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Energy Resilience, Vulnerability and Risk in Urban Spaces

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ABSTRACT

Nowadays, resilience is a necessary component for a sustainable development of cities. Achieving increased resilience requires improved risk assessment and modeling, better planning and design, increased communication and collaboration. The aim of this study is to propose a flexible methodology in order to analyse the energy sustainability and the risks of the metropolitan cities, in this case the method has been applied to the City of Turin. The main objectives are to evaluate the characteristics of the existing energy systems, their impact on sustainability and to understand how to satisfy the high-energy demand in a critical urban environment with few available renewable energy sources. This work describes a methodology to identifying energy risks, vulnerabilities and resilience for residential and tertiary buildings in Turin. Three indicators to evaluate the energy resilience and security assessment were used. In particular, the assessment of impact of individual indicators was conducted by using the aggregation and weighting method. To improve energy resilience, two future scenarios were assumed: the expansion of the existing district heating and the exploitation of roof-integrated solar-thermal collectors. The first results on historical trend show that the annual thermal energy consumption depends on climate data but also on per capita earning, with an annual decrease of 3% after 2007. A similar trend can be observed in natural gas consumption, in fact every year, natural gas decreases by 3%, while the district heating network increases by 8%. The results of future scenarios show an improvement of energy resilience, with a reduction of greenhouse gas emissions up to 12% with district heating expansion and 39% with also the use of solar collectors.

KEYWORDS

Energy models, Energy security, Energy sustainability, District heating, Urban scale, Geographic information system.

INTRODUCTION

One of the goals to improve the sustainability of cities is to invest in developing the resilience (capability to handle and respond to various disturbances) in order to substantially reduce disaster damage to critical infrastructure and disruption of basic services, such as the supply of energy [1]. The energy sector can be evaluated through three issues: energy security, energy sustainability and energy equity (Energy Trilemma) [2]. In Italy, to reduce energy risks, prior actions remain energy efficiency and renewable

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energy sources issues encouraged also by public subsides [3]. The energy sector also shows emerging risks, these include technical disruptions, extreme weather events, and also citizen and consumer awareness and concerns about the localization and the use of energy infrastructure. In the last years, these risks had a growing impact on the energy sector through:

- Energy-water-food nexus (the interdependency of the human use of water, food and energy that impacts on economy, society, environment, health, and wealth);
- Extreme weather events (disastrous, unusual or not seasonal events);
- Cyber risks (offensive actions to maneuver infrastructure, information systems, computer networks and devices).

The resilience implies a functioning and stable system, providing continuity and minimizing interruptions to service. The concepts of resilience are tightly linked to sustainability and energy is one of the key features in urban sustainability. Then an energy resilient urban system should be able to ensure availability, accessibility, affordability and acceptability of energy supply, under varying conditions of uncertainty, through enhancing its ability to plan/prepare and absorb the effects, with a rapid recovery of the service with minimum costs [4]. In fact, the policies for resilient cities are those strengthening the urban system's capacity to change in response to economic and natural shocks to the system. The various human-built systems of a city and the natural system are complex [5].

Availability denotes the existence of adequate supplies of energy resources and reserves and proper infrastructure for transforming them into energy services (i.e., diversification on energy sources).

Accessibility refers to the importance of spatial proximity of energy supply and demand.

Affordability refers to the capacity of population to meet their energy needs at reasonable costs (i.e., the stability/predictability of energy prices helps in ensuring energy affordability).

Acceptability refers to efficiency of energy systems (generation, transmission and distribution) minimizing environmental impacts (i.e., new clean technologies and smart systems).

Cities are the major energy consumers and the continuity of energy service is essential for their effective functioning. As energy is an important driver of current economic activities, it is important for countries to secure their energy sources. This is particularly true for EU countries in light of geopolitical considerations and ongoing reforms in the EU energy market [6]. This is primarily related to the rapid economic growth and at the same time, a high degree of dependence on import of energy generating products [7]. Access to energy is one of the most important aspects of the well-being and sustainable development of modern societies. The role of energy is directly linked to the economic, social and environmental development of a country [8]. Moreover, in urban areas, with the increase of population, the demand of energy will consequently increase. To ensure sustainability, precautionary measures should be taken in order to acknowledge future uncertainties and avoid potential risks caused by the low availability of energy sources.

Therefore, achieving sustainability requires an integrated approach that covers multiple, interrelated environmental, social and economic dimensions. Precautionary measures to respect uncertainty, promoting inter- and intra-generational equity, minimizing adverse impacts on the environment, maximizing efficiency and economic benefits through resource management and adopting bottom-up and participatory approaches are the main criteria used for assessing achievement of sustainability goals.

To address the energy risks, various energy-related aspects could be analysed, such as:

- Resources (energy, water-energy nexus, food-water-energy nexus);
- Land use, urban geometry and morphology (land use, urban morphology, urban design);
- Infrastructure (supply, transmission, distribution, backup and storage, green and blue infrastructures, transportation, innovation);
- Governance (management, monitoring and planning, standards and laws, subsides, fuel price);
- Socio-demographic aspects and human behavior (demographics, health and equity, behavioral aspects).

In the last years, mitigation and adaptation to climate changes should also be considered as further aggravating risks. If the climate change depends on energy-related emissions, the reduction of energy risks, with deep emission cuts across various sectors, will be also crucial for climate stabilization [9, 10].

In Figure 1, an energy resilient system has been represented by the four components (i.e. availability, accessibility, affordability, and acceptability) considering five themes for the interventions: urban infrastructures, resources, land use and urban morphology, urban governance, socio-demographic aspects and human behavior. In this study, the energy components have been evaluated considering these five themes, for the definition of an energy security index.

