Urban energy performance monitoring for Smart City decision support environments

RESEARCH AND EXPERIMENTATION

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Abstract. In this essay we wish to present an interdisciplinary study carried out in the framework of two Interreg Italy-Austria projects which were intended to design methodologies, simulation tools and decision support instruments to face energy challenges within the overall Smart City concept.
The proposed strategy uses a physical model ("City Model") and an energy behavior model ("City Sensing") of the urban environment. They were developed using two different approaches: the first is mainly based on analysis of surveys data and the second one on simulations and processing of large-scale datasets. "City Model" and "City Sensing" were then merged to provide an Urban Building Energy Model - that we called "City Energy Model" - integrated with a Participatory Public GIS platform.

Keywords: Energy in cities, City energy demand, Simulation tools, Energy networks, ICT

Scenario

There is still no common understanding about the definition and concept of Smart City. In a study aimed at providing background information and advice on Smart Cities in the European Union, the European Parliament acknowledges that there are many definitions, some focusing on ICT as a technology driver, while other broader definitions include socio-economic and governance aspects, such as the use of social participation to enhance sustainability, quality of life and urban welfare. The study concludes that a Smart City is a city «seeking to address public issues via ICT-based solutions on the basis of a multi-stakeholder, municipally-based partnership» (European Parliament, 2014). In accordance with this definition, but shifting the emphasis onto sustainability, we support the idea that «the smart city is intended to deal with or mitigate, through the highest efficiency and resource optimization, the problems generated by rapid urbanization and population growth, such as energy supply, waste management, and mobility» (Calvillo, 2016).
Translated into architectural terms and considering the context of European cities characterized mainly by an old, energy-inefficient building stock, it means optimization of processes, systems and conditions related to heating and cooling. Technically, this process can take place through retrofitting of private buildings undertaken by householders - either spontaneously or prompted by public regulations and incentives, or else through retrofitting of public buildings by direct intervention of local authorities.
While these are optimization processes to be carried out on single buildings, to achieve tangible results they must be applied pervasively at urban level. It follows, that an appropriate decision support environment capable of estimating energy demand and building energy behavior can better drive the operation.
On the other hand, another alternative or additional optimization process could be the improvement of energy systems at urban level, such as the creation or integration of mixed energy networks to obtain "holistic energy systems" where, once again, single buildings represent the terminal elements of the whole system. In this case, the estimation of buildings' energy demands is a key aspect, wherein estimation methods could be based either on a top-down or bottom-up approach (Swan and Ugursal, 2009). But considering that single buildings represent the terminal elements of the city system and a «scenario analysis for retrofit or new design is only possible at the building scale» (Monteiro et.al., 2018), decision support environments must be based on "bottom-up approaches" aimed at understanding the details of energy consumption and the effects of potential retrofitting actions on buildings (Reinhart and Davila, 2016).
Even the design of a "holistic energy master plan" needs to start from information at building level. In fact, in a smart city scenario, houses and buildings may play the role of "prosumers" because they both consume and produce electricity. Once again, bottom-up approaches are fundamental to investigate supply-demand dynamics properly.

State of the Art

Working on an urban scale with bottom-up approaches means considering thousands of buildings and calculating the energy demand for each of them. The solution is to rely on «urban building energy models (henceforth referred to as UBEMs) [that] are expected to become a key planning tool for utilities, municipalities, urban planners and even architects working on campus level projects» (Reinhart and Davila, 2016).
Recent research has developed several methods for UBEM construction. They are quite similar to each other; what is different is the information source and data processing, where «data conversion, mapping procedures and building stock data collection still represent technical barriers in the development of UBEMs» (Cerezo et. al., 2016).
The "New York City Building Energy Map!" project (Sustainable Engineering Lab, 2012) subdivides buildings according to functional typology and fixes a standard energy demand per floor area for each specific typology. Values are derived from the "Residential Energy Consumption Survey (RECS)" and the "Commercial Buildings Energy Consumption Survey (CBECS)".
The "SusCity" project (SusCity, 2017) used data from national census to determinate the age and construction type of buildings, but «although this information was accessed at buildings level, due to privacy requirements, the information is publicly available only at statistical subsection level, corresponding to a small aggregation of buildings, typically a quarter block» (Monteiro et.al., 2018). To fill that gap, many other local data sources were used.
From an analysis of the state of the art, it emerges that many of the studies apply elaborated procedures tailored to place-specific conditions; they can be considered prototypes. As a re-

