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Urban energy mapping through the implementation on complex networks

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Abstract

Climate change is one of the major challenges facing with the human health and the environment. According to the Fifth Assessment Report of the IPCC, cities are key players in tackling climate change being responsible for a significant percentage of the level of energy-related CO_2emissions.From this viewpoint, it is desirable that cities are planned through energy models able to achieve the efficiency in the use of sources and able to minimize GHG emissions. Hence, considering the modern cities as complex systems, the high variability of the energy demand is taken into account evaluating the dynamic evolution of the energy flows. Thus, this paper presents the development, evaluation and application of a flexible mathematical procedure able to characterize the energy profile of an urban area and its dynamic evolution through the implementation of the network theory. The obtained results allow proper scenario analysis for the definition of energy planning strategies focused on the promotion and installation of cogeneration systems and in favor of renewable sources.

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Keywords: Energy; Cities; Complex networks; Climate change

1. Introduction

Climate change is a global issue that represents a serious threat to human health and the environment; as such, it constitutes a common concern for the entire international community.

According to the Fifth Assessment Report of the IPCC (International Panel on Climate Change), a strong contribution to the greenhouse gas emissions results from urban areas [1]. In fact, in 2014, 54% of the world population lived in cities and this fraction is estimated to grow to 66% until 2050 (UNDESA, 2014). Furthermore, the built-up areas are responsible for 67% of energy consumption (IEA, 2008) and for 71% of CO2 emissions (IPCC 2013).Therefore, cities are key players in tackling climate change, being responsible for a significant percentage of the level of emissions [2,3].

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The European Commission has become aware of the central role of cities in decreasing global total energy-related CO_2 emissions and has launched several initiatives to address this problem [4, 5]. The proposals ,focused on the decrease of the emissions levelin conformity with the guidelines of the Plan 20 20 20 [6], are oriented towards both the implementation of appropriate mitigation measures and the development of adaptation strategies. Hence, energy use in cities has attracted significant research in recent years. However such a broad topic inevitably results in a great number of interpretations of the problem and, as a consequence, in a manifold models. Generally, the studies deals with the energy demand estimation in the built environment [7, 8, 9] or with the urban planning and policy [10, 11]. In order to implement energy efficiency measures, a proper action plan has to develop planning strategies. From this viewpoint, an appropriate energy audit allows the definition of urbanization trajectories and urban forms of modern cities. Therefore, it is desirable that cities are planned through energy models able to achieve the efficiency in the use of sources and able to minimize GHG emissions.

In this context, a detailed knowledge of the energy demand in urban areas plays an important role in order to develop efficient energy management plans. The urban energy profile modeled so far in literature on the ground of static representation techniques [12] is enlarged to evaluate the dynamic evolution of energy consumptions. For this reason, considering the modern cities as complex systems [13],the hourly and seasonal variability of the energy flows are broaden by considering interactions and connections, i.e. by networks. However, while the network paradigm is the cutting edge to new representations and models in many fields, a model for handling ways in which interactions relate to energy use in urban areas are barely emerged[14].

Thus, the aim of this paper is to develop a flexible tool able to characterize the energy profile of an urban area and its dynamic evolution through the implementation of the network theory in order to allow proper scenario analysis for the definition of energy planning strategies focused on the promotion and installation of cogeneration systems and in favor of renewable sources.

2. The mathematical model

The mathematical model developed in this paper follows an approach based on the science of complex networks [15]. The urban area is divided into connected municipalities and represented with the aid of a graph. Graph theory is the formalism adopted for the mathematical treatment of complex networks [16].Hence, the municipalities are symbolized as nodes characterized by a particular energy profile, while arcs define the energy transmission lines. In particular, the nodes indicate points of consumption and potentially points of energy production.

A graph $G = (V, L)$ consists of two set $V$and L, such that$V = \{0, \dots, N\}$ are the nodes of the graph G, while$L = \{(i, j): i, j \in V, i \neq j\}$ are its arcs. Two nodes can be joined by an arc. To picture a graph a dot is drawing for each node and two dots are joined by a line if the corresponding nodes are connected by a link. It is often usual to consider a matricial representation of a graph. For these reason, a graph can be completely described by giving the adjacency matrix A, i.e. a NxNsquare matrix whose elements $aij = 1$ when the arc lij exists and 0 otherwise. The diagonal of the adjacency matrix contains zeros.