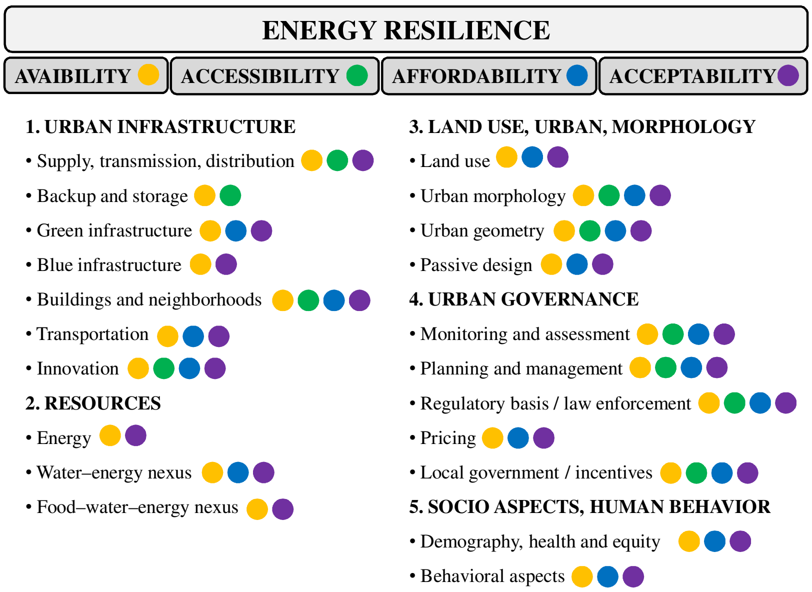

Figure 1. An energy resilient system

The definition of energy sustainability is based on three core dimensions – energy security, energy equity and environmental sustainability. Taken together, they constitute a 'trilemma', and achieving high performance on all three entails complex interwoven links between public and private actors, governments and regulators, economic and social factors, national resources, environmental concerns and individual behaviors [11]. Therefore, the challenge for a future sustainable and smart energy sector will be represented by [12]:

- Energy security, the effective management of energy supply with reliable energy infrastructures to meet current and future energy demand;
- Energy equity, accessibility and affordability of energy supply across all population;
- Environmental sustainability, encompasses the achievement of supply and demand-side energy efficiencies and the development of energy supply from renewable and low-carbon sources.

The current European climate and energy policies EU-2020 and EU-2030/2050, demonstrate that climate changes, energy efficiency and renewable energy sources are currently influencing the energy sector due to a strong and constant political agenda on the road to a sustainable, inclusive, affordable and resilient energy system [12]. In this context, it must be considered that locally, specific low-carbon technologies or energy savings interventions appear preferential and then more suitable to reach EU objectives.

In this study, the concept of energy resilience is developed considering the following themes:

- Sustainable cities (environmentally, economically, and socially healthy and resilient cities);
- Energy efficiency (energy efficient systems and energy saving measures);
- Renewable energy (exploiting the available renewable energy sources with low greenhouse gas emissions);
- Smart grids (innovative models for demand-supply management).

Energy efficiency and renewable energy are also solutions to reduce energy dependency from abroad, ensuring energy security and reducing the energy risk, in line with the EU policies on energy and climate changes.

For the city of Turin, to promote a sustainable development, the trend of energy efficiency measures, the use of the available renewable resources and the reduction of CO_2 emissions, together with the reduction of energy import dependency were analysed [12]. To address the issue of smart grids, a study on the expansion of the District Heating (DH) network has been provided, the development of integrated energy systems are seen as a key option to provide operational flexibility to the energy system and improve its overall efficiency to the thermal and electrical users [13]. The aim of this study is on energy systems and their impact on sustainability and to understand how to satisfy the high energy demand in complex urban contexts with low temperatures outdoor spaces through the available renewable energy sources [14, 15].

In the first phase of the work, an analysis of the characteristics of the buildings of the City of Turin and their energy consumptions from 2000 to 2013 is presented. Energy consumptions are analyzed taking into account renewable and non-renewable resources, types of users (residential and non-residential), CO_2 emissions, microclimatic conditions (climate data from 6 weather stations) and socio-economic conditions (number of inhabitants, earning and income).

In the second phase of the work, the optimization of the existing energy supply network together with the potential of the available renewable solar technologies have been evaluated. The historical evolution of the DH network of the city of Turin was analyzed with the objective to develop future scenarios at 2030 and 2050. The results of this analysis will consent to evaluate current and future energy policies and the possible actions to achieve energy security and resilience reducing energy risks and vulnerabilities [16]. Energy security is important for all countries and substantially more important for countries that are simultaneously exposed to multiple supply vulnerabilities [8].

In the third phase of the work, the energy security index was calculated, considering different indicators and using the aggregation and weighting method [17]. Energy security is an extremely complex phenomenon that itself is neither clearly defined, nor are its limits clearly identified. Furthermore, the very energy security is affected by a large number of factors that are different in types and levels of influence, whereby most of them are very complex by their nature [7]. The energy security index consents to aggregate and to quantify more indicators as energy efficiency, environmental sustainability and energy equity to. To each of these indicators it is possible to give a certain weight according to its perceived importance and with the aggregation technique can be defined a composite index.

MATERIALS AND METHODS

This paper shows a method to evaluate energy resilience in urban spaces, in particular how the energy system dependency can affect resilience capacities was investigated. The resilience of the system is its ability to reduce both the magnitude and duration of the deviation as efficiently as possible to its usual targeted system performance levels. As resilience increases, the degree of damage for a given intensity hazard decreases.

Three properties or capacities are used to define, quantify and design for better resilience [18]:

- Absorptive capacity, or the ability of the system to absorb the disruptive event;
- Adaptive capacity, or the ability to adapt to the event;
- Restorative capacity, or the ability of the system to recover.

The proposed method focuses on the concept of adaptive capacity, considering relationships between the different energy systems: the heating systems may have the adaptive capacities that allow the systems to reorganize themselves (using renewable energy sources or more efficient systems as DH) to reduce its dependency upon existing system (old inefficient boilers using gas oil or fuel oil). In this paragraph, the methodology applied to the case study of the City of Turin is presented.

Energy consumptions analysis

Turin's energy consumptions were analyzed considering the data available from 2000 to 2013 mainly from the project Data4Action. Consumptions were distinct in electricity consumptions and thermal consumption, for thermal consumptions, energy sources were also distinguished: non-renewable sources (natural gas, DH, fuel oil, diesel/gas oil, LPG, petrol) and renewable sources (solar, biomass, biofuels). The trends of each energy resources have been analyzed considering: number of inhabitants, per capita earning and income, user typology and Carbon dioxide (CO_2) emissions. Then for all sectors (residential, tertiary, transport and agricultural), energy consumptions and CO_2 emissions have been evaluated over the period 2000-2013. The trend of thermal consumptions was analyzed considering the microclimatic conditions for five weather stations in the City of Turin. Thermal consumptions were normalized considering 2,620 °C Heating Degree Days (HDD) at 20 °C, the average HDD for the years 2004-2013 of Reiss Romoli weather station.

For the calculation of greenhouse gas emissions, considering the thermal consumption of the different energy sources, emission coefficients from Italian National Agency for New Technologies, Energy and Sustainable Economic Development, ENEA [19] in t CO_2/MWh were used: gas oil = 0.280, LPG = 0.240, carbon = 0.370, fuel oil = 0.290, electricity energy = 0.460, natural gas = 0.210, solar thermal = 0.0, for the DH, the results of Data4Action project with 0.153 t CO_2/MWh.

