Applying exergy analysis

to an urban district thermodynamic system

Marta Giulia Baldi [a]

[a] *Department of Civil and Environment Engineering-University of Florence, Florence, Italy, marta.baldi@unifi.it*

Abstract:

The exergy analysis method has been contemplated to evaluate the energy impact on the environment of an urban district. The second Law analysis evaluates rational energy use from a thermodynamic point of view decreasing energy carriers' quality levels. The urban district scale has been chosen for two main reasons: the first is the importance to evaluate complex system where buildings are a part of a surrounding network. The second one is urban district scale includes highly integrated solutions that are not apparent on the scale of a building. The model is carried out considering the control volume as an open thermodynamic quasi-stationary system, not in thermodynamic equilibrium to the environment. The environment can be considered as a closed dynamic system: the urban district system continuously utilizes and exchanges energy with the environment. The ultimate aim of the model construction is to estimate surrounding impact of energy saving strategies and measures and to evaluate their "energy unsustainability".

Keywords:

Exergy, Urban district, Thermodynamics, Environmental impact, Energy needs.

Introduction

Green buildings, NZEB (Net-Zero Energy Building) and sustainable buildings are the main topics in building engineering research. The real building heritage energy problems are concentrated urban areas, which make up our city. They are articulate systems, consisting of macro-elements such as infrastructure and buildings and micro-elements such as networks, users ... etc. This interpretation of the territorial systems is an example of Very Large Complex System (VLCS).

A city is a system composed of mono-functional urban areas, but is often mixed residential, crafts, services and industry. An urban area is analysed as a unit. It's a macro-element. The urban district scale has the same complexity as the system's largest "city", but reduced to technical feasibility. This consideration will be best explained later.

If we exclude old town centres, if they exist, the cities are made up of buildings constructed in the last century with poor or medium energy quality. These make up large areas. These parts of the city were born in different years and often didn't have modern rules in place yet. Unfortunately, urban planning unfortunately in the past, and often even now, does not consider environmental impact and/or networks efficiency. Even today urbanism does not look at the configuration and layout of the form of macro and micro-elements and networks, but is based on other considerations, like landscaping and others.

Ultimately, planners cannot address spatial problems in cities without first understanding environmental issues, and energy and socio-economic dynamics. Therefore, more effort is required to coordinate transportation, energy and land use planning and to create more "sustainable" cities [1]. The ultimate aim of this work is to use exergy to address urban planning, especially requalification of existing areas [2].

Anthropic action has an impact on the natural environment [3]. From a thermodynamic point of view the natural environment destroys its potential due to natural processes. Anthropic processes

increase the destruction velocity of this potential [4]. Anthropic actions may be more or less tolerable by the environment: it may take more or less time to neutralize them.
In this scenario, the anthropic action would be sustainable if decreases the natural degradation of thermodynamic potential: in this sense it would help Nature. The anthropic action increases the destruction velocity of resources and it cannot be sustainable for the natural environment. In our opinion and according to author of [9] it is thus more appropriate addressing the anthropic action as "unsustainability concept". The unsustainability of anthropic action and its impact on the environment are directly proportional.

1. Environmental Impact evaluation

Weighing out anthropic actions on the environment is very difficult. The systems complexity distances the model solution from the reality. Currently in the building sector, "unsustainability" of an action on the environment is still undefined. There are environmental certifications, rating systems, energy certifications and other environmental indicators used to try to define what is sustainable. These evaluation techniques all arise from two streams of logic:

• qualitative;
• quantitative.

Some of them include both, weighting subjectively the two logics.

1.1 - Sustainability assessment

Most of these methods evaluate exclusively through qualitative logic. The evaluations that can be made through these systems are not entirely objective. The buildings, neighbourhoods or otherwise, are classified in response to many requirements of "good". Some of these classification systems also affect urban districts, extending the analysis to the presence of and eventual quality of urban services (public transport, cycling, distances, services, etc. …). The calculation of the cumulative energy demand is derived from a quantitative logic, often from a dynamic analysis of consumption that integrates the subjectively derived to scoring approach.
Among them the most famous are the BREEAM (Building Research Establishment Environmental Assessment Methodology), assessment method of sustainable buildings, and LEED (Leadership in Energy and Environmental Design). They are rating systems. More than 600 sustainability ating systems are available worldwide [5]. All these are made up of subsystems that have different requirements depending on the scale, building type, and whether or not it is a renovation or new construction. These methods are sometimes shaped as a function of the thermo-physical properties or laws of the country that endorses them. They can be adopted as mandatory or optional methods.

