \geqslant 0$. Indeed, the central node produces the energy directed to satisfy the overall net demand of the network.

As consequence of the distribution of surpluses, an amount of energy, $X_{ij} = -X_{ji}$, flows through a generic link between a node i