Scenarios analysis

Starting from the study on the potential expansion of the DH network of Turin [20, 21], two scenarios were hypothesized. The first scenario considers the current trend of the development of the DH network and the second scenario considers the current development of the DH network plus the trend of installation of solar-thermal collectors.

Turin consumption data (MWh/year) and volumes served (m^3/year) are provided by the DH Iren Company. These data were used to analyze the residential and tertiary volumes of heated buildings with a Geographic Information System (GIS) tool. The constraints for a future expansion of the DH network were also considered (Figure 2a): the presence of individual heating systems (28.4%), the territorial limits given by the Po river and the hills (12.9%), the high density historical old town in the center of Turin (8.1%), the non-connectable buildings with a volume smaller than

2,500 m^3 (4.8%) and the diameter of the existing pipelines. In Figure 2a the limit on autonomous heating systems in yellow can be noted on the hill (South-East) and in the suburbs areas. Considering these constraints, the residential and tertiary volumes and number of buildings connectable and non-connectable to the DH network have been calculated (Figure 2b). The number of the connectable buildings to DH, in the medium-term scenario, will be 17,870, equal to 35,679,069 m^3, in the long-term scenario, the number of the addition connectable buildings will be more than 6,558, equal to 12,802,847 m^3.

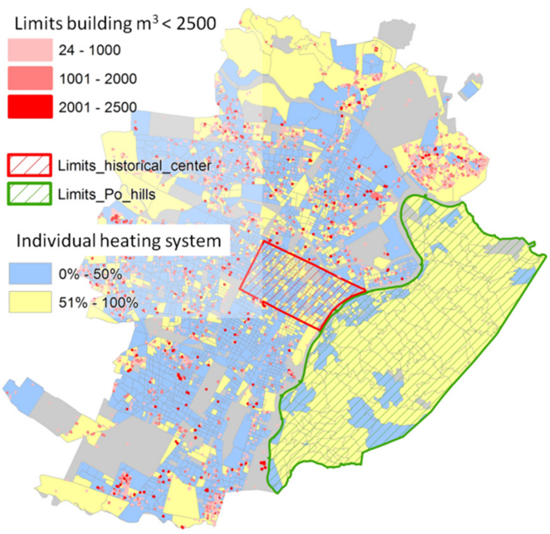

Figure 2a. DH network expansion constraints: individual heating systems (in yellow), Po river and hill (in green), historical centre (in red) and buildings with a volume < 2,500 m^3

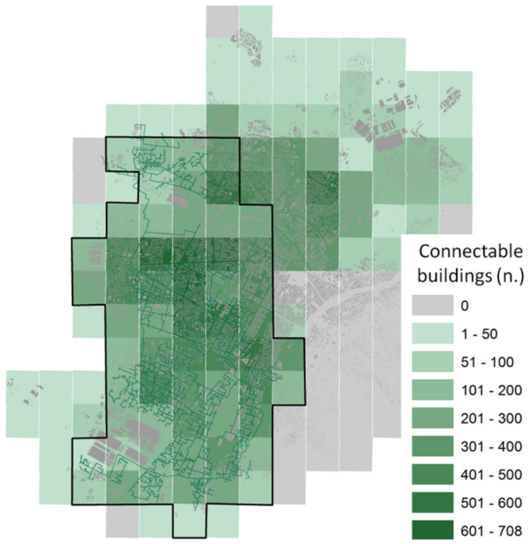

Figure 2b. The expansion of the DH network starting from the existing network and the future expansion in the medium-term (marked with black outline) and long-term

For the medium-term to 2030, the volumes connected to the existing DH network, the potentially connectable volumes, the non-connectable volumes (due to territorial, technical and economic constraints) and total volumes have been considered (Table 1). Thermal consumptions and emissions (state of fact and future scenarios) have been calculated, including residential and tertiary volumes that could be connected to the existing DH. In 2030, only the buildings reachable from the existing network will be connected to the DH, in the long-term scenario at 2050 all the "connectable" buildings in Turin will be served by the DH network.

Table 1. Volumes, consumptions and CO_2 emissions analyses of connectable and non-connectable buildings by the DH network for the City of Turin

		Tot. res./tertiary buildings	Connectable to DH network	Non-connectable to DH network	Buildings connected to DH network
DH existing areas	Volume [m^3]	87,226,609	35,679,069	10,733,500	40,814,040
	Consumption [MWh/y]	-	2,018,823	607,332	2,309,374
	Emissions [t CO_2]	-	455,263	136,959	353,334
DH non-served areas	Volume [m^3]	50,984,035	12,802,847	38,181,188	0
	Consumption [MWh/y]	-	724,421	2,160,400	0
	Emissions [t CO_2]	-	194,419	474,710	0
Total	Volume [m^3]	-	48,481,917	48,914,688	40,814,040
	Consumption [MWh/y]	-	2,743,244	2,767,731	2,309,374
	Emissions [t CO_2]	-	649,682	611,669	353,334

Finally, the solar-thermal collectors trend of diffusion was also added considering a +20% of installations at 2030 and +30% at 2050. Currently in Italy, the market of solar collectors offers solar modules with efficiency of 0.8-0.85 and with a global system efficiency of 0.5-0.55 taking into account also the heat storage, exchange and distribution.

Energy security index

For the energy resilience assessment, four themes are considered for energy systems to contribute to improve resilience in a complex urban context as Turin: sustainable cities, energy efficiency, renewable energy and smart grids. From the analysis of energy resilience indicators, the energy security index for the City of Turin was calculated creating a compost index, calculated with several indicators to analyze different impacts. The indicators used in this study are energy consumptions (residential and tertiary), energy resources and environmental sustainability. Through the aggregation method [17], the indicators are used to calculate the energy security index for the City of Turin in the medium-long term.

