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ScienceDirect

Energy Procedia 111 (2017) 730 – 739

Energy Procedia

8th International Conference on Sustainability in Energy and Buildings, SEB-16, 11-13 September 2016, Turin, ITALY

The Second Law and the energy use mapping for sustainability planning

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Abstract

City sustainability is an inherently complex process, yet increasingly robust computational tools and digital data are emerging to assist with analysis and planning. Broadly speaking, scholars and urban planners have been developed a large variety of models that can estimate the building energy use aiming the implementation of urban energy reduction strategies and policies. In this paper we propose a brief up-to-date review of the aforementioned models, particularly focussing on spatio-temporal observation. The goal of this paper is to show how to integrate the urban energy use models and the growing attention towards to environmental impact, using Second Law of Thermodynamic for a more rational metric of city sustainability.

Peer-review under responsibility of KES International.

Keywords: Energy use; Exergy; Entropy; Sustainability; Environmental Impact; Urban planning; Rational use

1. Introduction

Energy is more and more essential for the wellbeing of growing urban citizens. The growing size of cities and the increasing attention to the environment, as a consequence of the climate change and pollutions, pushes towards the needs to minimize the urban footprint and to improve the energy resilience for citizens' social security. Buildings and mobility energy uses are main contributions of the overall urban energy use. Urban morphology and topology have also significant effects on urban climate. Recently urban planners first understand energy and socio-economic dynamics and environmental issues before the resolution of spatial issues in order to create more sustainable cities modifying mobility, energy and land use.

City sustainability is an inherently complex process, yet increasingly robust computational tools and digital data are emerging to assist with analysis and planning. Various modelling techniques are developed in order to estimate the building energy needs and to implement urban energy reduction strategies and policies. In the last decade, scholars and urban planners developed a large variety of models with different approaches and with specific purposes. The

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Peer-review under responsibility of KES International.
doi:10.1016/j.egypro.2017.03.235

citywide building energy model creates a very useful database. Various techniques of modelling and mapping at urban-scale energy use will be summarize as described in some reviews [1] [2] and in main articles that developed models for use efficiency in urban scale [3] [4] [5].

The goal of urban energy use analysis is the definition of energy saving, energy efficient strategies and urban planning strategies reducing the energy use and emissions. We propose a brief up-to-date review of the aforementioned models suggesting their strengths and weaknesses. In particular, we identified two distinct approaches: i) top-down and ii) (the most relevant) bottom-up. The common feature of these models is that they are able to compare the sustainability of different energy saving scenarios at building, district and urban scale, using the First Law of Thermodynamics (FLT) approach. The spatio-temporal observation and prediction is possible thanks to the Geographical Information System (GIS), using as a data allocation. Traditionally only energy analysis (FLT) is used in the buildings and urban system analysis: its efficiency is associated to a smaller environmental footprint, green construction, sustainability, the use of renewable resources, etc..

In order to derive an overall and complete environmental evaluation we can make use the Second Law of Thermodynamic (SLT) to investigate the relationships between material transformations, energy uses, waste generations and pollution into urban systems. We associate the environmental impact of energy use and the achievement of increased efficiency in energy system, evaluated by the SLT. In this way, a rational energy use scenario can be developed and evaluated in order to reduce the environmental impact of anthropogenic energy use. Irreversibility of the processes depends on the energy degradation rate, quantifying a scale of energy quality by SLT Law analysis. Exergy and entropy are both used to evaluate the energy sustainability of urban areas.

The indexes form a SLT analysis address towards a rational use of energy, but it falls for some environmental aspects as an ecological indexes. The goal of this paper is to show how to integrate the urban energy use models and the growing attention towards to environmental impact, in order to analyse a so large and so complex energy-environment systems. The necessary data for a SLT analysis can be easily integrated in the urban energy mapping, mostly are already included in existing energy use mapping. This modus operandi will allow us to define a metric of city sustainability which is not based only on the urban energy use but also on the overall environmental impact suggesting a more rational energy use. The thermodynamic tools from the SLT are useful for enhancing city sustainability in operation and design of the city of the future. It will also support policy-making and planning for managing energy consumption and use. The geographical location of energy and energy quality needs and complete thermodynamic analysis opens up new opportunities for rational use, for cascading plant, less waste heat and more energy resilience in order to pursue real sustainability.

