UNIVERSITA' DEGLI STUDI DI CATANIA

DIPARTIMENTO DI INGEGNERIA ELETTRICA, ELETTRONICA ED INFORMATICA

Dottorato di Ricerca in Ingegneria dei Sistemi, Energetica, Informatica e delle Telecomunicazioni

XXX Ciclo

A methodology for the design of an urban energy distribution network of prosumers

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Abstract

Since cities are responsible for the 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; moreover, their integration gives to consumers the possibility to exchange their own produced energy. This permits to configure a network of energy interactions among "prosumers", i.e. consumers with production capabilities. In order to design the optimal energy distribution network among prosumers and, 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 both complex networks theory and agent-based models to provide a suitable solution of the energy distribution problem. The study is conducted for static and dynamical scenarios and the theoretical simulations are then compared to a real case study.

Overall, the proposed model offers significant insights for the definition of proper urban action plans centered on the efficient usage of energy and favouring the exploitation of renewable energy, thus allowing urban planners to make reasoned investment decisions.

Acknowledgements

I would like to express my sincere gratitude to my tutor Prof. Ing. Alberto Fichera for the continuous support during my Ph.D. study, for his patience, motivation, and knowledge. His guidance helped me in all the time of research and writing of this thesis.

Besides my tutor, my gratefulness goes to Prof. Mattia Frasca for his insightful comments and teaching, but also for having motivated me to widen my research from a different perspective.

I also thank Prof. Alessandro Pluchino, who provided me the opportunity to join his field of research to mine.

I am grateful to my colleague and friend Valentina Palermo. The time spent with her has enriched me.

Thanks to my family who supported and encouraged me every day and to my son Sergio, to whom I dedicate this thesis.

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1. Introduction

1.1 The background

Energy is a key element in growth and development of cities, being essential for industrial and commercial activities, transports, as well as buildings and infrastructure. In particular, the residential sector encompasses more than the 67% of the world's energy demand [1] and emits more than the 70% of the world's total greenhouse gases [2]. Moreover, it is expected that the world's population living in cities will increase from the actual percentage of 55% to the 66% within the 2050 [3], thus strengthening the impact of the problem.

The intense urbanization worldwide pushes towards the question of how to use the energy sources in a sustainable way reducing both the dependence on fossil fuels and its following impact on the atmosphere. Besides, the depletion of fossil resources is also becoming an increasingly real issue. However, despite these concerns, many cities have not yet properly addressed the climate change. The reasons include a lack of both energy policies to manage the environmental pollution and public awareness on the risks deriving from the climate change. Nevertheless, cities are the driving force behind the targets of energy efficiency and sustainability [4], especially by encouraging the diffusion of low carbon or even renewable energy production technologies.

The shift from the actual carbon-based energy production systems towards renewable energy systems needs to be supported by a change in the energy consumption habits of citizens on one side, and by both efficient technologies and energy distribution infrastructures on the other side. In this direction, buildings have a significant potential in rendering cities sustainable places, especially when dealing with the installation of onsite renewable energy systems, such as photovoltaic panels on their roofs. The installation of such systems allows producing energy that is consumed in proximity to the points of production [5], thus reducing the costs associated to the distribution of energy, as well as the carbon emissions [6]. Furthermore, installers gain twofold advantages by achieving the energy self-sufficiency and by distributing the excess of produced energy [5, 7].

To the purpose, city governments have promoted policies and standards to encourage the diffusion of sustainable energy production technologies in their territories [8 – 11], along with both the design of decentralized energy systems and their infrastructure. The installation of autonomous energy production systems gives rise to a network of energy exchanges among consumers, due to the fact that the produced energy not consumed may be locally distributed. In this direction, purpose-built models aiming at orienting urban planners in the design of an energy distribution network among consumers need to be properly developed.

Therefore, the guide principle of this thesis concerns this issue and proposes a methodology for the definition of energy planning strategies focused on the insertion of distributed energy systems on urban territories for both encouraging the energy exchanges among consumers and achieving energy efficiency targets in cities. Actually, the cornerstone of the developed approach focuses on the application of a network vision to the occurrence of energy exchanges among consumers. In this sense, a consumer equipped with autonomous energy production systems has the chance not only to satisfy its own energy needs, but also to distribute the eventual excess of production to requiring neighbours. This configuration permits to model the consumers and their energy interactions as a network. In this sight, two different modelling approaches, i.e. the complex network theory and agent-based models, have been adapted to the topic of this study, dealing the former with static applications and the latter with dynamical simulations.

1.2 State of art

The issues of both energy distribution and autonomous energy production systems are widely treated topics in the scientific community. A comprehensive literature is hereafter carried on to cover these arguments. In particular, the review is aimed to outline planning procedures, as well as National and European Directives, methods and optimization techniques surrounding the concept of the energy distribution on urban territories.

Subsequently, the states of art regarding both the modelling techniques embraced in this thesis, i.e. the complex network theory and the agent-based modelling, are presented.

1.2.1 Energy distribution and energy distribution systems

The topics of CO_2 emissions reduction and energy efficiency in cities have been addressed in different way from both researchers and governments in the last decades. Focusing on the contributions that may derive from the building sector, proposed solutions include structural interventions to reduce thermal losses (e.g. thermal insulation, double glazing) or applications of energy systems for the 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” [12], not encompassing the feasibility of energy exchanges deriving from the installation of autonomous energy production systems. Actually, the increased accessibility of renewable energy sources yields urban areas able not only to consume, but also to distribute the produced energy. Within this context, city governments have promoted several action plans for the integration of renewable energy production systems in their territories [13 – 15]. For the case of Italy, an energy policy initiative focuses on the possibility to produce and distribute energy locally, i.e. within a delimited neighbourhood of consumers [16]. In this way, Distributed Energy Systems (DESs) based on renewable sources have gained particular attention [17], and their role in both improving the efficiency in urban energy consumptions and, consequently, decreasing the GHG emissions has been widely recognized [18, 19].

A definition of Distributed Energy System is provided in the work of Alanne and Saari [5]; in particular, they define a DES as a sustainable alternative to traditional energy systems and composed of energy production units located in proximity to the energy consumers. Numerous papers treat the diffusion of DESs, as in the work of Webb et al. [20], where an empirical overview of DESs is presented. The paper of Adil and Ko [21] deals with the integration of DESs in urban planning and policies, especially those addressing the climate change mitigation and adaptation strategies. Han et al.

[22] provides a systematic summarize and analysis of the research status, application and policies about DESs in China. On the same topic, Chmielewski et al. [23] analyse the installation of DESs in Poland.

Moving forward, various publications deal with either the design or the operation of DESs technologies, or they integrate the two aspects. Within these works, some authors focus on a single technology, whilst other address the selection among different DESs available technologies.

The optimal design of a single technology is treated in manifold papers [24 – 27]. Among these, Kanters and Wall [24] develop a process map for the design of solar energy systems to be considered in the urban planning practises. La Gennusa et al. [27] propose a calculation method for evaluating the geographical energy potential of building roofs in urban areas. The aim, in particular, is to investigate the feasibility of installing solar systems designed to exploit the maximum achievable energy production. When dealing with the design of the optimal technology among a set of available alternatives, significant results are achieved by the following studies. Zhou et al. [28] propose a model for the design of DESs towards the optimal combination of a wide set of distributed energy technologies. Also the works in [29 – 31] focus on the same topic. In detail, Weber and Shah [29] study the optimal mix of technologies that ensure the reduction of the emissions and, simultaneously, the efficiency and resilience of the supply. Similarly, Stadler et al. [30] present a multi-objective optimization model to determine the size of both thermal and electrical systems in relation to different component and sizes. In the same direction, Villatoro Flores et al. [31] addresses the selection of generation technologies for a distributed energy system based on local renewable sources.

As regard to the operation of a single DES, Chauhan and Saini [32] develop a system operation strategy for the size optimization of integrated renewable energy systems. In addition, they present, as a case study, the optimal DES installation for rural areas in India. In the meantime, Katsolulakos and Kaliampakos [33] present a linear optimization model for the improvement of distributed energy systems in mountainous areas. Khalilpour and Vassallo [34] propose a mixed-integer linear programming model to determine the optimal operation schedule of a DES. On the same topic, Ren et al. [35] present an optimal operating strategy of a DES system while combining the minimization of energy cost with the minimization of its environmental impact. With respect to the operation of a mix of technologies, Ren et al. [36], in a subsequent work, illustrate the effectiveness of an analytic model for estimating the efficient operation pattern for distributed energy systems with different technology combinations. Similarly, Alvarado et al. [37] develop a model for the optimal selection and operation of technologies from a portfolio of available technologies.

Finally, papers that deal with an integrated vision that couple the design and the operation of distributed energy systems are henceforward deepened. In this direction, the contributions [38, 39] tackle the issue for a single technology, whilst the authors in [40, 41] consider a mix of different technologies. With reference to a single technology, Bracco et al. [38] introduce a mixed-integer linear programming model to optimally design and operate a distributed energy system which provides heating, cooling and electricity to a neighbourhood. Honold et al. [39] minimize the operational energy costs of an household by determining the on-site renewable electricity production. On the insertion of a mix of technologies, Ren et al. [40] propose a model to minimize the overall energy costs selecting the units of candidate DES to be installed and determining their operating schedules. Morvaj et al. [41] present a model for the optimal design and operation of different DESs with calculations of electrical grid constraints and building energy use.

The aforementioned studies mainly deal with the design or operation of DESs installed at the service of a building; in addition, they disregard the chance for consumer to distribute the produced energy to neighbours. When both enlarging the scale of application to broader neighbourhoods and considering the occurrence of energy exchanges among consumers, valid contributions may be find in the papers in [42 – 49]. Ren et al. [42] develop a model for the optimization of a distributed energy system while taking into consideration the energy exchanges between neighbouring buildings. Yang et al. [43] 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. [44] optimize both the insertion of DESs in a neighbourhood and the resulting distribution of energy. The paper of Omu et al. [45] introduce a model to choose the optimal set of energy production technologies and evaluate the amount of energy distributed among buildings. Shizimu et al. [46]

propose a method for designing a local energy cooperative network for heat and power distribution. In the study of Falke et al. [47], an optimization model for the investment planning and operation management of distributed heat and electricity systems is presented; furthermore, heating networks are considered as an alternative to conventional and individual heat supply for each building. Similar outcomes may be detected in the papers of Mehleri et al. [48] and Brange et al. [49]. The former deals with the design of DESs that satisfy the heating and power demand and consider the design of a heating pipeline network for the heat exchange among consumers. The latter evaluates the potential for district heating network from small scale consumers and based on exceeding heat.

However, the listed literature is technology driven, i.e. it mainly focuses on the design and optimization of DESs and considering both economic and environmental perspectives. The reported studies 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 processes and, for the case of broader neighbourhoods, in the number of buildings contemplated for a possible energy 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 as those characterizing the neighbour of municipal level.

On the other hand, well-defined urban plans aiming at integrate DESs in urban areas should focus, in a 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 efficient energy targets.

To this purpose, models able to focus on the neighbour scale and to define optimal configurations of distributed energy systems, without having to infer conclusions on technological details, are necessary.

1.2.2 The framework of complex networks

Complex networks theory is a relatively young field of research, embracing a wide set of disciplines, such as informatics, chemistry, biology, epidemics, social sciences and so on. Applications on energy issues, typically focusing on the energy distribution and transmission, as well as on the topology of the energy infrastructures, are also available [50]. In this direction, the paper of Xu et al. [51] demonstrates the complex architecture of the Florida high-voltage power grid by both measuring the transmission lines and analysing the mix of generators and loads. The authors investigate the optimization design principles that characterize the structure of the grid, thus inferring the difference from the random models architecture. Similar results are obtained in the work of Kim et al. [52]. Actually, they analyse the topology of the Korean Power Grid (KPG) network by comparing it with the degree distribution of the random and scale-free reference networks. Their analysis reveals that the KPG degree distribution is characterized by an exponential distribution that differs from the random networks, although being not equal to the scale-free networks.

Implementing the energy issues within a network framework has also been pursued by Pedersen et al. [53]. Into details, their work proposes a control scheme for achieving power balance in a grid with high penetration of distributed renewable resources. Such control strategies are based on the definition of a communication network for the exchange of control information. Research efforts on control schemes within electrical networks are also presented in [54 – 57]

Yet, the diffusion of distributed energy systems at urban scale results on the creation of energy interactions among consumers, due to the fact that they gain the chance to exchange their own produced energy [58]. At this level, the complexity of relationships between consumers and producers and the availability of different energy solutions require proper mathematical tools to address the decisional planning process towards the optimal insertion of distributed energy systems on urban areas [59]. In particular, such tools have to both take the energy exchange among consumers into account and optimize the energy flows exchanged in the neighbourhood. In this direction, the framework of complex networks [60, 61] may fit for the purpose. Indeed, although in many scientific fields 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 analyse the way in which the interactions characterize the energy use in an urban area are barely emerged [62]. Being networks characterized by nodes and links [63], the matching to the energy problem is possible by considering nodes as the buildings, districts and municipalities and links as the energy interactions aimed at the energy exchange among citizens [64].

1.2.3 Agent-based models

Besides the framework of the complex network theory, agent-based models have been widely proposed in literature as a valid technique to study energy systems characterized by interactions among the involved parts [65, 66], 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. [67] 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. [68] 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. [69] explores the emerging rise of prosumers, namely consumers with a renewable energy production potential, and its implications for the grid management.

Moving forward, more detailed works also include financial issues in their studies. For instance, in Lopez-Rodriguez et al. [70], 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. [71], 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. [72] 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. [73] simulates the impact of prosumers agents minimizing their energy costs. The study of Misra et al. [74] 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 [67, 68].

The main body of the listed literature in ABSs focuses on either the definition of management programs 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. 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, as well as the variability of the energy demands and energy production during the day [75].

Therefore, a multi-layer agent-based model able to simulate the network of the energy exchanges occurring among buildings equipped with autonomous energy production systems is developed. The variability of energy demands and productions during the day are properly taken into account; indeed, the model considers the 24h energy cycle, which is relevant in case of a network of renewable sources.

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2. Methodological approaches

The insertion of renewable energy production systems on urban territories changes the way energy distribution is conceived. Indeed, the recent European and National Directives [1 – 3] encourage consumers to install autonomous energy production systems in order to both satisfy the own energy needs and, eventually, distribute the energy produced and not consumed to requiring neighbours. In this respect, consumers in their role of producers are also defined as *prosumers* [4]. The rise of prosumers with distribution capabilities yields a network of energy exchanges that need to be properly designed to orient energy planning actions for the reduction of the emissions and the achievement of energy efficiency targets of cities. The proposed methodology constitutes a step in this direction and, in particular, is oriented to design the energy distribution network that reduces the supply from the traditional power plant by ensuring the maximum distribution among prosumers. In particular, two different approaches are developed to achieve the above mentioned objectives. The former deals with the definition of a mixed-integer linear programming model that pursuits a static simulation of the energy distribution problem and is developed on MatLab [5]; the latter relies on an agent-based model for the dynamical analysis of the energy distribution implemented on the NetLogo platform [6].

2.1 The framework of complex network – static analysis

2.1.1 The formalism

The elaborated methodology aims to design the network of energy exchanges among consumers in their possible chance to be also producers. Generally, at the core of the model, prosumers are connected to eventually exchange their exceeding energy, still maintaining the connections with the traditional power plant. The energy interactions of prosumers emerge in the hereinafter-called urban energy distribution network. An exemplificative network is depicted in Fig.1, where the distinction between the nodes/consumers (equipped with photovoltaic panels on their roofs) and the central node/power plant is highlighted. In particular, red lines represent the links of the energy distribution network, i.e. the links responsible for the exchange of energy among nodes, whilst green lines symbolize the connections that each node has with the central node.

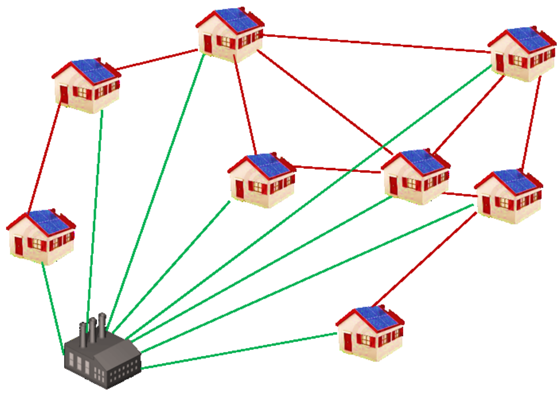


Fig.1 Exemplificative urban energy distribution network

Networks are mostly represented with the aim the graph theory [7]. A graph is a mathematical structure deployed to model pairwise relations between two entities [8] and consists of *nodes* or *vertices* and *edges* or *links* [9]. Accordingly, in the context of the urban energy distribution network, nodes may be identified with apartments, buildings or neighbourhood, depending on the level of details of the study. Generally, nodes stand for consumers with a given energy demand and the potential to install renewable energy production systems. The produced energy is primarily used by consumers for the satisfaction of their own energy demands and, eventually, for the distribution of energy to their neighbours. The distribution is permitted by the links of the networks that represent the transmission lines for the exchange of energy.

The so defined representation applies to this study and, by convention, an urban energy distribution network is described by means of a graph $G = (\mathcal{N}, \mathcal{L})$, where $\mathcal{N} \equiv \{n_1, n_2, \dots, n_N\}$ is the set of nodes of the graph and $\mathcal{L} \equiv \{l_1, l_2, \dots, l_L\}$ the set of links. The number of elements in $\mathcal{N}$ and $\mathcal{L}$ are indicated, respectively, with N and L. Moreover, for the sake of simplicity, a node may be also denoted in accordance with its order i and a link between a node i and a node j as l_{ij}.

About the given formalism, the network of Fig.1 may be represented as a graph in which each node is depicted as a dot and each link by a line joining two dots.

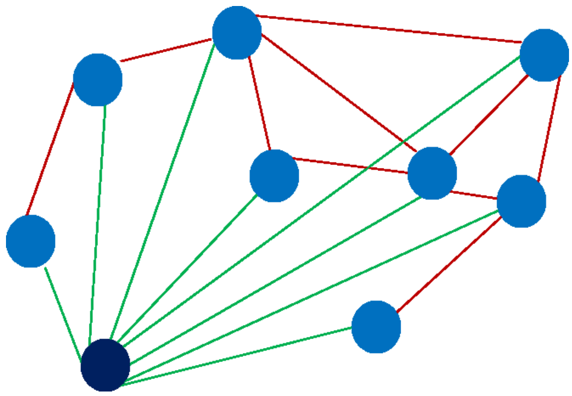


Fig.2 Graph depiction of the urban energy distribution network in Fig.1

At this stage of the problem formulation, a fundamental distinction needs to be remarked. As also highlighted in the graph of Fig.2, the power plant is represented with darker colour intensity to indicate that this node differs from the other nodes of the network. Actually, this node symbolizes the traditional power plant and is, from now on, called *central node* and labelled as $i = 1$ to distinguish it from the other nodes of the network. The peculiar characteristic of the central node lies in the fact that it has a nil energy demand and has the potential to satisfy the energy demands of all nodes.

2.1.2 The adjacency matrix

The links of the network are established according to a metrical criterion for which two nodes are connected if their reciprocal spatial distance respects a chosen threshold distance d. It is defined as the maximum admitted distance below which nodes may exchange energy and is previously determined by the designer. Concurrently with the potential connections with neighbours, each node gains a further connection with the central node, notwithstanding their distance. The connected neighbouring nodes constitute the starting topology of the urban energy distribution network.

The matricial representation of a graph is commonly obtained by its *adjacency matrix* [9]. Accordingly, all energy interactions that may occur within the graph are described by introducing the adjacency matrix A, i.e. a $N \times N$ square matrix defined as

$$A = \begin{bmatrix} 0 & a_{1,2} & a_{1,3} & \cdots & a_{1,N} \\ a_{2,1} & 0 & a_{2,3} & \cdots & a_{2,N} \\ a_{3,1} & \cdots & \ddots & \cdots & a_{3,N} \\ \vdots & \vdots & \vdots & 0 & \vdots \\ a_{N,1} & a_{N,2} & \cdots & a_{N,N-1} & 0 \end{bmatrix} \tag{1.1}$$

Each element of the adjacency matric indicate s whether a link has been established or not. In particular,

$$a_{ij} = \begin{cases} 1, if\ the\ link\ l_{ij}\ connects\ node\ i\ and\ node\ j \\ 0, otherwise \end{cases} \tag{1.2}$$

No interactions may take place between a node and itself; this condition is ensured by setting zeros in the diagonal of the adjacency matrix.

The so defined connections constitute the starting topology of the energy distribution network, in which the connected nodes gain the ability to exchange energy, following the direction $i \rightarrow j$ or vice versa. Indeed, at this stage, the graph may be considered as bidirectional, due to the fact that the energy across a link has the chance to flow in one direction or in the opposite, depending on the energy requirements of the connected nodes.

2.1.3 Energy demand, energy production and energy surplus

Once the topology of the energy distribution network has been determined, the following step is related to the energy characterization of the nodes. In this direction, each node $i = 2, \dots, N$ is characterized by an energy demand $D_i \geq 0$ and, eventually, by an energy production $P_i \geq 0$, deriving from the installation of renewable energy production systems. The energy produced by each node aims primarily to the satisfaction of its own energy demand and, secondly, to the distribution towards the connected neighbouring nodes. The central node is assumed to have a nil demand and an energy production at least equal to the total energy demands of all nodes of the network. The assumptions regarding the central node are expressed in Eqs.(1.3) and (1.4) below.

$$D_1 = 0 \tag{1.3}$$

$$P_1 \leq \sum_{i=2}^{N} D_i \tag{1.4}$$

The central node satisfies the energy demands of the nodes if either none of the nodes of the network has installed autonomous energy production systems or the energy production of nodes does not fully satisfy the demands.

To determine whether a node has exceeding energy to distribute or not, the energy surplus parameter S_i is introduced and indicated as

$$S_i = P_i - D_i, \forall\ i = 2, \dots, N \tag{1.5}$$

In particular, the following conditions may occur:

- If $S_i > 0$, the node i is called *source node* and distributes its exceeding energy to other neighbouring nodes;
- If $S_i < 0$, the node i is called *destination node* and has no exceeding energy to distribute. A destination node has only partially fulfilled its energy demand and needs, therefore, to receive energy either from the other nodes or, as last instance, from the central node in order to satisfy its residual demand;
- If $S_i = 0$, the node has neither exceeding energy to distribute nor energy demand to satisfy; in this case the node has consumed the whole produced energy for own purposes.

As regards to the central node, the energy surplus is not-negative, i.e. $S_1 \geq 0$, being it responsible for the production of energy used to satisfy the overall net demand of the network.

The sign of the energy surplus of each node permits to determine the direction of the energy exchanged along the links of the network. In particular, the energy exchanges take place from a node with a positive energy surplus towards a node with a negative energy surplus, i.e. the energy flows according to the direction $source\ node \rightarrow destination\ node$ and not backwards.

In order to simplify the problem formulation, a second matrix W is introduced. The elements of this matrix are characterized by the definition

$$w_{ij} = \begin{cases} 1, if\ a_{ij} = 1 \wedge\ S_i > 0 \wedge S_j < 0 \\ -1, if\ a_{ij} = 1 \wedge\ S_i < 0 \wedge S_j > 0 \\ 0, otherwise \end{cases} \quad (1.6)$$

According to the definition in Eq.(1.6), the element $w_{ij} > 0$ represents a link through which energy flows from node i to node j; in the opposite, $w_{ij} < 0$ holds for a link in which the energy flows from node j to node i. Note also that, if a link from node i to node j exists, but the energy surpluses S_i and S_j have the same signs, the correspondent element w_{ij} is set to zero. The construction of the matrix W permits to relate to each link of a network a non-negative energy flow $X_{ij} = X_{ji} > 0, \forall\ l_{ij} \in \mathcal{L}$. The direction, instead, is given by $w_{ij}X_{ij} = -w_{ji}X_{ji}$.

2.1.4 The optimization model

The optimization problem is formulated as a linear programming model and aims at determining the optimal energy flows exchanged among the nodes of the network in order to reduce the energy supplied from the central node. With regard to the energy flows X_{ij} exchanged between a node i and a node j, the following energy balance has to be respected

$$S_i = \sum_{\substack{j=1 \\ i \neq j}}^{N} w_{i,j} X_{i,j}, \forall\ i = 1, \dots, N \quad (1.7)$$

Rewriting Eq.(1.7), the following system of equations may be obtained

$$
\begin{cases}
S_1 = w_{1,1}X_{1,1} + w_{1,2}X_{1,2} + \cdots + w_{1,j}X_{1,j} + \cdots + w_{1,N}X_{1,N} \\
S_2 = w_{2,1}X_{2,1} + w_{2,2}X_{2,2} + \cdots + w_{2,j}X_{2,j} + \cdots + w_{2,N}X_{2,N} \\
\cdots \\
S_i = w_{i,1}X_{i,1} + w_{i,2}X_{i,2} + \cdots + w_{i,j}X_{i,j} + \cdots + w_{i,N}X_{i,N} \\
\cdots \\
S_N = w_{N,1}X_{N,1} + w_{N,2}X_{N,2} + \cdots + w_{N,j}X_{N,j} + \cdots + w_{N,N}X_{N,N}
\end{cases}
\quad (1.8)
$$

The first row of Eqs.(1.8) represents the energy balance at the central node, whereas the remaining $N-1$ equations are the energy balances at the other nodes. In the system (1.8), the unknown variables are the energy flows exchanged through the links, X_{ij}, and the energy produced by the central node, S_1, whilst the data are the surpluses at each node.

By introducing the matrix M in Eq.(1.9),

$$
\begin{matrix}
w_{1,1} & w_{1,2} & w_{1,3} & w_{1,4} & \vdots & w_{1,N} & 0 & 0 & \vdots & 0 & 0 & 0 & \vdots & 0 & \vdots & 0 \\
0 & w_{2,1} & 0 & 0 & \vdots & 0 & w_{2,3} & w_{2,4} & \vdots & w_{2,N} & 0 & 0 & \vdots & 0 & \vdots & 0 \\
0 & 0 & w_{3,1} & 0 & \vdots & 0 & w_{3,2} & 0 & 0 & 0 & w_{3,4} & w_{3,5} & \vdots & w_{3,N} & \vdots & 0 \\
0 & 0 & 0 & w_{4,1} & \vdots & 0 & 0 & w_{4,2} & 0 & 0 & w_{4,3} & 0 & \vdots & 0 & \vdots & 0 \\
0 & 0 & 0 & 0 & \ddots & 0 & 0 & 0 & \ddots & 0 & 0 & \ddots & \vdots & 0 & \ddots & 0 \\
0 & 0 & 0 & 0 & \vdots & w_{N,1} & 0 & 0 & 0 & w_{N,2} & 0 & 0 & 0 & w_{N,3} & \vdots & w_{N,N}
\end{matrix}
\qquad (1.9)
$$

Eq.(1.8) may be rewritten as

$$
M\begin{bmatrix} S_1 \\ X_{1,2} \\ \vdots \\ X_{1,N+1} \\ X_{2,3} \\ \vdots \\ X_{N+1,N+1} \end{bmatrix} = \begin{bmatrix} 0 \\ S_2 \\ \vdots \\ S_{N+1} \end{bmatrix} \qquad (1.10)
$$

The determination of the unknown variables allows defining the energy flows between each node pair, thus permitting to establish which links are used for the exchange of energy. Accordingly, the objective of the model is to find the optimal configuration of the energy distribution network that minimizes the energy production of the central node. Thus, the objective function is expressed as

$$min \sum_{w_{1j}>0} w_{1j} X_{1j} \quad j = 2, \dots, N \tag{1.11}$$

The term $\sum_{w_{1j}>0} w_{1j} X_{1j}$ represents the energy that flows from the central node to the nodes having a negative surplus. Minimizing this term avoids any exchange between a node i with a positive energy surplus S_i and the central node.

As additional constraint, the energy flows exchanged through the links assume non-negative values

$$X_{ij} \geq 0, \forall\, l_{ij} \in \mathcal{L} \tag{1.12}$$

2.1.5 The network index

The optimization model introduced in the previous paragraph ensures the reduction of the energy produced by the central node by determining the energy flows exchanged among the nodes. The detection of the energy flows allows identifying which links are used for the exchange and, therefore, constitute the optimal energy distribution network. Indeed, the topology of the optimized network may differ from the starting topology, for which all links have been established in accordance with the neighbourhood criterion. Actually, among all feasible links of the starting topology, the sole links with a non-zero energy flows form the optimized distribution network. The activation of the links in the optimized network has to be considered as a favourable condition, since it assures that the energy produced by the nodes is directly and locally distributed. In order to evaluate the percentage of the links that are effectively exploited for the energy distribution, a network index, called *fraction of activated links* I_N, is introduced in the analysis and expressed as

$$I_N = \frac{links_{activated}}{links_{neighbourhood}} \tag{1.13}$$

The *fraction of activated links* I_N is the ratio between the number of links activated after the optimization, $l_{activated}$, and the number of links of the starting topology, $l_{neighborhood}$, established due to the neighbourhood criterion and regardless of the links with the central node. It assesses the proportion of links that are effectively used for the exchange of energy out of the total potential links defined through the mere spatial criterion. The *fraction of activated links* I_N assumes values within the interval $[0,1]$; being $I_N = 0$ if none of the connections among the nodes are exploited and the central node entirely provides the energy for the satisfaction of the energy demands of the nodes. Instead, $I_N = 1$ means that all established links of the starting topology are involved in the energy exchange and the central node does not provide energy. Intermediate values indicate different percentages of the exploitation of the links. Besides the definition of I_N, the *fraction of activated central node-links* I_{CN} is defined and meant to evaluate the percentage of remained links among the central node and the node of the network after the optimization. The *fraction of activated central node-links* I_{CN} also varies within the interval $[0,1]$; in particular, $I_{CN} = 0$ means that the energy distribution network is able to satisfy the energy demand of the whole network and that the central node has a nil energy production. Vice versa, $I_{CN} = 1$ indicates that all nodes satisfy their energy demand solely from the traditional supply from the central node.