The steps for the creation of the composite energy security index were:

- Identification of the energy security definition: from the state of art, the following seven major energy security themes or dimensions were identified: energy availability, energy efficiency, infrastructure, energy prices, environment, societal effects and governance. Sustainability and environmental issues are closely associated with energy consumptions and CO_2 emissions that contribute to global warming and air pollution [17];
- Selection of the appropriate indicators and collection of the needful/available data:
    - Energy consumptions, by reducing quantities of energy consumed without compromising socio-economic growth, improvements in energy efficiencies towards a sustainable development with investments in energy infrastructure and reduction of costs, as well as, of environmental impacts. Efficiency improvements can be achieved by changes in energy-related technologies and processes; improvements in energy intensities are realized by higher energy efficiency and by shifts in economic fluxes, in the fuel mix and in consumer behavior [22];
    - Energy resources, non-fuel-based renewable energy technologies are less hazardous, both during operation and in a natural disaster situation. However, renewable energy technologies have vulnerabilities that may make them particularly susceptible to poor performance during natural disasters. Energy supply from local sources is positive for rapid recovery but distant sources may be preferred from a vulnerability perspective [23]. This indicator focuses also on individual energy sources but an aggregate index for total primary energy sources can be formed by weighing the different individual sources [17];
    - Environmental sustainability, relates to the maintenance of the natural capital and so is concerned with the impact and risk of processes on the environment and issues around use of resources and emissions [24]. With the growing importance of sustainability, environmental and sustainability indicators have increasingly become part of the energy security and environmental concerns [17]. Energy indicators of sustainable environmental address the themes of energy-related impacts on the atmosphere, water and land. For assessing the atmosphere, greenhouse gas emissions, linked to climate change and pollutants that degrade air quality can be considered [22].
- Normalization of the indicators with the "Min-max method": the selected indicators have different units and are on different scales. A transformation is needed before they can be aggregated to form a composite index. In this study, the normalization

using the "Min-max method" was used, with the minimum set to "0" and the maximum set to "±1".
- Weight the normalized indicators (equal weights method): equal weights to all indicators have been assigned; this hypothesis will be discussed in future research;
- Aggregation of the normalized indicators: aggregation involves the combination of the weighted indicators into a composite index, in this work, the additive aggregation method has been used and the indicators are first multiplied by the assigned weights and then summed to arrive at the final index.

CASE STUDY

The City of Turin is located in an area of about 130 km^2, mostly flat. It is surrounded by the Alps and by the hills and it is crossed by four rivers (Po, Dora Riparia, Stura and Sangone). Turin's climatic conditions are strongly influenced by the presence of the Alps, the climate is continental temperate, typical of mid-latitudes, with cold-dry winters and hot-wet summers. The Urban Heat Island (UHI) phenomenon influences the Turin climate with significantly higher temperatures in the city center and the lowest temperatures in the suburbs and in the surrounding rural and hilly areas. Considering the various weather stations in the city, there are differences in the outdoor air temperatures, mainly due to human activities (residential or industrial areas), the presence of UHI and the proximity of parks and rivers [25].

In this study, the residential and tertiary sectors were analysed as the most critical ones. Particularly, energy efficient and low-carbon measures were evaluated on thermal consumptions, the most important and difficult to solve energy issues in a high-density urban context.

Turin has about 60 thousand heated buildings (232 Mm^3), the residential sector is constituted from more than 45 thousand buildings equal to 164 Mm^3, while the non-residential buildings are around 14 thousand equal to 68 Mm^3 (CTC of Turin, 2015). The residential sector is mainly characterized by large and compact condominiums (surface to volume ratio: $S/V \leq 0.45$) and detached houses ($S/V > 0.71$). Considering the period of construction, Turin has a very old building stock, with 57% of the buildings built before 1960 and more than 80% built before 1970. The residential buildings built in 1970-2000 reach about 15% and after 2006 only 2%.

Turin is also characterized by 40 homogenous urban micro-zones (Figure 3a) reported in Table 2. For each micro-zone, the number of buildings, the heated volumes, the number of inhabitants, the type of building: residential or non-residential (Figure 3b), the main period of construction and the main level of maintenance are reported. Also, the nearest weather station (Figure 3a) was also identified to analyse the energy consumptions taking into account the different microclimate characteristics. As it is possible to observe in Table 2, few micro-zones are characterized by: new buildings built after 1970 (only in the micro-zone *n*, 39 "Spina 1" there are new buildings) and detached houses (only micro-zones: 22, 23, 24, 25, 26 and 40 near the hill in the Eastern part of the city). Moreover, the buildings are occupied and heated for about the 80% of their gross volume and they are mainly residential buildings with the exception of micro-zones 17, 30 and 38 that are mostly industrial (as reported also in Figure 2b).

Data about energy space heating consumptions are derived from the research projects, Cities On Power (www.citiesonpower.eu), Data4Action (www.data4action.eu) and ENERDATA (www.enerdata.net). Also data about single buildings or blocks of buildings with monthly period were given by the DH Iren company. Data about the energy consumption at municipal scale for the City of Turin were also taken from [26].

The population resident in Turin in 1991, equal to 979,839 inhabitants, fell down to reach the historical minimum in 2002 with 866,134 inhabitants but in the last 10 years the population is approximately constant (±1%). In 2000, Turin registered 879,285 residents and in 2013 the total number of inhabitants of Turin were 872,091 (Figure 4a). Per capita earning from 2000 to 2007/2008 has been growing, but after 2008, it has decreased slightly due to the economic crisis (see Figure 4b, 1,000 EUR/cap from demographic statistics, ISTAT: http://dati.istat.it/). Also per capita income and other indicators have been analysed with the results of the research projects, Odyssee-Mure (www.indicators.odyssee-mure.eu) and ENERDATA (www.enerdata.net).

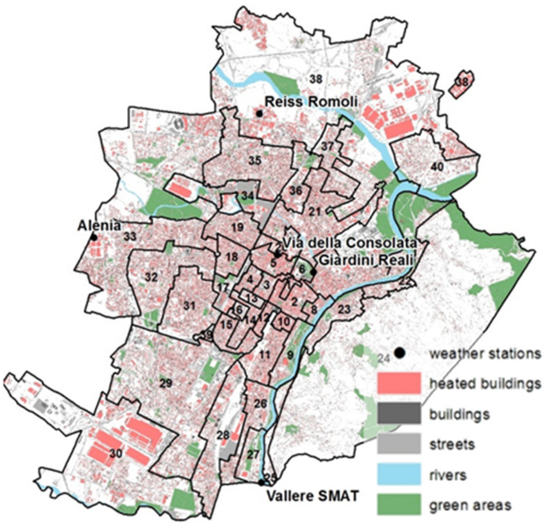

Figure 3a. Localization of the five weather stations in the 40 urban micro-zones of Turin