All these aspects increase the evaluation uncertainty and the definition's complexity of criteria ever more ad hoc doc according to the object under analysis.

The existence of a lot of sustainable assessment methods complicates a uniqueness required for an international comparison.

From the analysis of sustainability assessment's analysis, it is derived that the classification of the sustainability of buildings is very different from the quantification of its energy impact on the environment, such as it is been defined in the next section.

The existence of this type of evaluation, even unique, is powered by a simple and intuitive approach. Sustainability building certification programs and rating system are used worldwide, with the only exception being Africa and Latin America (left out South Africa and Brazil). Among the positive aspects is that the dissemination of these assessment has increased awareness of the concept of "sustainability".

1.2 - Ecological Indicators

Ecologists have developed and tested methods for monitoring, assessing, and managing ecological integrity through the use of indicators of ecological change, referred to as Ecological Indicators (EI). In literature [6] *a concise and unambiguous definition of an EI is the following: an EI is an aggregate, quantitative measure of the impact of a "community" on its surroundings (environment)*.

The proper use of EI is to measure the impact of a "community" on its environment. EIs ought not to be used to establish value rankings or to provide guidance in ethical or social issues. It can only be used to assess an industrial process, a societal sector, an economic strategy applied to a society or other, inserted in a completely specified environment. Within these bounds, it may be used to compare alternative scenarios.

In literature, an analysis [6], based on exergy, of some main existing EIs (Material Throughput Analysis, Embodied Energy, Emergy and Environmental Footprint) was presented.

1.2.1. Material Throughput Analysis

This is based on the assumption that the lifestyle of any community can be measured by the global equivalent material flow needed to produce the commodities on which the group thrives. The method is based on disaggregated accounting of the material inputs and outputs in a community and requires detailed knowledge of its production processes. The material flows are connecting to the primary resources from which they originated. MTA is expressed by a numerically expression and can be calculated on the basis of a univocal method.

1.2.2. Embodied energy

The method evaluates the amount of energy used to construct a building, or other product, in terms of extraction of materials, manufacture, transport, and on-site construction. It also includes proportions of the energy consumed in manufacturing the machinery and vehicles involved in these processes together with the construction and maintenance of the associated buildings and roads. A limit is system complexity: a full evaluation of the Embodied Energy of any realistically relevant process can be very onerous.

1.2.3. Emergy

This EI is another way of accounting for energy, based on the assumption that the only input that matters is the solar radiation. Emergy is the availability of energy of one kind that is used up in transformations directly and indirectly to make a product or service [7]. Calculations of emergy production and storage provide a basis for making choices about environment and economy following the general public policy to maximize real wealth, production and use [8]. The EI of a commodity is the emergy content. Emergy does not include any measure of the different qualities of the energy flows it includes in its accounting. The definitions and the procedures employed in Emergy Analysis are First Law-based, and they neglect or misrepresent Second Law issues [9].

1.2.4. Ecological footprint

Ecological Footprint is defined as the amount of land and water area a person or a human population would need to provide the resources required to sustainably support itself and to absorb its wastes, given prevailing technology [10]. Ecological footprint estimates how much we have to reduce our consumption, improve our technology, or change our behaviour to achieve sustainability [11].

1.3 - Life Circle assessment

Life Cycle Assessment (LCA) was mainly developed to examine the environmental cradle to grave consequences of making and using products or providing services. As products, buildings are special since they have a comparatively long life. They often undergo changes, have multiple functions, they contain many different components, they are locally produced, they are normally unique, they cause local impact, they are integrated with the infrastructure, and have unclear system boundaries, etc. This implies that making a full LCA of a building is not a straightforward process like for many other consumer products [12].

The Exergy Life Cycle Assessment (ELCA) uses the same framework as the LCA, but the only criterion is now the life cycle irreversibility, the exergy loss during the complete life cycle [13]. In the ELCA it is shown in which component the losses of natural resources take place. With this information better proposals for reducing the loss of natural resources can be obtained. The ELCA can be used together with the LCA. When the ELCA is used separately, it is often used to reduce the use of natural resources or the costs associated with their use [14].

2. Buildings evaluation

The building interaction with environmental context and with energy infrastructure, which leads to an energy sources consumption and to a greenhouse gases emission, implies its non-neutrality on the environment. In the referenced European scenario, the renewable energy will be having a more and more important role. A building interacts bi-directionally with energy infrastructures. The building requires energy during its useful life: it has a double impact on the environment for its emissions and for the use of non-renewable energy resources.