2.1.6 The definition of node degrees and hubs

The fraction of activated links I_N measures the exploitation of the links of the network and, therefore, guides the design of the energy distribution network, especially for decisions about the convenience to connect nodes and for chosen conditions of both distances among the nodes and productions of the nodes. However, to support the decision process, it is also advisable to couple such a global information with a more focused measure concerning the number of links used by each node. This is useful in order to understand which nodes is preferable to connect. In particular, the number of links is calculated for those nodes that have a positive energy surplus, as it means that they are able to distribute their exceeding produced energy to requiring nodes. In the following, the amount of these links is shortly indicated as *node activated degree* and expressed as

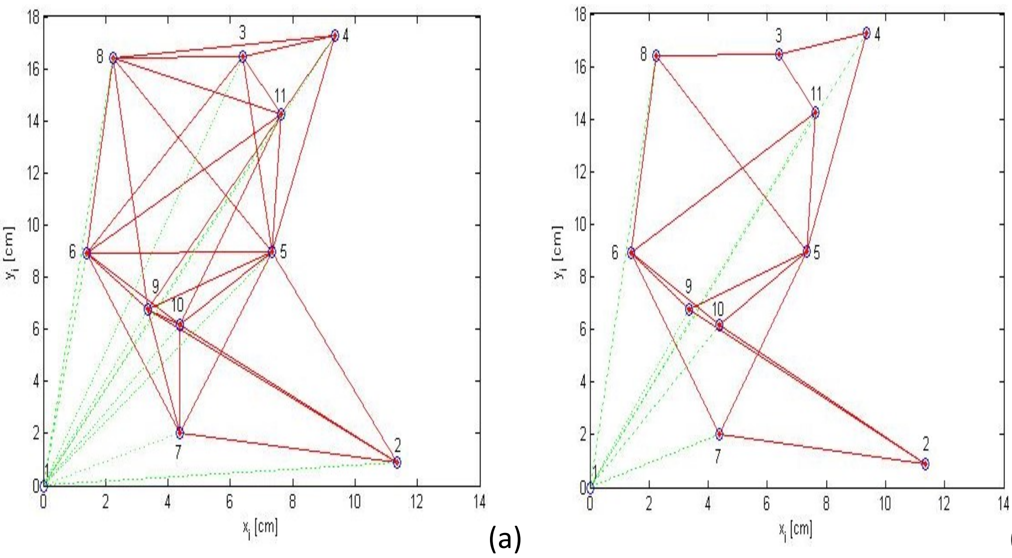
$$k_i = \sum_{j \in \mathcal{N}} w_{ij} \tag{1.14}$$

In this direction, it is possible to determine if any nodes show the attitude to collect a major number of connections at varying the boundary conditions, i.e. if either the production of the nodes or the distance of connection varies.

A node with high number of connections in comparison with other nodes of the network is defined *hub*. To be considered a hub, a node have to display the maximum number of exiting links compared to all the other nodes of the network. As regard to the possible number of hubs, it should be noted that, generally, the larger the network, the bigger is the chance to have more than one hub. The importance of detecting a hub consists in the fact that they effectively improve the distribution of energy within their neighbourhood, since they are responsible for a significant exchange of energy towards are requiring nodes that, otherwise, would be supplied from the central node. In this direction, hubs are nodes in which the installation of renewable energy production systems should be promoted.

2.1.7 An illustrative example of the introduced methodology

The introduced methodology is applied to an illustrative example of an energy distribution network composed of ten nodes beyond the central node, as represented in Fig.3(a).



(a) (b)

Fig.3 (a) Starting topology of the energy distribution network with $N = 11$ nodes; (b) Optimized energy distribution network with $= 11$ nodes

The nodes of the energy network in Fig.3(a) are distributed on a two-dimensional space in a random position. The central node is figured in the bottom eft of the figure and is labelled as 1, according with the previous defined convention. Nodes are connected if their reciprocal distance is below 1 cm. The connections among nodes are represented with red links, whilst each green dotted link represents the connection each node has with the central node. For simplicity, the energy demands D_i, the energy productions P_i and the surpluses S_i characterizing each node of the example energy distribution network are dimension-less. Their values are exposed in Table 1.

Table 1. Energy demands, energy productions and energy surpluses for each node of the example network

Node i	Energy demand D_i	Energy production P_i	Energy surplus S_i
2	1	1	0
3	1	3	2
4	6	5	-1
5	14	17	3
6	5	7	2
7	2	0	-2
8	1	0	-1
9	2	0	-2
10	15	12	-3
11	5	2	-3

The output of the optimization gives as result the links exploited for the energy exchange. In order to report which links constitute the energy distribution network, the indexes of the interacting nodes are listed in Table 2, whereas the resulting energy distribution network is shown in Fig.3(b).

Table 2. Interacting nodes

Interactions with the central node	Interactions between nodes
1 – 4	3 – 4
1 – 7	3 – 8
1 – 8	3 – 11
1 – 9	4 – 5
1 – 10	5 – 7
1 - 11	5 – 8
	5 – 9
	5 – 10
	5 – 11
	6 – 7
	6 – 8
	6 – 9
	6 – 10
	6 – 11

As can be observed from Fig.3(b) and in comparison with Fig.3(a), the number of red links, i.e. the links exploited for the energy distribution among users, are a subset of the starting network. Similar consideration may be advanced for the links involving the central node. The fraction of activated links is $I_N = 0.5667$, whilst the fraction of the central node links is $I_{CN} = 0.6$. This means that the number of links that effectively account for the distribution of energy among users is the 56% of all feasible connections established due to the neighbourhood criterion, whilst the connections with the central node are the 60% out of the total connections.

The following step of the analysis consists in determining the nodes behaving as hubs. In this sense, the sole links exiting from the node and pointing towards other nodes are counted. The node activation degree of each node is reported in Table 3.

Table 3. Nodes activation degree, expressed in terms of exiting links from the node i

Node i	Nodes activation degree
3	3
5	5
6	5

The sole nodes with a positive energy surplus, and therefore able to distribute energy to their neighbours, are reported in the first column of Table 3; the second column lists the nodes activation degree, i.e. the number of links pointing towards requiring nodes. As can be observed from Table 3, the nodes 5 and the node 6 are to be considered as hubs, since they distribute their energy surplus to a major number of nodes.

2.2 The agent-based model – dynamic simulations

2.2.1 The formalism

As stated, 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 [10], represented in Fig.4, 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 $t = 0, \dots, T$ 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. As shown in Fig.4, in the top layer of the energy distribution network each node-agent equipped with renewable energy production (in green) interacts with all its neighbours (green or red) included in a circular area with a given radius, while in the bottom layer all the nodes-agents interact with the central-agent. Notice that in the top layer the central-agent is an isolated node and also some other node without its own energy production (in red) can be isolated.

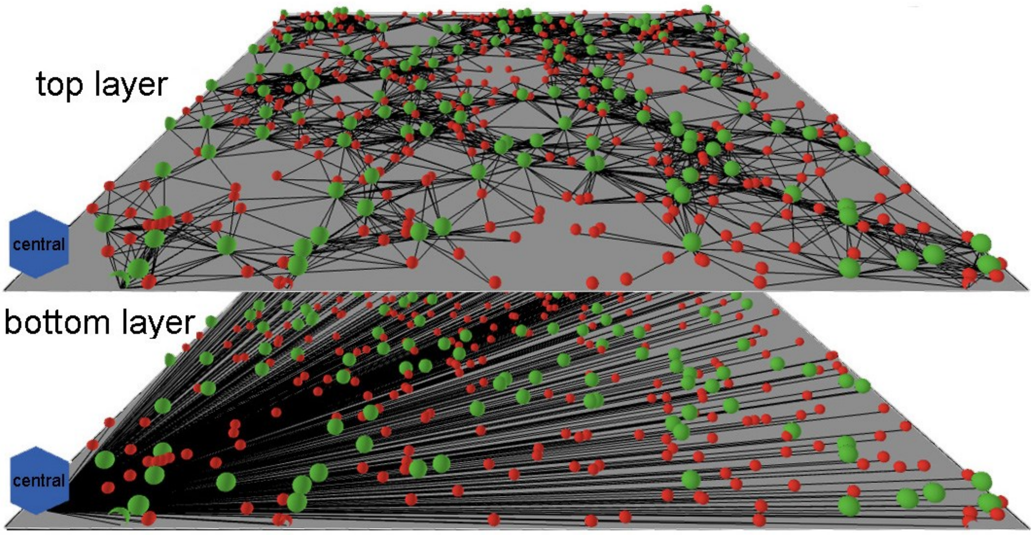


Fig.4 An example of the double-layer *energy distribution network*: in the top layer, the nodes-agents equipped with renewable energy production systems (called *producers*, in green) are connected with other producers or with non-producers nodes (in red) inside a given area; in the bottom layer, all the nodes are connected with the central-agent (in blue). Therefore, in total, the network has *N* + 1 nodes

2.2.2 Energy demand, energy production and energy surplus

At each time t, the agent i ($i = 0, \dots, N$) is characterized by an energy demand, $demand_{it}$, and an eventual energy production, $production_{it}$. Agents equipped with renewable energy production systems, hereinafter called *producers*, primarily satisfy their own energy demands by drawing energy from the own produced. If their demands have not been satisfied, the remaining gap is fulfilled from other producers and, at last instance, from the central-agent. Agents that are merely consumers receive energy either from producers or from the central-agent. Regarding the central-agent, the model assumes that its energy supply is unlimited, and, in particular, it corresponds to the energy demands not satisfied by the producers. The amount of energy that the central-agent supplies at time t is defined as $central\_energy\_supply_t$.

As before introduced, agents take decisions to achieve the collective task of exchanging the produced renewable energy. They act according to a set of rules which depend on two main features: the energy status of each agent i and the distance among agents.

The energy status of each agent i at time t is defined through the following variable:

$$energy\_surplus_{it} = production_{it} - demand_{it} \tag{2.1}$$

If the $energy\_surplus_{it}$ assumes a positive value, the agent is able to distribute its exceeding energy to other agent of the network; on the contrary, a negative value means that the agent has not fulfilled its energy demand and requires energy either from other agents of the network or from the central-agent. Null values indicate that the agent either has used the entirely produced energy for the satisfaction of its own energy demand (if it is a producer) or has exactly fulfilled its energy demand by external sources. Of course, only producers can have positive values of energy surplus, while for normal agents this variable can be either negative or null.

2.2.3 The distance of connection

The second important feature is the metrical distance among agents in the urban area. In fact, each agent can interact only with other agents present inside a given circular area, whose radius is fixed by a control parameter called $connection\_radius$. Actually, the top layer of the energy distribution network is built by randomly distribute the nodes-agents within the whole urban area and then by connecting producers nodes with all and only the other nodes located in the area limited by the connection_radius, which are considered as neighbours with whom to potentially exchange energy. In addition, as already said, in the bottom layer each agent is connected with the central-agent; this assumption is made to follow the actual configuration of the traditional energy grids. The set of agents and the set of links that connect agents into the two layers constitute the starting topology of the energy distribution network before each simulation run, i.e. at time $t = 0$.

2.2.4 The simulation process and the indexes

Once the network of the feasible connections has been defined, the simulation starts and, at each time t > 0, agents behave in order to exchange the produced renewable energy and, consequently, decrease the energy supply from the central-agent. To properly describe such a dynamical process, the following three indexes are introduced. Each of them is evaluated for the entire time interval, i.e. from time $t = 0$ to time $t = T$.

The first index measures the fraction of links that agents really use for the exchange of energy, calculated with respect to the total number of links existing in the network; it is called $links\_percentage$ and is defined as

$$links\_percentage = \frac{active\_links}{active\_links + inactive\_links} \tag{2.2}$$

where the variables $active\_links$ and $inactive\_links$ express, respectively, the links that are characterized by a number of energy exchanges which exceeds a given threshold (called *activation threshold*) during the total time interval $[0, \mathrm{T}]$ and the number of the links that are not. In other words, setting up an activation threshold of 10%, for example, means that the model counts links as active if they are used *at least* the 10% of the total operating time. The evaluation of this index allows making assumptions on the effectiveness of the energy distribution network, in order to avoid unnecessary and costly interventions on territory. From its definition, it follows that the $links\_percentage$ varies within the interval $[0,1]$: the higher is its value, the more exploited is the energy distribution network.

The second index takes into account that the energy produced by the agents may be wasted, in the sense that there may be exceeding energy with respect to that needed by all the agents (included the producer) within the neighbourhood. This index is, therefore, influenced only by the producers that still have a positive energy surplus after the energy exchange and is indicated as

$$energy\_loss\_percentage = \frac{\sum_{t=0}^{T}\sum_{i=1}^{N}(production_{it} - demand_{it} - exchange_{it})}{\sum_{t=0}^{T}\sum_{i=1}^{N} production_{it}} \quad (2.3)$$

where $exchange_{it}$ is the amount of energy that agent i distributes to the set of its neighbouring agents at time t. More in detail, the (producer) agent i distributes its energy surplus to the set of neighbouring agents which require energy (i.e. with negative surplus) according to a priority list, in the way that agents with the smaller absolute value of surplus are supplied before the others. The $energy\_loss\_percentage$ may assume values within $[0,1]$. Of course, being renewable energy produced whatever the demand of the agents; it is preferable to have minimum values of energy loss. Therefore, this index is an operating indication aiming to measure the efficiency in the exploitation of the renewable energy system.

Finally, the third index estimates the percentage of energy supplied by the central-agent during the entire time interval and is indicated as

$$supply\_percentage = \frac{\sum_{t=0}^{T} central\_supply_t}{\sum_{t=0}^{T}\sum_{i=1}^{N} demand_{it}} \quad (2.4)$$

where the variable $\mathrm{central\_supply_t}$ expresses the amount of energy that the central-agent supplies to all the nodes-agents at each time t, i.e.

$$central\_supply_t = \sum_{i=1}^{N} energy\_surplus_{it}, \forall\, energy\_surplus_{it} < 0, t = 0, \dots, T \quad (2.5)$$

As for the previous indexes, the values of the $supply\_percentage$ varies within the interval $[0,1]$: low values mean low supply, that is, the agents distribute a major amount of energy produced by means of renewable based systems.

In order to evaluate the best trade-off among the before introduced indexes, a further global measure with values in the interval [0,1] is introduced and expressed as:

$$index_{mix} = links\_percentage * (1 - energy\_loss\_percentage) * (1 - supply\_percentage) \quad (2.6)$$

The formulation of Eq.(2.6) considers that the $links\_percentage$ index is desirable to assume the highest value whilst the other two indexes, i.e. the $energy\_loss\_percentage$ and the $supply\_percentage$, are preferred to assume low values. To this purpose, they are considered as the complement to unity so that the ultimate goal becomes that of maximizing this global index.

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3. Numerical case study – application of the methodology to a test area

3.1 Static simulations

The methodology introduced in Section 2.1 is applied to a fictitious urban area of $L \times L = (1000\ x\ 1000)\ m^2$ with a random uniform distribution of 1000 householders, each identified by the spatial coordinates (x_i, y_i). Simulations run on the MatLab environment [1]. The area is shown in Fig.5; nodes are represented with blue circles and connected with the central node, located in the bottom left of the figure. The links among the nodes and the central node are depicted as green dotted lines. The energy demand D_i of each node i is considered as the yearly electricity consumption of a medium number of consumers living in a household [2]. To vary the energy demand of the nodes, a random uniform distribution with mean $\overline{E_d} = 4.5\ MWh/y$ and standard deviation $\sigma_d \cong 2\ MWh/y$ is considered.

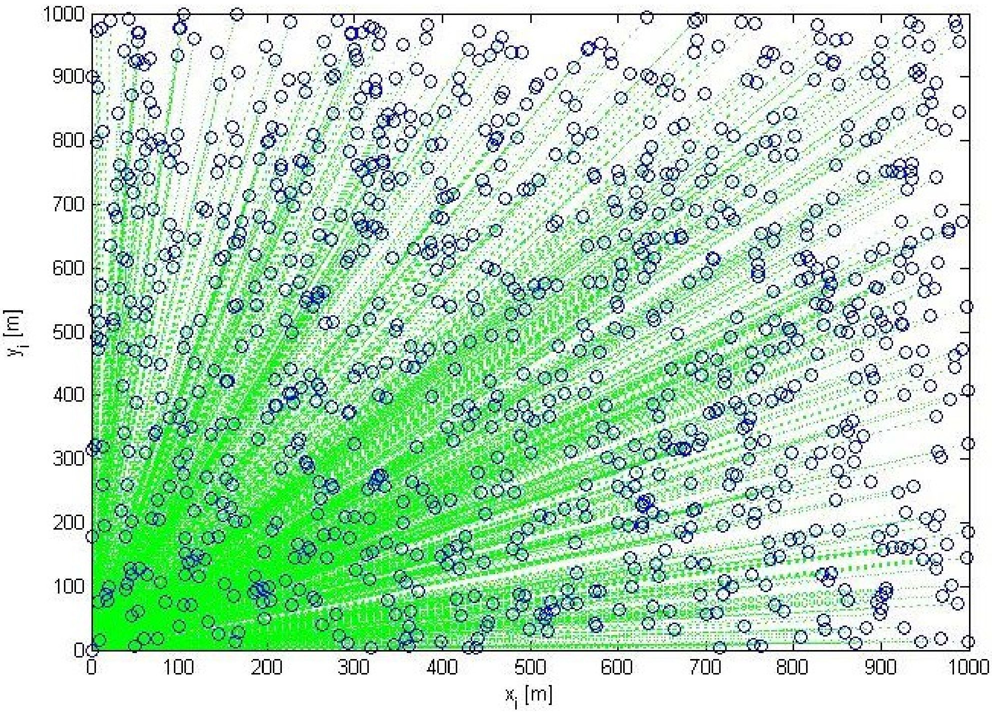


Fig.5 Fictitious urban area with $N = 1000$ nodes randomly distributed on the space and connected with the central node

Each node i is considered as a potential producer and the total electricity production of the nodes is calculated as a percentage of the total electricity demand of the network, i.e. $\sum_{i=2}^{N} D_i$.

3.1.1 Analysis of scenario: the electricity production of consumers

The analysis of the network of energy distribution among prosumers is studied according to the variation of operating scenarios. In this paragraph, the percentage of electricity that is produced by installers is taken into account and two different applications are discussed: in the first case, the electricity produced is randomly assigned to the producers and, in the second case, the assignment follows a geographical criterion, i.e. producers are influenced by neighbours as regards to the choice of installing a renewable energy system.

3.1.1.1 Random assignment of electricity producers

Six scenarios representative of the percentages of energy production are considered and reported in Table 4. The chosen scenarios respect the energy production percentages commonly included in planning interventions involving autonomous energy production systems [1]. The percentage of 0%, i.e. scenario $H = 1$, means that no node has installed energy production systems. The percentage of 20% considered in scenario $H = 2$ intends that the amount of the 20% of the energy demand of the entire set of nodes is produced altogether and not that each node produces the 20% of its own demand. Similarly considerations can be carried out for the remaining percentages. For each scenario, the node i has an energy production that varies according to a random uniform distribution with mean $\bar{P}_i$ and standard deviation σ_i.

Table 4. Energy production corresponding to each of the six scenarios investigated

Scenario H	Energy production	$\bar{P}_i$	σ_i
1	0% of the total demand	–	–
2	20% of the total demand	1 MWh/y	0.75 MWh/y
3	40% of the total demand	1.9 MWh/y	0.75 MWh/y
4	60% of the total demand	2.8 MWh/y	0.75 MWh/y
5	80% of the total demand	3.7 MWh/y	0.75 MWh/y
6	100% of the total demand	4.5 MWh/y	0.75 MWh/y

As described, each node is primarily connected to the central point and to its neighbors according to the defined criterion. In this case study, two nodes are connected if their reciprocal distance is below 100 m. In Fig.6, the obtained energy distribution network is illustrated. In addition to the graphical convention explained for the Fig.5, the red links of Fig.6 represent the connections among nodes.

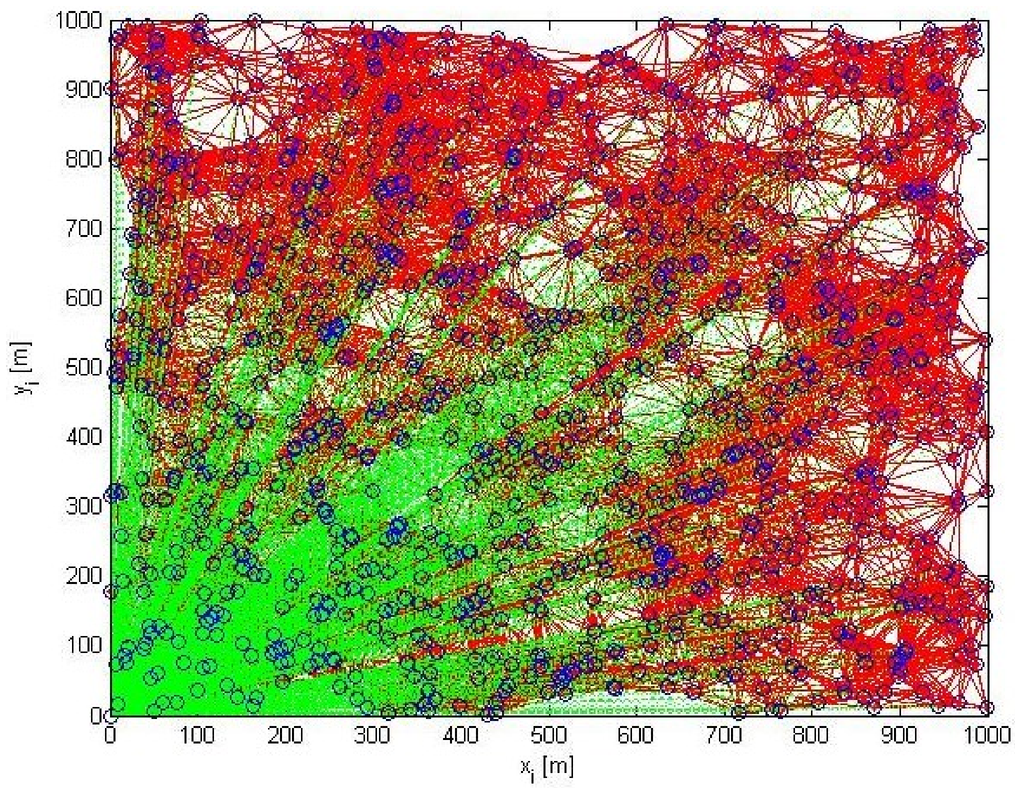
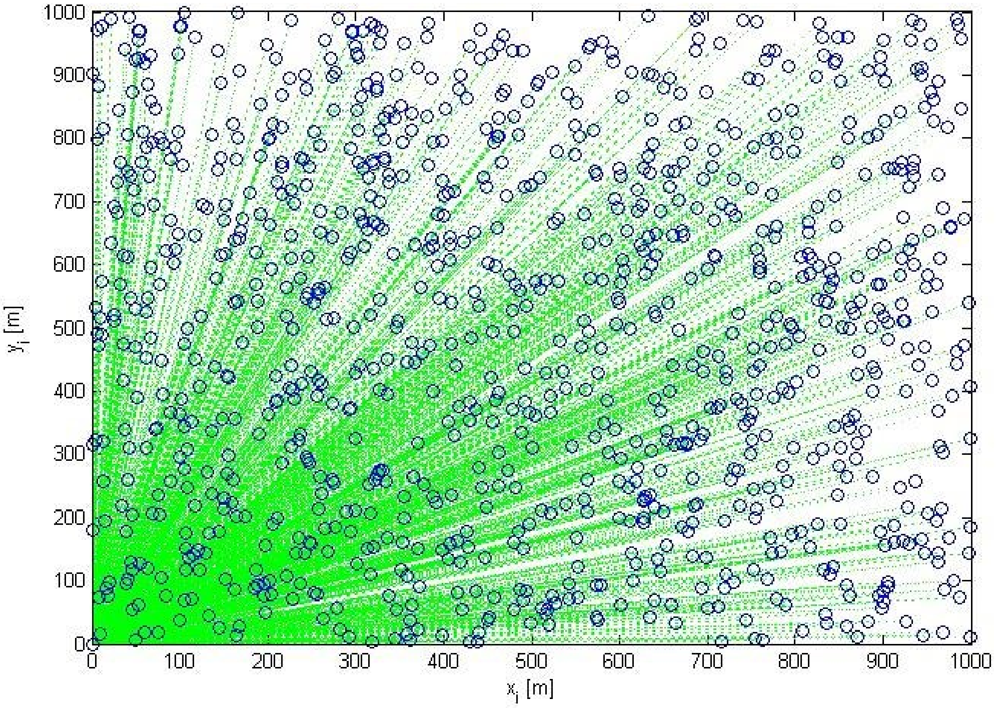
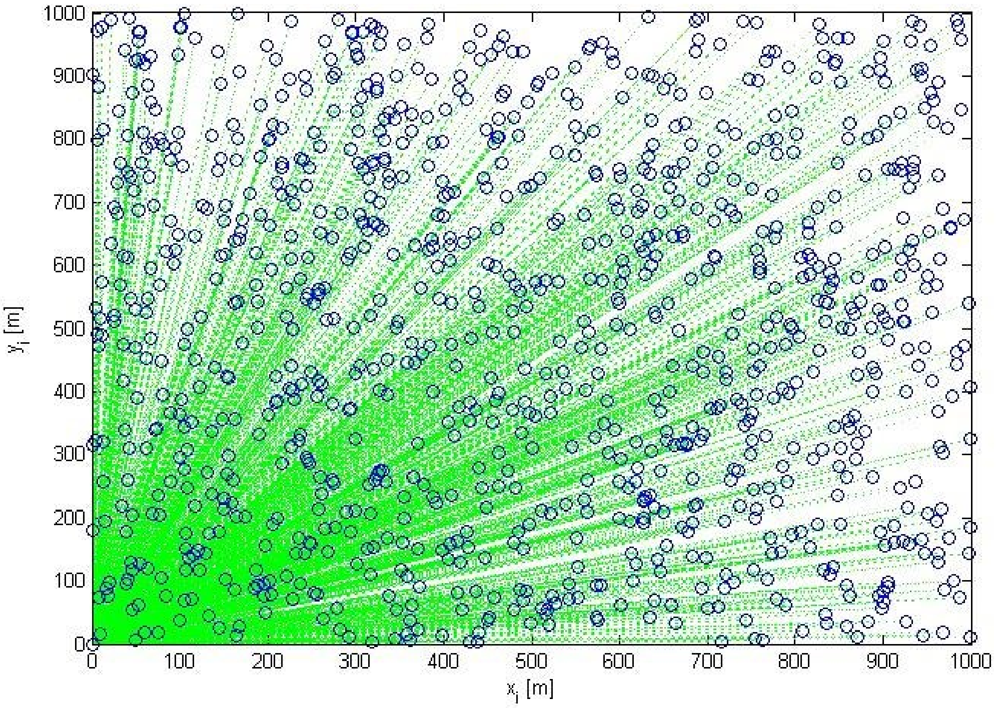


Fig.6 Starting topology of the electricity distribution network for the fictitious urban territory

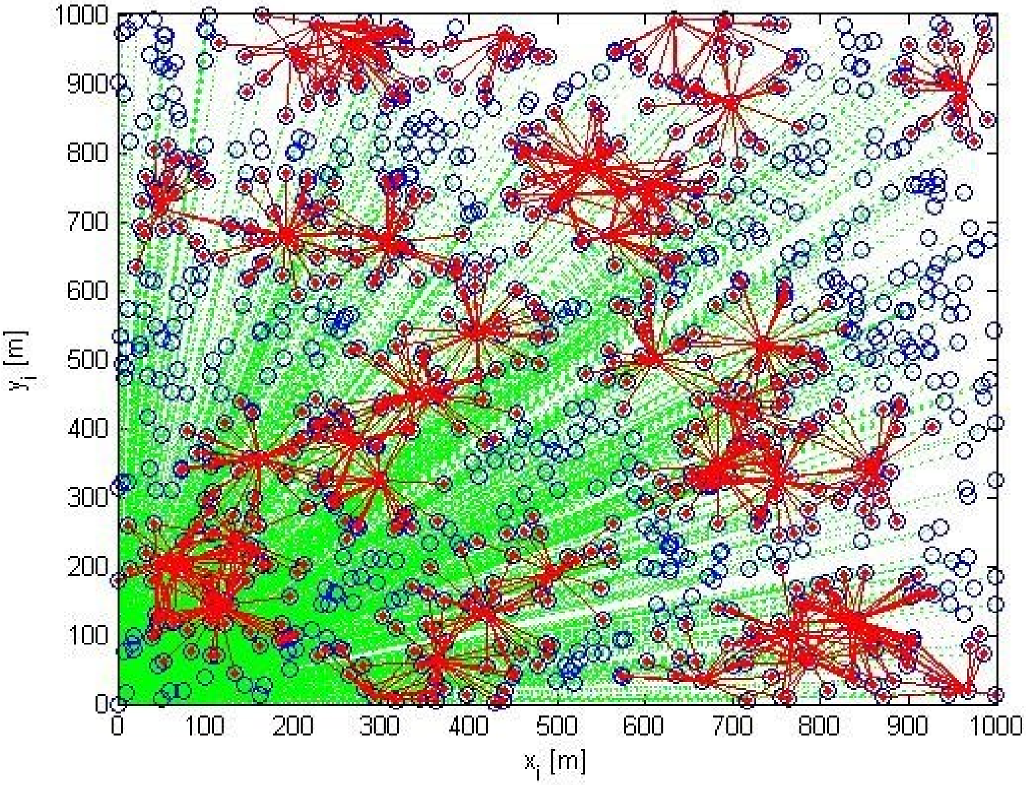
The energy distribution network reported in Fig.6 represents the starting point for the model. After the optimization, only those links characterized by an energy flow are taken into account and the optimized topologies of each network for the six scenarios of Table 4 are illustrated in Fig.7.