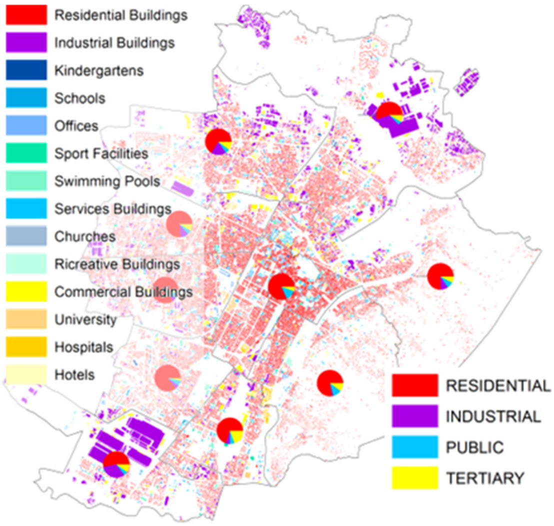

Figure 3b. Types of building users (residential, industrial, public and tertiary) analyzed for the districts

Table 2. Buildings' characteristics in the 40 micro-zones of Turin (number buildings, heated volume, surface to volume factor S/V, occupancy %, inhabitants, percentage of residential buildings, period of construction, main level of conservation, weather station)

Micro-zone	No. of buildings	Heated volume [m^3]	$S/V_{(avg)}$ [m^{-1}]	No. of inhab.	Occupancy [%]	Residential buildings [%]	Period of construction (main)	Main level of maintenance (1-4, bad-good)	Weather station
1	272	1,721,810	0.549	891	77.3	56.81	< 1945	4	Giardini Reali
2	2,067	8,013,852	0.308	10,478	82.8	70.61	< 1945	4	Giardini Reali
3	625	2,767,689	0.346	3,674	80.1	81.08	< 1945	4	Consolata
4	643	3,656,065	0.292	3,523	76.2	74.90	< 1945	4	Consolata
5	1,601	6,272,748	0.268	8,863	78.2	71.01	< 1945	3	Consolata
6	257	1,428,739	0.289	988	57.0	72.87	< 1945	4	Giardini Reali
7	5,096	12,224,823	0.295	38,301	75.8	76.93	61-70	3	Giardini Reali
8	510	1,724,061	0.371	2,386	67.6	86.34	< 1945	3	Giardini Reali
9	953	3,331,158	0.314	3,292	81.1	53.36	61-70	3	Giardini Reali
10	837	2,169,541	0.608	5,439	87.3	89.90	< 1945	2	Giardini Reali
11	2,362	7,844,626	0.398	26,852	89.7	78.82	61-70	3	Giardini Reali
12	839	2,527,199	0.354	5,126	79.8	90.69	61-70	2/3	Consolata
13	256	474,056	0.396	1,440	78.1	48.30	61-70	4	Consolata
14	1,200	4,313,279	0.329	10,332	85.0	96.03	< 1945	3/4	Consolata
15	1,890	5,436,386	0.345	11,641	88.6	86.70	61-70	3	Consolata
16	224	369,133	0.493	133	76.1	82.06	< 1945	3	Consolata
17	353	2,391,638	0.331	3,593	81.8	11.01	61-70	3	Consolata
18	1,894	5,784,518	0.362	14,335	87.8	85.04	< 1945	3	Consolata
19	3,012	6,673,217	0.341	27,379	89.2	85.75	46-60	3	Consolata
20	897	3,050,612	0.318	5,943	77.2	60.54	61-70	3	Consolata
21	7,452	15,603,319	0.415	51,915	80.4	69.17	61-70	3	Giardini Reali
22	1,151	1,703,919	0.716	3,518	83.3	86.86	< 1945	3/4	Giardini Reali
23	2,384	3,381,827	0.709	5,937	77.0	85.22	< 1945	3	Giardini Reali
24	15,005	817,753	0.519	20,803	80.8	82.72	61-70	4	Vallere
25	712	639,636	0.687	693	63.2	67.04	61-70	2	Vallere
26	2,423	7,204,840	0.791	22,203	81.1	57.60	61-70	2	Vallere
27	424	2,577,213	0.531	2,528	68.7	51.65	61-70	2	Vallere
28	3,630	10,626,892	0.352	28,705	86.3	49.36	61-70	4	Vallere
29	9,727	31,775,564	0.379	133,575	89.5	84.13	71-90	4	Vallere
30	4,801	30,364,979	0.409	22,297	76.4	15.45	61-70	4	Vallere
31	5,956	11,765,484	0.357	41,980	86.4	77.34	61-70	2	Consolata
32	4,818	14,495,778	0.355	49,480	89.4	86.00	61-70	3	Alenia
33	10,740	18,000,974	0.381	74,346	89.8	75.60	61-70	3	Alenia
34	1,213	5,681,819	0.325	5,566	76.2	26.92	61-70	2	Consolata
35	8,187	15,036,105	0.411	62,934	90.6	84.63	61-70	3	Reiss Romoli
36	1,422	3,451,890	0.631	8,933	84.7	49.67	61-70	3	Reiss Romoli
37	2,292	5,261,987	0.606	24,356	92.7	82.71	61-70	3	Reiss Romoli
38	15,862	45,798,491	0.405	116,559	77.4	29.68	61-70	4	Reiss Romoli
39	64	284,506	0.424	3,544	73.3	90.78	> 1991	3	Consolata
40	4,039	3,243,962	0.863	7,612	77.1	70.31	61-70	4	Giardini Reali

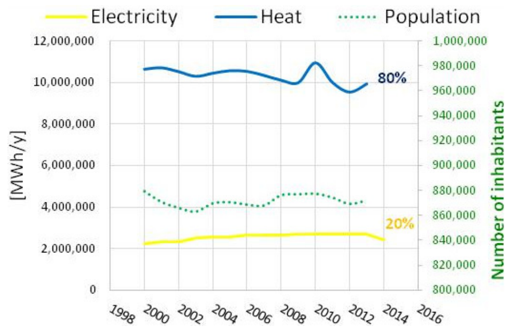

Figure 4a. Electricity and thermal energy consumptions (MWh/y) for the years 2000-2013 considering number of inhabitants

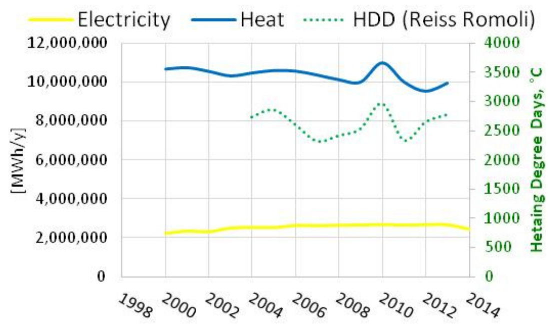

Figure 4b. Electricity and thermal energy consumptions (MWh/y) for the years 2000-2013 considering HDD at 20 °C

Energy consumptions and climate conditions

Electricity and thermal energy consumptions of Turin depend mainly on the number of inhabitants and on climate conditions. As shown in Figures 4a and 4b, thermal consumption depends on HDD at 20 °C and on per capita earning, while electricity consumption is more constant with a slight increase. Thermal consumption represents 80% of total energy consumption and electricity 20%.