Nomenclature

ESM Entropy Sustainability Method
FLT First Law of Thermodynamics
GIS Geographical Information System
SLT Second Law of Thermodynamic
UHI Urban Heat Island

2. Urban Modelling

In last decades, urban planners cannot solve spatial distribution of our cities apart from the knowledge of energy and environmental issues and socio-economic dynamics. So, they are forced to focus on a citywide mapping to create and to quantify a real sustainability. Every built environment is a complex and interrelated systems from the thermodynamic viewpoint, therefore complete models need to assess the impacts of the adoption of energy efficiency measures. Cities are open thermodynamic systems, they are composed of a high number of buildings and the energy performance of each building is very significant. From urban viewpoints, buildings can be seen as energy users, in which therefore energy carriers enter and leave obviously degraded. There are two main categories for urban energy use modelling: top-down and bottom-up. The two approaches are identified by IEA [6] as schematically shown in Fig.

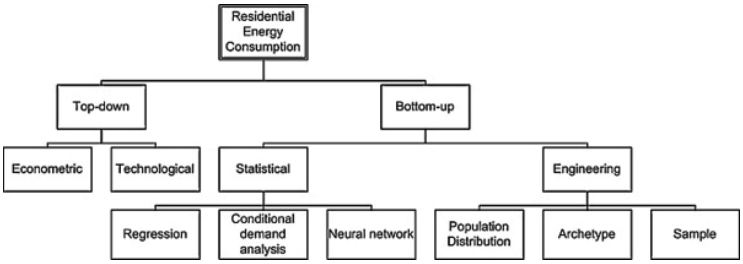

Fig. 1. Top-down and bottom-up modelling techniques for estimating the regional or national residential energy consumption [7]

1. Top-down and bottom-up approaches have the same purpose: the evaluation of energy uses of the energy sector as a whole.

2.1. Top-Down approach

A top-down approach works at an aggregate level. It aims to a historical trend construction of energy use considering the residential sector as a single sink of energy, so different end-uses are not considered. This method uses aggregate data of overall energy use associated with macro economy indicators (econometric models), such as the gross domestic product, the unemployment rate or the inflation, or the price of energy and the climate profile. These approaches identify an urban environment as a black box and the detail level is not at building scale [7].

2.2. Botton-Up approach

For urban analysis, a bottom-up approach is the most widely used and accurate. All the bottom-up approaches use an input data a lower hierarchical level data than the top-down approach. Through the bottom-up approach is possible to extrapolate the energy use not only at national, but also at regional, municipal or through the estimation of a representative set of buildings. A significant number of bottom-up approaches have been developed in order to achieve a space-time characterization of buildings energy services at the urban scale. The most relevant applications based on statistical, analytical or hybrid methods, proved simple and robust methods [8][4] [9] [10].

2.2.1. Statistical and analytical models

The statistical models are based on historical data. They provide energy uses of each building according to the building type, users profile and used equipment. They require a relatively small amount of information, and have a natural *inertia* estimating energy uses at urban scale [7]. Anyway, their resolution of space-time analysis [11] [12] provides a difficult characterization of energy services [13] [14] [15] and, consequently, not high accuracy. They prevents a not broad use for the study of energy efficiency at smaller scale then cities.

In contrast to statistical models, analytical models are based on a physical approach, studying complex urban thermodynamic relations and describing energy and material exchanges between buildings and users into the surrounding environment. The complexity of urban analytical models has to take in account a micro-climate resulting by urban geometry and energy uses. The *heat island* (UHI) is an urban climate phenomenon most widely studied [16], and the urban canyon between buildings [17]. Solar radiation, reflections, convention, and the amount of waste heat by energy users etc. are the main causes of a particular urban micro-climate. Many of these aspects define non-linear aspects because they depend on solar path, they are strictly related to the urban geometry and to their geographical location. All these aspects are interconnected, and a realistic thermodynamic behavior of an urban system is very complex. Some of these effects can be analyzed separately using specific software. The analytical model generally can produces a complete thermodynamic description of the urban system in almost any spatial or temporal scale [2]. The applicability of these models to the urban scale is limited because large amounts of data are required and because of the complexity in the integration of thermodynamic models.