(a)



(b)



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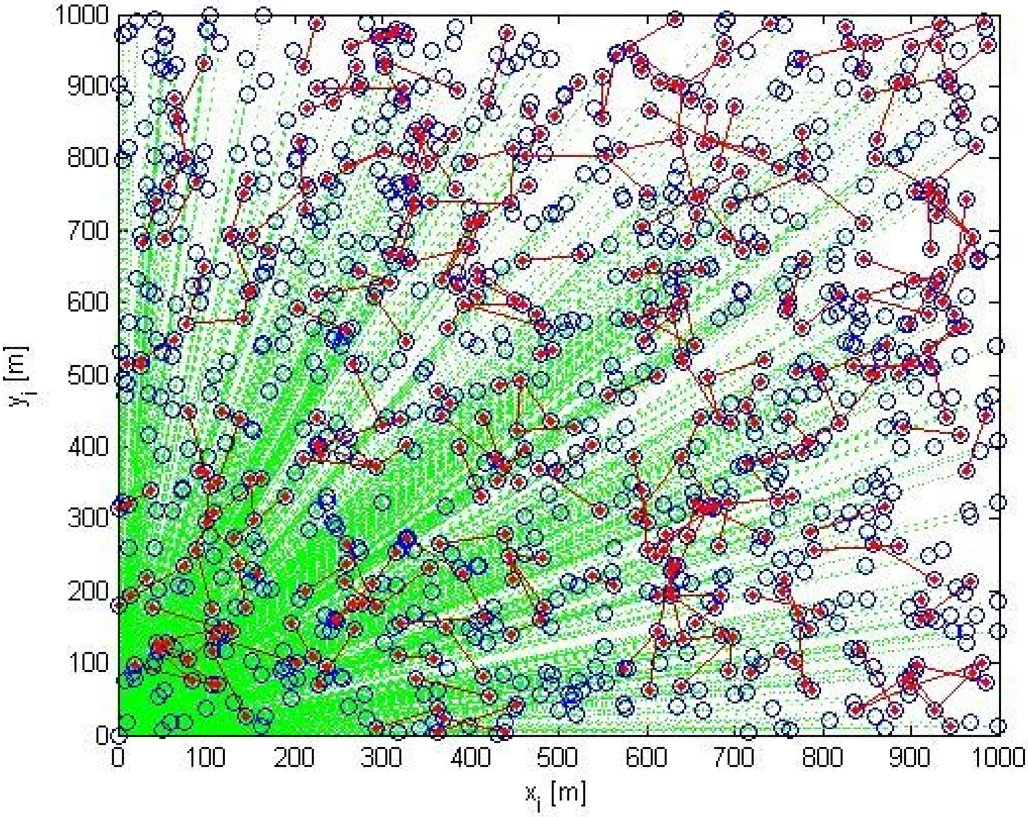
(c)



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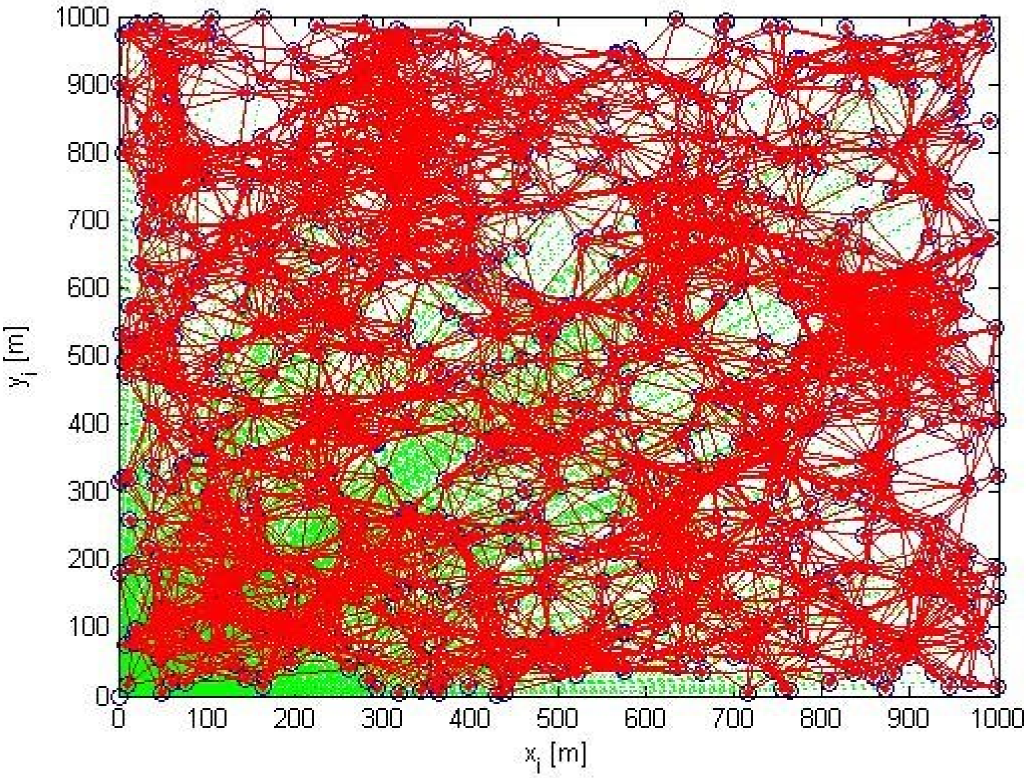
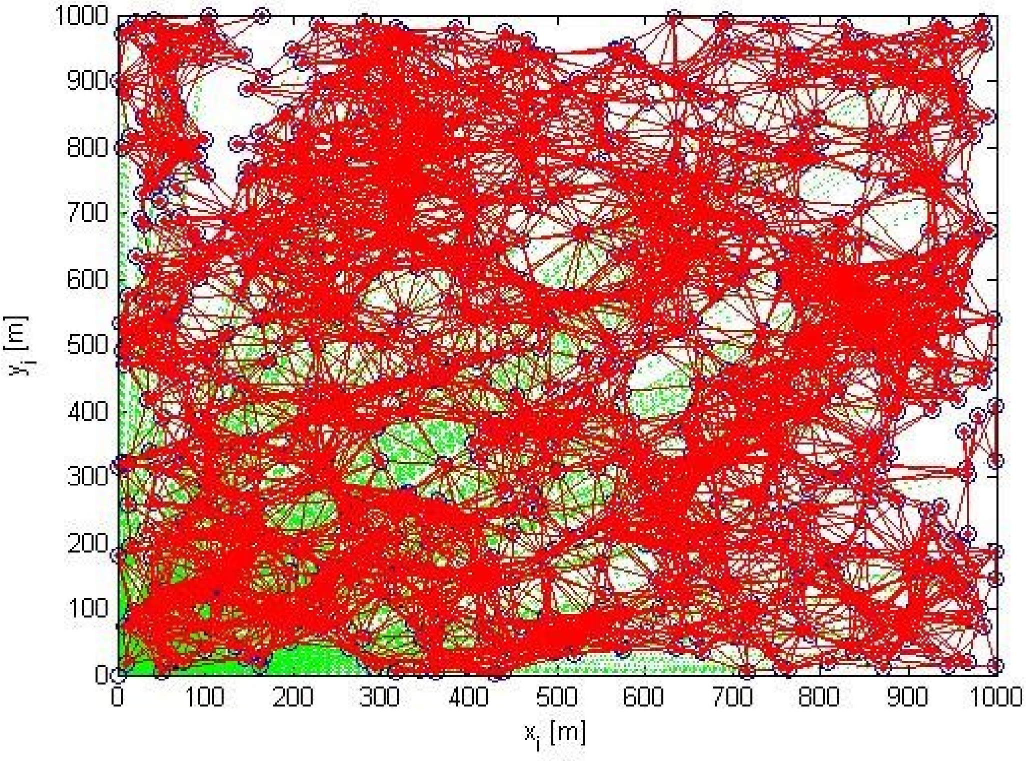
(d)



(e)



(f)

Fig.7 Energy distribution network for the scenario: (a) $H = 1$; (b) $H = 2$; (c) $H = 3$; (d) $H = 4$; (e) $H = 5$; (f) $H = 6$

For the scenario $H = 1$, the network does not have energy production and the energy demand of the nodes is totally fulfilled by the central node. Consequently, the energy flows are exchanged from the central point to the nodes and not among the nodes. In Fig.7(a), the connections among the nodes are not activated and so removed in the visualization and the connections with central point are unchanged. The fraction of activated links is $I_{N,H=1} = 0$ and the fraction of central-node links is $I_{CN} = 1$.

Fig.7(b) reports the results of the scenario $H = 2$, corresponding to an energy production equal to the 20% of the total energy demand of the whole network. The fraction of activated links for this scenario is $I_{N,H=2} = 0$. This result means that, even if the nodes are able to produce energy, this production is insufficient to guarantee the exploitation of the energy distribution network. In fact, nodes use that produced energy for the partial satisfaction of their demands, i.e. they are not able to distribute energy since they have residual demand to be satisfied. The fraction of central-node links is $I_{CN,H=1} = 1$, given that the connections between the central node and each node of the network remain unvaried.

For the scenario $H = 3$, the nodes produce the 40% of the total energy demand of the network. Fig.7(c) shows that there are connections among nodes, represented with the red links, indicating links connecting pairs of nodes exchanging energy. The fraction of activated links corresponding to this scenario is $I_{N,H=3} = 0.11$, or, rather, the percentage of connections for which an energy exchange occurs is the 11% of all available connections shown in Fig.6. Instead, the fraction of central-node links is $I_{CN,H=3} = 0.94$, i.e. after optimizing the network, the 6% of the users does not need to be connected with the central node, as the demands of such users are satisfied by their own production plus that exchanged with their neighbors.

Fig.7(d) shows the result for the scenario $H = 4$ where the energy production is the 60% of the total energy demand of the network. Increasing the surplus of energy the number of activated links among the nodes grows and the connections at central point decrease. In this case, the value of the fraction of activated links is $I_{N,H=4} = 0.30$, and the fraction of central-node links is $I_{CN,H=4} = 0.80$.

Fig.7(e) refers to the results deriving from scenario $H = 5$ and corresponding to the 80% of the total energy demand of the network. The value of the fraction of activated links is $I_{N,H=5} = 0.46$, corresponding to the 46% of all feasible connections that may be exploited for the energy exchange among nodes and the value of the fraction of central-node links is $I_{CN,H=5} = 0.65$, corresponding to the 65% of all feasible connections exposed in Fig.5.

Finally, Fig.7(f) illustrates the results for scenario $H = 6$ corresponding to an energy production almost equal to the 100% of the total energy demand of the network. The fraction of activated links is $I_{N,H=6} = 0.42$ and the fraction of central-node links is $I_{CN,H=6} = 0.53$. Both values have decreased with respect to the values obtained from the previous scenario.

Fig.8 summarizes the obtained results showing the values of the indexes I_N and I_{CN} for the considered values of the percentage of energy production P_i. For low values of P_i, the links among the nodes of the network are not activated. Increasing the percentage of energy production beyond the value of 20%, the number of links with energy flows increases linearly with a peak for $P_i = 80\%$, suggesting that there is an optimal value of the activated number of links. For the assigned neighborhood criterion and in correspondence to an energy production around the 80% of the total energy demand, the largest value of I_N is 0.46, meaning that only the 46% of all available links are at most activated in network. According to this result, the number of the connections at the central node, I_{CN} decreases until 0.47 for $P_i = 100\%$. Although the global energy production is equal to the global energy demand, the 47% of the links to the central point are in any case still activated.

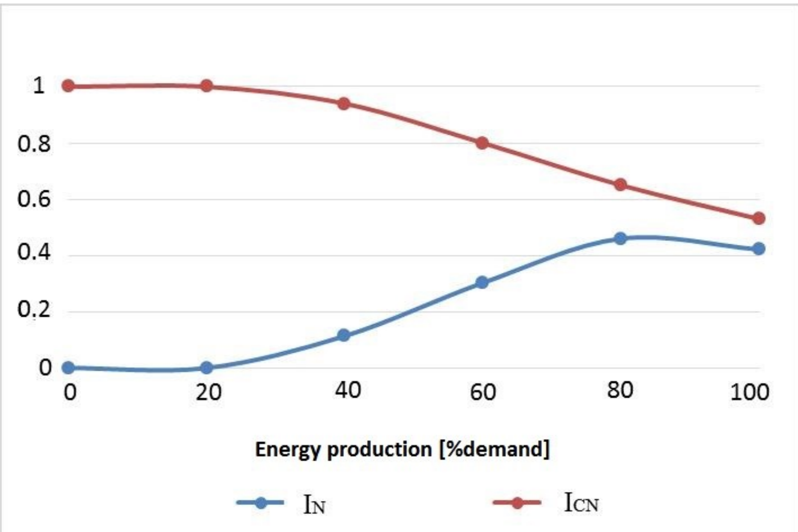


Fig.8 The fraction of activated links I_N and the fraction of central-node links I_{CN} for each scenario H

3.1.1.2 Geographical assignment of the electricity producers

The random assignment of electricity producers analysed in the previous paragraph considers, as input factor for the electricity production, a percentage of nodes that has installed renewable energy production systems; in that case, the nodes were randomly selected among the consumers of the network. Differently, in the geographical assignment proposed as follows a different rule is adopted: the simulation assigns a renewable energy production system to a randomly chosen node and, then, sequentially fixes the other producers. At iteration, the producer is selected, with probability p among the neighbours (if any) of nodes that, in the previous steps, have become producers, and with probability $(1-p)$ among the nodes not yet transformed into producers (also including neighbours of producers). For $p = 0$, this rule is the same as the random, whereas for $0 < p \leq 1$ the rule accounts for geographical correlations among the producers. The motivation for including such correlations is related to the characteristics of the territory as well as to the presence of social influence among the consumers of the urban energy distribution network. Actually, the installation of renewable energy production systems may be favoured in some parts of a city than in other. Analogously, when a user is informed on the installation of an energy production system in a neighbouring site, then he can receive a kind of social promotion to follow the strategy of his neighbours.

Numerical simulations were performed to investigate the effects of the geographical assignment on the network index; in particular, three different values of p are compared, as reported in Fig.9. The comparison among the different networks obtained for each scenario have been here neglected since the results, in graphical terms, are similar to the results of Fig.8 and do not add substantial information. Rather, the trends of the network indexes are straight discussed below.

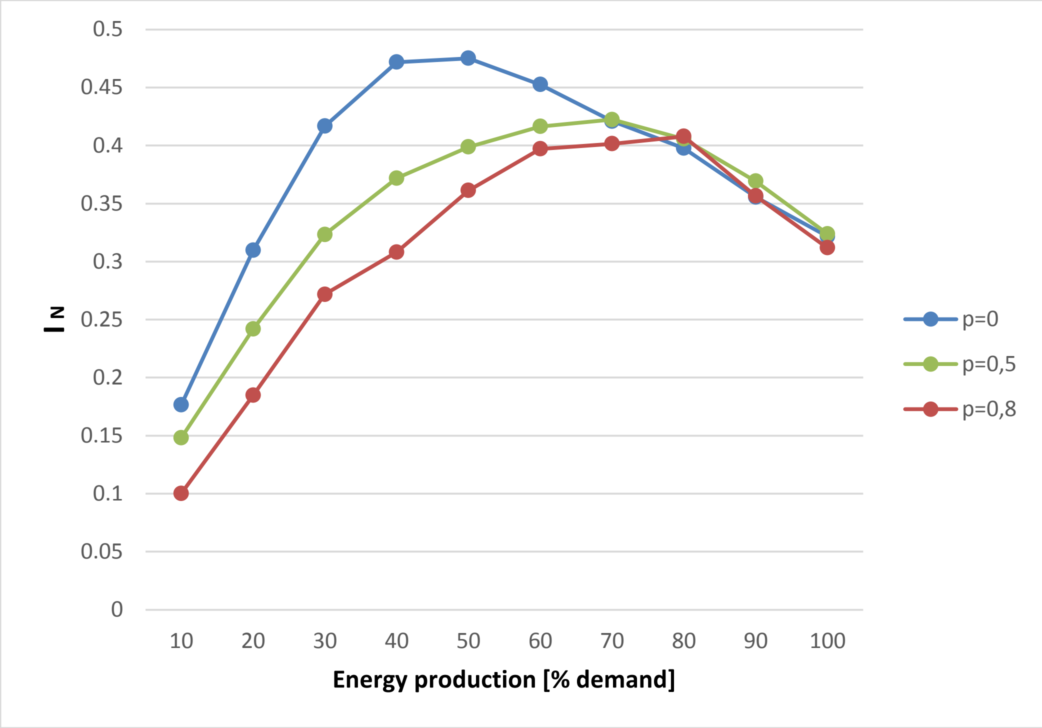


Fig.9 Network index at varying the percentage of energy production and for different values of the probability p of neighbour selection

The curves in Fig.9 are non-monotonic with a peak suggesting that there is an optimal value of the fraction of producers for the exploitation of local links. Importantly, for $p \neq 0$ lower values of the network index I_N than the case with $p = 0$ are obtained almost in the whole range of percentages of producers. It may observed that $p \neq 0$ leads to correlations in the position of the producers, as nodes close to a producer have a higher probability to become themselves producers. The results suggest that the correlations in the position of the producers reduce the performance of the urban energy distribution network with a decrease that is more significant the large is p. When the percentage of producers is large, the differences among the three curves of Fig.9 are smaller as almost all nodes are producers.

3.1.2 Analysis of scenario: the number of consumers of the network

The performance of the energy distribution network in relation to the variation of the number of nodes is then analyzed. To this aim, the fraction of activated links is evaluated at different values of N, while keeping constant the percentage of global energy production P_i. The number of nodes N was chosen within the interval $[100, 1000]$.

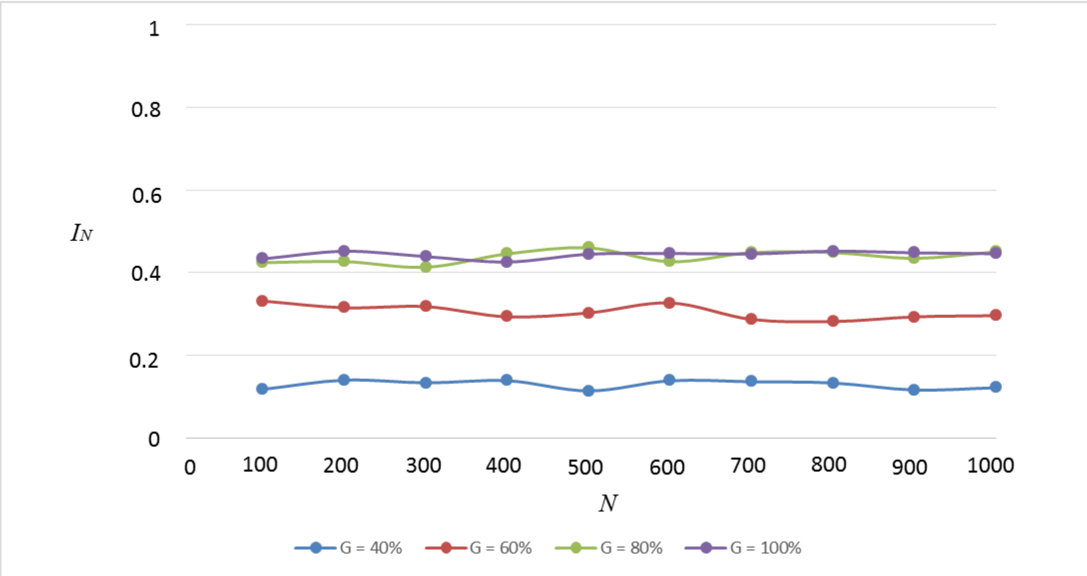


Fig.10 Fraction of activated links I_N with respect to the number of nodes N

In Fig.10 the value of the fraction of activated links, I_N, vs. the number of nodes, N, for four values of P_i is shown. For fixed P_i, I_N is almost constant. As consequence, N is not a discriminating factor for the behavior of the network that is the activation of links. Instead, the greater P_i, the higher I_N. Increasing the number of nodes of the network, the number of the activated links rises proportionally since I_N is almost the same.

3.1.3 Analysis of scenario: the distance of connection among consumers

The investigation about the influence that the distance of connection has on the exploitation of the links of the urban energy distribution network is taken into consideration by simulating four values of the distance, i.e. 25, 50, 75 and 100 m, by fixed percentages of energy production. The results of the simulations are summarized in Fig.11.

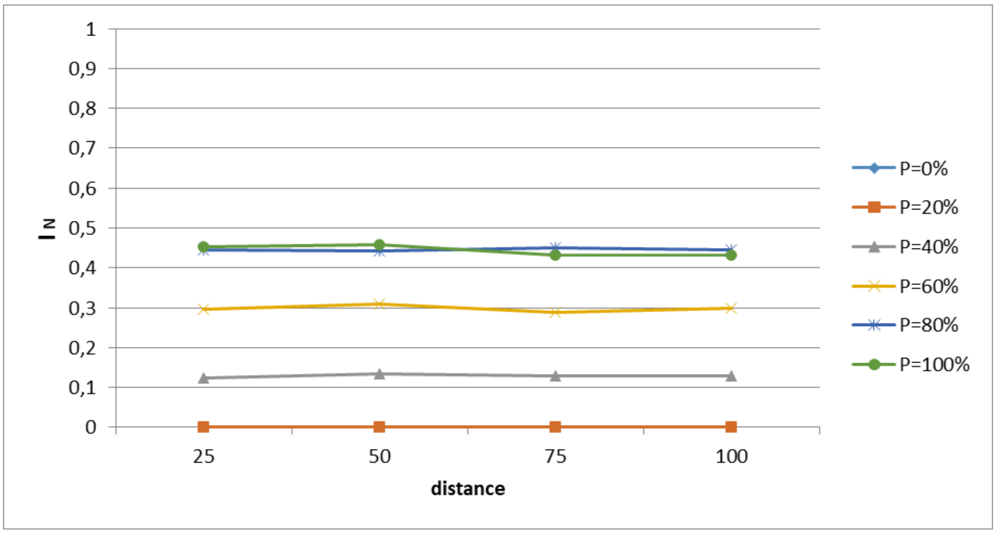


Fig.11 Network index by varying the distance of connection among nodes at given percentages of energy production

The graph permits to infer different considerations. First, by increasing the distance of connection, keeping constant the percentage of energy production, not any increase of the network index values is obtained. In this sense, the distance of connection is not a discriminating factor when a major exploitation of the links of the urban energy distribution network are desired. Thus, by varying the distance of connection among the nodes, the number of exploited connections is proportionally the same. This is true, at least, for the selected distances. Unlike the distance, the percentage of energy production seems to have a considerable effect on the network index. Indeed, except for the percentages of 0% and 20% (coincident with the *x*-axis), a greater number of links are used for the distribution of energy whenever the percentage of energy production increases. At rigor, the percentage of 0% of energy production does never activate the links of the urban energy distribution network, since it returns the energy configuration correspondent to the condition for which all nodes are supplied from the central node, i.e. the traditional energy distribution configuration. For the percentage of 20%, the links of the network still remain inactivated, because of the fact that the percentage of energy production is low and nodes use the produced energy merely for the satisfaction of their own demand. Differences may be recorded in correspondence to higher percentages of production; already for the 40% and until the 80% of production percentages, the links of the urban energy distribution network are more frequently exploited. Anyway, a further increase of the energy produced beyond the 80% does not significantly influence the distribution and, therefore, the exploitation of the links. This is due to the fact that the neighbourhood is already served from the nodes at their maximum possibility.

3.1.4 Summary of results

In this application, the develop methodology has been tested on a hypothetical territory with a homogeneous distribution of householders with the aim of minimizing the energy output from the central node through the optimal energy distribution among consumers that have installed DESs. Results suggest two interesting observations; firstly, increasing the energy production the number of activated links increases up to the threshold value of 46% that is almost the half of all available links. Secondarily, this value does not depend on the number of nodes.

3.2 Dynamic simulations: the agent-based approach

The introduced agent-based model aims at elaborating the most suitable strategy when dealing with the design of an energy distribution network among the buildings of an urban area. Buildings equipped with renewable based energy systems acquire the opportunity to exchange the own produced energy, beyond the chance to satisfy their demands. With the objective of designing an energy distribution network, it is essential to determine both which buildings may install renewable energy systems and which buildings to be connected for the exchange. To this end, a theoretical application is proposed to test the model and, precisely, an urban territory of $1000\ m \times 1000\ m$ with $N = 1000$ randomly placed nodes-agents is considered. Agents are representative of buildings characterized by an energy demand and a potential energy production deriving from the installed renewable energy systems. Simulations run on the NetLogo platform [3].

The main idea of the simulations is to reproduce the daily exchange of electricity among agents, in their capacity as consumers or producers.

Each agent corresponds to a building with 10 apartments and is characterized by the electricity demand profile of Fig.12. The electricity profiles are related the average household size and average electricity demand pro capita defined in the Eurostat 2016 [4]. Household demand covers the use of electricity for space and water heating and all electrical appliances. As regards to the electricity production, agents equipped with a photovoltaic panels exhibit an electricity production profile as the one in Fig.13, also obtained from the Eurostat statistics of 2016 [6]. In the intent of the present case study, two different electricity consumption and production are considered. Precisely, in the first scenario each agent (both consumer and producer) is characterized by the same electricity consumption profile of Fig.12 and each producer by the electricity production profile of Fig.13. This scenario is hereinafter called *constant profiles scenario*. In the second scenario, called *variable profiles scenario*, each agent varies its electricity production and consumption still according to the profiles of Figures 12 and 13, but also agreeing to a random uniform distribution with mean equal to the hourly value of the electricity consumption or production profile and standard deviation equal to one-third of the mean. Agents may exchange electricity within the neighbourhood defined by means of the chosen $connection\_radius$. Each agent, during the time simulation, searches for other agents located within the defined neighbourhood and takes action to distribute its electricity surplus.

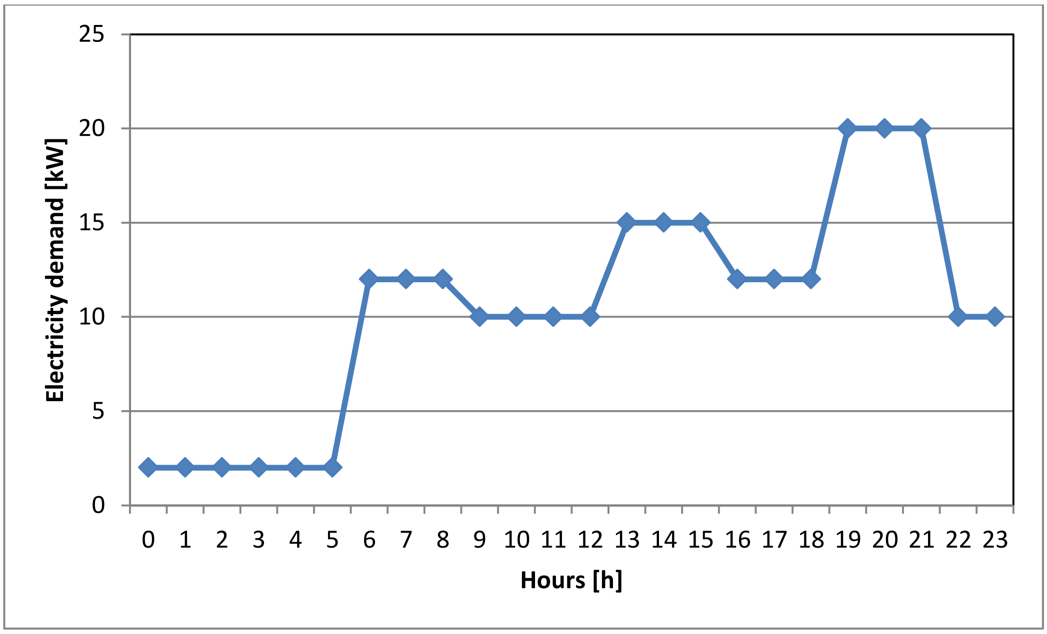


Fig.12 Electricity demand profile of each agent

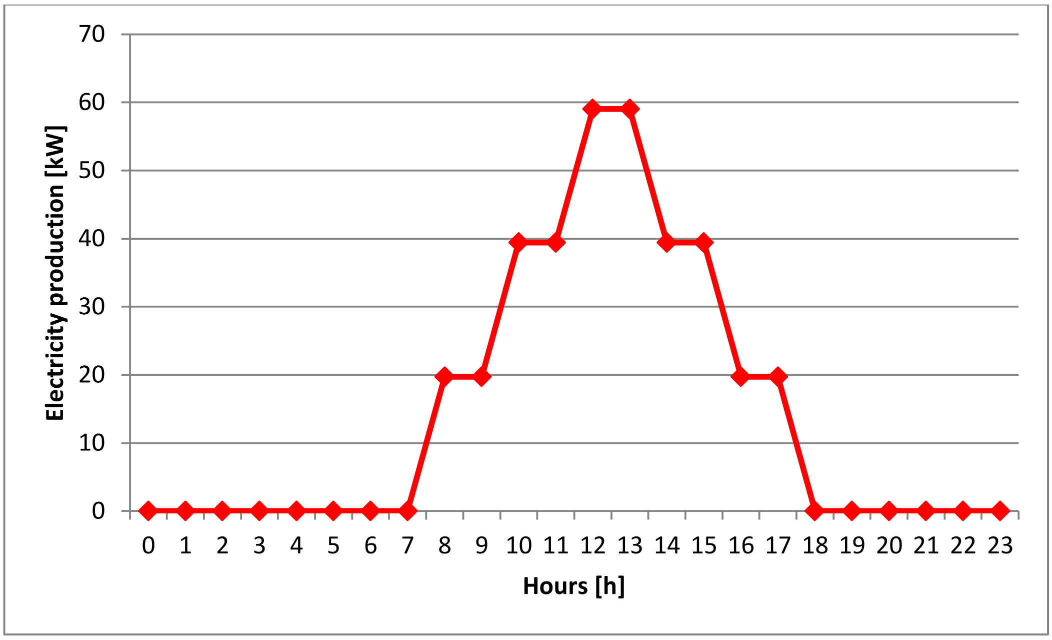


Fig.13 Electricity production profile of each agent equipped with a photovoltaic energy production system

The model has been implemented by considering the two following variables: the percentage of agents equipped with electricity production systems, briefly named *producers*, and the distance among agents.