A building uses energy throughout its life, i.e. from its construction to its demolition. The building energy needs during its life cycle are both direct and indirect. Direct energy need is for construction, operation, rehabilitation and demolition. Whereas indirect energy need is for the material production used in its construction [15,16].

Currently, the building energy efficiency is measured by the amount of direct energy it uses, in line with legislation. The European Union has defined Energy Performance (EP) through two indices [17]. The concept of “efficiency” in the current regulations is interpreted by limiting energy demand and greenhouse gases emissions. The current normative methods for building Energy Performance assessments are able to evaluate the impact in terms of primary energy and greenhouse gases. They should not ignore the energy sources appropriate use of energy sources. This aspect is not considered by the European Directive.

Evaluating only primary energy and CO_2 equivalent emissions is not sufficient on learning to the energy sources appropriate use. In addiction to an energy analysis, some researches [18,19] have accounted for other measurement units, such as exergy or emergy.

3. Buildings direct energy impact on the environment

The European Union has defined Energy Performance: this assessment is a quantitative method related to the First Law: it is only a small part of the complex evaluation to the computing the environmental impact.

The result of EP assessment is a partial and ineffective response to the requirements of appropriate and rational use of energy sources. The rational and appropriate use of energy sources is the key element of our definition Building Energy Impact (BEI) on the environment. We [20] believe that to build or to renovate an “efficient” building means to minimize the Building’s Energy Impact on the environment.

Currently, ideas about a building’s impact on the environmental (such as a process or otherwise) are following different paths. The most complete approach is the life cycle assessment, which accounts for direct and indirect energy and natural resources. Exergy Life Cycle Assessment ("ELCA") is a method based on LCA and on the first law and second law. It is reliable and realistic and could be a good guide for future development. In literature, it was proposed to "extend" the Second Law analysis to exergo-economics criteria. [6]

The extension of the Building's Energy Impact is a environmental impact, which also includes the Second Law analysis.

The Building's Energy Impact considers all the energy used construction phase, during the useful life and in the process of demolition. It should also include both direct and indirect energy. This paper analyses only direct energy: Building's Direct Energy Impact is defined, referred a year of useful life. The Building's Direct Energy Impact includes an analysis based on 1° and 2° law of Thermodynamics, for this reason it includes EP (Fig.1): it includes two complementary analysis: energy and exergy ones.