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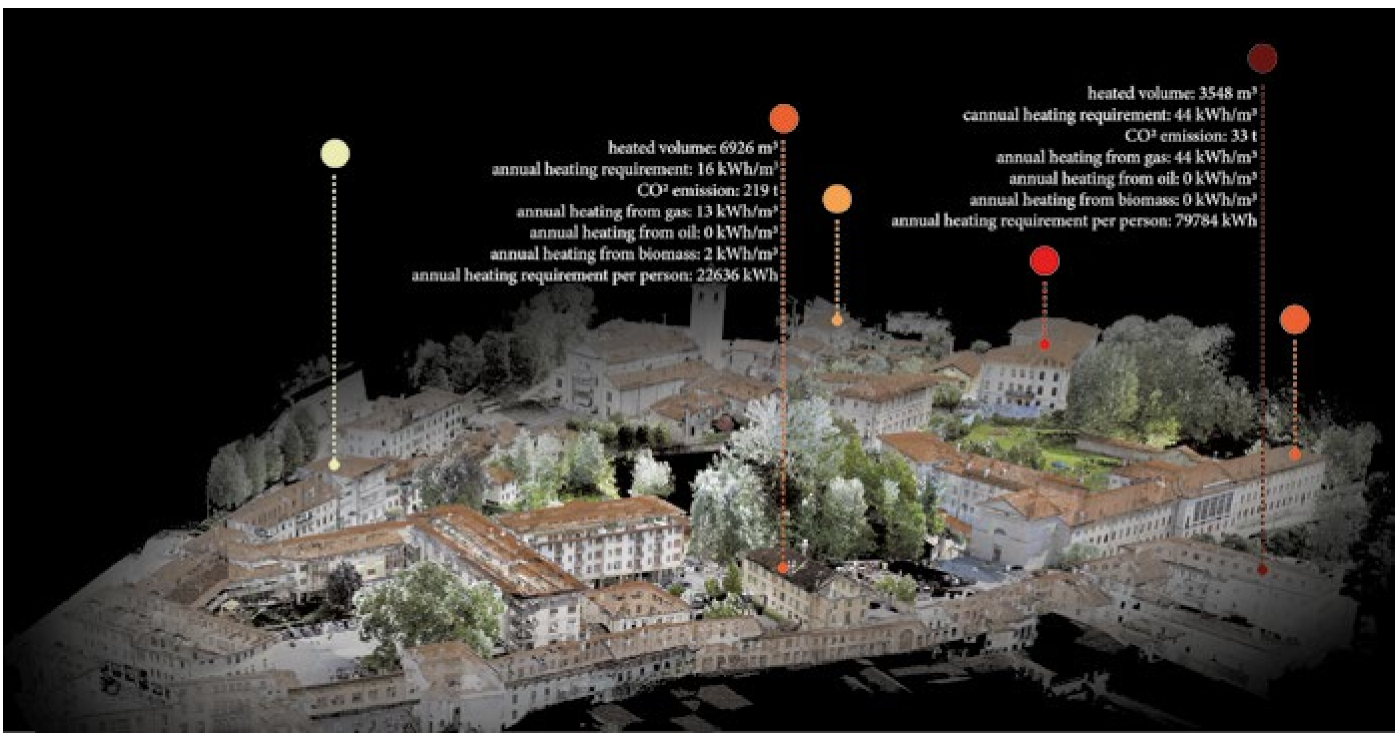
01 | An elaboration of the "City Model" used to calculate solar irradiation

02 | A conceptual representation of the "City Energy Model"

sult, these procedures are feasible in the case of experimental research but are not suitable for use as standard methods to be carried out by city administrations or communities at national or European level.

Research and Experimentation Objectives

The study presented in this article aims at improving energy efficiency approach by developing scalable and "easy-to-use" methodologies and simulation tools for decision support systems to face energy challenges within the overall Smart City concept.
The work was carried out in the framework of two joint European research projects; one has recently been concluded and the second, a spinoff project from the first one, is still ongoing. The first project is UEb: "Urban Energy Web, shared knowledge for the reduction of energy consumption and development of renewable energy on an urban scale"[1]. The second one is the IDEE project: "Network of research institutions for planning efficient energy systems in urban areas"[2]. Both projects have been financed by the Interreg V-A Italy-Austria programme and are being applied and tested in the city of Feltre (Belluno, Italy).
The main objective is the development of new methodologies and simulation tools to create decision support environments based on a detailed understanding of the energy performance of urban areas. Tools and methodologies have to be user-friendly, suitable for use by experts and urban stakeholder/communities, and they need to be replicable.
A further objective is to set up strategies and tools to approach the design of hybrid supply systems. Expected scenario applications are both the planning of the best possible configuration of any energy network and assessing whether it is more cost-effective to create an energy network or invest in the retrofitting of buildings.
The overall objective of the research is to develop methodologies and tools able to trigger some of the elements that characterize Smart Cities: "Better planning", "Participatory approaches", "Pervasive use of Information and Communication Technologies".