A study in London [18] shows that downtown energy uses are so intense that the released heat cannot be overlooked. The density of energy use in rural areas is smaller and in urban areas is much higher than the energy received from the sun. The UHI is purely an urban phenomenon. The increases of average and peak air temperatures are the direct consequences, resulting in increases of cooling demands of urban buildings. Therefore, the air temperature varies from location to location within the same city, especially in the complex cities. The study concerning the city of London has found on an experimental campaign by sensors: the air temperature was measured continuously for one year in 80 locations on a radial grid. The result [19] shows that the London downtown is warmer than the surrounding areas (about 2K during all year, compared to average values). The measured data were used as input for a thermal simulation model to evaluate the variation of heating and cooling loads. The urban cooling load is 25% higher than results from reference year temperature and the yearly load decreases by 22%.

Through these models a full characterization of energy services in buildings is possible at any spatial or temporal scale. However, a vast amount of required data, the complexity and the computationally intensive modelling limited their implementation, especially of overall urban built environment [2] [1]. In order to overtake these issues and to reach significant results, some analytical models adapt existing software ([20]) or develop simplified simulation methods [21] [22], [23]). Adaptation and simplification processes usually consist in an integration of a large number of assumptions in the existing calculation routines, reducing the complexity of the model, and increasing uncertainty [2].

2.2.2. Hybrid models

New modelling approaches integrate statistical data input. These new generations of models are so-called "hybrid" in order to address the uncertainty of analytical methods, resulting from the necessary assumptions to reduce the complexity of urban physical phenomenon. Some of them make detailed energy audit use of buildings to build reference buildings to include in analytical models [7] [5]. Two categories of hybrid models can be identified according to spatial dimension: models with or without geographical referenced.

2.2.3. Hybrid geo-referenced models

An essential aspect characterizing some hybrid models, is a geo-referenced spatial dimension. By a GIS framework they can be necessary as a platform for the allocation and the future dissemination of space-time data. A geographical mapping allows to model an urban area using an intuitive data visualization. A statistical and analytical model has been presented by Balocco et al. [8] [3]): it estimates the energy requirements of each building based on a probability statistical stratied and simple random sampling design method, using the weighted allocation among the various classes of buildings and extending to the universe using a numerical map. The energy use map of the urban population of buildings is a useful tool for energy programming. It can be used to evaluate the retrofitting solutions and to quantify the influence of modifications of the building thermo-physical features. Moreover, a more realistic analysis and implementation of low environmental impact strategies using thermodynamic indicators are possible. An application of the method has been developed into *Energy and Environmental planning tool* of the Municipality of Florence [24]. In Fig. 2, buildings energy needs are mapped and many other data, as traffic, air pollution, CO_2 emission data etc. can be displayed (Fig. 3). All this information come from different database that the model integrates and can be extracted from the model.

Heiple et al. [25] implemented nearly 30 US reference commercial and residential buildings with an adapted version of eQUEST software. The authors calculate the power demand of space heating, domestic hot water and electricity in Houston and displays the results in a geo-referenced map using GIS. The Columbia University in New York [15] developed a geographical referenced model in order to analyze and to highlight the local energy use and to define the feasible solutions in the existing energy infrastructure. The model estimates the end-use intensity (kWh/m_2 floor area) for space heating, domestic hot water, electricity for space cooling and electricity for non-space cooling applications in New York City. The main assumption of the model is that end use is primarily dependent on building function and not on building age and construction type. The ZIP code level electricity and fuel use data come from the NYC Mayors Office of Long-Term Planning and Sustainability and other available data on energy performance in relation to the building's function. Fig. 4 shows the distribution of the yearly energy use of Manhattan. The spatially results of energy use can be a tool in order to determine energy policies and cost-effectiveness for realizing energy saving and sustainable solutions.