For each node of the graph, the following assumptions are formulated. Every node is connected directly to the node $V = 0$. More specifically, $V = 0$ is the node representing the power plant and is hereinafter called central node. A node i, being$i = 1, \dots, N$, in addition to the connection to the node $V = 0$, can also be linked to a node j, with $i \neq j$.Each node i, being$i \in V - \{0\}$ has an energy demand E_{di}; also, it is able to realize an amount E_{gi} of energy production through the exploitation of renewable energy sources or through the installation of CHP systems. Relatively to node $V = 0$, $E_{d0}=0$. Thus, the energy behavior of the central node is determined by the possibility of being able to produce or to purchase energy flows. The production is intended for sale on the network, while the purchase is aimed at the redistribution on the network. Moreover, a node $i$provides for the possibility to produce energy in an autonomous way. This production aims, firstly, to meet the energy demand E_{di} of the node. Hence, the energy profile of the node can be represented by the value of the surplus parameter

$$S_i = E_{g_i} - E_{d_i} \tag{1.1}$$

If $S_i > 0$, the node $i$has an energy surplus that can be allocated in the network and consequently node $i$is a source node. Opposite is the case for which$S_i < 0$in which the node behaves as a destination node as it has fulfilled only partially its energy demand and has therefore to interact with the network in order to purchase energy. Finally, for the condition$S_i = 0$ the node could met its energy demand through its autonomous production.

The elements a_{ij} of the adjacency matrix are updated according to the sign of S_i, in order to highlight the nature of the energy exchange between the node $i$and the node j. Therefore, the sign of the elements of the adjacency matrix specifies the direction on the arc and the resulting graph is indicating a direct network. In this model, the convention has been chosen to assume $a_{ij} = +1$ if node i is a source node and node j is a destination node. In this case, the direction of the arc is ingoing toward the destination node. Under the chosen agreement $lij = -lji$, so $a_{ji} = -1$ and the direction of the arc is consequently outgoing from the source node. The condition $a_{ij} = 0$ indicated no connection between node $i$and node j. With regard to the interaction, the model is built in order to favor the purchase of electricity from the nodes and only subsequently from the central node.

The total output of the central node must be able to satisfy the remaining energy demand of the nodes. This assumption is expressed as follow.

$$P_{CN} = \sum_{j=1}^{N} a_{0j}\, l_{0j} \tag{1.2}$$

The proposed mathematical model is solved using Matlab R2010a [17] on a 4 GB dual core 2.20 GHz personal computer. In order to solve the problem, the network has been formulated in a matrix form expressed as

$$MX = S \tag{1.3}$$

The matrix M contains the explicit connections between the nodes of the network. The column vector S represents the energy surplus of each node after the satisfaction of the energy demand through its autonomous production. Finally, the column vector X represents the solution of the network.

$$X = M^{-1}S \tag{1.4}$$

Because matrix M is not a square matrix, it is necessary to solve the problem using the generalization of the inverse matrix. For this reason, the solution is obtained through the pseudoinverse.

$$X = M^{T}S \tag{1.5}$$

Hence, the objective of the developed model is to determine the mapping of the urban energy network and to define which connections are activated between the nodes, which can behave, in a dynamic way, as source or destination nodes. The final energy balance of the central node consists in the energy production of the power plant. Therefore, the energy mapping obtained through the model allows to configure scenarios and elaborate energy and policy strategies in order to improve energy efficiency in urban areas.

3. Case study

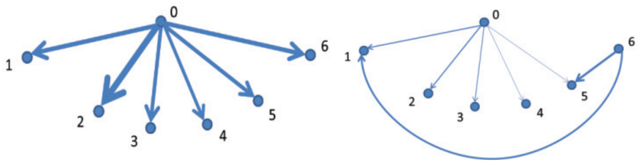
The described procedure has been tested for the municipality of Catania, a city in southern Italy with about 300,000 inhabitants. According to the regulation of the municipality of Catania [18], the urban area has been subdivided into 6 district. The elaborated model has been implemented by considering electrical energy as energy flows. Table 1 provides the total inhabitants and the yearly electrical energy demand, calculated considering a medium energy demand of 3 $kWh/day \cdot person$ [19].The energy generation is calculated in reference with a percentage of the yearly electrical demand [20]. In Table 1, node 0 represents the central node corresponding to the power plant. The central node has a nil energy demand, as explained in the previous paragraph.

Table 1. Inhabitants, energy demand and energy surplus for all node

Node		Inhabitants		Yearlydemand		Percentage of production	Energy generation		Energy surplus
Powerplant	0	-		0	MWh/y				
Centro	1	48334	p	52925,73	MWh/y	0%	0	MWh/y	-52925,73
Ognina-Picanello, Barriera-Canalicchio	2	66887	p	73241,265	MWh/y	30%	21972,3795	MWh/y	-51268,8855
Borgo Sanzio	3	44205	p	48404,475	MWh/y	10%	4840,4475	MWh/y	-43564,0275
San Giovanni Galermo, Trappeto-Cibali	4	37831	p	41424,945	MWh/y	20%	4142,4945	MWh/y	-37282,4505
Monte Po-Nesima, San Leone-Rapisardi	5	43011	p	47097,045	MWh/y	10%	4709,7045	MWh/y	-42387,3405
San Giorgio-Librino, San Giuseppe La Rena-Zia Lisa	6	53190	p	58243,05	MWh/y	130%	75715,965	MWh/y	17472,915

According to the existing configuration of the electricity grid, each node is connected to the central node. Therefore, the electricity demand of each node i, being $i = 1, \dots, N$, is entirely satisfied by the central node. Figure 1 a) depicts the electricity flows for the electricity networkof the municipality of Catania.