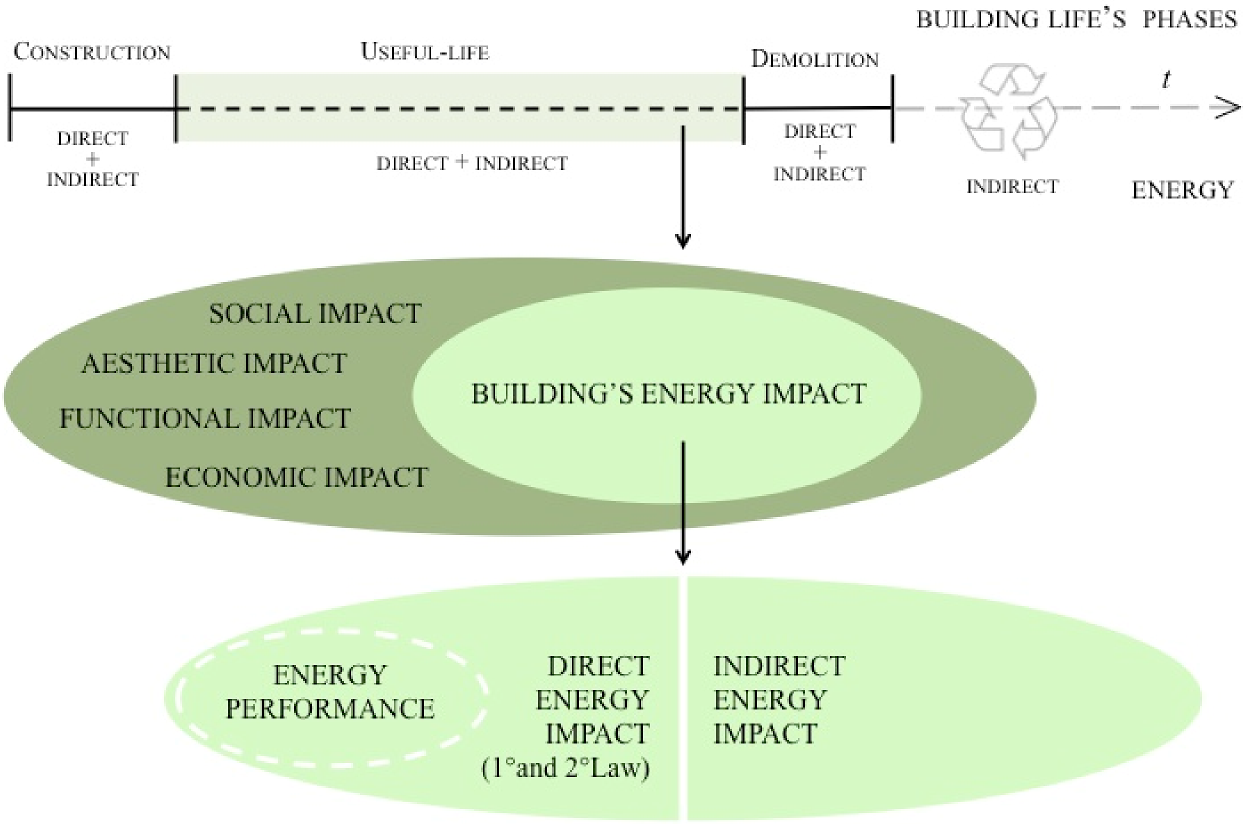

Fig. 1. Building's Environmental impact scheme.

The second is able to solve some problems present in the first one. At the same time the exergy analysis application as an evaluation parameter allows a complete thermodynamic assessment of a building's energy use, because it accounts the potential of the energy carriers that cross the system boundary and their degradation, in addition to the energy conservation equations [20]. Second law analysis is the basis to measure the energy carrier's quality and rationalize energy use from thermodynamic point of view.

3.1. Exergy performance

Exergy is defined [21] as *an extensive property of a system such its change in value between two states is equal to the adiabatic work between these states*. Energy manifests itself in several forms: the Second Law of Thermodynamics evaluates the quality of energy. Exergy efficiency is calculated as the ratio between the thermodynamic potential output to input one.

The concept of exergy has been developed to provide a congruent and coherent quantification to the quality of energy form [22]. Nowadays in literature, many authors [23, 24, 25] write of exergy. They define an exergy order to energy forms, from highest to lowest quality. Mechanical, electrical energy forms can be ideally converted into each other with maximum efficiency. There are other low quality energy forms, such as internal, chemical and thermal energy, that cannot be converted into a high quality energy form without transformation loss.
In comparison to energy (energy is a function of the state of the considered matter only), exergy is a function of the state of the considered matter and of the common components of the environment [26].

Once you define the energy need for a given building, it is possible to use different energy carriers to fuel it, obtaining the same overall energy efficiency, but different overall exergy efficiency. The building energy performances expressed by the First Law indices are not able to give a complete Building Energy Impact assessment. The calculation based on the Second Law efficiency allows reducing the ”quality” of the energy source used in a building reaching the same useful effect. The second Law analysis evaluates rational energy use from a thermodynamic point of view decreasing energy carriers’ quality levels.

4. Exergy on Buildings, urban district and city scale

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 [27]. Many scientific publications and research projects on the topic have taken place. Annex 37 “Low-Exergy Systems for heating and cooling”[28], Annex 49 “Low Exergy Systems for High Performance Buildings and Communities”[29] and Cost C24 “Analysis and Design of Innovative System for LOW- EXergy in the Built Environment: COSTeXergy” [30] are European research projects.

The application of exergy related to large-scale spatial planning and on built environment can be considered an emerging field: recent works are ”Energy Potential Mapping methodology” developed by Dobbelsteen [31,32] and publications resulting from the SREX project ”Synergy between regional planning and Exergy” (www.exergieplanning.nl), such as Stremke [33].

4.1. Urban district direct energy impact

A city is a system composed of macro and micro elements: buildings and communication networks on one side, and information networks, water system and users on the other...etc. The distinction between ”micro” and ”macro” refers only to the physical scale. A city is an example of VLCS (Very Large Complex System) on the territorial scale, where energy and urban systems, micro and macro elements are connected. A city is composed of many urban areas. There are some mono-function and others multi-functional (residential, crafts laboratories, services and industry). An urban area has the same complexity as the system’s largest ”city”: the difference between ”city” and ”urban district” is but reduced to a technical feasibility. An urban area is a unitary entity of analysis.