A research group at the University of Zurich has developed an integrated model for the characterization of the spatio-temporal energy consumption for neighbourhoods or entire cities. In order to a multi-dimensional and multi-scale analysis, the model integrates existing methods in urban and energy planning such as a geographical analysis

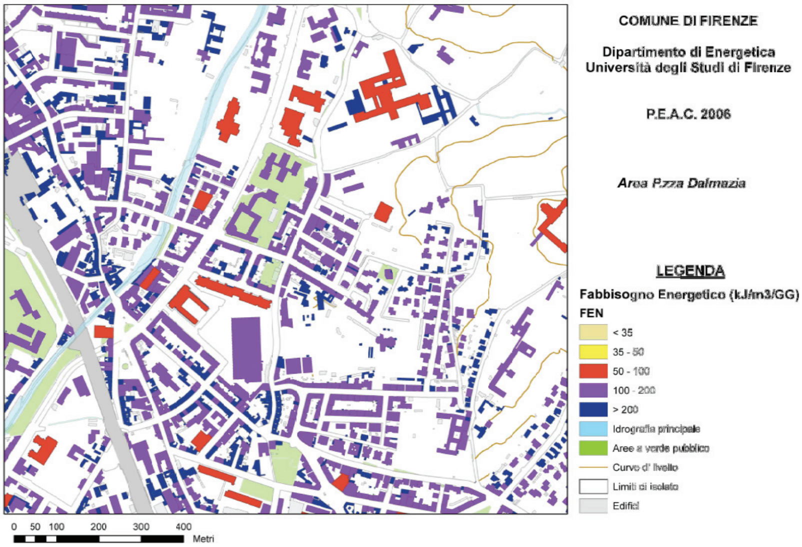

Fig. 2. Energy needs of an area of the city of Florence [PEAC Firenze, 2006]. (Translation of italian words: GG (Gradi Giorno) = DD (Degree Days), Fabbisogno Energetico FEN = Normalized Energy Needs, Idrologia principale = Main Hydrology, Aree a verde Pubblico = Public Gardens, Curve di Livello = Contour Lines, Limiti di isolato = Limits of block, Edifici = Buildings).

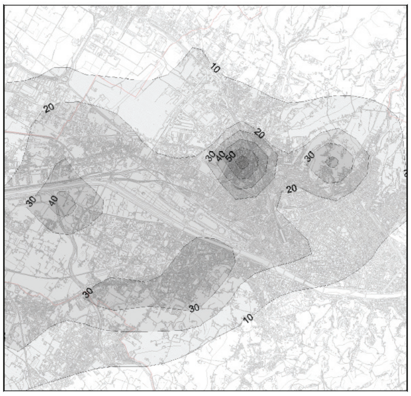

Fig. 3. Average PM10 concentration [$\mu g/m^3$] in Florence urban air [PEAC Firenze, 2006]

and dynamic energy simulation of buildings. This approach guarantees a good platform for the allocation and diffusion of spatio-temporal data. The quality (temperature) and the quantity (power) of six energy services of residential, commercial and industrial buildings are described, including heat waste sources. The model involves reference buildings (building archetypes), they are used in the dynamic energy simulation model. Furthermore, the model integrates spatial clustering algorithms to facilitate the analysis of energy usage patterns at a district scale. In addition, the model is innovative 4D interface to visualize the analysis of spatio-temporal data. The model is validated against measured data. An explanatory application has been made for a Swiss city of Zug (Fig. 5).