For the analysis of microclimatic conditions, the HDD at 20 °C of five weather stations in Turin urban context – Alenia, Vallere, Giardini Reali, Consolata, Reiss Romoli (in Figure 3a) – for the last ten years have been considered (ARPA Piedmont Region: https://www.arpa.piemonte.gov.it/). As reported in Table 3, to normalize the annual energy consumptions with the relative HDDs, the Reiss Romoli weather station has been chosen with an average HDD of 2,620 °C and with more availability data, considering the years 2004-2013.

Table 3. Climatic data: HDD at 20 °C for five weather stations in Turin for the last decade

Year	Alenia	Vallere	Giardini Reali	Consolata	Reiss Romoli [HDD_{avg} = 2,620 °C]	Average
2004	-	2,956	-	2,590	2,733	-
2005	-	3,085	2,880	2,703	2,855	-
2006	2,594	2,870	2,648	2,425	2,605	2,628.4
2007	2,364	2,683	2,418	2,195	2,324	2,396.8
2008	2,633	2,933	2,680	2,472	2,419	2,627.4
2009	2,560	2,943	2,674	2,456	2,534	2,633.4
2010	2,972	3,215	3,007	2,767	2,963	2,984.8
2011	2,482	2,768	2,584	2,287	2,337	2,491.6
2012	2,684	2,947	2,764	2,473	2,649	2,703.4
2013	2,811	2,960	2,884	2,595	2,776	2,805.2
2014	2,337	2,481	2,448	2,116	2,283	2,333.0
2015	2,516	2,705	2,626	2,303	2,484	2,526.8
2016	2,581	2,753	2,589	2,366	2,552	2,568.2
Average	-	-	-	-	-	2,609.0

Energy sources and greenhouse gas emissions

Considering the different sectors, energy consumptions data for the city of Turin show that, the residential sector (Figure 5a in red, 59%) and the tertiary sector (Figure 5a in blue, 18%) have a major impact on total consumptions, the transport sector is decreasing and the agricultural sector is irrelevant. Relating to greenhouse emissions, the residential sector affects for 52% of total emissions and the tertiary sector affects for 25%, overall, the trend of emissions follows the trend of energy consumption (Figure 5b).

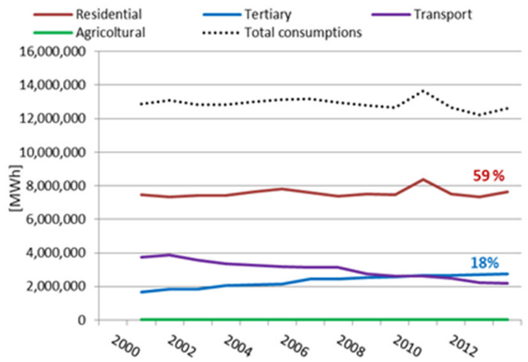

Figure 5a. The trend of thermal consumptions considering the different sectors: residential, tertiary, transport, agricultural

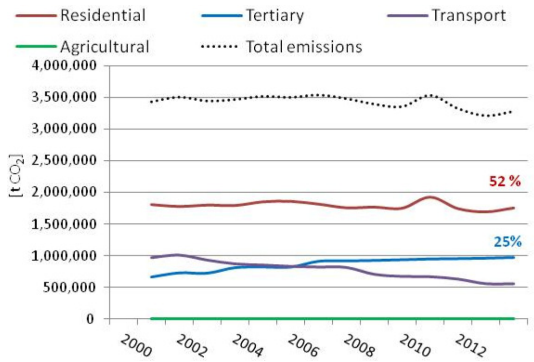

Figure 5b. The trend of greenhouse gas emissions due to thermal energy consumptions considering the different sectors

About energy sources, natural gas represents 56% of the energy resources, in particular, the residential sector and the tertiary sector are responsible for 79% of natural gas consumptions (Figure 6a). As shown in Figure 6b, after 2010 natural gas decreased due to microclimatic conditions and the increase of renewable sources. DH is steadily increasing and represents 15% of the energy sources (residential and tertiary are responsible for 20% of DH). Diesel, gas oil, petrol and fuel oil are decreasing. LPG has a non-uniform and slightly increasing trend. Solar, biomass and biofuels (renewable resources) constitute a small proportion of total consumption in 2013, but solar-thermal data shows that from 2000 to 2013 there has been a constant increase with a peak in 2011.

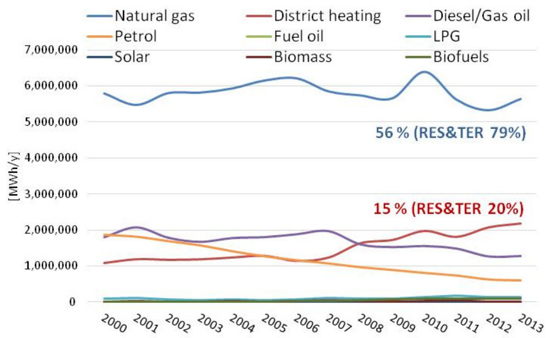

Figure 6a. The trend of thermal consumption distinguishing by energy sources and type of user

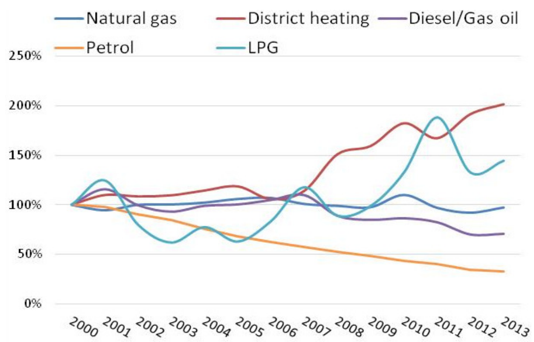

Figure 6b. Trend percentage of thermal consumption distinguishing by energy sources

District Heating network

The development of DH contributes to achieve energy saving, emission reductions and, therefore, a more sustainable development. Turin's DH network has been steadily increasing thanks to significant investments that have contributed to the economic development of the territory. Today, all cogeneration plants and DH distribution networks are one of the most advanced models at European level. The DH is continuously evolving, data supplied by the Iren company show that in 2013 the network was serving about 52 Mm^3 of buildings, in January 2016 it was serving about 59 Mm^3 through a network of over 500 km and 5,700 heat exchange substations, about 2,000 GWh/y of thermal energy are distributed by the network and over 98% of that energy is produced through cogeneration plants powered by natural gas. To define the trend of DH, real consumptions data available from the DH Iren company on 59 meshes of 1 km × 1 km in Turin have been used [20].