4.2. Thermodynamic system and surrounding

An urban area is defined as a sum of buildings, they are control volume. Physically the system includes only buildings and infrastructures. The model structure is very similar to that of a standard energy analysis. Urban area is an open thermodynamic system: it exchanges with the environment energy and material fluxes. Each exchange has an associated exergy (thermo-mechanical and/or chemical) defined with respect to a reference environment (1). Thermo-mechanical exergy is composed from physical, kinetic and potential exergy (2). Kinetic and potential exergy are not computed. The rate of physical exergy exchanged from buildings excluding mechanical exergy (3) is defined. The useful output from the system is always equal (for high quality energy) or lower (for low quality energy) than the useful input. In exergy balance of a system, the difference is dissipated as a low temperature flux into the environment.

$$Ex = Ex^{TM} + Ex^{CH}, \quad (1)$$

$$Ex^{TM} = Ex^{PH} + Ex^{KN} + Ex^{PT}, \quad (2)$$

$$\frac{dEx_{cv}}{dt} = \sum_j \left(1 - \frac{T_0}{T_j}\right) \dot{Q}_j - \dot{W}_{cv} + \sum \dot{m}_i\, ex_i - \sum \dot{m}_e\, ex_e - \dot{Ex}_D, \quad (3)$$

The urban area is not considered to be in thermodynamic equilibrium with its surrounding and continuously utilizes and converts energy. Physically the system includes only buildings and infrastructures. Air and land are considered part of the surrounding. Exergy can be considered a property of the interactions between the open system and its surrounding [2]. It is defined at constant pressure p_0 and temperature T_{0h} variable hour by hour during a Test Reference Year. A diagram that shows the temperature range T_s of system changes from 20°C to 25°C (Fig.2) and T_{0h} is been elaborated.

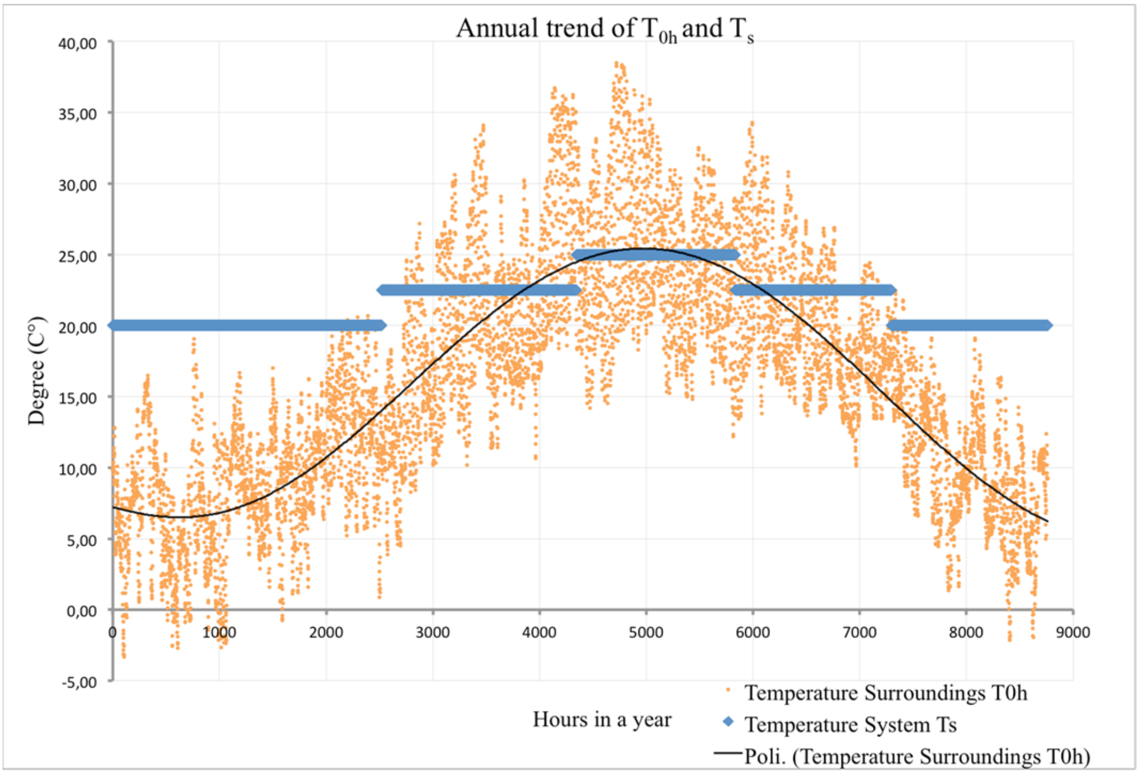

Fig. 2. System temperature T_s and surrounding temperature T_{0h} trends.