3. Critical analysis of modelling approaches

The main energy analysis approaches at urban scale were analysed and classified. Often, they are limited to residential and commercial applications, and they identify energy services such as heating, space cooling, domestic hot water and electricity. These aspects limit the detailed characterization of all energy services as a whole at building

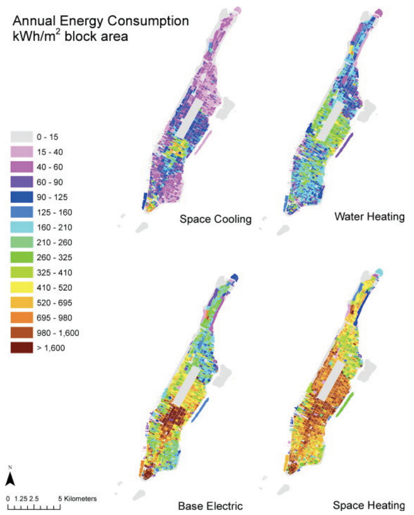

Fig. 4. Annual space cooling (top left), water heating (top right), base electric (bottom left) and space heating (bottom right) energy use by block area of Manhattan NYC (kWh/m2) [Howard et al., 2011]

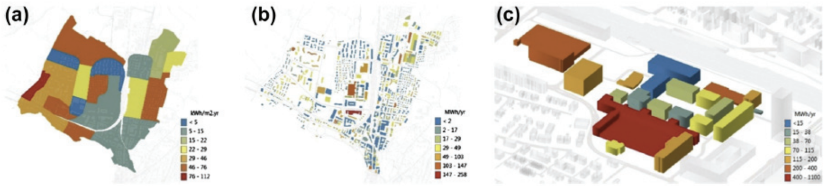

Fig. 5. Energy reduction potential due to retrofit of building envelope, (a) zones in the area of study, (b) buildings in the area of study and (c) buildings in the zone of interest [5]

and city scale. The detection of waste heat at low temperature as a heat sources is often lost. The model [5] identifies and includes the lost heat by buildings as a good energy resource potential. To obtain a detailed characterization of the energy use in order to analyse building and urban energy efficiency strategies, the construction of the urban geometry [8] [26] [25] [5] is essential for the evaluation of solar radiation intensity, of urban shading parameter and for the temporal response of energy services. The cornerstone of the urban energy analysis is the availability of data. One issue is often the lack of some kind of data determining the complete analytical structure of the models: some hypothesis are necessarily implemented in the urban energy use model [1]. In particular, three major issues have to be addressed: the first is the lack of public detailed data relating to all energy and materials flows into the buildings. In addition, assumptions and algorithms used in models make problematic any attempt to reproduce the results and validate models. The last concerns the uncertainty of the socio-technical drivers of energy use, i.e. how people use energy in buildings, and the way they react to changes in buildings as a result of energy conservation measures and how their behaviour change. At the same time, an important aspect concerns a possible development of data analysis into models. In addition to the traditional energy analysis for which they were built, the environmental preservation can be investigated. Thermodynamic indicators can be decision variables. The entropy variation or other parameters related to the SLT can address towards the strategy for a sustainable energy use at building and urban scale [27]. Thus, the energy use mapping can have benefits in terms of urban planning and rational energy planning. The use of an energy use mapping as a tool, also allows to predict the flows of energy demand of urban areas and to put in relation with the built environment. It permits to identify some possible solutions for improvement of energy infrastructure, for energy efficiency strategies for planning purposes. The results of the spatial and temporal models of demand can be linked to optimisation models of energy systems which may include a conversion systems and to an advanced storage analysis, an integration of local resources and energy use analysis by mobility analysis including electric vehicles. The results of GIS maps are also a cognitive tool to analyse and to collect spatial data with other areas of expertise [28]

[29]. For example, specialized software for infrastructure management can be used (as an example TERMIS [termis, 2012]) and to map the real time data, from sensors, can be implemented. In terms of urban-energy design, a geo-referenced tool provides the opportunity for planners to analyse the environmental impact of urban forms. The local variables can be analysed to demonstrate that the energy efficiency is possible through the analysis and optimization of local infrastructure and energy use. In addition, to get more and more complete picture of urban energy services, the layout of the service networks, resource allocation and public mobility [30] can be integrated to the same mapping of buildings energy uses, thus identifying sustainable forms of urban development.