Simulations run for both the constant profiles and the variable profiles scenarios at different percentages of producers and distances. Moreover, each scenario is also analysed for different links activation thresholds during the time period. In particular, the chosen threshold values correspond to the percentages of 0%, 5% and 10%.

All simulations are conducted for the 24 h cycle; however, since the electricity production of agents occurs in the time period from 8:00 to 18:00, the $links\_percentage$ index for every links activation threshold, the $energy\_loss\_percentage$ index and the $supply\_percentage$ index are here reported in relation to this specific time period. Indeed, since the time slots from 0:00 to 8:00 and from 18:00 to 24:00 are not characterized by renewable solar production, in these periods the demands of agents are solely satisfied from the central-agent, as in the traditional grid.

With the aim of illustrating the functioning of the model, a T=24 h simulation is carried on. To the purpose, the electricity distribution within the introduced hypothetical area populated by $N = 1000$ agents is reproduced for a fixed distance of connection, chosen as $connection\_radius = 150\ m$, and for a percentage of 30% of agents that have installed photovoltaic panels. Results are briefly summarized through the graphical interface of NetLogo in Fig.14.

Fig.14 reports the NetLogo environment at the end of a 24 h (i.e. 1440 min) simulation. The map displays both green and red nodes, representing respectively buildings that are responsible for the exchange or not, together with the corresponding links of the top layer. Counters for nodes, activated and inactivated links, time and demand are shown on the left of the interface. In the central part of the interface, three plots show the behaviour of the main indexes ($links\_percentage$, $supply\_percentage$ and $energy\_loss\_percentage$) as function of time, with a print time-step (called *supply_time*) of 15 minutes.

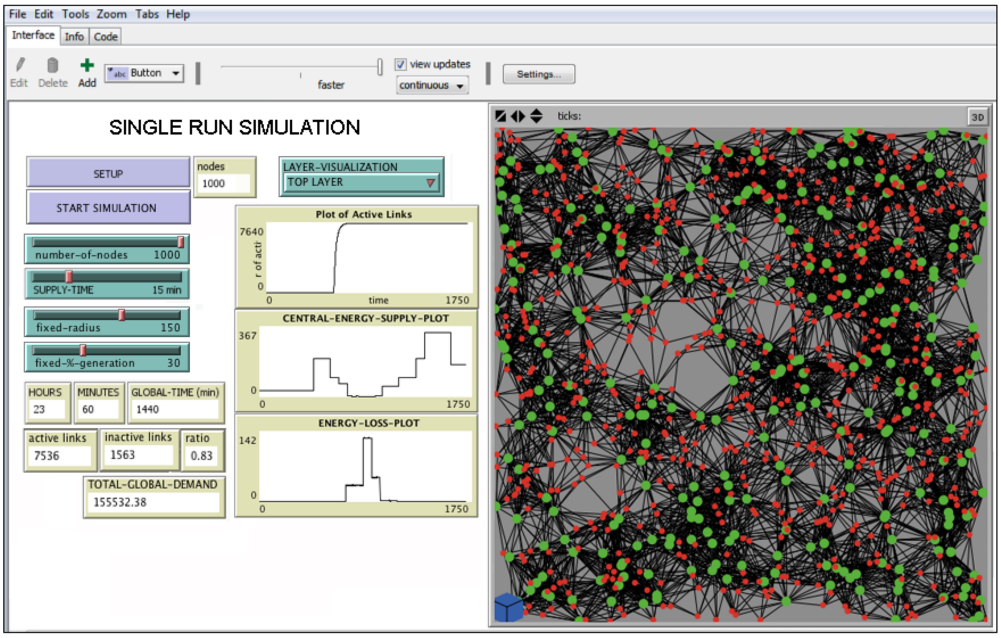


Fig.14 Graphical interface of NetLogo for a 24 h simulation, a $connection\_radius = 150\ m$, and for a percentage of 30% of producers and for the 0% of the links activation threshold

In particular, it results that: the links activation starts at 8:00 in the morning and rapidly reaches its asymptotic value (83%); the supply from the central-node starts to increase from its low night level around 6:00 and stays quite high for a couple of hours until, at 8:00, the renewable energy production becomes effective: then, as expected, this supply decreases towards zero due to the local energy exchange but, after 12:00, it increases again until it reaches its maximum value during the evening hours; consequently, the profile of the energy loss is concentrated in the central part of the day and reaches a maximum around 12:00. Finally, by integrating the last two curves over time and using Eq.(2.6) one could extract the final value of the global $index_{mix}$. In the next two paragraphs the behaviour of all these quantities will be studied as function of either the connection radius or the percentage of producers and within two distinct scenarios, considering first a constant profile of energy consumption and production, then a variable one.

3.2.1 Scenario 1: constant profiles of both electricity consumption and production

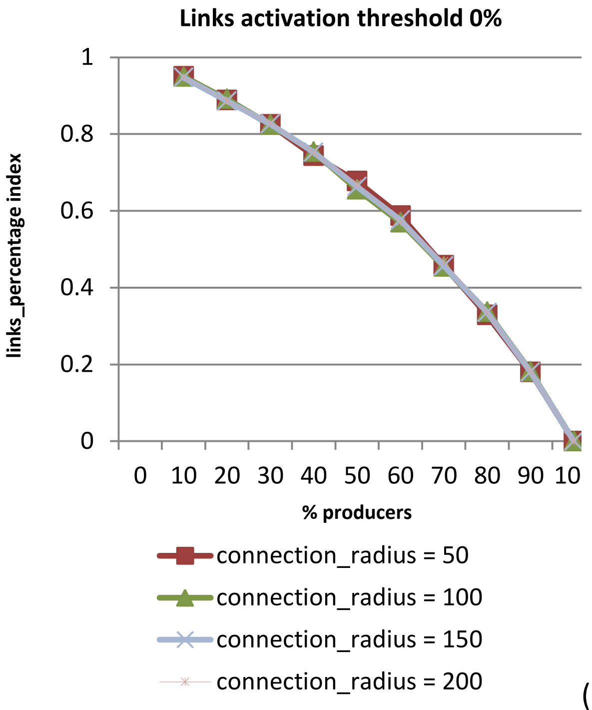
In the first set of simulations, the electricity consumption profile is equal for all agents of the network and corresponds to the profile of Fig.12. Similarly, agents equipped with photovoltaic panels display the electricity production profile of Fig.13 with no distinctions. The simulations are performed, on each occasion, for fixed values of the $connection\_radius$, i.e. the maximum distance along which agents may exchange energy, and considering different percentages of producers. The fixed values of the $connection\_radius$ are reported in Table 5, whilst the percentage of producers varies from 0% to the 100%. The increase in the values of the $connection\_radius$ indicates that at each simulation step a larger area is gradually considered and, therefore, a major number of connections are established. The percentages of producers are related to the total amount of agents of the network. In particular, increasing the percentage of producers implies that a major amount of agents installs photovoltaic panels.

Table 5. Values of the $connection\_radius$

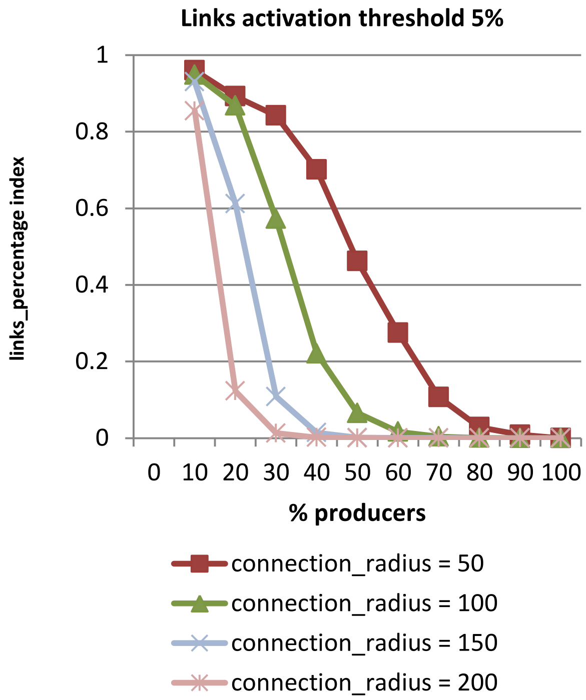
$\boldsymbol{connection\_radius}$ **[m]**
50
100
150
200

For each set of simulations, the trends of the $links\_percentage$ index, the $energy\_loss\_percentage$ index and the $supply\_percentage$ index at different links activation thresholds are recorded. The graphs of the $links\_percentage$ index are the only reported graphs that contain the specification of the considered threshold. Regarding both the $energy\_loss\_percentage$ and the $supply\_percentage$ indexes, instead, a unique graph is representative for all the thresholds. As a reminder, this choice derives from the evidence that the links activation threshold influences only the $links\_percentage$ index, since it corresponds to the calculation of how many times links are used for the energy distribution and does not account for electricity quantities.

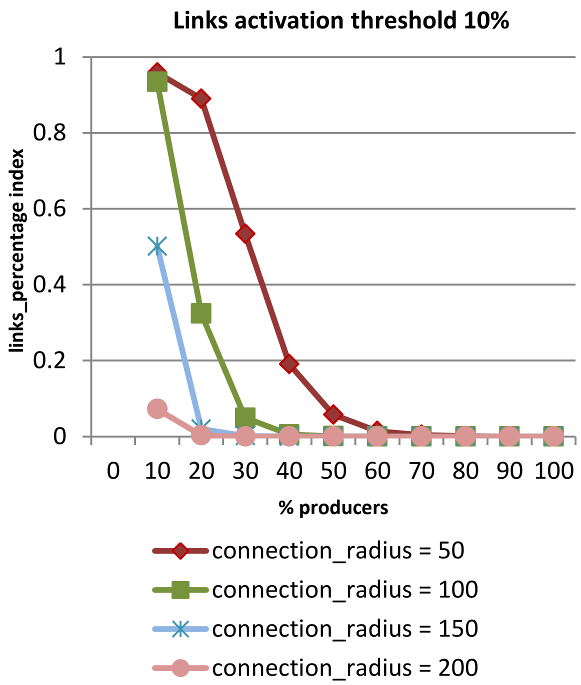
The links activation threshold is initially set to 0%, i.e. each link is counted as active if it is characterized by *at least* one electricity exchange during the time period $[08{:}00, 18{:}00]$. Subsequently, the threshold is enlarged to the 5% and 10%. The trends of the $links\_percentage$ index for the three chosen links activation thresholds are reported in Fig.15.



(a)



(b)



(c)

Fig.15 Trends of the $links\_percentage$ index in correspondence to: (a) links activation threshold 0%; (b) links activation threshold 5%; (c) links activation threshold 10%

The $links\_percentage$ index decreases as a function of the percentage of producers until the nil value in correspondence of the 100% of agents; i.e. the electricity produced by each agent is used for own purposes and, therefore, not distributed. As a result, not any link of the distribution network is used and the $links\_percentage$ index is null. Vice versa, the maximum values of the $links\_percentage$ index are recorded in correspondence of small percentages of producers. Into detail, the consideration of the links activation threshold significantly discriminates the results. Accordingly, when threshold is 0% (Fig.15a), the trends of the $links\_percentage$ index are similar independently of the $connection\_radius$ values. In these cases, the maximum value of the index is yielded in correspondence with the 10% of producers. The insertion of a links activation threshold greater than 0% (Fig.15b and Fig.15c), instead, returns a reduction of the $links\_percentage$ index at increasing the $connection\_radius$; this is even truer for the threshold 10% in Fig.15c. This means that the majority of the links of the network is used less than the 5% or the 10% of the entire operating time interval. However, as a general result, the percentage of 10% of producers guarantees the maximum exploitation of the links of the distribution network. This is all the more true when distances equal to $connection\_radius = 50$

or $connection\_radius = 100$ are considered and for which the $links\_percentage$ index is almost near to the 0.93, i.e. the 93% of the total links established in the initial topology of the network are characterized by an electricity exchange.

The following graphs of Fig.16 and Fig.17, respectively representing the $energy\_loss\_percentage$ index and the $supply\_percentage$ index, are reported by way of example for the threshold 0%. The $energy\_loss\_percentage$ index rises when increasing the percentage of producers. In point of fact, a major electricity production yields a major surplus compared to the demands of the agents in the neighbourhood, thus resulting in an increase of the electricity that is not immediately distributed and, therefore, "lost". Concerning the distance of connection, instead, the amount of electricity that is considered as "lost" is slightly greater for $connection\_radius = 50$ compared to the higher distances.

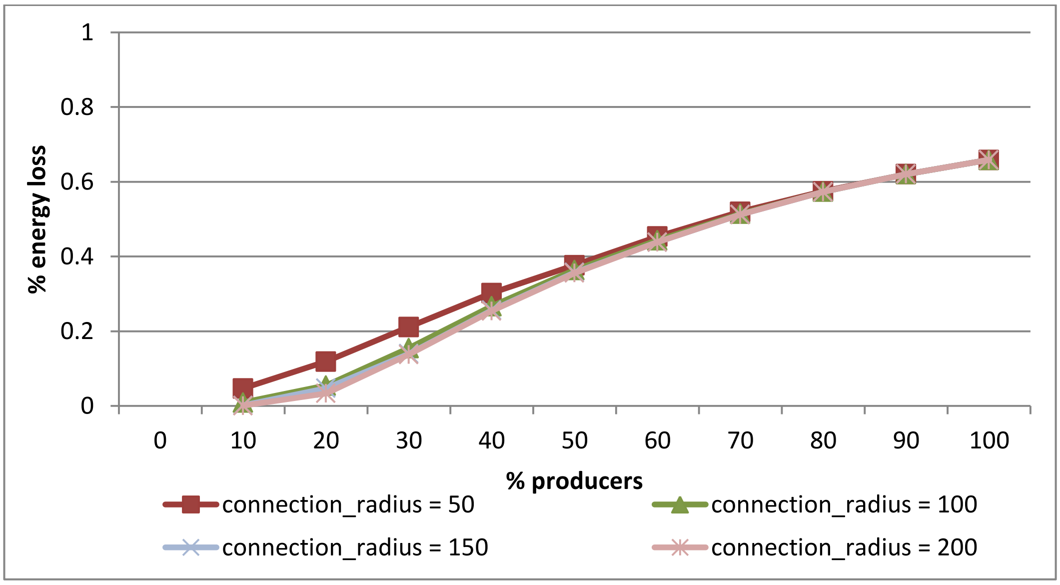


Fig.16 The $energy\_loss\_percentage$ index at the different $connection\_radius$ values

Finally, the $supply\_percentage$ index in Fig.17 diminishes at increasing percentages of producers. This is manifested in the fact that the increase of the installation of renewable systems allows agents to achieve the energy self-sufficiency, thus reducing the supply from the central-agent. Anyway, the central-agent keeps its significant role in the time interval occurring between 18:00 and 8:00, when the photovoltaic panels have a nil production.

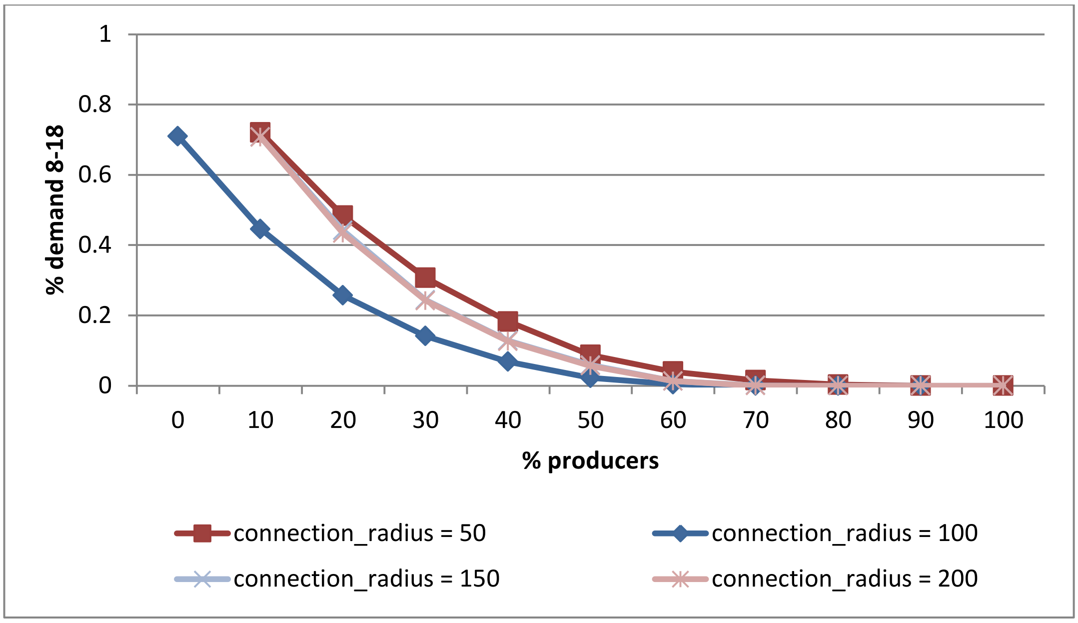
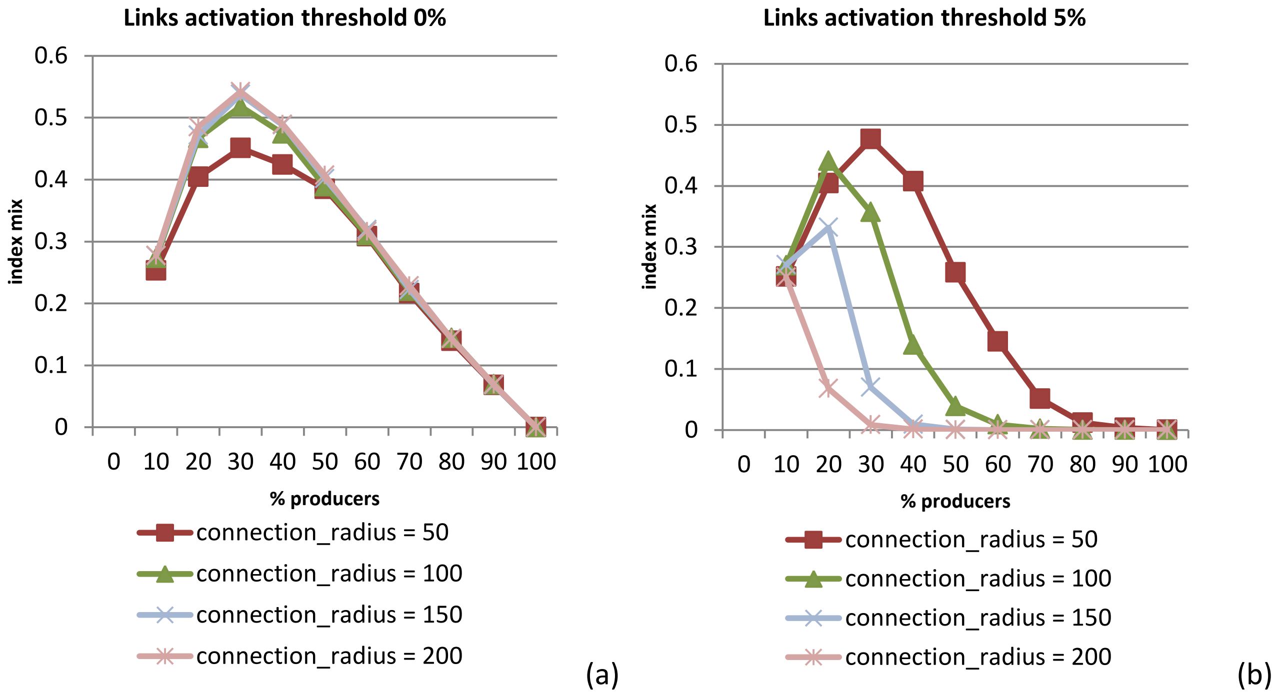
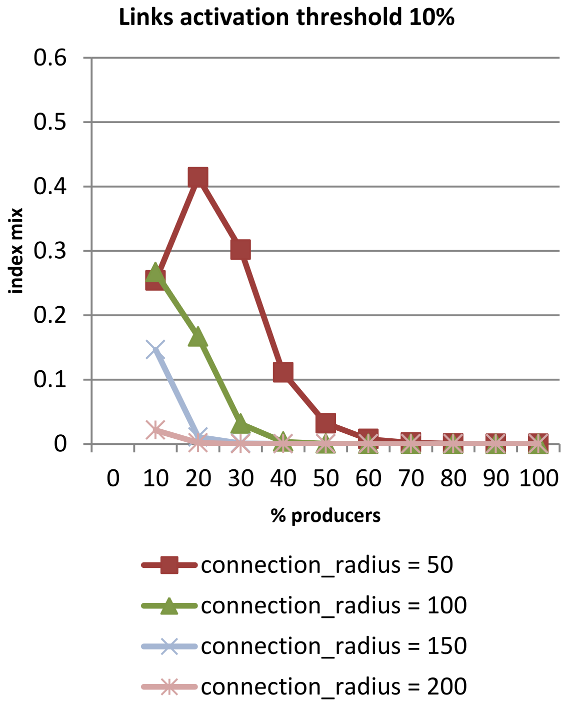


Fig.17 The $supply\_percentage$ index at the different $connection\_radius$ values

As concluding remark, the $index_{mix}$ reporting the best trade-off among the indexes is considered and shown in Fig.18.





(c)

Fig.18 Trends of the $index_{mix}$ in correspondence to: (a) links activation threshold 0%; (b) links activation threshold 5%; (c) links activation threshold 10%

The examination of the $index_{mix}$ allows inferring conclusions about the relationship between the thresholds and both the distance of connection and the percentage of producers. It comes clearly out how the higher values of the $connection\_radius$ are preferable when no restrictions about the links activation are assumed. Vice versa, when considering thresholds greater than the 0%, the value of $connection\_radius\ = 50\,m$ returns the maximum value of the $index_{mix}$ and, as a confirmation, at increasing distances, the $index_{mix}$ decreases. This result means that the electricity distribution network performs more efficiently, i.e. with major activation of the links and with both minor electricity loss and demand to the central agent, when agents act in a spatial limited neighbourhood. Moreover, the percentage of producers that guarantees the best performance is around the 20% and the 30%.

The trends of the $index_{mix}$ for the different thresholds at fixed values of the $connection\_radius$ are compared in Fig.19.

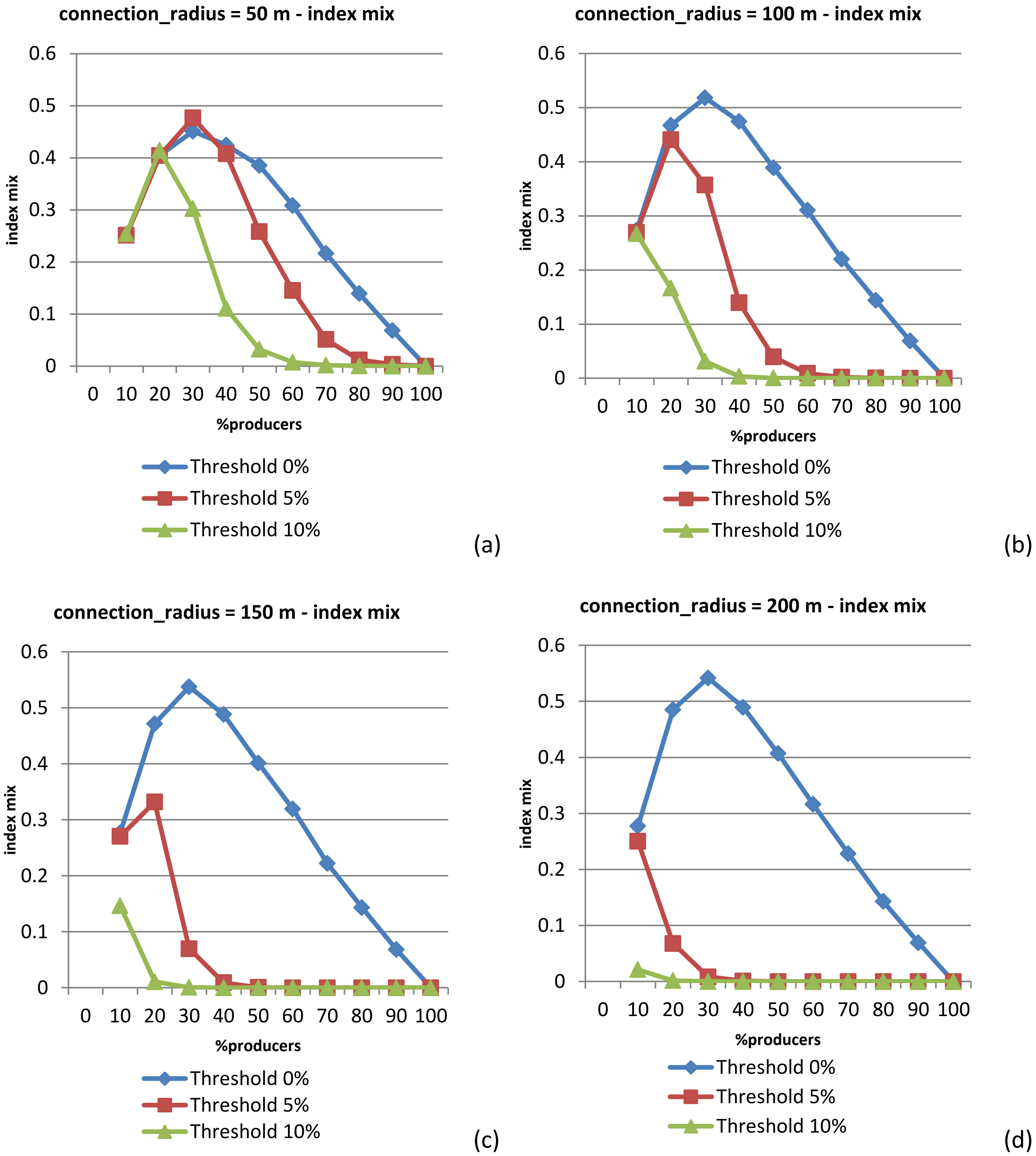
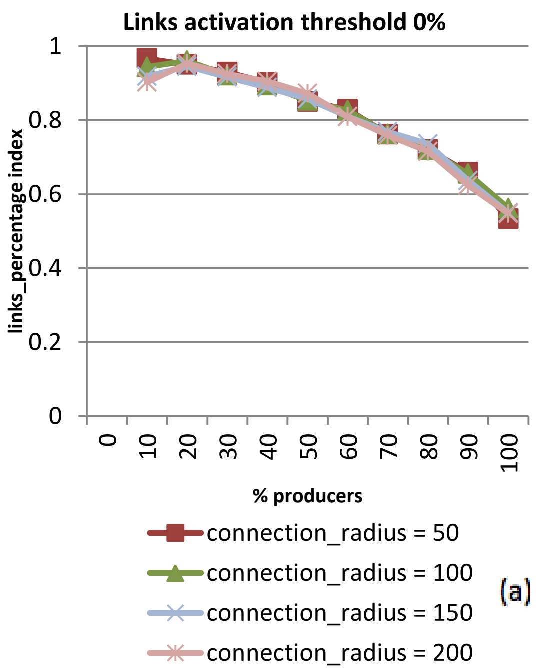


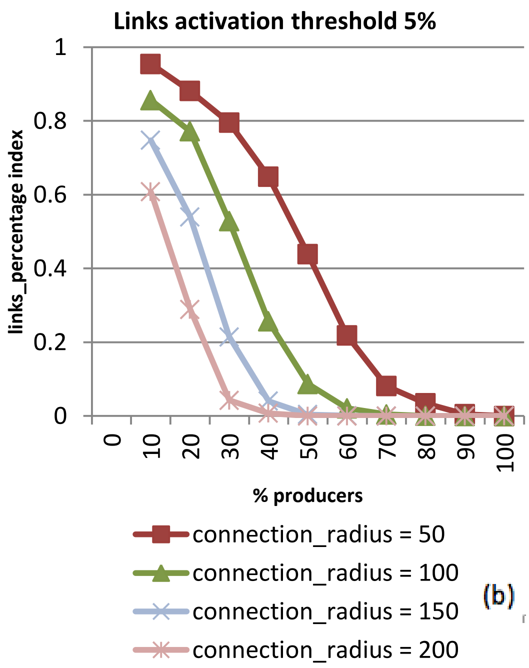
Fig.19 Threshold comparison for the $index_{mix}$ at: (a) $connection\_radius = 50\ m$; (b) $connection\_radius = 100\ m$; (c) $connection\_radius = 150\ m$; (d) $connection\_radius = 200\ m$

In Fig.19a the insertion of the links activation thresholds causes a decrease of the $index_{mix}$ for fixed percentages of producers are considered (excluding the percentages of 10% and 20% for which the curves are almost identical). At increasing values of the $connection\_radius$, the diversity among the thresholds is even more evident. In particular, in the case of 200 m (Fig.19d), the $index_{mix}$ is about null when threshold 10% is applied.

3.2.2 Scenario 2: variable profiles of both electricity consumption and production

The second set of simulations runs considering variable profiles of both electricity consumption and production for fixed values of the $connection\_radius$, by varying the percentages of producers. The values of the $connection\_radius$ are the same applied to the precedent scenario and reported in Table 5. Similarly, the percentage of producers varies from 0% to the 100% and the links activation is set to the 0, 5 and 10% in each simulation step. The $links\_percentage$ indexes are reported in Fig.20.