As before explained, the connection among nodes are represented through arcs. To highlight the energy significance of each arc, a proper convention has been chosen. In agreement to this convention, each arc is characterized by a thickness depending on the amount of electricity that flows among the nodes. A thicker link is indicating a major electricity exchange among the connected nodes, vice versa a thinner link corresponds to a minor exchange of electricity.



a) b)

Fig. 1 a) Existing electricity network for the municipality of Catania b) Electricity network resulting from the application of the mathematical procedure

In order to apply the mathematical procedure developed in this paper, the following assumptions are formulated. Nodes are supposed to be linked on the ground of a connection pattern exposed in Table 2. Each district has a certain percentage of electricity generation capacity obtained by the exploitation of renewable sources or by the installation of combined heat and power systems. In the first place, the autonomous production of a node aims at the satisfaction of its electricity demand. Subsequently, the node may distribute the exceeding electrical production towards destination nodes. On the other hand, a node may receive electricity if its demand has been not entirely satisfied. It has to be specified that the preferential electrical supply for a destination node derives from source nodes and, secondly from the central node, namely the power plant. Thus, once the internal energy demandis satisfied, each node may assume two different behaviors according to the sign of its energy surplus S_i. If the node has a positive surplus indicated by (+), then it is configured as a source node, vice versa it is configured as a destination node and characterized by the (–) sign. The details of electricity production and of energy surplus are reported in Table 1.

Table 2. Connection pattern

Connection pattern		
0	↔	1
0	↔	2
0	↔	3
0	↔	4
0	↔	5
0	↔	6
1	↔	6
2	↔	3
2	↔	4
5	↔	6

Fig. 2 reports a graph depicting the connection pattern described in Table 2. However, the represented energy network only illustrates the simple connection among nodes, without considering in this first place, the energy characterization of the arcs before highlighted through the thickness of arcs.

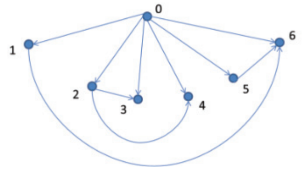


Fig. 2 Energy network for the initial connection pattern

Depending on the dynamicity of the adjacency matrix, the resulting network activates only the links able to transfer electricity in the direction subject to the established convention, i.e. from a source node to a destination node and, if necessary, drawing electricity from the central node. The resulting network is shown in Figure 1 b). Each district has a certain percentage of electricity generation capacity obtained by the exploitation of renewable sources or by the installation of combined heat and power systems. Once the internal energy demandis satisfied, each node may assume two different behaviors according to the sign of its energy surplus S_i. If the node has a positive surplus indicated by (+), then it is configured as a source node, vice versa it is configured as a destination node and characterized by the (–) sign. The details of electricity production and of energy surplus are reported in Table 1.

The comparison between the real network and the modeled network shows a strong reduction of electricity flows on each arc. Specifically, the connection among nodes permit the decrease of energy demand at the expend of the central node. Thus, this analysis allows to define strategies for the correct installation of cogeneration systems and the exploitation of renewable sources.

4. Conclusion

In this paper the energy mapping of the urban energy flows is studied through the implementation of the network theory in order to permit a scenarios analysis for the elaboration of energy strategies for the promotion and installation of cogeneration systems and in favor of renewable sources.

A flexible tool was developed in order to characterize the energy profile of an urban area and the validity of the proposed model was tested within the municipality of Catania. Thedeveloped model is able to define the dynamic evolution of the interactions between nodes and allows the formulation of the urban energy trajectory relatively to the energy demand of each district.

Further in-depth analysis are necessary in order to involve the heat demand of each district and to determine a criterion according to which nodes choose their connections, as for example a cost and environmental criterion. Moreover, a deeper analysis may involve the study of proper network measures, as the centrality of a node.

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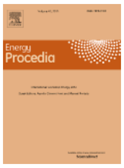

Biography

Rosaria Volpe received the Laurea degree in Engineering, summa cum laude, from the University of Catania in 2014. She is holding a Ph.D. in Systems Engineering, Energy, Informatics and Telecommunications. She has coauthored two under review scientific papers. A participation to previous project includes the 3° CongressoNazionaledellaMeccanicaItaliana and the participation to the Summer School of FisicaTecnicaand to the Lipari Summer School on Computational Science.