4.2.2. Boundaries definition

The main rules for the definition of an urban district are: area confined by physical barriers such as rivers/canals, railways or major communication roads. The urban area considered is into the Municipality of Florence. The data from the analysis of the urban area of Florence was used in model construction. The model is the function of the place upon where it is applied. The urban system positively meets requirements just written and includes 1600 buildings. Figure 3 shows the system boundaries with a blue line: red lines identify the 5 neighbourhoods of Florence Municipality. The downtown is in the central neighbourhood, crossed by the river Arno.

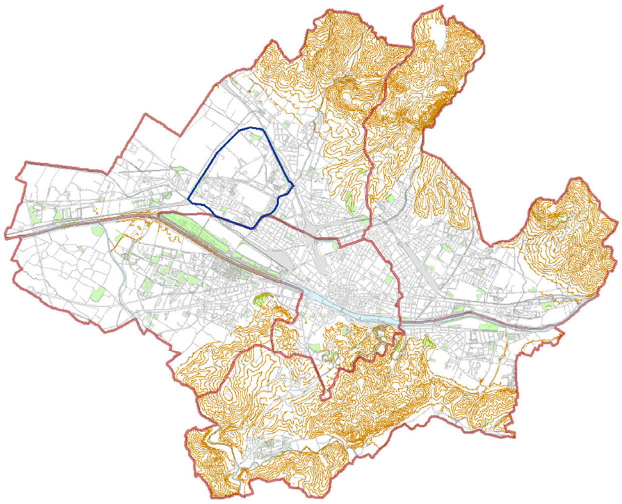

Fig. 3. Municipality of Florence: blue line identifies analysis area.

4.2.3. Control Volume definition

The system ”urban area” is crossed by energy and material flows. In this article only the heat flux is analysed. The heat flux is exchanged by conduction through the buildings envelope with the environment air or with the ground.

The database used is part of the Florence Municipality energy-environmental plan 2006. It includes a geo-referenced database. The Department of Energy Engineering of the University of Florence worked on the Plan preparation, in particular for energy consumption assessment. A statistical method to evaluate urban energy needs is the basis of the data [34]. Using the ARC/INFO program, it was possible to obtain the energy use maps of the population of buildings in the urban area chosen. The database includes buildings vintage, energy use, thermo-physical parameters, power and heating systems vintage.

4.3. Thermal Exergy model

The model calculates thermal and exergy fluxes in and out of system boundary. Currently, buildings require mostly low quality energy for thermal uses at low temperatures and nowadays their energy demand is mainly satisfied with high quality sources. In this paper the thermal exergy model considers only a bi-univocal energy flux: heat flux through the buildings envelope. The heat flux is exchanged by conduction through the building envelope with the surrounding air or with the ground. Globally the Thermal Exergy Balance considers only thermal exergy of all energy and matter fluxes: in this paper the model considers only heat flux (4). The chemical component of exergy is not calculated.

$$\frac{dB_{cv}}{dt} = \sum_j \left(1 - \frac{T_0}{T_j}\right) \dot{Q}_J - \dot{B}_D, \qquad (4)$$

Through energy use data, the urban district exergy loss is calculated. (Fig.4). This amount of exergy is mainly a function of the building’s envelope’s thermal performance.