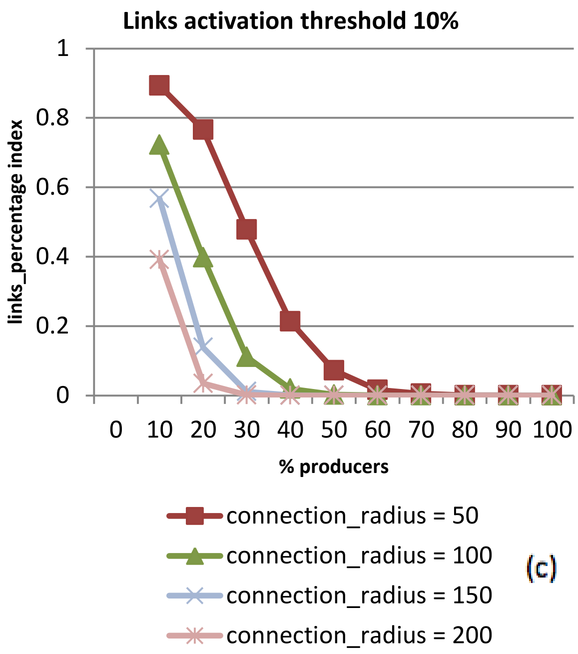


Fig.20 Trends of the $links\_percentage$ index in correspondence to: (a) links activation threshold 0%; (b) links activation threshold 5%; (c) links activation threshold 10%

The $links\_percentage$ index when threshold 0% is considered, i.e. Fig.20a, displays similar trends at increasing values of the $connection\_radius$. Moreover, its trend indicates how low percentages of producers ensure a higher exploitation of the links of the distribution network. Differently from the previous scenario (Fig.15a), the $links\_percentage$ index does not assume nil values due to the fact that the electricity demands and productions of the agents are here variable. Instead, being scenario 1 characterized by constant demands and productions, all agents are producers and consumers in the same way; therefore, given that the 100% of the agents are producers, no electricity exchange is feasible. When thresholds are included in the simulations (Fig.20b and Fig.10c) the maximum values of the $links\_percentage$ index are recorded in correspondence to a distance equal to $connection\_radius\ = 50\ m$, and, anyway, for the 10% of producers. Moreover, compared to the previous scenario (Fig.15b and Fig.15c), the $links\_percentage$ index decreases more uniformly at increasing the $connection\_radius$. Or rather, a minor number of links are used for the distribution although the permitted distance of connection is higher.

The $energy\_loss\_percentage$ index and the $supply\_percentage$ index for the threshold example 0% are reported in Fig.21 and Fig.22.

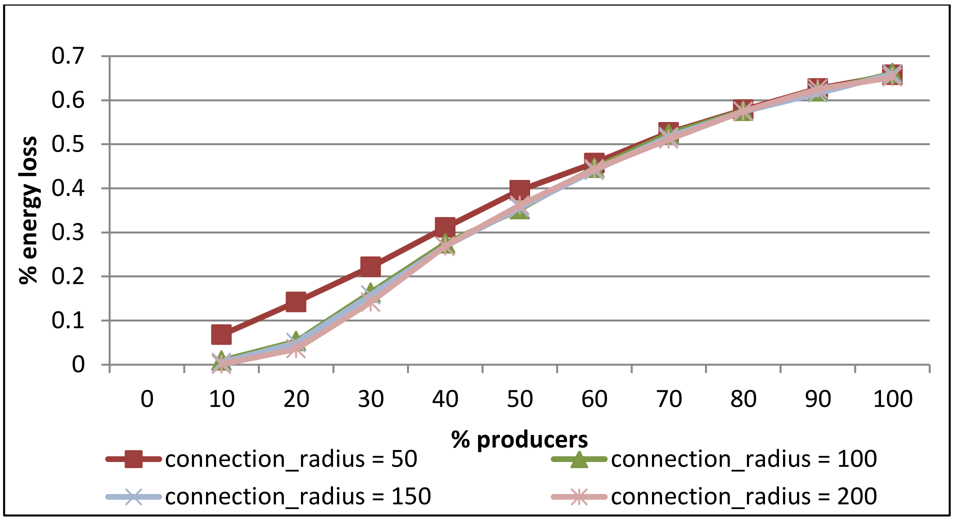


Fig.21 Trends of the $energy\_loss\_percentage$ index in correspondence to links activation threshold 0%

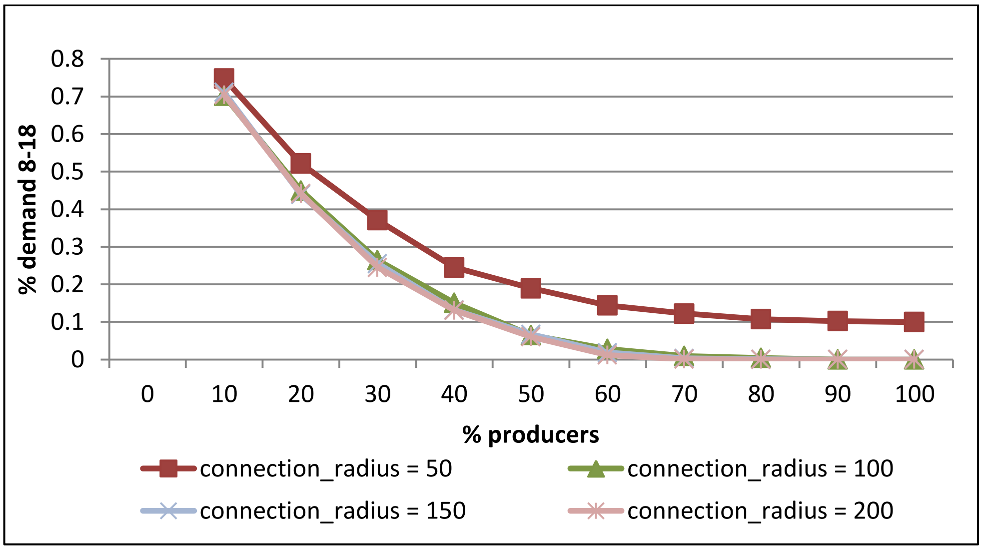
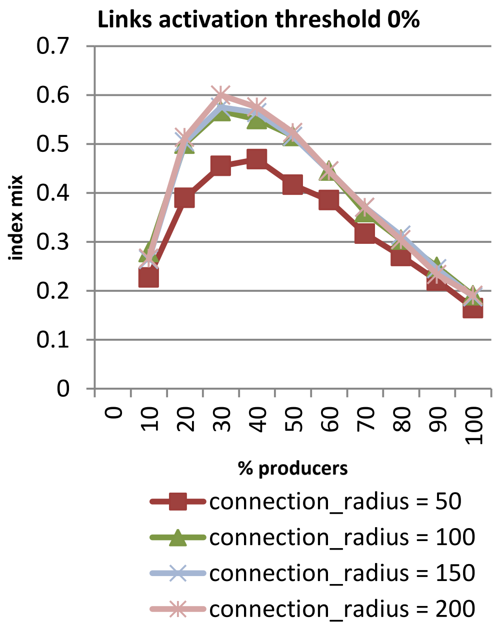


Fig.22 Trends of the $supply\_percentage$ index in correspondence to links activation threshold 0%

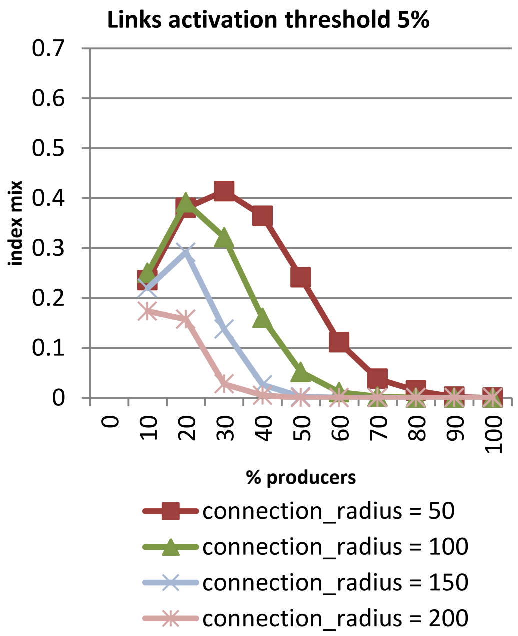
The $energy\_loss\_percentage$ index, approximately for each links activation threshold, shows an increasing trend. Actually, the value of the $connection\_radius$ equal to 50 m is responsible for a major (although limited) electricity loss. Nevertheless, beyond 50 m, the electricity losses are almost similar at the different distances. In addition, the increase of the percentage of producers does not avoid electricity loss; rather, the exceeding electricity is not distributed since neighbouring agents also produce electricity on their own and do not need to receive from the other producers.

The $supply\_percentage$ index exhibits an initial decrease and then performs a nearly constant trend. Generally, low percentages of producers mean a major amount of electricity supply from the central-agent in order to satisfy the demands of the agents of the network. However, the increase of the percentage of producers is a convenient choice up to the point, around the 60-70% of producers, beyond which no further advantages may be achieved (also because, for non-zero links activation thresholds, the supply becomes null). Therefore, although producers are able to reach a broader neighbourhood of agents, the supply from the central-agent does not decrease; this is due to the fact that agents have already distributed their exceeding electricity to closer neighbours and do not use further links for the distribution or they do not have further exceed to distribute.

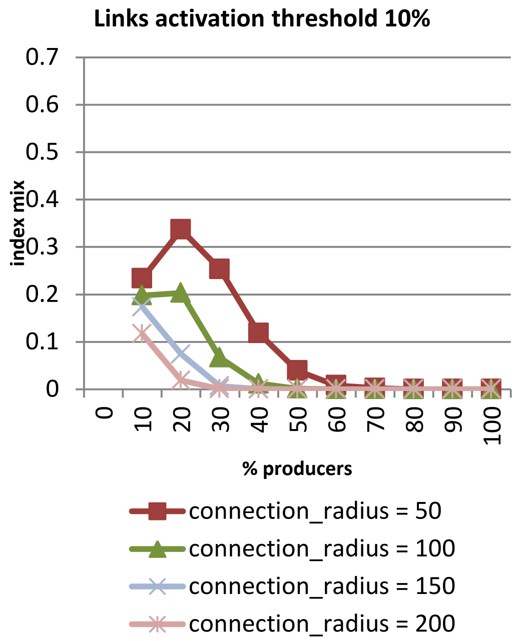
Finally, the comparison of the $index_{mix}$ behaviour for different links activation thresholds by varying the radius of connection and the percentage of producers is shown in Fig.23.



(a)



(b)



(c)

Fig.23 Trends of the $index_{mix}$ in correspondence to: (a) links activation threshold 0%; (b) links activation threshold 5%; (c) links activation threshold 10%

The results are qualitatively similar to the corresponding ones of scenario 1, shown in Fig.18; all curves show an initial increment and then a decrement that is more evident the higher becomes the considered links activation threshold. The best performance in terms of the $index_{mix}$ is generally attained in correspondence with the 30% of producers and distances higher than 50 m, when no links activation threshold is considered. However, the insertion of the thresholds diminishes the value of the $index_{mix}$; in these cases, the best trade-off among the three indexes is found for every configuration that plans the insertion of a percentage of producers equal to 30% and 20% (respectively for threshold 5% and 10%) and a $connection\_radius = 50\ m$.

The curves of the $index_{mix}$ for the different thresholds at fixed values of the $connection\_radius$ are reported in Fig.24.

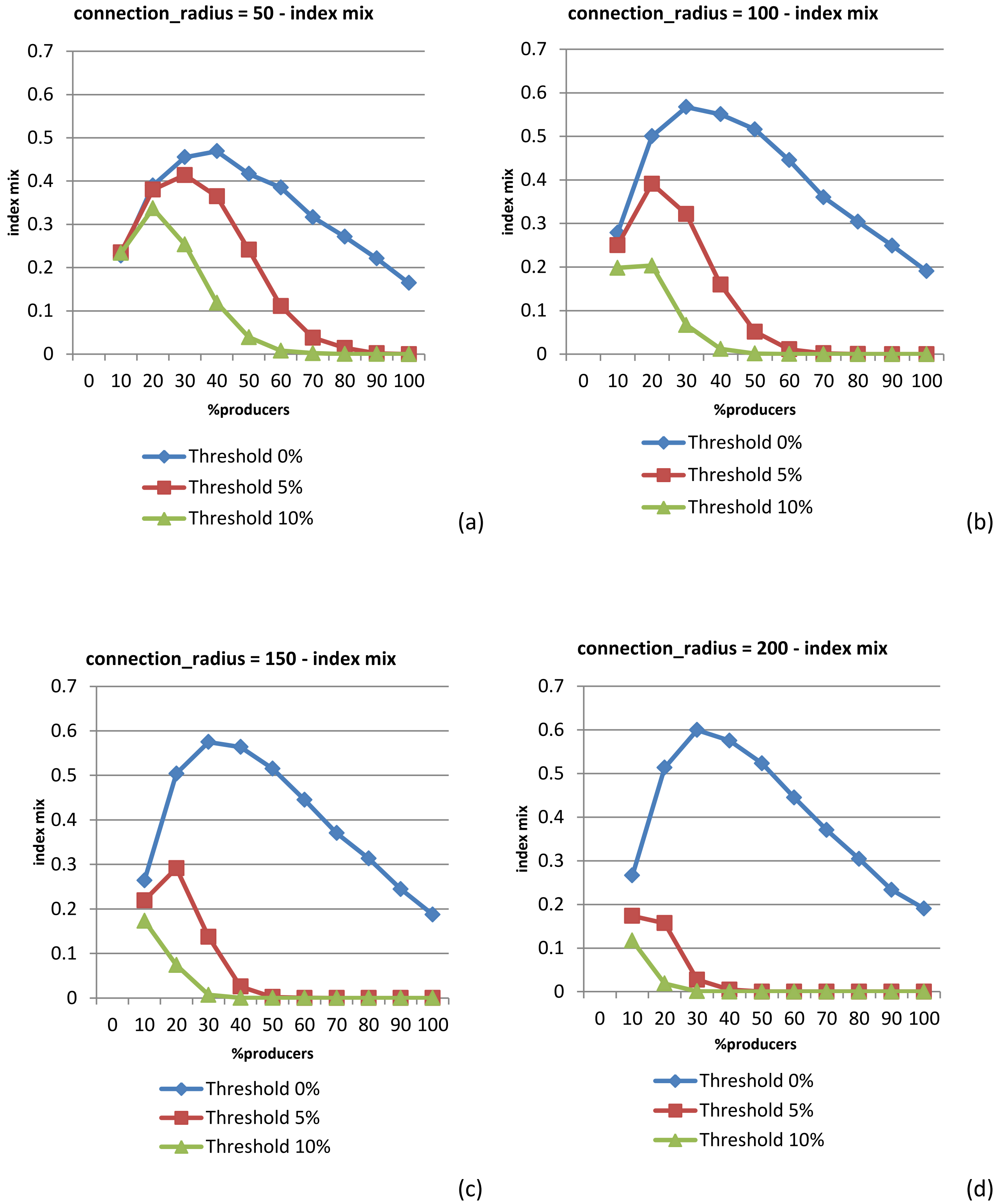
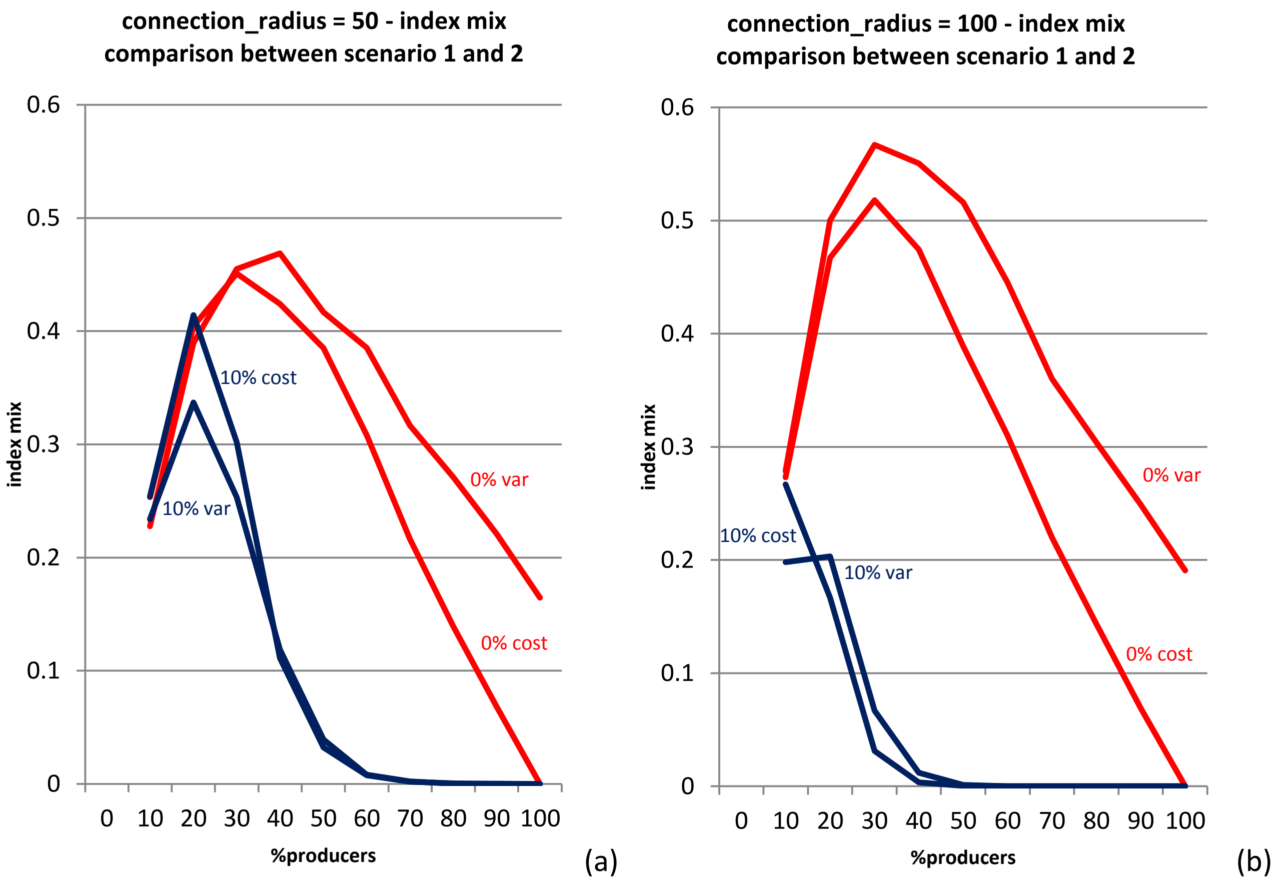


Fig.24 Threshold comparison for the $index_{mix}$ at: (a) $connection\_radius = 50\ m$; (b) $connection\_radius = 100\ m$; (c) $connection\_radius = 150\ m$; (d) $connection\_radius = 200\ m$

As previously highlighted in the discussion of Fig.19 for scenario 1, the thresholds produce a decrease of the recorded values of the $index_{mix}$. The decrease becomes more significant at increasing values of the $connection\_radius$. Hence, as also noticed, the higher the distance the lower the $index_{mix}$.

3.2.3 Comparison between scenario 1 and scenario 2

The analyzed scenarios are compared in Fig.25. The $index_{mix}$ is reported in these graphs since it combines the major values of the links exploitation with the minor values of both the electricity losses and electricity supply from the central agent. To highlight the impact that the thresholds have on the evaluation of the performance of the distribution network, the sole 0% and 10% activation thresholds are compared and reported in the graphs.



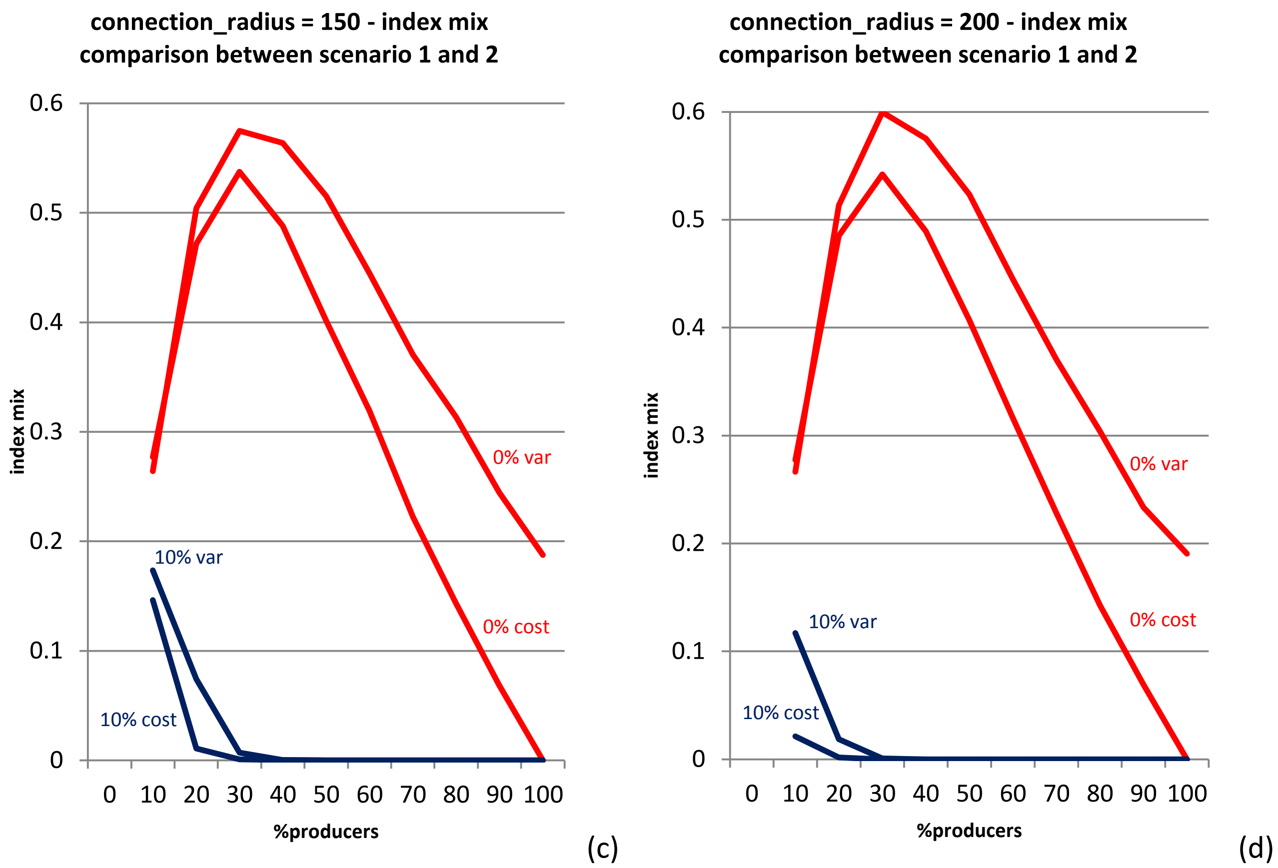


Fig.25 Constant and variable threshold comparison for the $index_{mix}$ at: (a) $connection\_radius = 50\ m$; (b) $connection\_radius = 100\ m$; (c) $connection\_radius = 150\ m$; (d) $connection\_radius = 200\ m$

As a general observation, high distances combined with a nil threshold permit to achieve better performance of the distribution network, in terms of links exploitation and of both minor losses and central supply. As regard to the percentage of producers, instead, the 30% of producers among the totality of agents guarantees the maximum values of the $index_{mix}$in every case. In details, a nil threshold means that every link that is used for at least one exchange during the operating time [08:00, 18:00] is included in the $links\_percentage$ index. Inserting the threshold of 10% is, however, a good argument to avoid fully unused links, since all links used less than the 10% of the time are excluded. Under this hypothesis, the best performances are recorded, oppositely, in correspondence with low distances, in particular for $connection\_radius = 50\ m$ and for the 20% of producers. Therefore, the planning of a network of energy distribution has also to consider the real exploitation of its links in order to avoid costly interventions that do not bring advantages in terms of energy distribution.

3.2.4 Summary of results

The results of the simulations permit to conclude that the design of the distribution network within urban areas should consider the practical usability of the energy connections, beyond the evaluation of both the preferable distance of connection and percentages of producers. Indeed, from this point of view, the number of links used for the energy exchange strongly decreases when a constraint on their activation is posed. Therefore, planning long-distance connections may be considered as the best condition at a first glance, but, actually, the insertion of activation thresholds (such as the 10%) permits to conclude that the majority of the links is used less than the 10% of the time. Rather, low distances, typically around 50 m coupled with the 20-30% of producers, ensure best performances in terms of exploitation of the distribution network.

References

[1] Mathworks, 2010. MATLAB Version R2010a. The Mathworks, Inc, Natick, Massachusetts (2010)

[2] Data available at www.autorita.energia.it (in Italian)

[3] Wilensky U. NetLogo. Northwestern University, Center for Connected Learning and Computer-Based Modelling, Evanston 1999

[4] Data available at

http://ec.europa.eu/eurostat/tgm/table.do?tab=table&plugin=1&language=en&pcode=tsdpc310

[5] Data available at

http://ec.europa.eu/eurostat/tgm/table.do?tab=table&init=1&plugin=1&pcode=ten00081&language=en

4. The urban energy distribution network – the area of Nesima

4.1 Static application

4.1.1 The territory, the electricity demands and the electricity production

The methodology introduced in Chapter 2 has been applied to the neighbourhood of Nesima, in the city of Catania, with the main purpose of demonstrating how urban planners can implement the methodology and evaluate the results. The chosen neighbourhood has an extension of $0.67\ km^2$ and is represented in Fig.26.

Fig.26 Location of the selected urban area

This area has been selected because of its similarity to other neighbourhoods in Catania or in other cities. There are no particular features of this territory that make the results unique, therefore any other territory may account for similar outcomes.

The analysed urban area includes 343 buildings, the majority of them belonging to social houses built in early sixties. However, a large group of non-residential building is located north-east. The electricity demands and the potential electricity production of consumers are determined with the aim of a GIS database, representing the geographic and energy characteristics of the buildings occupied by the consumers and located within the urban area [1]. The data regard specific characteristics of buildings (geometry, architecture technology and climate) that derive from both survey s and documents and general information about the study area (land use and construction). In particular, for civil buildings, heterogeneous data provided by National Statistical Institute [2] and by Terna S.p.A. [3] are processed. For public buildings the SEAP of Catania [4] has been referred to, and for non-residential buildings average data developed by Confcommercio and ENEA have been employed [5]. In detail, the electricity demands D_i are calculated as the electricity consumed for a year on the basis of a medium value per inhabitants in relation to the residential area within a given census district, as in the Eq.(4.1)

$$D_i = \frac{E_{el} * ab}{Census_{district}} \tag{4.1}$$

The obtained medium value has been applied to all building within the given census district. The overall electricity demand consumption for Nesima is $80{,}079.44\ MWh/y$; Fig.27 shows the electricity map for the neighbourhood.

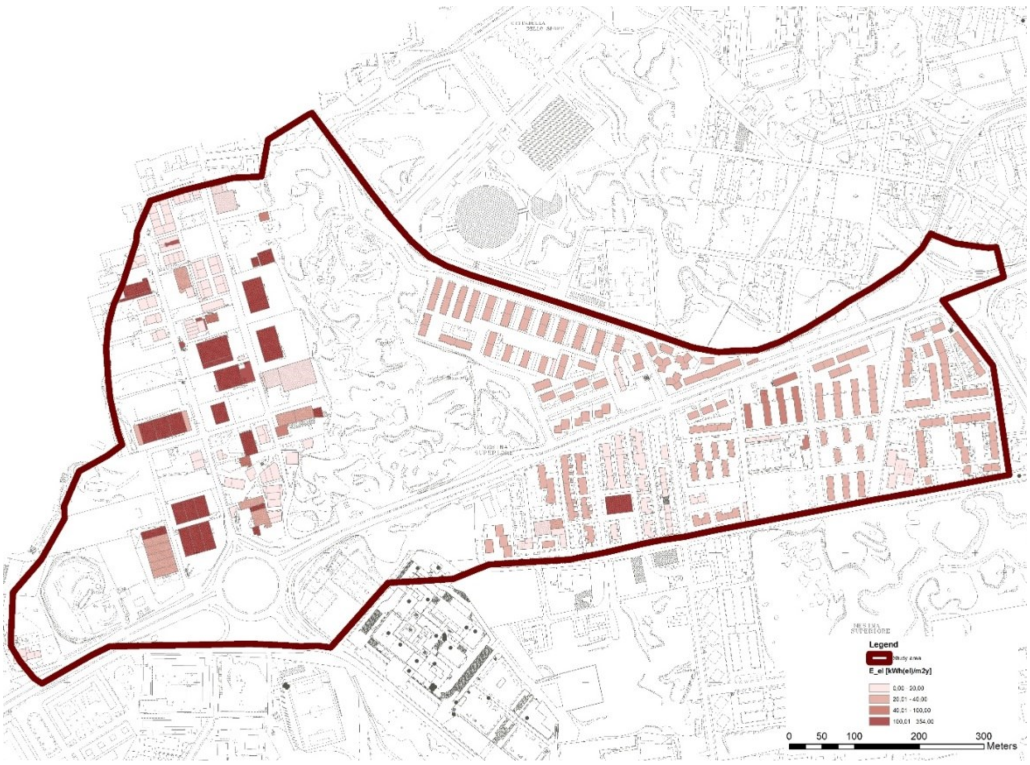


Fig.27 Map of the electricity consumption of buildings

The map increase the understanding of current electricity demand of the neighbourhood and is a key step for defining future urban measures that may improve the energy efficiency of the area. To this aim, buildings are identified as potential electricity producers by installing solar PV systems on the rooftops. Moreover, solar energy source is considered the renewable energy source with the least negative impacts on the environment [6, 7].

The electricity productions P_i due to the installed solar system has been determined referring to geometrical characteristics and constrains of the buildings. The southern orientation of roofs and the average value of production for Sicily is $1500\ kWh/y$ per $10\ m^2$ of surface for photovoltaic panels [8]. This study does not consider the typical seasonal and hourly fluctuations of the photovoltaic production. Actually, the aim of the application to this case study does not consist neither in the estimation of the photovoltaic potential of the edifices nor in the assessment of the convenience to install PV panels on edifices, issues for which detailed production data are necessary. In this study, rather, the goal is on applying the developed methodology for the design of the network of energy distribution that minimizes the supply from the central node; reasonably, aggregated yearly data fit for the purpose. With this assumption, the four potential electricity production scenarios chosen for the analysis of scenarios are reported in Table 6.