This analysis allows evaluating the buildings' volumes connected to the existing DH network and, therefore, the CO_2 emissions as a function of the energy consumption.

RESULTS AND DISCUSSION

Taking into account the residential sector and the tertiary sector, the energy resilience of Turin has been evaluated, as they affect for 79% of Turin's thermal consumption. The results show that heat energy consumption depends on HDD but also on per capita earning, as shown in Figures 7a and 7b, in fact for the year 2010 the thermal consumption was higher because of cold temperature (higher HHD). In Figure 7b, thermal consumptions have been normalized with 2,620 HDD and, after the 2007, an average decrease of 3% can be observed on normalized thermal energy consumption.

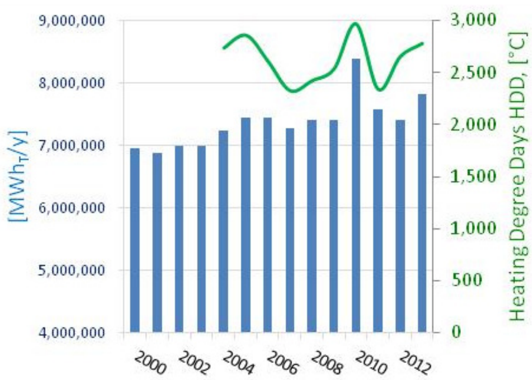

Figure 7a. Thermal energy consumptions (MWh/y) considering the HDD for the years 2000-2013

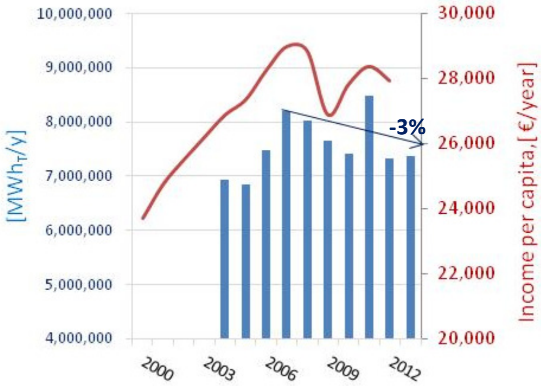

Figure 7b. Thermal energy consumptions (MWh/y) normalized on 2,620 HDD considering earning per capita

A similar trend can be observed on natural gas consumption, as natural gas is the most used fuel in Turin with an average percentage of 78% (2000-2013), while the 20% of the thermal energy is distributed by the DH network (Figure 8a). Every year, natural gas decreases by 3% while, in the last years, the DH network is expanding and then thermal energy distributed by DH is increasing by 8% (Figure 8a). Gas oil, LPG and all other fossil fuels are declining but they are negligible compared to natural gas and DH.

Electricity consumption depends on population but also on per capita income. As reported in literature, the exponential trend of per capita electricity consumption is a function of per capita income, energy price of the electricity and by the saturation impedance of electricity service (red dotted line in Figure 8b) [27].

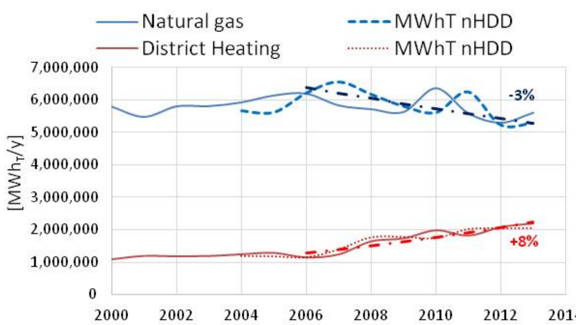

Figure 8a. The trend of thermal consumption (with HDD normalization) distinguishing by natural gas and DH for residential & tertiary buildings

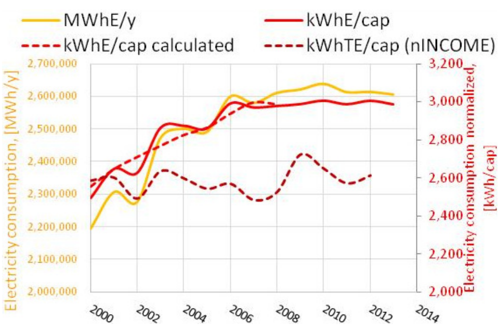

Figure 8b. The trend of electricity consumption normalized by per capita income for residential & tertiary buildings

As shows Figure 9a, greenhouse gas emissions are generally increasing but observing separately, the thermal ones are fairly constant if normalized with HDD and income, while electrical ones increase. In particular, thermal emissions depend on HDD and per capita earning or income, while electric emissions mainly depend on per capita income and on the electricity market (in Turin the population does not vary, ±1%).

Four future scenarios on DH expansion and on solar thermal collectors use have been assumed (Figure 9b): the first in 2030 considers the connection of the existing DH network to all "connectable" residential/tertiary buildings (35,679,069 m^3), the second in 2050 with the expansion of the DH network to all the city of Turin with the connection of other 12,802,847 m^3 of residential/tertiary buildings (see Table 2). Due to urban and technical/economic limits [20], 35% of residential/tertiary buildings cannot be connected to the DH network. In this work, the considered limits for the city of Turin are: the presence of territorial barriers as rivers and hills, the historic center of the city, the autonomous heating system installations and the buildings with a volume < 2,500 m^3.

The last two scenarios consider also a further use of +20% of consumption with solar technologies in 2030 and +30% in 2050. Finally, with this last scenario, greenhouse emissions will be reduced of 27% in the medium-term and of 39% in the long-term.