4. Thermodynamic indexes

The urban energy use mapping could be improved using a complete thermodynamic approach. The built environment together with the urban-social organization can be considered a complex open thermodynamic system [31]. A geo-referenced tool can be useful for a geographical identification in order to develop a real spatial analysis, taking in account different location of each building, urban physics aspects and urban energy forms [31]. The ultimate aim of energy use map can be to quantify and to evaluate the energy use efficiency and the sustainability of urban areas. The energy analysis and most of the sustainability and ecological indexes are based on FLT. Consequently, the building energy saving solutions are based only on energy balance. In order to an overall evaluation of sustainable energy uses, the SLT aim to a rational energy use quantifying the energy quality. Also the national energy planning is based on the FLT. Introducing the SLT, a more complete urban energy evaluation is developed by some authors [3] [31][32].

4.1. Exergy

According to the FLT, energy is neither created nor destroyed like everything else in nature, but is conserved. Therefore, it is difficult to say that an amount of energy is wasted, unless it is not directly dispersed into the environment. As a result there is the problem of defining the criteria for assessing the efficiency of energy conversion. For the SLT all forms of energy are equivalent. The exergy, provides a measure of the quality of energy, which can be more or less available, depending on the conversion efficiency into mechanical work. The mechanical work is the most precious form because it can be converted entirely into heat, while reverse is not possible. The loss of quality connected to internal transformations in a building is represented by the increase in entropy due to the system performing the transformations.

Bejan's [33] definition is *Exergy is the maximum theoretical useful work (shaft work or electrical work) obtainable as the systems interact to equilibrium, heat transfer occurring with the environment only*. Exergy is a measurement of how far a certain system deviates from a state of equilibrium with its environment. The concept of exergy is widely explained.

By using the exergy concept, various types of resources used in a society in terms of a common physical unit can be described [34]. Exergy allows the description, using a single indicator, of the contributions of thermal, chemical, physical, etc. ...of human - environment interactions[35]. In the real processes, exergy consumption is related to entropy production due to irreversibility [36]. So the exergy takes into account the entropy increase in the environment due to the natural and anthropic process. The connection of the exergy concept with the broader sense of *environmental issues* is also likely to be explored in more depth. [37]. Others several authors have linked the exergy concept with insights on sustainable energy supply and sustainable development [38] [39] [40]. A definition of *exergy sustainability* is given by Robinett [41]: *the continuous compensation of irreversible entropy production in an open system with an impedance and capacity-matched persistent exergy source*.

Among the biophysical metrics, exergy has been widely used as a thermodynamic property of a system, and some authors ([40]) have advocated using the exergy concept as a sustainability indicator, while others have based their buildings designs on exergy (e.g. *Minimum-energy house* built in 19821983 by architect Jon Kristinsson).

Exergy and buildings are strictly connected: exergy is a thermodynamic concept that clearly identifies the improvement potential of an energy system, thus opening up the possibility of increasing building efficiency. For this aim, all energy flows involved, fossil and renewable, must be analysed. This allows showing the thermodynamic efficiency of using different energy sources, independently of their renewable or fossil character, and allows a common basis for the comparison of different energy sources and uses.

The application of the concept of exergy in the built environment, on buildings scale, is growing, although it is still mainly in the field of research rather than used in daily practice [**?**]. Many scientific publications and research projects on the topic have taken place. Annex 37 *Low-Exergy Systems for heating and cooling* [42], Annex 49*Low Exergy Systems for High Performance Buildings and Communities* [43], Cost C24 *Analysis and Design of Innovative System for LOW- EXergy in the Built Environment: COSTeXergy* [44] and Annex 64 *LowEx Communities* [45] are European research projects.

From anthropocentric point of view, exergy is indeed a direct measure of the irreversible entropy generation of a process, but it is not a completely acceptable evaluation of its environmental impact, because it fails to properly account for toxicity-related chemical pollution phenomena and for non-energetic externalities (*non-thermodynamic effects*).

Finally, the evaluation of energy and material flows through the urban system and internal transformations describe the variation of available natural resources and constitute a good support for energy and urban policy.