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03 | The "Urban Energy Pattern" as displayed by the PPGIS of the UEb project; on the right the info box for customization of the index parameters

Methodology, Originality and Research Output

Conceptually, the whole research is based on the dual "City Model"/"City Sensing" strategy.

When assessing a city, City Model and City Sensing are two specific information clusters that can help design geo-data models dealing with complex urban issues like those related to energy. The City Model cluster is based on an intensive data retrieving phase aimed at acquiring high-density/low temporal resolution information about morphological and physical city characteristics. The City Sensing cluster is based on the integration of heterogeneous datasets that are continuously updated by technological systems (e.g. sensors), measurement campaigns, surveys and content-enriching processes that provide information on specific elements of a city, such as, for example, buildings. It is reasonable to assume that their integration produces a very complete information framework of a city called "City Energy Model", which is basically a thematic characterization of a UBEM.

In UEb, the approach is based on a massive survey campaign. The City Model is therefore built up by processing hi-res avionic orto-photos, avionic and drone laser scanner point cloud datasets and the result is a 3D model of the city that can be managed and elaborated using processing software. The City Sensing, on the other hand, consists of several geocoded datasets such as gas/wood/oil real consumption and a series of thermographic images of the urban building stock.

UEb City Model, City Sensing and City Energy Model feed data into a geo-web interactive platform which provides social network tools to administrators, technicians, energy companies and citizens, so they can better understand the energy behavior of their city. Through the UEb platform, users can browse several thematic interactive maps; one of these maps shows the so-called "Urban Energy Pattern", which is a parametric index that helps to understand the correlation between consumption, dispersions, emissions and inhabitant behavior (Figure 3).

In this respect, «in recent years, there is a concern to bring academic practices of GIS to the public realm, usually known as Public Participation Geographic Systems (PPGIS)» (Monteiro et. al. 2018). The UEb portal is basically the implementation of a PPGIS

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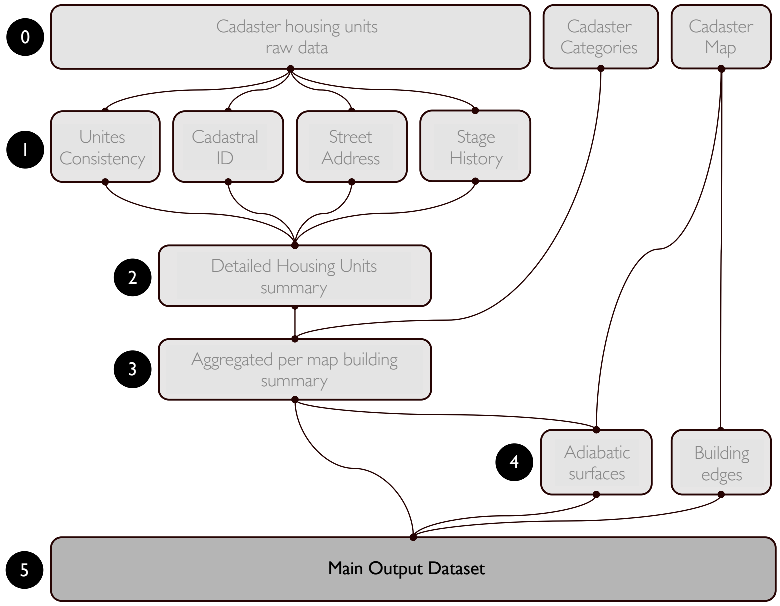
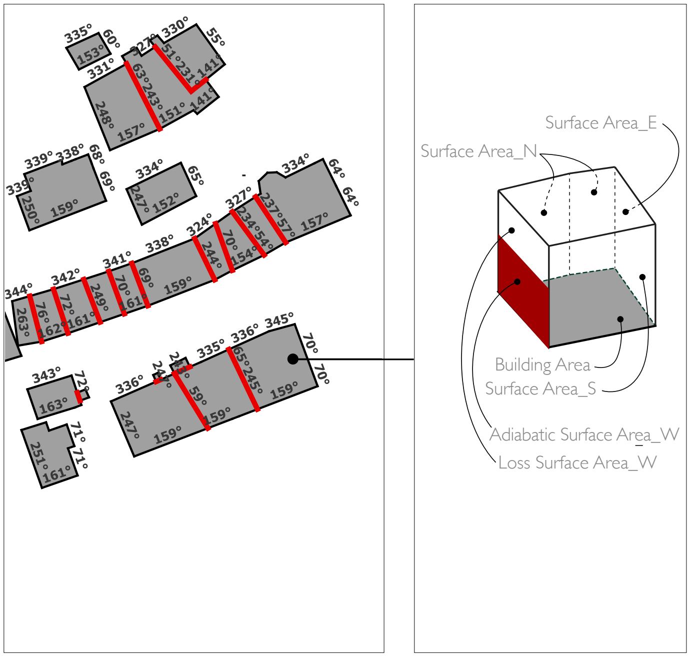