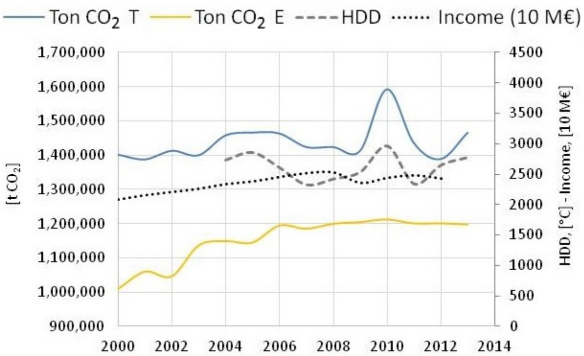

Figure 9a. Thermal and electrical emissions considering HHD and per capita income

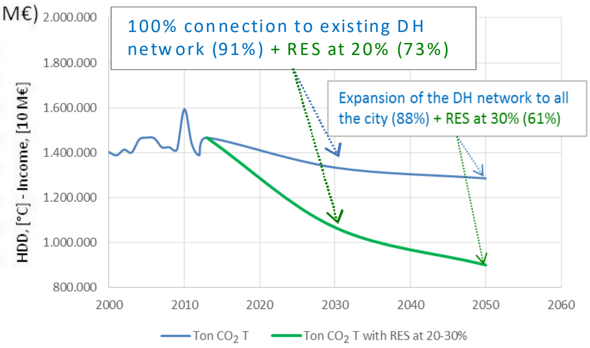

Figure 9b. Future scenarios on evolution of TLR and solar thermal technologies in medium (2030) and long-term (2050)

Results on Energy Security Index

In the last part of this work, the energy risk was assessed through the Energy Security Index (for the years 2000-2013, using Odyssee database for Italy). In particular, the method of aggregation of the normalized indicators was used to create the International Energy Security Index [28], an annual energy risk indicator used to identify the policies and other factors that contribute positively or negatively to energy security.

Two indexes for all sectors (residential, municipal, tertiary, industrial) and for residential sector have been calculated considering the following four indicators based on energy security and environmental sustainability:

- Energy security:
  - The importance of energy to individuals measured by energy consumption per capita (or per dwelling) – **1**;
  - The importance of energy to economic growth measured by primary energy per GDP – **2**;
- Environmental sustainability:
  - The importance of policies and economy on greenhouse gas emissions measured by CO_2 emissions annual trend – **3**;
  - The join effect of consumption per capita and carbon intensity measured by CO_2 emissions per capita (or per dwelling) – **4**.

All annual data of energy consumption, primary energy and GHG emissions were normalized with climatic corrections.

As mentioned previously, the different indicators have been normalized with the "Min-Max" method, equal weights were assigned to all indicators and, to evaluate the Energy Security Index, the additive aggregation method has been used.

In Figures 10a and 10b, the Energy Security Index was calculated for all sectors, while Figures 11a and 11b report data only for residential sector. The Energy Security Index is decreasing, for both analyses, mainly because all energy consumptions and the GHG emissions are decreasing, also due to the economic crisis (after 2008). This trend was confirmed by analyses on other OECD countries with an increase of the Energy Security Index up to 2008 and then a decrease [28].

The energy sector could be a good opportunity to give a boost to the economy also towards sustainability. In Italy, the energy sector needs to focus on more reduction of energy consumption boosting the available renewable energy sources, in particular, solar technologies (available also in urban spaces). Also efficient systems with low environmental impact, as DH, could be promoted in big cities together with smart urban planning to reduce energy consumption, CO_2 emissions with a mitigation of Urban Heat Island effects for a more sustainable and livable urban environment.

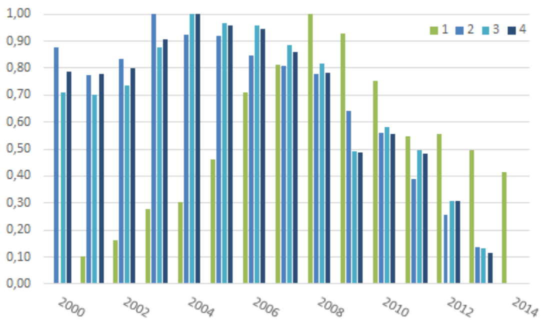

Figure 10a. Indicators of energy security and environmental sustainability for all sectors

Figure 10b. Energy Security Index for all sectors

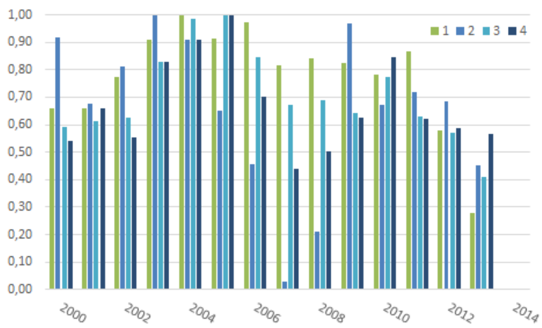

Figure 11a. Indicators of energy security and environmental sustainability for residential sector

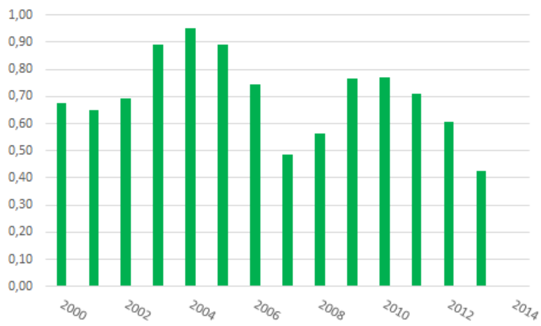

Figure 11b. Energy Security Index for residential sectors: (I1 + I2 + I3 + I4)/4

CONCLUSIONS

This analysis is based on a GIS tool, allowing one to associate the buildings information, from different sources and information levels, with a multivariate analysis, interpreting socio-economic data, technical building parameters (e.g. surface to volume ratio, period of construction, percentage of heated volume and energy demand) and the real characteristics of urban environments.

The procedure evaluated the energy resilience considering the ability of energy systems to absorb and recover from the impact of disruptive events without fundamental changes in function or structure. The method can be applied to other urban contexts, allowing a representation of the energy resilience taking account the energy risk, the sustainability environment, the socio-economic variables, the climatic conditions and the availability of different energy sources for a more sustainable city.

This study could be useful for identifying policies and practices to improve environmental and energy sustainability, for example, the results of consumption data showed that thermal and electrical consumption data depend on per capita income/earning then energy price could play an important role on energy security.

Indicators are useful tools for communicating energy issues related to sustainable development to policy-makers and to measure sustainable development strategies.

Energy security is difficult to measure using a simple indicator. If the number of indicators is small, the energy security index is generally very sensitive to changes in any of the indicators, conversely when number of indicators used is large. This study could be a starting point for future research by implementing the energy security index balancing stability and sensitivity of the index.

The methodology proposed in this study is influenced by the availability of data at urban scale. One of the main limitations in the use of indicators to quantify the energy risk is the need of data. Further research may be conducted to develop indexes that are robust against incomplete information and missing data.

Energy efficiency is essential for improving climate change. DH represents an opportunity for rational use of energy resources and local pollution control in critical urban contexts with high concentration of energy demand but it should be associated to energy consumption reduction and a larger use of renewable energy sources.

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