Table 6. Conditions for the development of scenarios of electricity production

	Characteristics of PV installation
C1	50% of rooftop area for a flat roof 25% of rooftop area for a span roof
C2	70% of rooftop area for a flat roof 25% of rooftop area for a span roof
C3	90% of rooftop area for a flat roof 25% of rooftop area for a span roof
C4	90% of rooftop area for a flat roof 30% of rooftop area for a span roof

The percentages of rooftop area used for the installation of the PV panels vary depending on the typology of the roofs, i.e. for flat or span roofs. All percentages of the scenarios have been selected by a mere convention. Into the details, the exploitation of flat roofs varies from a minimum percentage of 50%, i.e. the half of the area, to a maximum percentage of 90%. A portion of the rooftop area (approximatively the 10%) has been considered occupied by cables and used for the operations of mounting and maintenance. Instead, span roofs are exploited, in the first three scenarios, for the 25% of their total area (that is the area of the roof that has a Southern exposure), whilst in the fourth scenario the percentage is enlarged to the 30% by including a portion of the area of the roof with a Southern-East exposure. For the sake of argument, it has also been hypothesises that all buildings are equipped with PV panels, excluding any restrictions; such assumption is justified insofar as this case study points to illustrate the effectiveness of the proposed methodology and not to dimensioning PV systems on buildings. Indicatively, it is useful to point out to what extent the electricity production from PV systems covers the demand of the network, besides the information about the rooftop areas of buildings used for their installation. To the purpose, Table 7 provides a generally overview; the percentages, in this case, refer to the electricity demand of the whole network that may be covered by the totality of the PV systems installed on buildings.

Table 7. Total electricity production expressed as a percentage of the total electricity demand of the network

	Percentages of electricity production
C1	60% of the electricity demand
C2	70% of the electricity demand
C3	80% of the electricity demand
C4	90% of the electricity demand

Once the electricity demands and productions have been determined, the selected urban area has been modelled as an energy distribution network. Therefore, buildings are hereinafter defined as nodes and connections as links. Due to the installation of PV systems, it is assumed that nodes become able to exchange electricity through links. In particular, the exchanges may occur through the links that are established according to the spatial metric criterion and under the condition for which nodes have exceeding production to be distributed. The main objective of the methodology is to configure the optimal configuration of the network of the electricity exchanges that guarantee the minimization of the electricity output at the central node.

4.1.2 The distance of connection

As far as the establishment of the network links is concerned, the threshold distance *d* of connection is chosen within an interval of 25 m < *d* < 400 m, and varied at steps of 25 m for each scenario. As an example, the electricity network of neighbouring nodes for a threshold distance *d* of 25 m is reported in Fig.28. The illustrated electricity network shows all feasible links due to the chosen threshold distance *d* and preceding the optimization. In particular, neighbouring nodes are connected by red links, whilst green links represent the connection each node has with the central node, placed in the bottom left for convenience of representation.

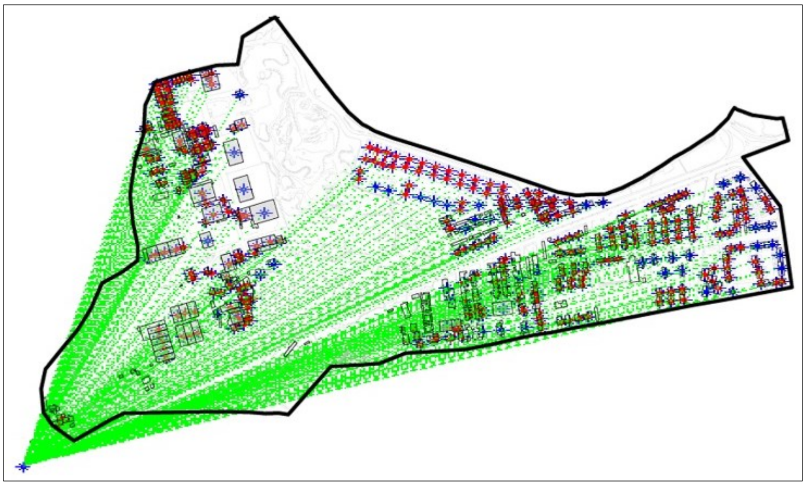
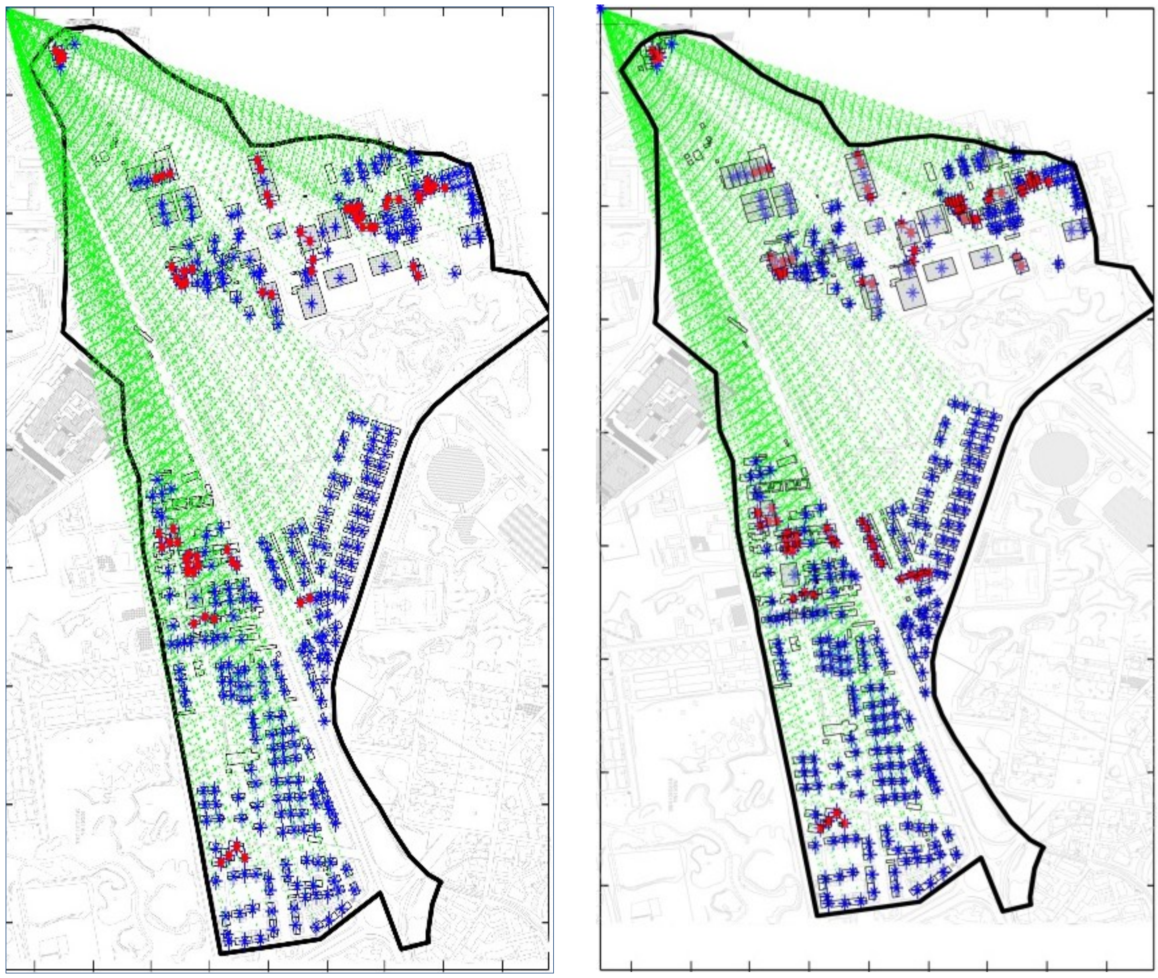


Fig.28 Initial electricity distribution network established when the threshold distance is set to 25 m

4.1.3 The optimization – results and discussion

The results of the optimization at the fixed threshold distance $d = 25\,m$ and for each scenario of Table 6 are shown in Fig.29. Compared to the initial network topology of Fig.28, it may be noticed that the majority of all feasible connections have been removed during the optimization. Actually, the remaining connections (at each scenario) are those that ensure the minimization of the electricity output of the central node.

(a) (b)



(c) (d)

Fig.29 (a) Optimized electricity network for 25 m for scenario C_1; (b) Optimized electricity network for 25 m for scenario C_2; (c) Optimized electricity network for 25 m for scenario C_3; (d) Optimized electricity network for 25 m for scenario C_4

The rate of effectively exploited links in the optimized electricity networks is evaluated by calculating the values of the network index I_L. The results for each scenario of electricity production by varying the threshold distance d are reported in Fig.30.

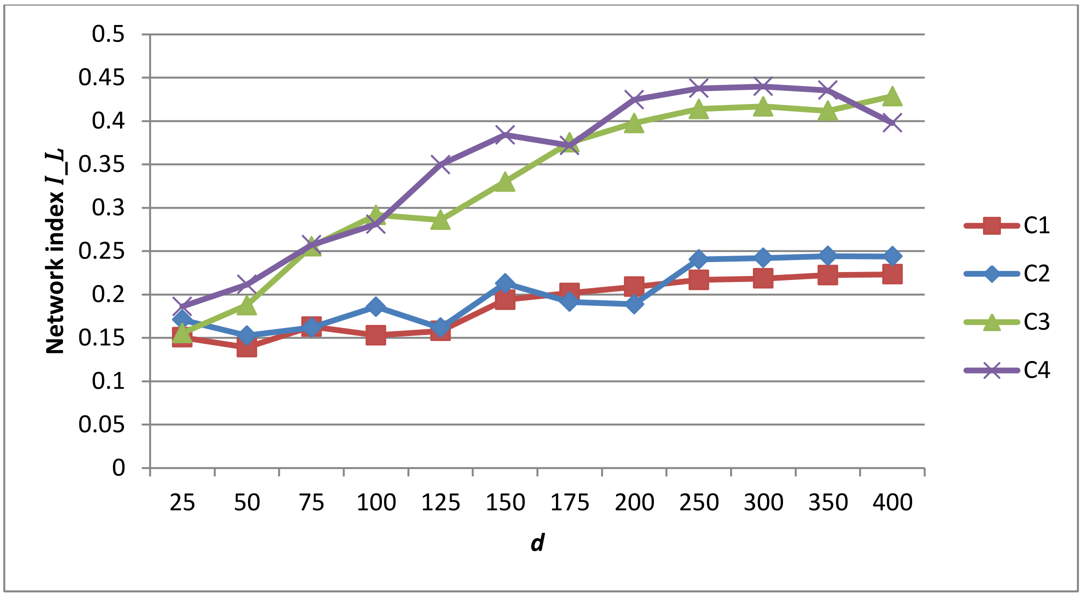


Fig.30 Network index I_L at different threshold distances *d* for the four scenarios

The curves of the network index I_L in Fig.30 lead to two important observations on the utilization of the links of the electricity network; the former concerns the electricity production and the latter the threshold distance d.

The impact of the electricity production in the configuration of the optimized electricity network is expressed by varying the scenarios of Table 6. The graph shows that the network index I_L increases with increasing values of the electricity production. In particular, a small increment is recorded for the scenarios C_1 and C_2, whereas the higher increment is mainly noted when dealing with the electricity production percentages of scenario C_3 and C_4. This condition is due to the particular geometry of the area, since, at fixed threshold distances d, the major diffusion of PV systems means a major number of buildings involved in the production and, therefore, in the potential exchange.

In addition, some observations are made on the influence of the threshold distance d on the design of the electricity network. At lower threshold distances d, the rate of exploited links for the exchange is almost the same for the four scenarios. At high threshold distances d, instead, the number of connections increases, due to the chance of nodes to reach a major number of neighbours. Moreover, Fig.30 indicates a threshold value of the threshold distance d beyond which the network index is almost constant. In particular, over 200 meters there are no significant improvements in the number of link activated. This information about the exploitation of the links of the electricity network related to the threshold distance d is useful to support the design process of the network. Actually, the insertion of electricity production systems on territory needs to be regulated mainly on the threshold distance d.

Results of the optimization also reveal that almost the 40% of all feasible established connections due to the neighbourhood criterion are effectively used for the electricity exchange. As a consequence, with this evidence unnecessary investments may be avoided, such as those for unexploited connections.

As a further point in question, it is useful to compare the results of Fig.30 with the effective reduction of the electricity supplied from the central node at each scenario. The outcomes are reported in Fig.31.

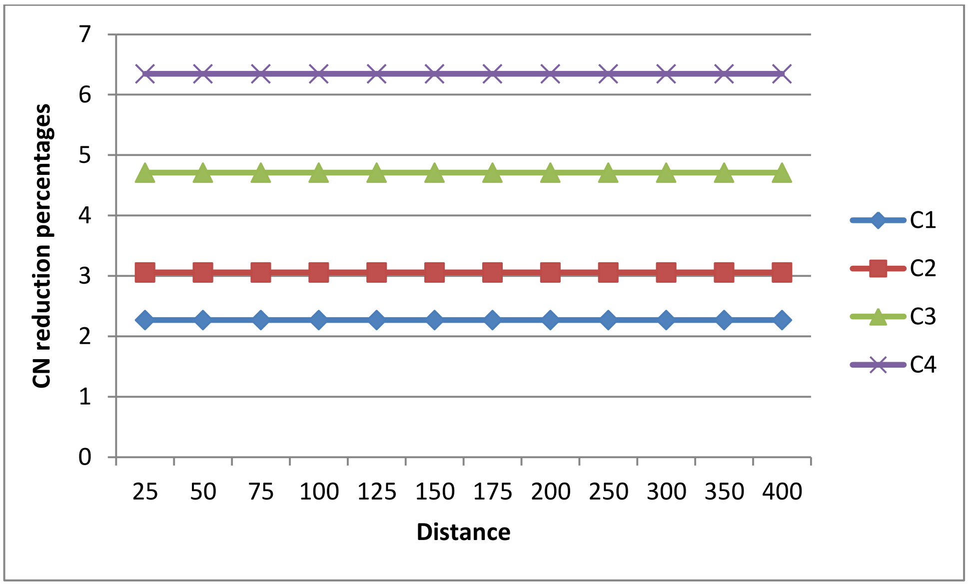


Fig.31 Percentages of electricity supplied from the central node for each scenario

The electricity supplied from the central node has a constant trend in each scenario, i.e. when the electricity production percentage is fixed. In other words, varying the permitted distances of the exchange does not yield a further diminishment of the production from the central node. However, as may be reasonably deducted, increasing the percentages of electricity production on territory (that is on changing the scenarios) produces a major reduction of the central supply, since a larger amount of production is ready to be distributed.

Therefore, the impact of PV systems on the urban area influences the design of the links of the electricity distribution network and reduces the electricity supply from the central node. Particularly, the distance d of connection plays a significant role when dealing with the activation of the links of the network, whilst it does not affect the central production. This is due to the fact that, at varying the permitted distance of exchange, the links of the network rearrange in a different way in order to minimize the supply from the central node. However, the rearrangement does not affect the amount of electricity exchanged but, rather, the way in which it is distributed.

4.1.4 The assessment of hubs

Besides the analysis of the exploitation of the links by means of the network index, the assessment of nodes with hub behaviour is carried out. A node with hub behaviour is substantially a node that exhibits a considerable number of links in comparison with the other nodes of the network. Therefore, the study highlights only the nodes that clearly behave as hubs and neglects nodes that, whilst owning a significant number of links for the exchange, they may not be compared to the links possessed by the hub (or hubs). To discuss the results, four maps are reported. In particular, as in the case of the network index, the hub performance is studied in relation to the impact of both the electricity production and the threshold distance d.

Fig.32 and Fig.33 show the maps of the analysed urban areas for the electricity production scenarios C_1 and C_4 at the fixed threshold distance $d = 25\ m$. As can be seen from the comparison, by varying the electricity production, the node that behaves as hub maintains this property regardless of the percentage of electricity production. In particular, the hub has 9 active links when scenario C_1 is considered, and 8 links when dealing with scenario C_4.

Secondly, the threshold distance $d = 250\ m$ is considered. Fig.34 and Fig.35 illustrate maps highlighting the positions of the hubs in scenarios C_1 and C_4, as well as the colour coded degree taking into account how many links are activated for each node. As also observed for Fig.32 and Fig.33, by varying the electricity production the node with hub performances does not differ. The hub activates 121 links for scenario C_1 and 97 links for scenario C_4. Moreover, it can be observed that the number of hubs for scenario C_4, shown in Fig. 35, increases if compared to Fig.34. This is due to the fact that higher percentages of electricity production coupled with higher threshold distances d of connections, allow the nodes to activate a major number of links.

Therefore, the occurrence of nodes with hub behaviour is higher than in the other cases.

Therefore, the tendency of nodes to perform as hub depends on the threshold distance d rather than the electricity production, confirming the significance of the parameter of threshold distance d. The analysis of the hub performances of nodes is significant within the planning process, since it contributes to increase the awareness on the role of the parameter of threshold distance d. In particular, when developing integrated energy-spatial measures, the design of the network of energy exchanges may be focused on the threshold distance d of connection among buildings and on those buildings for which the installation of renewable energy systems represents a convenient solution.

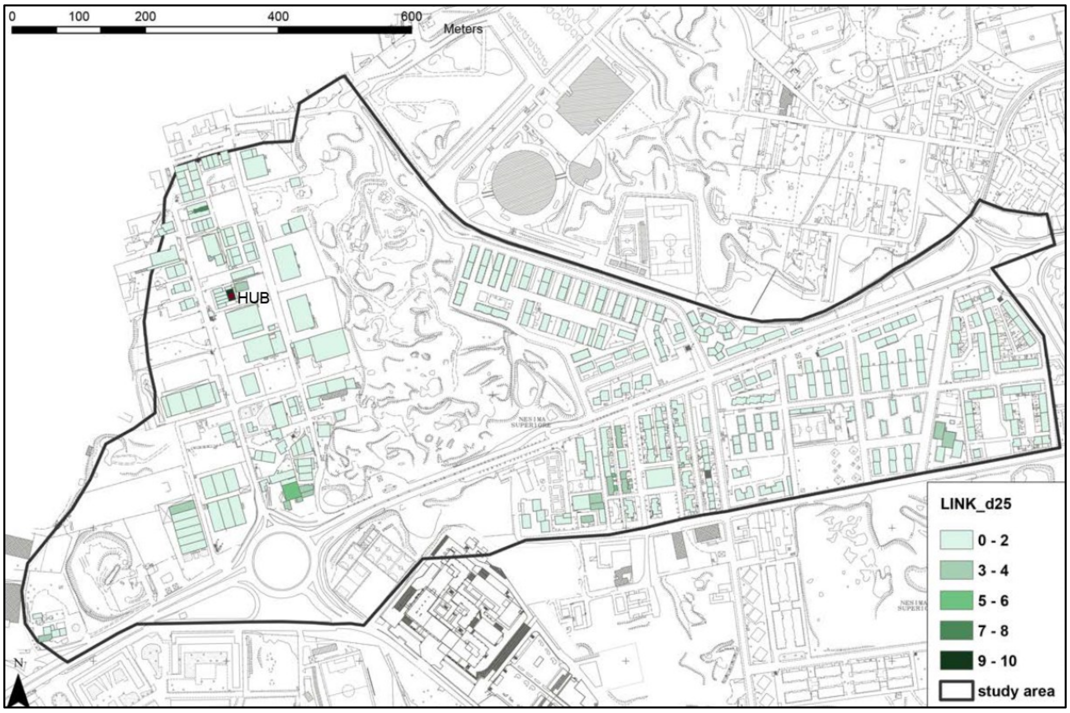


Fig.32 Map representing the node activated degree of nodes and the hubs for the configuration of scenario C_1 and at 25 m as maximum threshold distance d of connection

Fig.33 Map representing the node activated degree of nodes and the hubs for the configuration of scenario C_4 and at 25 m as maximum threshold distance d of connection

Fig.34 Map representing the node activated degree of nodes and the hubs for the configuration of scenario C_1 and at 250 m as maximum threshold distance d of connection

Fig.35 Map representing the number of activated links and the hubs for the configuration of scenario C_4 and at 250 m as maximum threshold distance d of connection

4.1.5 Summary of results

Through the optimization, the configuration of links that minimizes the energy output at the central node is identified. In particular, the design of the network of energy exchanges may be included in the decision making process, since it increases the awareness on the significance of the parameter of threshold distance *d* of connection among buildings. In addition, this study allows identifying the hubs, i.e. those buildings that are able to activate the major number of connections. Hubs may play a key role in the design of energy networks at local level, which has to be integrated in spatial planning processes.

4.2 Dynamic simulation

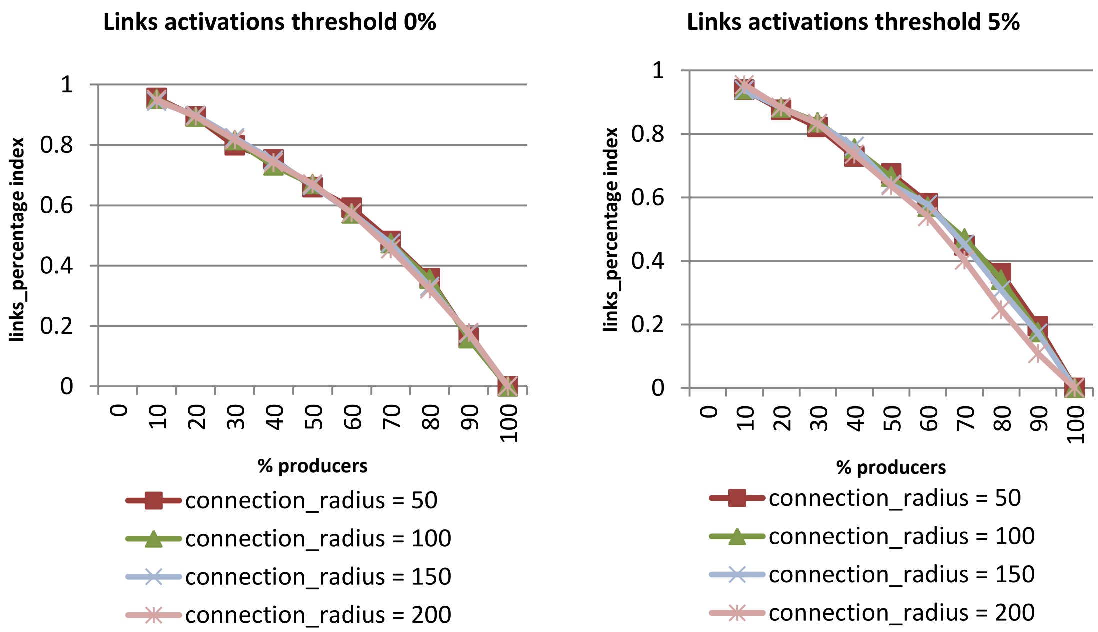
The methodology described in Chapter 2 is applied to a real urban territory. The characteristics of the area, as well as the electricity demand and production potentials, have been already introduced in the previous paragraph.

In accordance with the hypothetical case study, simulations run by varying the percentages of producer agents on the territory and the distance between each agent pair. The electricity demands and productions are varied according to constant and variable electricity profiles of agents. In addition, each scenario is analysed for the three different links activation thresholds defined in the hypothetical case. Finally, all conditions assumed for the fictitious area hold also in this real application.

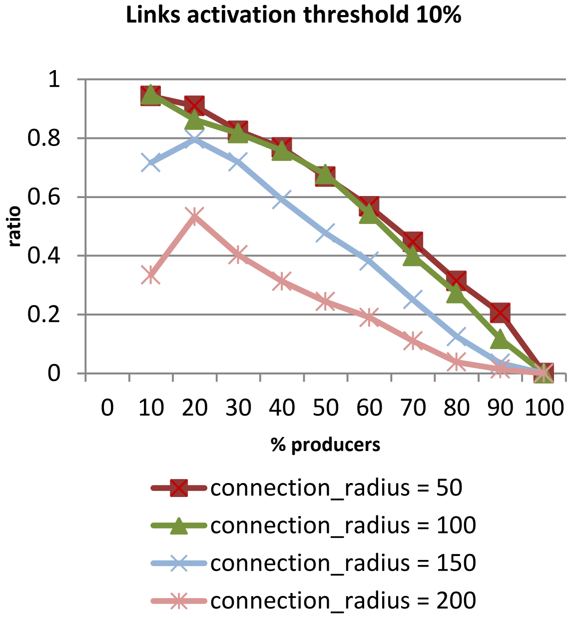
4.2.1 Scenario 1: constant profiles of electricity consumption and production

The urban energy distribution network of the urban area is firstly studied by assuming constant electricity profiles both for the consumption and production of agents.

The electricity distribution within the area is simulated by varying the percentage of electricity producers at different distance of connection among agents. The first index to be discussed is the $links\_percentage$ index reported in Fig.36.



(a) (b)



(c)

Fig.36 Trends of the $links\_percentage$ index in correspondence to: (a) links activation threshold 0%; (b) links activation threshold 5%; (c) links activation threshold 10%

As a reminder, the $links\_percentage$ index evaluates the number of activated links, i.e. the links effectively used for the exchange of electricity among the agents, in relation to the totality of the links established according to the neighbourhood criterion in the initial stage of the design of the distribution network. Fig.36(a) plots the trends of the $links\_percentage$ index when the links activation threshold is set to 0%, i.e. when each link is counted as active if it has been responsible for at least one exchange during the total time period. In this case (and similarly to the hypothetical area), the $links\_percentage$ index decreases as a function of the percentage of producers until the nil value for the 100% of producers. This means that at increasing the percentage of agents with production capabilities, the links of the distribution network are less used, due to the fact that agents become able to autonomously satisfy their electricity needs without having to receive it from neighbours. Accordingly, major exploitations are achieved for low percentages of producers. These considerations hold independently of the values of the $connection\_radius$. Similar trends are recorded in Fig.36(b), where the links activation threshold has been enlarged to 5%. This result differs from the fictitious case, where a significant decrease of the $links\_percentage$ index has been recorded for threshold equal to 5%. Nevertheless, the introduction of a stricter threshold, such as the 10%, gives rise to a change in the trends of the $links\_percentage$ index, as displayed in Fig.36(c). In this case, the majority of the links are used at low percentages of producers at fixed distance of connection among the agents. In addition, when compared to the trends of the hypothetical territory in Fig.15(c), the slopes of the curves of the $links\_percentage$ index are less severe. Actually, the number of links used for the exchange is significant, especially for low percentage of producers. Properly, as regard to the producers, the percentage that guarantees the maximum exploitation of the links is the 10% for distances below 100 m and 20% for distances between 100 m and 200 m.

The following graphs of Fig.37 and Fig.38 plot the $energy\_loss\_percentage$ index and the $supply\_percentage$ index at different values of the $connection\_radius$, respectively. There are no differences among the three thresholds; therefore only one graph for each index is reported.

The $energy\_loss\_percentage$ index of Fig.37 increases at increasing the percentage of producers, regardless of the distance of connection among the agents (except for the $connection\_radius$ equal to 50 m, somewhat higher in comparison with the other distances). Effectively, a major percentages of producers yield major amount of produced electricity; however, after the satisfaction of the own electricity needs and after the eventual satisfaction of the demands of requiring neighbours, the electricity that is not further distributed is considered as lost.

The $supply\_percentage$ index in Fig.38 has a decreasing trend at increasing the percentage of producers. Indeed, the electricity required to the traditional power plant diminishes due to the fact that agents autonomously provide to satisfy their electricity demand. This is true for all examined distances among the agents, being slightly higher for $connection\_radius$ equal to 50 m. As a final consideration, the trends of the $energy\_loss\_percentage$ index and the $supply\_percentage$ index for $connection\_radius$ equal to 50 m are further discussed. Indeed, their trends are due to the fact that at lower distances of connections (as 50 m) the producer agents satisfy their demands (totally or partially), but as regard to the distribution, they are able to reach a limited neighbourhood of agents; in this sense, some electricity maybe “lost”.

Conversely, these requiring agents receive electricity from the central agent (thus increasing the value of the index). However, high percentages of producers annul the differences among the distances of connection.

