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A multi-layer agent-based model for the analysis of energy distribution networks in urban areas

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HIGHLIGHTS

- Renewable energy-based systems permit the exchange of energy among prosumers.
- Models for the design of energy distribution networks within urban areas are required.
- A multi-layer agent-based model simulates the energy exchanges among prosumers.
- Practical usability of the connections of the energy distribution network is studied.

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ABSTRACT

Significant research contributions and Directives approach the issue of the insertion of renewable-based energy systems on urban territory in order to face with the growing energy needs of citizens. The introduction of such systems gives raise to installers to both satisfy their energy demands and distribute eventual energy excesses to close neighbours. This paper presents a multi-layer agent-based computational model that simulates multiple events of the energy distribution occurring within urban areas. The model runs on the NetLogo platform and aims at elaborating the most suitable strategy when dealing with the design of a network of energy distribution. Experimental data are discussed based on two main scenarios within an operating period of 24 h. Scenarios consider both the variation of the percentages of installers of renewable-based energy systems and the distance along which energy exchanges occur.

1. Introduction

The energy consumption in urban areas has significant implications for the transition towards environmentally sustainable cities [1], being the buildings sector acknowledged as one of the major contributor in CO_2 emissions. A way to face the growing carbon emissions of urban areas is recognized in the exploitation of renewable sources. As a consequence of the installation of renewable-based energy systems, such as photovoltaic panels, citizens shift from the condition of passive consumers to active producers [2], thus becoming able both to achieve the energy self-sufficiency and to exchange the own produced energy [3,4]. Indeed, the exchange of energy occurring from producer to consumer defines the basis for setting up a network of energy distribution and decreases the supply from fossil-fuelled plants. Accordingly, the design of a network of energy distribution among consumers requires appropriate models that aim at assessing both the impact of renewable energy systems on the traditional supply and the connections in the resulting network to outline energy strategies [5].

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The issue of the energy distribution among consumers and producers is treated in literature considering the optimization of the distributed technology from the economic and environmental viewpoint [des]. For instance, the tool introduced in the work of Bracco et al. [6] optimizes the annual maintenance and operating costs of a distributed energy system, which provides heating, cooling and electricity to an urban neighbourhood. The paper of Mehleri et al. [7] pursues the same topic also exploring the optimal choice among several candidate distributed technologies and, in addition, optimizes the network of heat exchanges. Along with the minimization of the operating costs, the studies of both Alvarado [8] and Weber and Shah [9] address the reduction of the carbon emissions.

The cited studies are mainly technology driven, since they aim at selecting the optimal distributed technology that minimizes its overall operating costs or the emissions. Moreover, the exchanges occur within small-scale areas, not comparable to urban neighbourhoods. Therefore, despite the validity of the considered optimization methods, the increasing complexity of the energy exchanges configuration pushes towards approaches able to obtain solutions in shorter computational times and for growing complexity of the energy d configurations, such as those characterizing a neighbourhood. In this direction, agent-based models have been widely proposed as a valid technique to study energy systems characterized by interactions among the involved parts [10,11], such as the interactions occurring due to the distribution of energy.

When attempting to provide a review of agent-based systems (ABSs) dealing with the exchange of energy, studies distinguishes from the role of agents in the distribution process. In the multi-agent model of Mbodji et al. [12] two agents aim at defining a management strategy to adapt the energy consumed to that supplied by renewable production sources of the system. In the paper of Sharma et al. [13] centralized agent guides all agents towards the balance of the demand for a peak shaving in a distribution system. The research of Bellekom et al. [14] explores the emerging rise of prosumers, namely consumers with a renewable energy production potential, and its implications for the grid management.

Moving forward, other works also include financial issues in their studies. For instance, in Lopez-Rodriguez et al. [15], customers may contact act with brokering agents in order to participate in the market of the energy exchanges. In the agent-based model of Ye et al. [16], the energy distribution problem is formulated to admit autonomously negotiation among agents with the main objective to achieve efficient energy dispatch. Similarly, the paper of Kumar Nunna et al. [17] presents an agent based market model with price sensitive consumers.

On the same topic, but including a time-dependent analysis, the work of Degefa et al. [18] simulates the impact of prosumers agents minimizing their energy costs. The study of Misra et al. [19] analyses the energy-trading problem with real-time demand estimation. A real-time control of the consumption and production of agents is also presented in the previous cited works [12,13].

The main body of the listed literature in ABSs focuses on either the definition of management programmes or financial aspects of the electricity exchanges. Nevertheless, although the issue of the energy exchanges has been widely considered, the energy distribution needs to be further deepened from a network perspective. Indeed, the energy exchanges occurring within the urban area configure a network of interactions among consumers that have installed renewable energy systems. Hence, to orient the design of a network of energy connections in the urban territory, appropriate models should examine the aspect of the energy distribution. The analysis of the network of energy distribution within a neighbourhood has been introduced in a previous work of the authors [20]. The model aims at both designing the optimal energy distribution network among consumers and minimizing the energy supply from the traditional fossil power plant. However, the study did not consider the variability of the energy demands and energy production during the day, which are instead included in this paper.

Therefore, this work defines a model that permits to determine practicable solutions for the design of the network of energy distribution within an urban area. To the purpose, the authors develop a multi-layer agent-based model able to simulate the network of the energy exchanges occurring among buildings equipped with autonomous energy production systems. The variability of energy demands and productions during the day are properly taken into account; indeed, the model considers the 24 h energy cycle, which is relevant in case of a network of renewable sources.

2. The agent-based model

The installation of renewable based energy systems allows consumers to both reach the energy self-sufficiency and immediately distribute the eventual excess of produced energy. Considering each consumer as a node and each energy exchange as a link, the urban area may be modelled as a double-layer network [21], hereinafter called *energy distribution network* (see Fig. 1), and simulated via an agent-based model. The main idea behind agent-based systems (ABSs) resides in the modelling of active entities, called *agent*, that interact in conformity to *rules* in order to achieve *tasks* within a defined simulation time. Each agent achieves the tasks through both its autonomous behaviour and the interactions with other agents.

In the elaborated model, the simulation time is denoted as $t = 0, \ldots, T$ and two kinds of agents are introduced: on one side, N nodes-agents and, on the other side, one central-agent. Nodes-agents, hereinafter simply called agents, refer to the nodes of the energy distribution network that are characterized by an energy demand and may install renewable energy systems, whilst the central-agent is representative of the power plant, which provides for the traditional energy supply. Fig. 1 shows an example of the double-layer *energy distribution network*. In the top layer, the nodes-agents equipped with renewable energy production systems (called *producers*, in green) are connected with other producers or with non-producers nodes (in red) included in a circular area with a given radius; in the bottom layer, all the nodes are connected