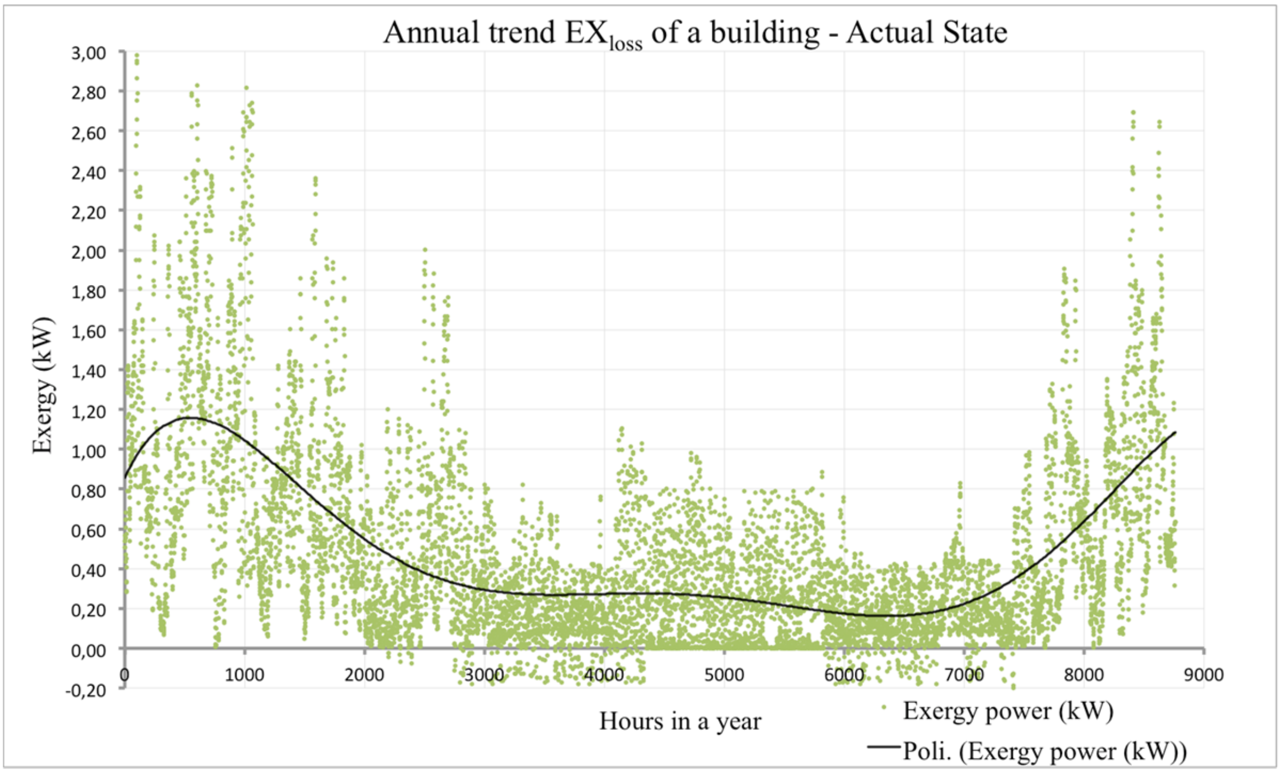

Fig. 4. Exergy power loss referred to heat flux.

The model's results become significant comparing the "Actual State" results with those of the "Varied State". The main energy saving interventions can be: building envelope and/or individual heating and cooling systems redesign, cogeneration and a district-heating plants build…etc.

The method allows the designer to compare different design solutions considering both quantity and quality of energy. Moreover the model is free from calculation uncertainties resulting from national energy infrastructure and/or from political decisions, because the energy sources are weighted by thermodynamic parameters.

4.4. Conclusions

In this paper we presented a research line that we intend to pursue, obtained from the combination of two important and large topics, such as environmental impact and energy performance.

Energy end-use data, geometric characteristic of building, statistics data of electricity use, standard data of water consumption and heating system typology, etc are the data required for the model. At present, we are ending up to define the model and completing the data collection. The research will be develop in next papers. The chemical component of exergy will be added to the thermo-mechanical component of exergy. The model will be developed by implementing all energy and material fluxes. The model is meant to analyse a "city" as a complex system, consisting of buildings, systems and communications networks and users.

Presently the model will be significant if the results of two or more configurations of the same system, or two different systems, will be compared. The results may be used to calibrate the environmental impact of an urban system: Urban District Direct Energy Impact will be defined.

Acknowledgments

We would like to thank Environment Office Administration of Municipality of Florence for data.

References

[1] Reynolds DG., Entropy and diminishing elasticity of substitution. Resources Policy 1999, 25(1):51–58.

[2] Balocco C., Papeschi S., Grazzini G., and Basosi R., Using exergy to analyze the sustainability of an urban area. Ecological Economics 2004;48(2):231–244.

[3] Balteanu D., Doguru D., Geographical perspectives on human-environment relationships and anthropic pressure indicators Romanian Journal of Geography 2011;55(2):69–80.

[4] Liu J., Dietz T., Carpenter SR., Folke C., Alberti M., Redman CL. et al., Coupled Human and Natural Systems. Royal Swedish Academy of Science-Ambio 2007;36(8):639-649.

[5] Saunders T., A discussion document comparing international environmental assessment methods for buildings. BRE; 2008.

[6] Sciubba E., Exergy-based ecological indicators: a necessary tool for resource use assessment studies. Keynote address to IEEES, 2009.