Some applications of exergy analysis to large-scale spatial planning can be considered an emerging field too: recent works are *Energy Potential Mapping methodology* developed by Dobbelsteen [46] [47] and some publications resulting from the SREX project *Synergy between regional planning and Exergy* (www.exergieplanning.nl), such as Stremke [48].

4.2. Entropy

Energy use, material transformation, waste and pollution generation can be investigate by a thermodynamic approach using the concept of entropy. A thermodynamic processes is said to be irreversible if there is not a way by which both the system and its surroundings can be exactly restored to their respective initial states [33] [49]. The sustainability of resources use is connected to low level of irreversibility according to the SLT and the Gouy-Stodola Therorem [50][51]. The irreversibility processes are related to the entropy assessment of a system, according to the SLT, that takes in account how the resources are used. In statistical mechanics, the information theory is tied to the entropy evaluation: for a thermodynamic system a reduction to lower entropy values means an information increase. Real sustainability can only be obtained if total irreversible entropy flux, due to human activities, is lower than the neghentropy flux from the sun. Using energy and also renewable energy, an irreversible entropy flux is always produced. It has to be reduced as much as possible to reach sustainability, in comparison with the flux due to solar energy degradation, when absorbed by the earth [52].

Therefore, an application of this thermodynamic index to urban system is useful. The entropy evaluation can be essentially used to quantify the impact of some building and urban energy saving solutions. The anthropogenic effect on energy and material use on urban system can be measured. In order to reduce the anthropogenic entropy flux due to irreversibility and to programme energy saving solutions, some data have to be collected in to a urban energy use mapping. Balocco et al. [27] proposed a method to evaluate and compare alternative project solutions that aim at energy saving technology applications to building-plant systems for the sustainable development of a studied urban area. The method, called Entropy Sustainability Method (ESM) uses a matrix technique by spread-sheet modelling. It is a possible application of information theory for urban system analysis using Shannon's entropy analysis. This method evaluates and compares project solutions using the information theory application proposed by Butera [53] and Brillouin [54] approach. The ESM, if applied to different urban areas, can provide a rational criterion to compare complex innovative and sustainable technologies for irreversibility reduction and energy efficiency increase.

Balocco et al. [27] [52] proposed some indicators, based on entropy: they allow evaluation of the sustainability of energy use. The defined parameters are useful for energy planning of urban areas, and for defining the scenarios of integrated low environmental impact energy strategies and actions in an urban area. . One entropy indicator quantifies the entropy variation due to the total energy losses of buildings and the entropy variation due to solar gains of the same urban area [3] [52].

5. Conclusion

An integrated model for the characterization of spatio-temporal models of energy use in buildings, should be in a multi-scale and multi-dimensional analysis of scenarios of energy strategies. In the planning process, a geo-referenced approach constitutes the basis for the collection of energy data and other areas of expertise. Any 4D visualization, including the dimension of time, results in excellent catalyst for discussions about the future of our cities, because it allows a more intuitive description of phenomena linked to buildings energy use and its spatial and temporal interaction between them and with other uses. Furthermore this allows the integration of real-time data. The main death of all these models is their lack of transparency regarding the data and quantification of the inherent uncertainties. The lack of public data, disaggregated and detailed input and output from the models, makes it difficult to attempt to reproduce the real scenario [1]. Some existing models show they can be a low-complexity tool using an intuitive interface, and help a preliminary analysis of energy efficiency measures, urban zoning and identification of energy waste. These tools will facilitate the quantification of energy use and CO_2 emissions, and in the future also the qualification of energy use using the SLT. Urban Energy Use Mapping can be used not only to visualize energy uses and what derives from energy use (emission and pollution evaluations) but also to visualize the quality of energy, i.e. the entropy through developed thermodynamic indicator, generation in order to achieve a rational urban energy saving solutions. Therefore the evaluation of energy and environmental retrofit options to finding a compromise between urban form, energy and/or mobility infrastructures, thus constituting an important instrument for the definition of urban policies, can be possible.

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