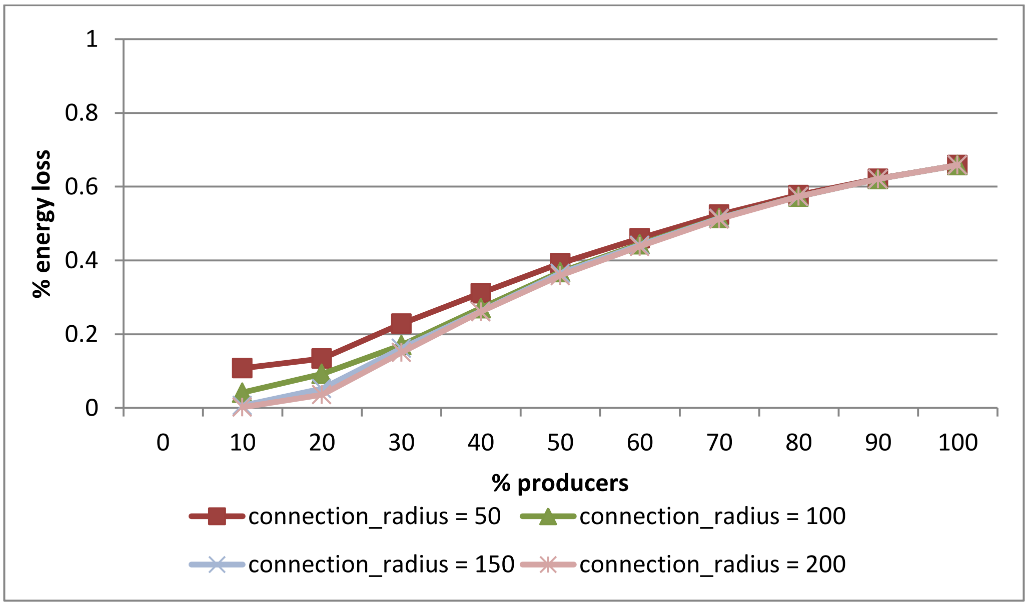


Fig.37 The $energy\_loss\_percentage$ index at the different $connection\_radius$ values

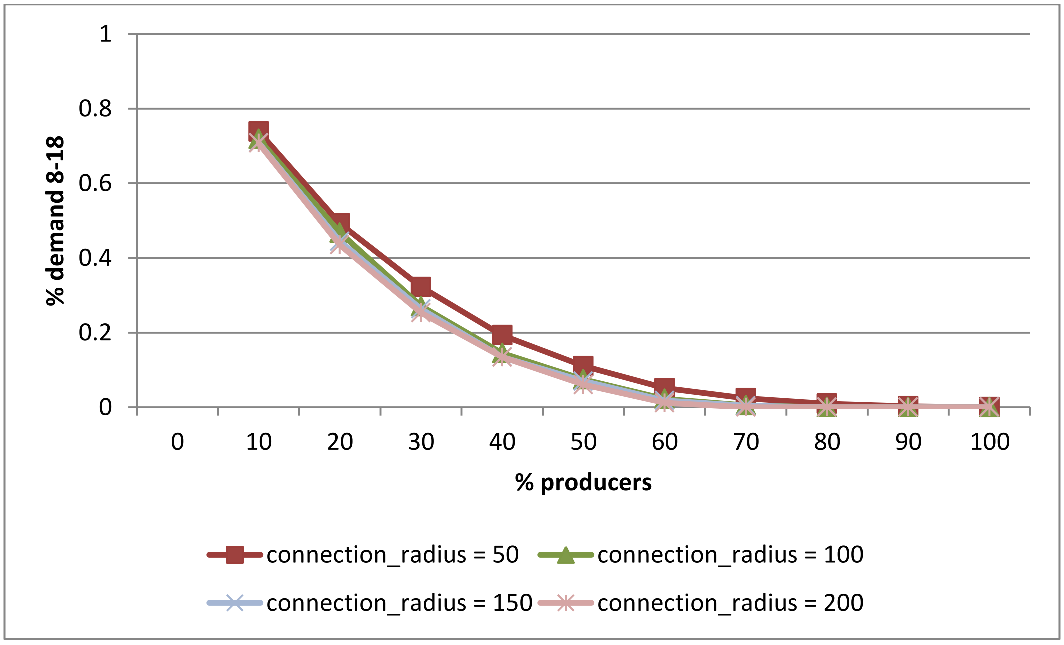
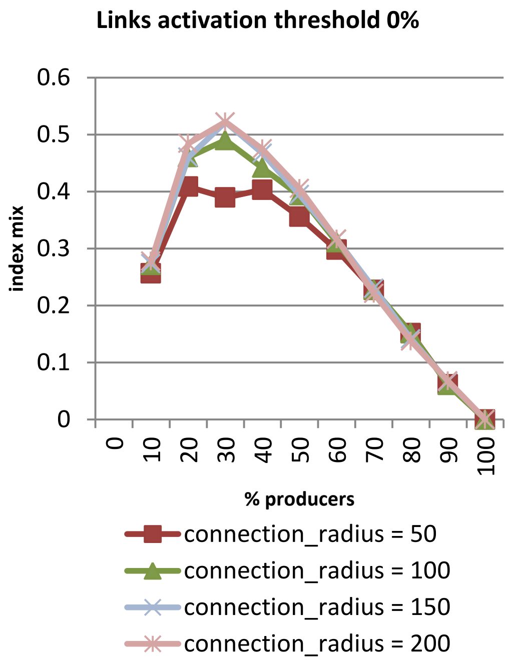
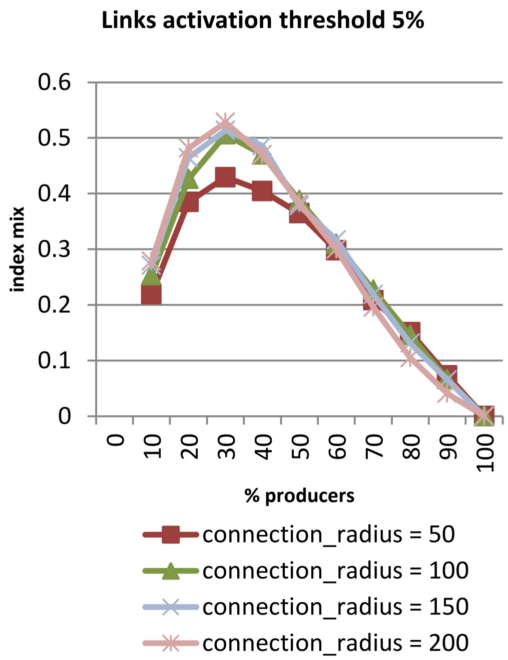


Fig.38 The $supply\_percentage$ index at the different $connection\_radius$ values

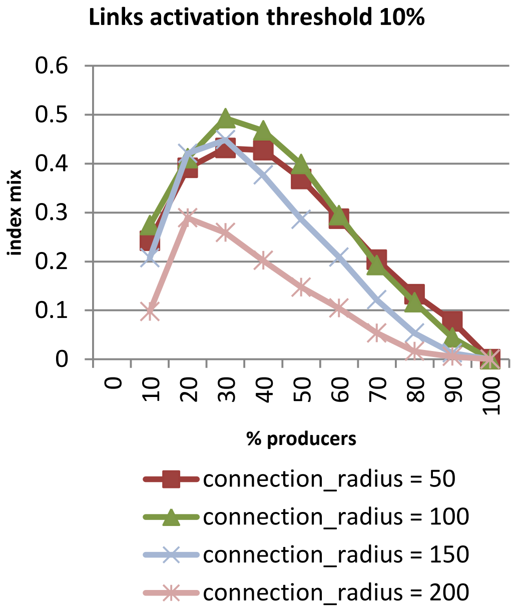
The trends of the $index_{mix}$, in correspondence to the different links activation thresholds, are illustrated in Fig.39. The graphs permit to assess the relationship between the thresholds and both the percentage of producers and the distance of connection. Since the $index_{mix}$ evaluates the best trade-off among the previous analysed indexes, it may be observed that the small distances of connection generally yield lower values of the $index_{mix}$, especially for thresholds equal to 0% and 5%. As regards to the threshold of 10%, instead, the distance of 200 m produces worse results. On the side of the percentage of producers, the trends allow concluding that having a percentage of 30% of producers within the territory ensures the best performance of the network in terms of distribution, electricity loss and supply from the central agent.



(a)



(b)



(c)

Fig.39 Trends of the $index_{mix}$ in correspondence to: (a) links activation threshold 0%; (b) links activation threshold 5%; (c) links activation threshold 10%

Finally, the values of the $index_{mix}$ are compared at each value of the $connection\_radius$ for the different thresholds; results are reported in Fig.40. The trends of the $index_{mix}$ for distances 50 m in Fig.40(a) and 100 m in Fig.40(b) do not show differences neither for the different thresholds, nor for the percentages of producers. In both cases, the best performance of the network is obtained in correspondence with the 30% of the producers. However, the $index_{mix}$ has different values in the two cases; in this sense, the distance equal to 100 m ensures higher values. This result differs from the one obtained for the fictitious case study, in which the thresholds had a significant impact on the $index_{mix}$ even at low values of the $connection\_radius$. A differentiation among the thresholds becomes more evident when the distance of connection increases, as in the Fig.40(c) and in Fig.40(d), where respectively the distances of 150 m and 200 m are taken into consideration. Actually, in these cases, introducing a link activation threshold equal to 10% affects the performance of the network, whilst the thresholds of 0% and 5% do not show variations as respect to the previous considered distances. In addition, the decrease of the values of the $index_{mix}$ is more significant for 200 m.

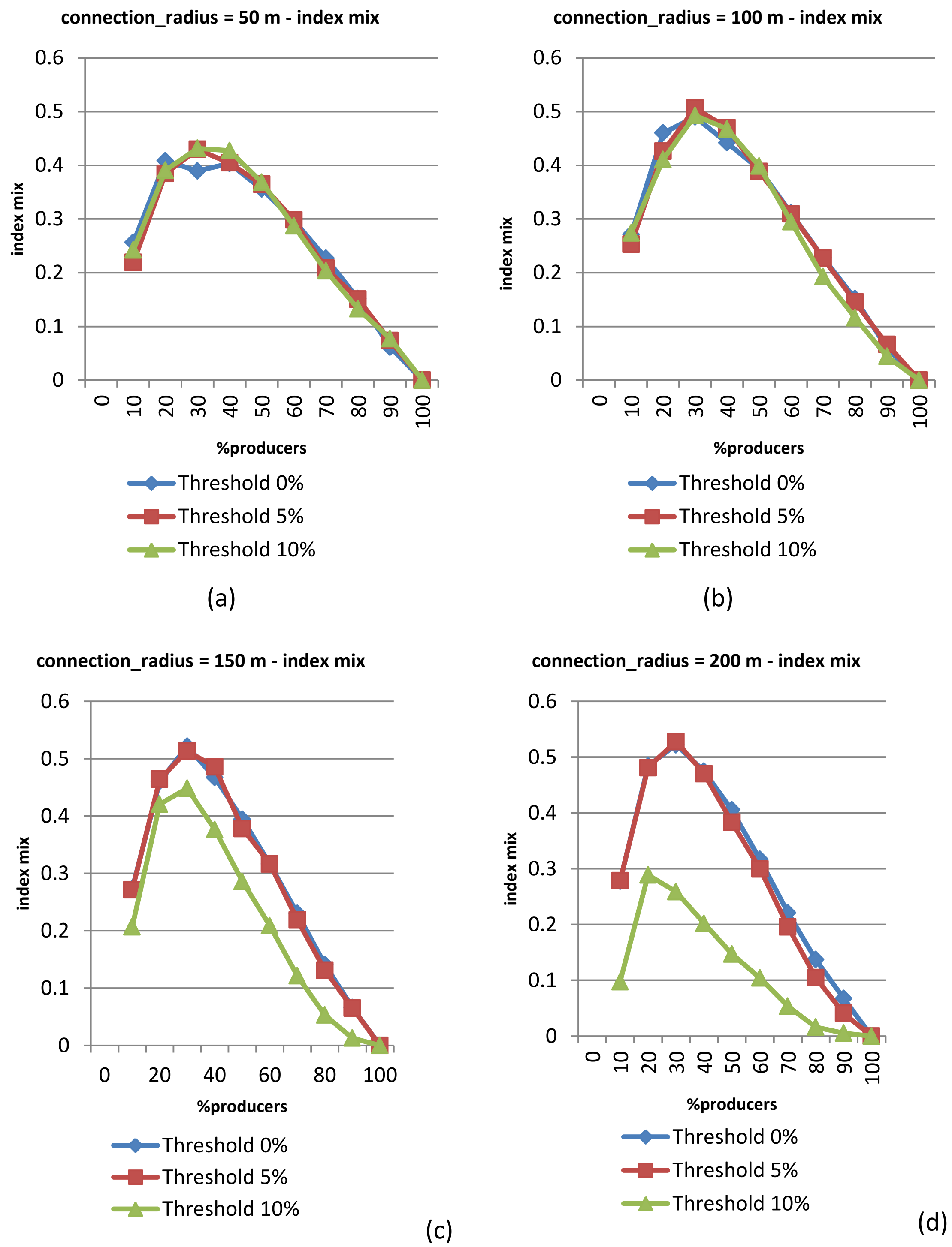


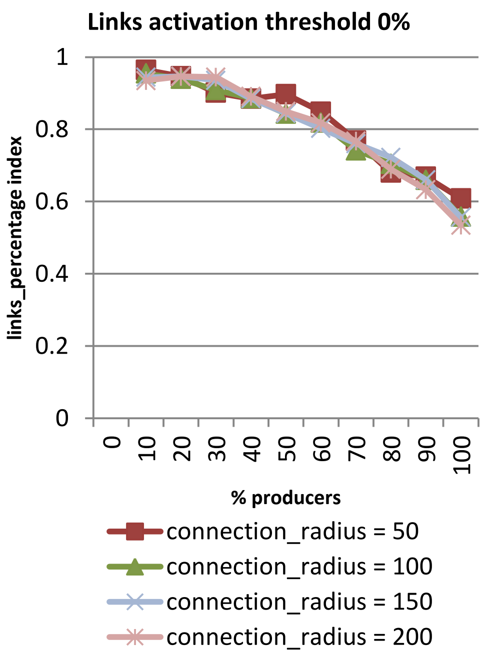
Fig.40 Threshold comparison for the $index_{mix}$ at: (a) $connection\_radius = 50\ m$; (b) $connection\_radius = 100\ m$; (c) $connection\_radius = 150\ m$; (d) $connection\_radius = 200\ m$

4.2.2 Scenario 2: variable profiles of both electricity consumption and production

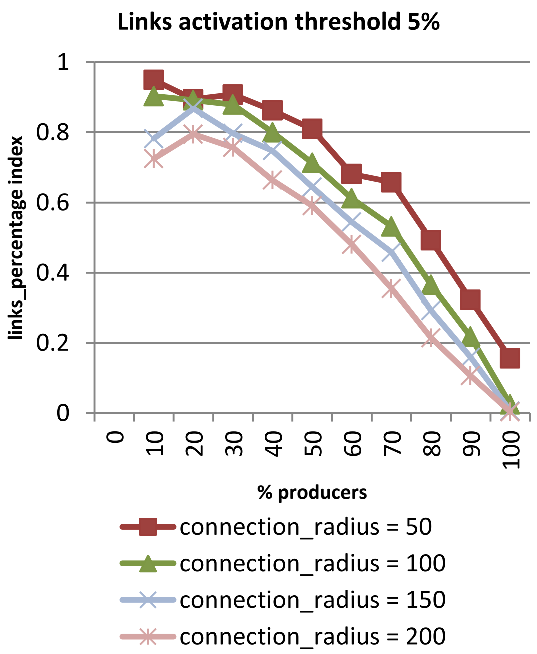
Variable profiles of both electricity consumption and production are considered in the second scenario and the results of the simulations are reported in the following graphs and discussed henceforward.

The first index to be analyzed is the $links\_percentage$ index in correspondence to the different links activation thresholds. Fig.41(a) displays the trends of the $links\_percentage$ index when the threshold is set to 0%. The results indicate that the number of links used for the exchange of electricity is higher when low percentages of producers (typically around 10% - 30%) are considered, regardless of the values of the $connection\_radius$. This result is similar to the hypothetical case study.

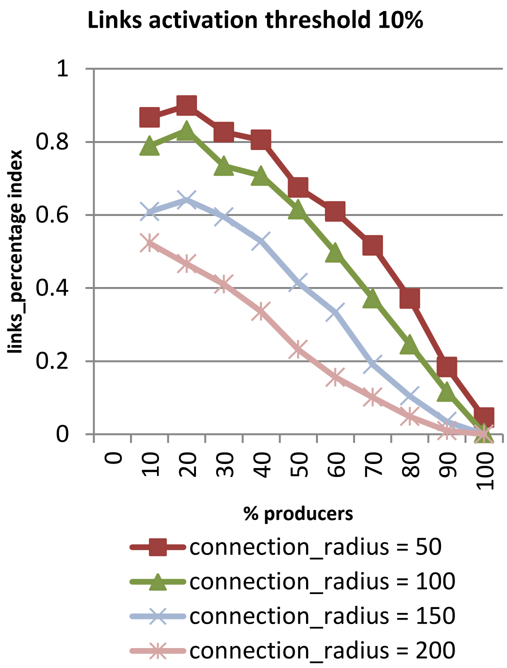
Fig.41(b) and Fig.41(c) plots the trends of the index for the thresholds of 5% and 10% respectively. In this case, as in the fictitious case study, the insertion of a links activation threshold produces a change in the values of the index. Precisely, the more high is the threshold, the less links are used for the exchange, especially for higher distances of connections. However, the trend of the $links\_percentage$ index decreases smoothly than the fictitious case study (for both thresholds).



(a)



(b)



(c)

Fig.41 Trends of the $links\_percentage$ index in correspondence to: (a) links activation threshold 0%; (b) links activation threshold 5%; (c) links activation threshold 10%

The $energy\_loss\_percentage$ index and the $supply\_percentage$ index at the different $connection\_radius$ values are reported in Fig.42 and Fig.43, respectively. Both indexes show a similar trend to the correspondent index of the fictitious case study; the trend of the $energy\_loss\_percentage$ index increasing and the trend of the $supply\_percentage$ index decreasing at increasing the percentage of producers. Small variations are to be observed for the distance of 50 m due to the limited neighbourhood to which distribute the electricity.

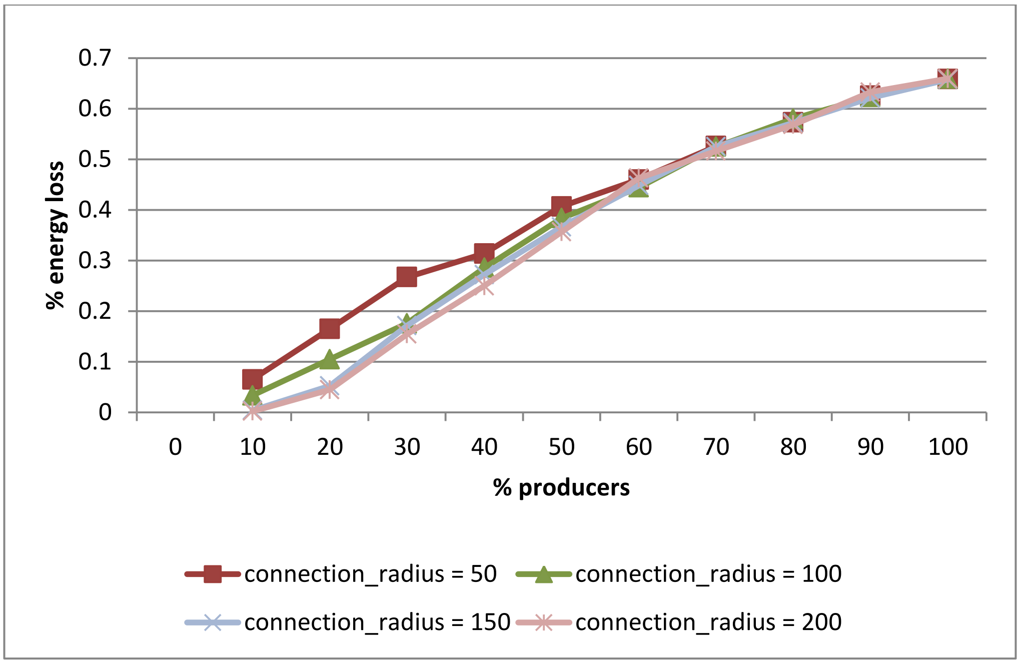


Fig.42 The $energy\_loss\_percentage$ index at the different $connection\_radius$ values

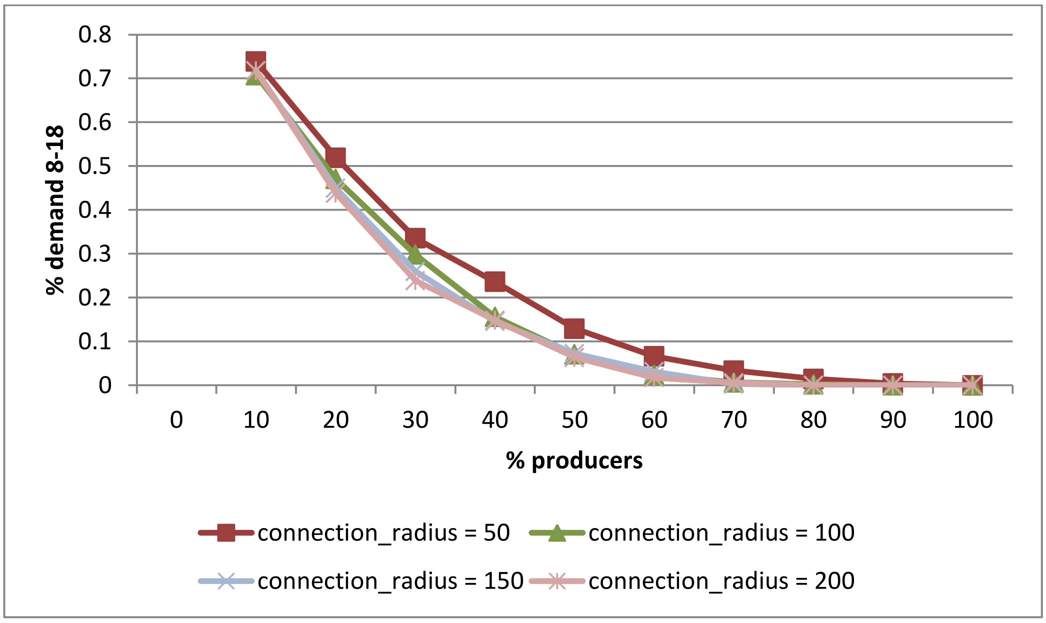
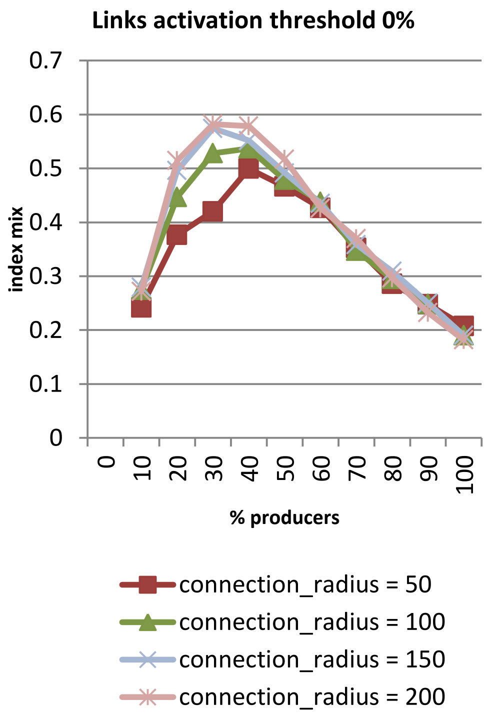
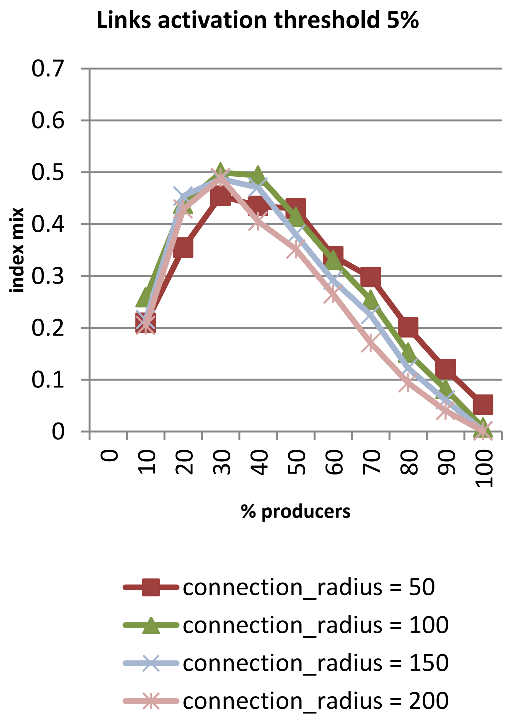


Fig.43 The $supply\_percentage$ index at the different $connection\_radius$ values

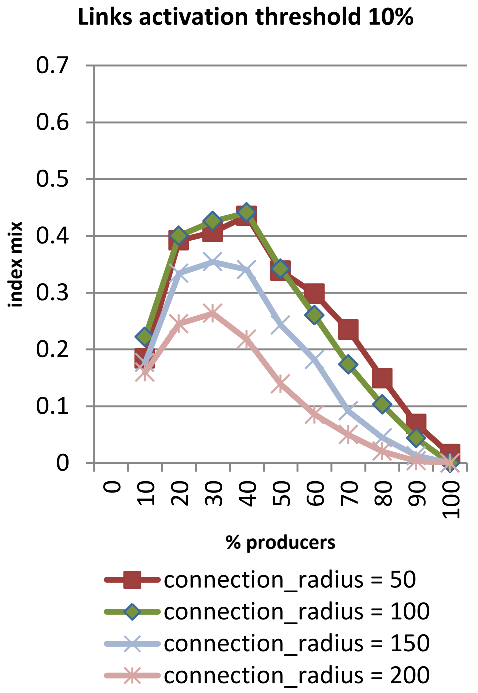
The trends of the $index_{mix}$ are compared in Fig.44 for the different values of the links activation thresholds. Fig.44(a) shows the trends of the $index_{mix}$ when threshold is 0%, i.e. when no restrictions about the frequency of the links used for the distribution are posed. In this case, and similar to the fictitious case study, no significant differences are observed in the trends of index at varying the percentage of producers for the diverse values of the distance of connection, excepting for the distance equal to 50 m, for which a small variation is recorded. Generally, the best results are achieved in correspondence with the 30% - 40% of producers. Analogous considerations apply when the threshold of 5% is introduced in the simulations, as reported in Fig.44(b). In this case, the difference is mainly due to the values of the $index_{mix}$ that are lower than the previous case. Finally, Fig.44(c) plots the values of the $index_{mix}$ when threshold 10% is concerned. Here, the $index_{mix}$ decreases when higher $connection\_radius$ are considered, that is the distribution network performs worse than the previous cases. However, in comparison to the fictitious case, the decrease is for any $connection\_radius$ less severe.



(a)



(b)



(c)

Fig.44 Trends of the $index_{mix}$ in correspondence to: (a) links activation threshold 0%; (b) links activation threshold 5%; (c) links activation threshold 10%

Finally, Fig.45 reports the $index_{mix}$ for the different thresholds at fixed values of the $connection\_radius$. As observed, the $index_{mix}$ decreases when enlarging the links activation threshold. In particular, the decrease is more evident if high values of the $connection\_radius$ are considered for the exchange.

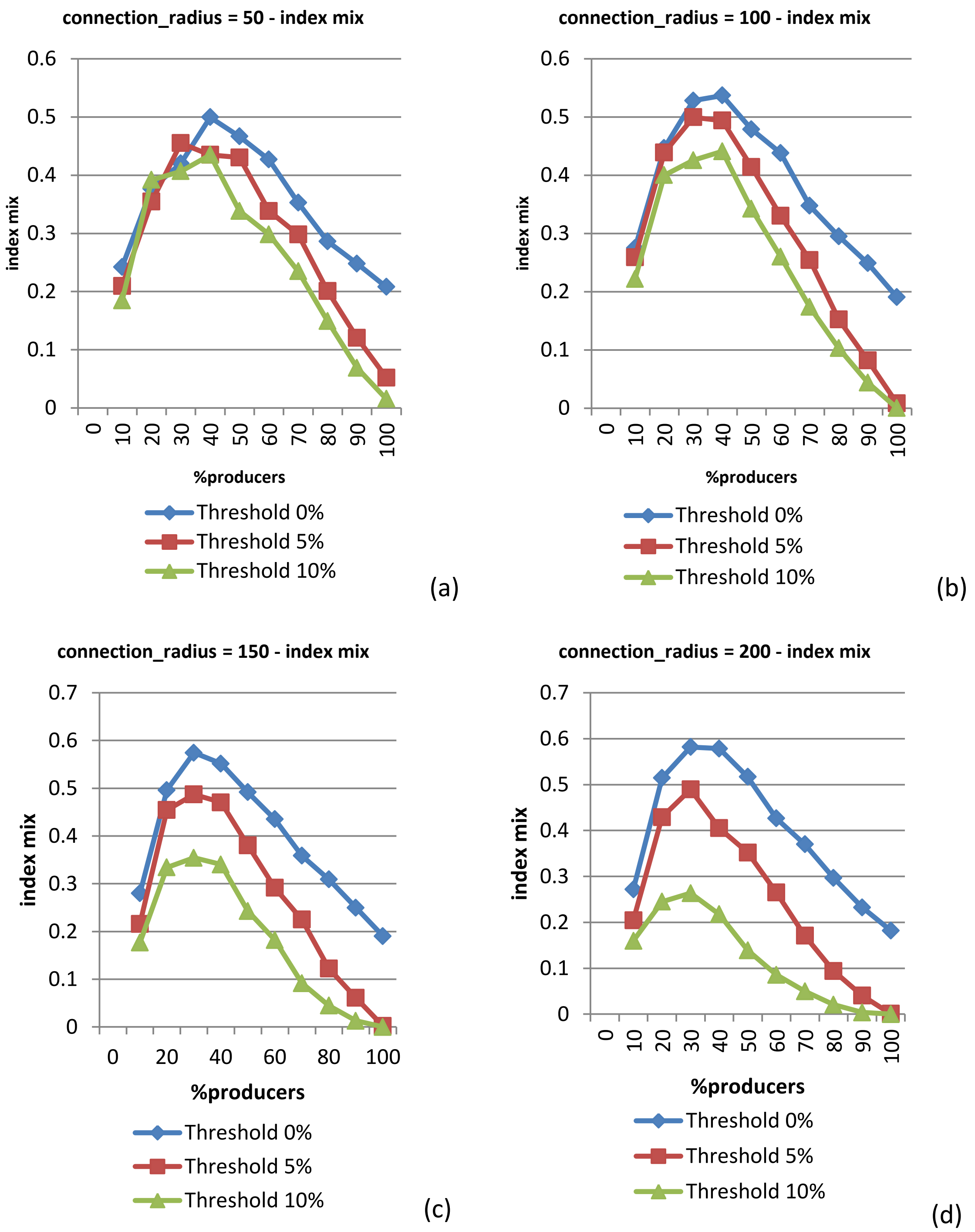


Fig.45 Threshold comparison for the $index_{mix}$ at: (a) $connection\_radius = 50\ m$; (b) $connection\_radius = 100\ m$; (c) $connection\_radius = 150\ m$; (d) $connection\_radius = 200\ m$

4.2.3 Comparison between scenario 1 and scenario 2

The graphs of Fig.46 permit to compare the results of the simulations for the operating scenarios 1 and 2 (i.e. for constant or variable profiles of electricity consumption and production, respectively) by highlighting the differences between the two links activation thresholds 0% and 10%.

Generally, the trends of the $index_{mix}$ in scenario 1 at varying the percentages of producers are similar for each links activation threshold and independently of the $connection\_radius$. This consideration, however, does not apply to the values assumed by the $index_{mix}$. In this condition, indeed, the performance of the electricity distribution network depends also on the $connection\_radius$ besides the percentage of producers. In this direction, the major performance of the network (expressed in terms of exploited links and of both minor electricity loss and minor electricity demand of the central agent) is achieved by the 30% - 40% of producers at a distance among agents usually around 150 m – 200 m.