[7] Brown M., Ulgiati S., Energy quality, emergy, and transformity: HT Odum's contributions to quantifying and understanding systems. Ecological Modelling 2004;178(1):201–213.

[8] Odum H., Brown MT., Williams SB, Handbook of emergy evaluation. Center for Environmental Policy; 2000.

[9] Sciubba E., On the second-law inconsistency of emergy analysis. Energy 2010;35(9):3696–3706.

[10] Wackernagel M., Our ecological footprint: reducing human impact on the earth, vol.9. New Society Publishers; 1996.

[11] Rees W., Wackernagel M., Urban ecological footprints: why cities cannot be sustainable–and why they are a key to sustainability. The Urban Sociology Reader 2012.

[12] Bribiàn IZ. , Usòn AA., and Scarpellini S., Life cycle assessment in buildings: State-of-the-art and simplified LCA methodology as a complement for building certification. Building and Environment 2009, 44(12):2510–2520.

[13] Cornelissen RL., Thermodynamics and sustainable development; the use of exergy analysis and the reduction of irreversibility. Universiteit Twente, 1997.

[14] Cornelissen RL., Hirs GG., The value of the exergetic life cycle assessment besides the LCA. Energy conversion and management 2002, 43(9):1417–1424.

[15] Xiao F., Wang S., Progress and methodologies of lifecycle commissioning of HVAC systems to enhance building sustainability. Renewable and Sustainable Energy Reviews 2009, 13(5):1144–1149.

[16] Sharma A., Saxena A., Sethi M., Shree V., et al., Life cycle assessment of buildings: a review. Renewable and Sustainable Energy Reviews 2011;1(15):871– 875.

[17] EN UNI. 15603: 2008, Prestazione energetica degli edifici - Consumo energetico globale e definizione dei metodi di valutazione energetica.

[18] Tronchin L., Fabbri K., Analysis of buildings' energy consumption by means of exergy method. International Journal of Exergy 2008;5(5):605–625.

[19] Pulselli RM., Pulselli FM., Rustici M, Emergy accounting of the province of Siena: towards a thermodynamic geography for regional studies. Journal of Environmental Management, 86(2):342–353, 2008.

[20] Leoncini L., Baldi MG., Exergy performance as a measure of building efficiency. YRSB 2013: Proceedings of Young Researchers in Sustainable Building; 2013 June 25-26; Prague, Czech Republic.

[21] Bejan A., Moran MJ., Thermal design and optimization. Wiley Interscience, 1996.

[22] Chen GQ., Exergy consumption of the earth. Ecological Modelling 2005;184(2):363–380.

[23] Bejan A., Mamut E., Thermodynamic optimization of complex energy systems. Springer, 1999.

[24] Tsatsaronis G., Definitions and nomenclature in exergy analysis and exergoeconomics. Energy 2007;32(4):249– 253.

[25] Kotas TJ., The exergy method of thermal plant analysis. Butterworth Publishers, Stoneham, MA, 1985.

[26] Szargut J., Exergy method: technical and ecological applications. WIT press; 2005.

[27] Jansen S., Exergy in the built environment [dissertation]. Delft University of Technology, 2014.

[28] IEA ECBCS Annex. 37, Heating and Cooling with Focus on Increased Energy Efficiency and Improved, 2003.

[29] IEA ECBCS Annex. 49, Low exergy systems for high- performance buildings and communities. Guidebook: Section, 6, 2010.

[30] CosteXergy C24, Analysis and design of innovative system for low-exergy in the built environment. European Cooperation in Science and Technology, 2011.

[31] Van Den Dobbelsteen A., Jansen S., Vernay AL., Gommans L., Building within an energetic context: low-exergy design based on local energy potentials and excess or shortage of energy. PLEA 2007: Proceeding of the 24^{th} International Conference on Passive and loe energy Architecture; 2007 Nov 22-24, Singapore.

[32] Broersma S., Fremouw M, and Van Den Dobbelsteen A., Energy potential mapping: visualising energy characteristics for the exergetic optimisation of the built environment. Entropy 2013;15(2):490–506.

[33] Stremke S., Van Den Dobbelsteen A., and Koh J., Exergy landscapes: exploration of second-law thinking towards sustainable landscape design. International Journal of Exergy 2011;8(2):148–174.

[34] Balocco C., Grazzini G., A statistical method to evaluate urban energy needs. International journal of energy research 1997;21(14):1321–1330.