Different is the case of scenario 2. In this case, the insertion of the links activation threshold produces a considerable change in the performance of the network. Despite the fact that the percentage of producers that permits to achieve the best performance of the network remains equal to the 30% - 40%, the insertion of the threshold significantly influences the network. Actually, a threshold equal to the 10% (i.e. the condition for which a link is counted as active if it used at least the 10% of the total time) diminishes the values of the $index_{mix}$ and this decrease is more prominent the more the $connection\_radius$ increases.

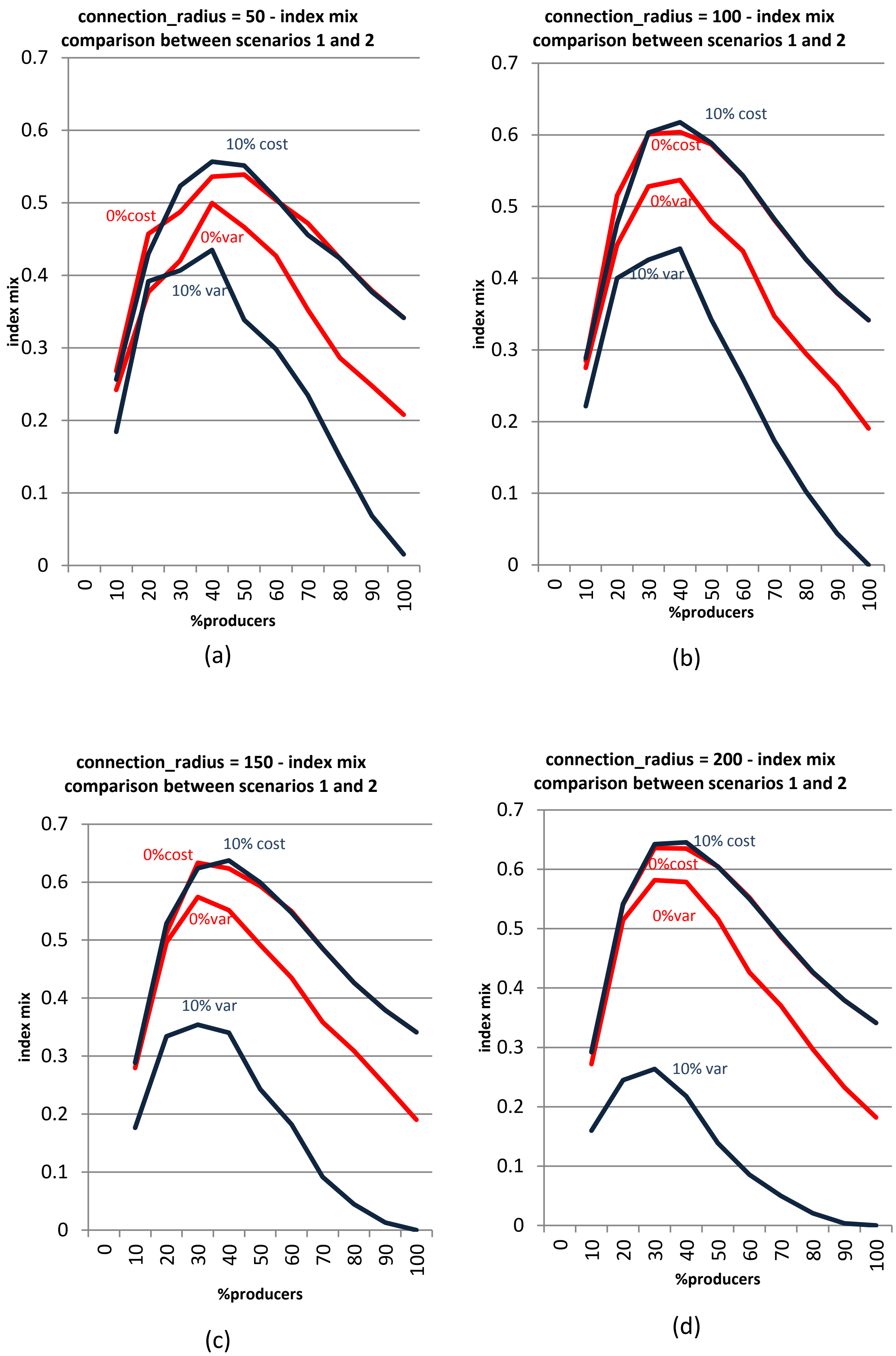


Fig.46 Constant and variable threshold comparison for the $index_{mix}$ at: (a) $connection\_radius = 50\ m$; (b) $connection\_radius = 100\ m$; (c) $connection\_radius = 150\ m$; (d) $connection\_radius = 200\ m$

4.2.4 Summary of results

The results obtained for the simulation of the real territory permit to infer some important conclusions.

When constant profiles of electricity consumption and production are hypothesized (scenario 1), short distances ensure higher exploitation of the electricity network, whilst the percentage of producers is around the 30% - 40%. Similarly, for scenario 2 (variable profiles of electricity consumption and production) short distances are preferable to obtain the maximum exploitation of the electricity distribution network , remaining unchanged the best percentages of producers (30% - 40%).

A further peculiarity regards the performance of the electricity distribution network for the different threshold progressively inserted in the study. Differently from the fictitious case study, in this application the insertion of the threshold does not bring any substantial worsening of the performance of the network when constant profiles of electricity consumption or production are considered. On the opposite, variable profiles yield distinct trends of the $index_{mix}$ when thresholds are introduced within the simulation and especially at increasing the values of the $connection\_radius$.

Therefore, to achieve the maximum exploitation of the electricity distribution network, short distances coupled with 30% or 40% of producers are to be preferred. This holds on for each threshold, being the 10% the percentage mostly affecting the performance of the network.

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5. Application: a cost analysis of the urban energy distribution network

5.1 The scientific background

The issue of the energy distribution in cities needs to be tackled from the economic point of view. To the purpose, an application including a cost analysis of the urban energy distribution network is considered in this Chapter.

As regards to the scientific contributions in this topic, many authors cope with the cost analysis of the energy distribution by focusing on the design of DESs.

Along this issue, Yang et al. [1] present a mixed integer linear programming (MILP) model for the optimal design of distributed energy systems for the minimization of the annual cost for investing, maintaining and operating the system. The model is tested for a network of four buildings that may interact in order to exchange the own produced energy. Ren et al. [2] handle the same issue and combine the minimization of the energy costs with the minimization of the emissions. However, they do not consider the possible energy interactions among consumers, but rather they merely plan to sell the produced energy directly to the public utility grid.

Other authors consider in their works the analysis of energy cost deriving from the supply mix of renewable and non-renewable energy. In this direction, the paper of Stich et al. [3] provides a power supply optimization model for the cost-effective integration of renewable-based energy systems. Bandyopadhyay et al. [4] introduces a Pinch Analysis based method to find the optimum mix between the renewable and non-renewable energy based systems. Both contributions [3, 4] consider a potential grid extension, but not involving consumers in the distribution. Moreover, they do not insert sale scenarios in the cost analysis and mainly focus on the cost saving of the energy supply.

A more enlarged vision is proposed in the work of Rasid et al. [5]. The authors analyse the cost reduction that is achieved by replacing the power from fossil fuel-consuming grid generators with renewable-energy distributed generators. The fossil fuel cost saving is evaluated as the expected value due to the renewable output uncertainty.

The cited works mainly deal with either the cost analysis of DESs or the cost analysis of renewable and non-renewable energy mix. They do not evaluate the network of energy distribution that derives from the installation of DESs and, therefore, from the chance of consumers to sell the own produced energy. Nevertheless, among the proposed literature, the paper of Yang et al. [1] considers the sale among consumers. Anyway the study is conducted for a small network that may be not compared to an urban neighbourhood.

In addition to these considerations, the impact of those energy interactions on the minimization of the energy supply deriving from the centralized power plants is not considered.

Therefore, while recognizing significant contribution of the previous works in the field of the energy distribution, the insertion of DESs requires a comprehensive evaluation of both the energy interactions that may occur among installers for the sale of the own produced energy and the impact that those interactions have on the traditional energy supply.

5.2 The mathematical model

The mathematical procedure is substantially similar to the static approach introduced in Chapter 2. However, some modifications occur in both the definition of the objective function of the model and the constraints of the model. In addition, a purpose-built index is defined.

The objective function of the model is expressed as

$$min \sum_{a_{ij>0}} a_{1j} e_{CN} X_{1j} \tag{5.1}$$

Where X_{1j} are the energy flows that the central node distribute to each node j of the network and e_{CN} is the cost of the energy supply from the central node. As constraint, the sum of the cost of both the energy supply from the central node and the energy from the neighbouring nodes should be lower than the traditional cost of the demand. This is formulated as

$$a_{1j}e_{CN}X_{1j} + \sum_{i=1}^{N}\left(a_{ij}e_{nodes}X_{ij}\right) \leq e_{CN}D_j, \forall j = 2, \dots, N \vee S_j < 0 \tag{5.2}$$

The term e_{nodes} is the unitary cost of the energy deriving from the nodes of the network. As in the model of Chapter 2, the model also imposes that all energy flows are non-negative.

The optimization problem firstly establishes the network of the energy exchanges among the nodes of the network and secondly evaluates the energy provided by the central node. The measurement of the supply from the central node is conducted in a double way: on one side by calculating the amount of the energy supplied and, on the other side, by determining which links are crossed by energy.

Therefore, from a network design perspective, it is interesting to figure out the impact that distributed energy systems have on the supply of the central node. To the scope, the index CN_{index} is introduced

$$CN_{index} = \frac{\sum_{i=2}^{N} links_{1\rightarrow i}}{N} \tag{5.3}$$

The index is expressed as the ratio between the links exiting from the central node that are crossed by energy and the links of the traditional centralized network. The denominator of the index in Eq.(5.3) corresponds to the number of nodes, since each node is connected to the central node in the traditional energy distribution network configuration. The CN_{index} varies within the interval $[0, 1]$; in particular, $CN_{index} = 0$ means that the central node does not supply any node of the network. This condition means that the DESs installed on territory are able to entirely satisfy the energy demands of the nodes. Vice versa, for $CN_{index} = 1$, the central node is still entirely responsible for the supply of energy to all nodes. This is true even when DESs are installed; indeed, the installed power is not sufficient to satisfy other nodes or is able to satisfy them only in part. Intermediate values indicate different rated of exploitation; however, as a general rule, the more small is CN_{index}, the more distributed is the network.

5.3 Numerical case study and discussion

The mathematical model introduced in the previous paragraph is tested in a hypothetical urban territory of $1\,km^2$ with $N = 500$ randomly placed consumers connected on the ground of a threshold distance of connection d, defined in the design stage. As an example, by setting $d = 50\,m$ as distance of permitted connection, the graphical representation of the case study area is exposed in Fig.47. In particular, to distinguish this application from the previous case study, the graphical symbolism has been modified. Fig.47 displays the consumers as green squares and the admitted connections for the energy exchanges are indicated as red solid lines. In Fig.48 the connections with the central node, located in the bottom left of the space, are added and illustrated as blue dotted lines.

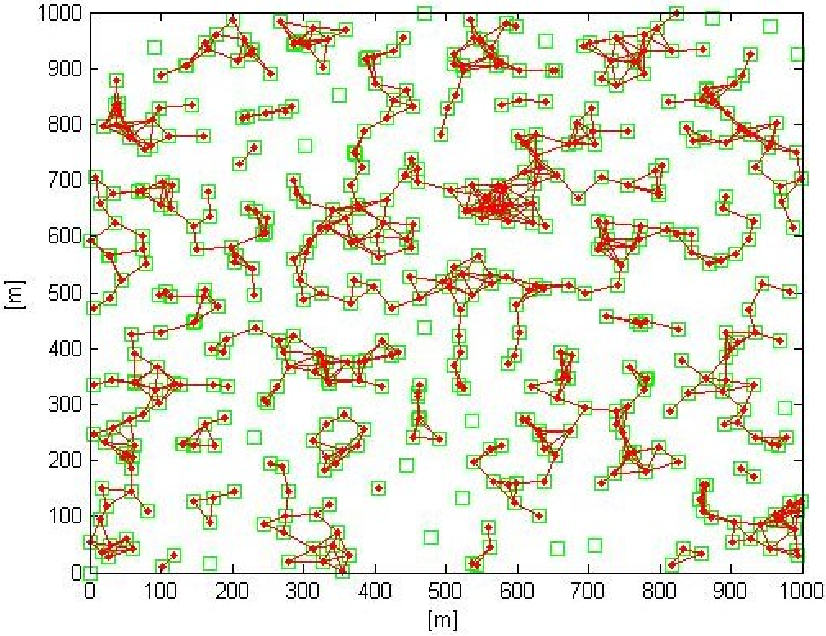

Fig.47 Connected nodes on the ground of the threshold distance d

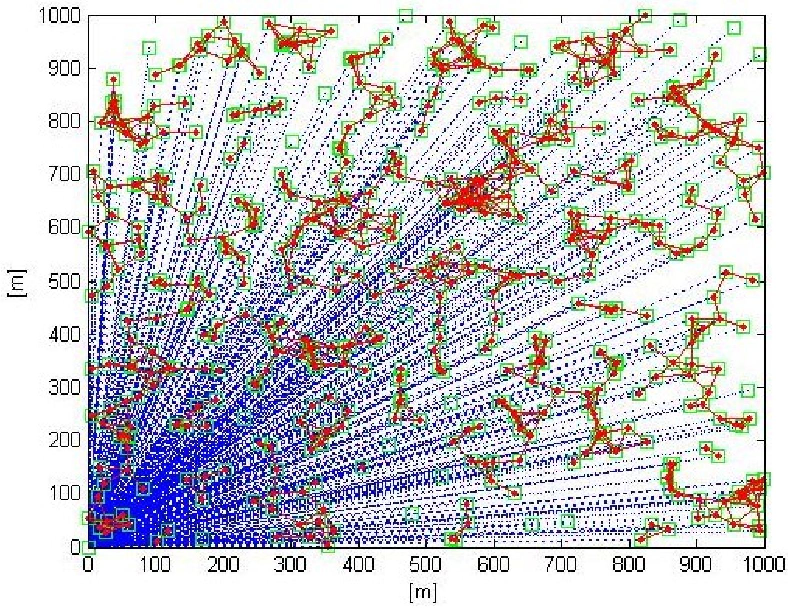

Fig.48 Connected nodes on the ground of the threshold distance *d* and connections with the central node

The energy distribution network of Fig.48 represents the starting point to run the model.

The energy demands of the nodes are varied within the interval [2 MWh, 7 MWh] according to a random uniform distribution [6]. Each node is considered as a potential installer of a distributed energy system and the total produced energy is expressed as a percentage of the total energy demand of the network; in the meaning that the 50% of the energy production does not indicate that each node produces the 50% of its own energy demand, but rather that the sum of the energy produced by the installer nodes is the 50% of the total energy requirements of the network. The installation of DESs is randomly assigned.

The connections among nodes are allowed in line with four chosen values, namely for $d = 50, 100, 150\ or\ 200\ m$. Regarding the costs of the energy, they are assigned in accordance with Table 8 [7].

Table 8. Values of the energy cost parameters

Energy costs	$c\text{E} / kWh$
e_{CN}	0.17
e_{nodes}	0.10

The model minimizes the energy provided from the central node and records the values of the central node index CN_{index}. Its values, obtained by varying the percentages of energy production and in correspondence with four different threshold distances, are shown in Fig.49.

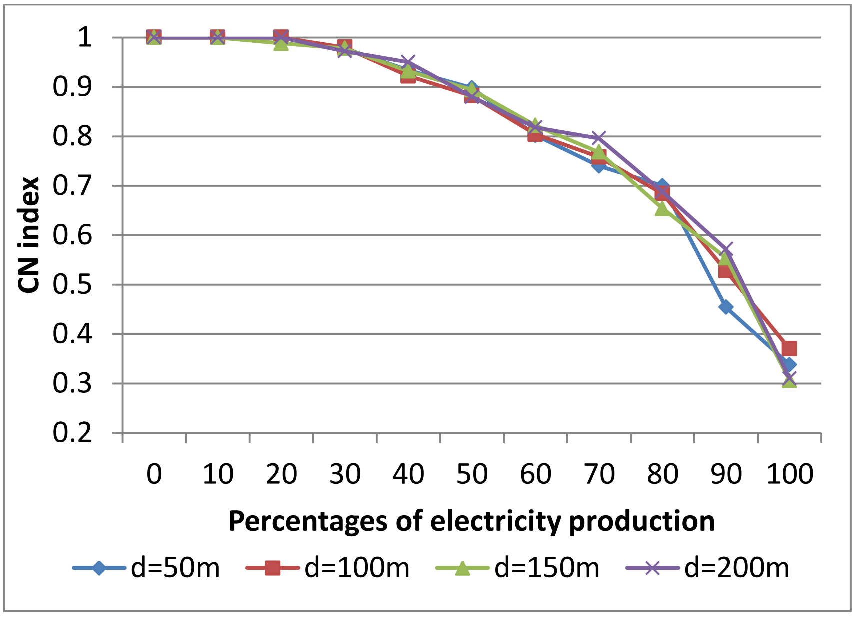

Fig.49 Trends of the CN_{index} by varying the percentage of energy production in correspondence with four threshold distances

The curves of Fig.49 have a similar trend independently of the considered threshold distance. The number of links that are responsible for the energy supply from the central node decreases for increasing values of the energy production percentages. More specifically, for percentages until the 20%, the central node index assumes the values $CN_{index} = 1$, i.e. the installation of DESs that account for the satisfaction of the 20% of the total energy demand of the network does not affect the supply fro, the central node. Indeed, within this range of installed power, nodes mainly satisfy in whole or in part their own demands and do not have exceeds to distribute. The increase of the percentage of installed power yields a decrease of the CN_{index}. Nevertheless, in correspondence with the 100% of the energy production, i.e. for a percentage that potentially satisfy the whole demand of the network, the supply from the central node still remains significant. This is due to a twofold reason; on one side, the energy supply from the central node may be more convenient in comparison to the supply from the network (as in the case of several links exploited for the exchange and, therefore, a higher cost in fees). On the other side, the distance of connection poses limits to the distribution and, consequently, not all produced energy is effectively distributed.

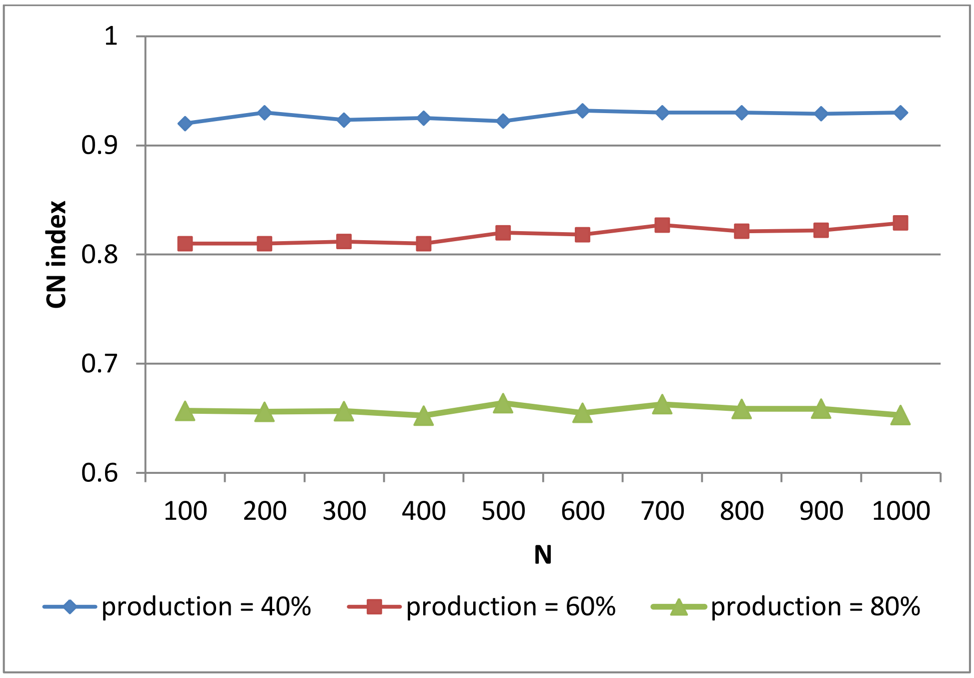

Fig.50 Trends of the CN_{index} by varying the number of nodes at the distance $d = 100\ m$ for different values of the energy production percentages

The CN_{index} has been studied at varying the number of node of the network and the results are exhibited in Fig.50 as can be observed from the figure, at fixed energy production percentage the number of nodes does not impact on the supply from the central node, since the curves display an almost constant trend.

5.4 Summary of results

The present chapter has proposed a cost analysis focused on the evaluation of the supply from the traditional fossil-fuelled power plant when distributed energy systems are inserted on territory. The general results permit to conclude that the insertion of DESs on urban territories allows achieving a reduction of the supply from the grid. However, this decrease is invariant with the distance of connection and with the number of nodes involved in the study.

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6. Conclusions

This thesis proposes a tool that combines spatial and energy issues with an optimization method to support urban planners in the decision-making process for urban energy strategies focused on both the achievement of the energy efficiency and the reduction of GHG emissions. In particular, the planning of the insertion of distributed energy production systems in urban areas (such as photovoltaic panels or combined heat power systems) requires mathematical models which optimize the structure of the energy distribution network among consumers and producers by minimizing the energy supply from the traditional power station. To this purpose, a methodology based on complex networks has been developed and proposed in this thesis. This approach allows representing the urban area as nodes connected through links. Each node is an energy user, such as household, building, or neighbourhood with an energy demand and an eventual energy production. The nodes are able to exchange energy through the links in order to either satisfy their own demand or to distribute the excess of energy production to other users they are connected with.

Two different approaches are pursued in this thesis; the former dealing with static mixed-integer linear programming technique implemented on MATLAB, the latter with dynamical simulations obtained by means of an agent-based model running on NetLogo. In both approaches, the output of the optimization gives as result which links are preferred to be exploited for the energy distribution in order to minimize the supply from the power plant. They differ in the time-period of application; actually, the static model considers a yearly aggregated data, whilst the agent-based model simulates a 24h cycle of the energy demands and productions of the network.

The two procedures were firstly applied to a speculative territory of $1\ km^2$, with a random uniform distribution of households equal to $N = 1000$. In addition, a territory in the city of Catania has been chosen to validate the results deriving from the hypothetical case study.

The static simulations were conducted for constant and fixed energy demands and by varying both the energy production of the nodes (according to four different scenarios) and the distance of connection. In general terms, the results of the static procedure confirm that the increase of the energy production among nodes cannot be planned indiscriminately, since a threshold of a maximum energy production equal to 80% of the energy demands of the network has been observed both in the numerical and the real case study. In addition, the nodes with a hub performance have been identified in the study.

As regard to the dynamical simulations; two main scenarios are identified, on one side constant profiles of electricity demands and production of agents over the 24 h and, on the other side, variable profiles. Both scenarios consider percentages of agents equipped with renewable energy systems between the 0% and 100% and four values of the admitted distance of distribution. Moreover, links activation thresholds are inserted in the model to evaluate how many links are exploited within the total operating period. Results allow concluding that the design of the energy distribution network should contemplate the usability of the links, beyond the evaluation of both the parameters of distance of connections and percentages of producers. Indeed, planning long distance connections may appear as the best solution at a first glance, but, actually, the insertion of activation thresholds shows that the majority of the links is used less than the 10% of the time. Rather, low distances, typically around 50 m, coupled with 20-30% of producers ensure a major exploitation of the energy distribution network.

An application that incorporates a cost analysis of the energy distribution network is then considered. The result permits to conclude that the insertion of DESs on territory allows achieving a reduction of supply from the grid. However, for the presented case study, this decrease is invariant with the distance of connection and with the number of nodes involved in the study.

In conclusion, urban actions focusing on the implementation of renewable energy on territory should consider the total amount of the exploited links of the energy distribution network. In this sense, a proper urban action plan aiming at inserting DESs on the territory should consider that the installation of such systems has to firstly evaluate the potential energy production that permits to optimize the distribution network, since it is the most impacting parameter that ensures the optimal distribution of energy among the nodes while minimizing the supply from the traditional power plant. Instead, the distance of connections and the number of nodes do not influence the exploitation of the links of the urban energy distribution network.

APPENDIX 1

Overview on the developed MATLAB code

The static simulations of the urban energy distribution network have been run on MATLAB. To illustrate the steps of the procedure, a brief explanation of the purpose-built code is presented hereafter.

As a first step, the number of nodes to be involved in the energy distribution and the dimensions of the space are defined. This early stage of the procedure is introduced in Fig.A1.

```
%Number of nodes settings and dimension of the territory
N=1000;
Lx=1000;
Ly=1000;
x=Lx*rand(N,1);
y=Ly*rand(N,1);
```

Fig.A1 Portion of the MATLAB code used for the definition of the number of nodes of the network and for the setting of the dimensions of the space

The number of nodes considered in the study is prior defined and established through the assignment of the parameter N. Subsequently, the dimension of the space is set to 1000 m on both the x-axis and y-axis, and the nodes are randomly placed within the space. Differently, when nodes have an exact position, as in the study of real urban areas, their positions are determined according to the code of Fig.A2, i.e. they are loaded from a separate Excel file containing the spatial coordinates of each building (node).

```
% Load of the urban area;
load nesima.txt

%Consider the columns x e y from the Excel file "Nesima_coordinates"
x=nesima(:,1);
y=nesima(:,2);
```

Fig.A2 Portion of the MATLAB code used for the load of the real urban territory

Moving forward, the next step regards the construction of the adjacency matrix, as in Fig.A3, in which the connections between each nodes pair are defined. A square portion of urban territory is defined through LL; then the reciprocal distance between each couple of nodes is calculated in the command $distance$. Once the distance of connection is chosen (in this code example of Fig.A3 it is set to 100 m), the procedure defines the adjacency matrix Ah, that is the matrix containing the information about the overall existing connections of the nodes. Indeed, if two nodes display a reciprocal distance that is below the chosen value, they are connected, otherwise they stay disconnected. The matrix Ah is then enlarging by adding the row (and the column) of the connections that each node has with the central node. As a reminder, in this stage of the optimization procedure, each node exhibits a connection with the central node, since in the traditional distribution configuration nodes either receive or sell energy exclusively to the central node.

```
%Construction of the adjacency matrix
LL=Lx*Ly;
X=x*ones(1,N);
Y=y*ones(1,N);
M(:,:,1)=abs(X-X');
M(:,:,2)=LL-abs(X-X');
dx=min(M,[],3);
M(:,:,1)=abs(Y-Y');
M(:,:,2)=LL-abs(Y-Y');
dy=min(M,[],3);
distance=sqrt(dx.^2+dy.^2);
%Definition of a radius of permitted connection
radius=100;
Ah=(distance<=radius)-eye(N);
%Insertion of the central node
A=[0 ones(1,N); ones(N,1) Ah];
```

Fig.A3 Construction of the adjacency matrix

Once the adjacency matrix has been constructed, its information is converted in a new matrix M containing the characterization of each node from the point of views of both the connections among the nodes and the direction of the energy flows. Indeed, energy may flow only from a source node to a destination node; moreover, no connections between either two source nodes or two destination nodes are allowed. The details of this step are reported in Fig.A4.

```
%Definition of the energy surplus of each node
S=G-d;
if S(j)>0,
Ah(i,j)=-1;  Ah(j,i)=1;
      elseif S(j)<0, Ah(i,j)=1;  Ah(j,i)=-1;
      else Ah(i,j)=0;  Ah(j,i)=0;
end
      else
```

```
if S(i)>0 && S(j)>0, Ah(i,j)=0;  Ah(j,i)=0;end
if S(i)<0 && S(j)<0, Ah(i,j)=0;  Ah(j,i)=0;end
if S(i)==0 || S(j)==0, Ah(i,j)=0; Ah(j,i)=0;end
if S(i)>0 && S(j)<0, Ah(i,j)=1;  Ah(j,i)=-1;end
if S(i)<0 && S(j)>0, Ah(i,j)=-1;  Ah(j,i)=1;end

end
```

Fig.A4 Coupling the information on both the adjacency matrix and the surplus vector for the definition of the matrix M

The energy distribution problem is then solved through a linear programming technique. As a case in point, the MATLAB expression used to pursuit this goal has been LINPROG. The linear programming model aims at minimizing the energy flows exiting from the central node. Therefore, the objective function of Eq.(1.11) is expressed in this direction by also including linear equality and inequality constraints (see Eq.(1.7) and Eq.(1.12), respectively). Subsequently, the solution of the linear programming problem is expressed in a matrix called "solution".

The LINPROG formalism is formulated as

```
%linprog for the energy distribution problem
z=linprog(Obj_function,sparse(size M),zeros[size M,1],M,S');
solution=zeros(N+1);
counter=2;
for i=1:N+1
    for j=i+1:N+1
        solution(i,j)=z(counter);
        solution(j,i)=z(counter);
        counter=counter+1;
    end
end
```

Fig.A5 LINPROG syntax

The following step consists in calculating the network index; to the purpose the corresponding code is reported in Fig.A6.

```
%Network index calculation
Link_activated=[];
for i=2:N+1
  for j=2+1:N+1
   if solution(i,j)~=0, Link_activated =[ Link_activated; i j]; end
  end
end
[ra,ca]=size(Link_activated);
[re,ce]=size(Link_connected);
index=ra/re;
```

Fig.A6 Network index calculation

Curriculum vitae

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List of publications

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2017	2nd AIGE – IIETA International Conference 2017, Genoa (international relevance)
2017	Summer Solstice 2017, 9th International Conference on Discrete Models of Complex Systems, Catania (international relevance)
2017	SICC Workshop 2017, 12th SICC International Tutorial Workshop "Topics in nonlinear dynamics", Control of complex networks of nonlinear circuits and systems, Catania (international relevance)
2017	Seminar "From brains to electronic circuits and back: connectivity-driven phase transitions, criticality and remote synchronization", Dr. Ludovico Minati (Complex Systems Theory Department, Institute of Nuclear Physics Polish Academy of Science, Krakow, Poland), Catania
2017	Seminar "Advanced Power Semiconductors: Applications and Driving from Theory to Practice", Dr. Ing. Petar J. Grbovic (HUAWEI Technologies Dusseldorf GmbH), Catania

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Chaos, Solitons and Fractals	1.455