In stage #1 it is calculated units consistency of each building (indeed each building may contain one or more housing units).
The result summary of stage #2 provides details per housing unit whilst aggregation in stage #3 filters-in proper residential units using a category list, and computes summary values per single building.
In stage #4, a GIS polygon analysis and a self-intersect geo-processing operation return building edges orientation and area of adiabatic surfaces.
Main Output Dataset (stage #5) contains buildings' physical dimensions, external surfaces, adiabatic surfaces and loss surfaces area per compass-point.

04 | Geo-DBMS multi-stage processing procedure

05 |

Field name	Field content description	unit
OverGroundFloors	Number of over-ground floors	number
UnderGroundFloors	Number of under-ground floors	number
TotalFloors	Total amount of floors	number
BuildingArea	Building base surface area	m^2
TotalFloorsSurfaceArea	Sum of each level surface	m^2
SurfaceArea_N	North-oriented surfaces total area	m^2
SurfaceArea_E	East-oriented surfaces total area	m^2
SurfaceArea_W	West-oriented surfaces total area	m^2
SurfaceArea_S	South-oriented surfaces total area	m^2
AdiabaticSurfaceArea_N	Adiabatic North-oriented surface total area	m^2
AdiabaticSurfaceArea_E	Adiabatic East-oriented surface total area	m^2
AdiabaticSurfaceArea_W	Adiabatic West-oriented surface total area	m^2
AdiabaticSurfaceArea_S	Adiabatic South-oriented surface total area	m^2
WindowArea_N	North-facing windows surfaces area	m^2
WindowArea_E	East-facing windows surfaces area	m^2
WindowArea_S	Soth-facing windows surfaces area	m^2
WindowArea_W	West-facing windows surfaces area	m^2
LossSurfaceArea_N	North-oriented loss surfaces total area	m^2
LossSurfaceArea_E	East-oriented loss surfaces total area	m^2
LossSurfaceArea_S	West-oriented loss surfaces total area	m^2
LossSurfaceArea_W	South-oriented loss surfaces total area	m^2



05 | Geometric parameters output list resulting from geo-database processing. The map shows azimuthal orientation of building edges used to compute areas per compass-point and adiabatic surfaces highlighted in red

aimed at improving public engagement in policy-making processes allowing participants to dynamically interact with the input, analyzing and visualizing alternatives.

The experience of the UEb research demonstrated that while, on the one hand, the approach used gives good results in terms of correspondence with reality, on the other hand, it is still affected by difficulties in data collection. UEb is based on "reconstructed models of the urban environment" that give important results but cannot be applied on a large scale. In fact, survey campaigns for City Model construction are time- and money-consuming, while data acquisition from energy companies most of the time involves complex operations.

For this reason, in IDEE, we devised and tested an alternative approach for the construction of UBEMs, relying on data that can be easily accessed and obtained by any public administration.

This approach is no longer based on surveys and measurement of real phenomena, but on "simulated models of the urban environment". In order to define a replicable methodology, the physical-morphological features of the buildings are firstly obtained by processing the national cadastral database that has homogeneous characteristics for almost all Italian municipalities.

The City Model is generated through the multi-stage processing procedure explained in Figure 4. The output of a geo-DBMS processing procedure is a building unit's dataset (see Figure 5) in which 21 different physical/geometric parameters are calculated for each building in the urban stock.

The City Sensing section contains the technical characteristics of buildings, that determinate their energy behavior. They were derived from public National Census data of 2001 and 2011; starting from this information, thermal transmittance for building components are determined according to each of the seven construction periods into which we have subdivided the building stock; U-values result from literature review and research (TABULA, 2017).

The City Energy Model is the result of multiple dynamic energy simulations (using Design Builder software) based on a parametric model for the definition of typical dispersions of the external envelopes of buildings. This model is built up considering typology, number of levels (floors), construction period and building use, but it also takes into account building orientation and the influence of adiabatic surfaces (calculated in the GIS procedure and explained in Figures 5 and 6). In this way, multiple dynamic energy simulations give an overview of the typical energy demand for each combination of building types and characteristics.

Simulations are based on a set of typical buildings with a 100 m^2 gross basement area and a WWR (wall to window ratio) of 10% for each external wall. The set includes three main types of buildings, depending on the number of levels (L1, L2, L3). Simulations are performed for each of the three building models and for each construction period. In this way, for each construction period it is possible to calculate the typical energy loss due to transmission per square meter of each external surface, also considering wall orientation. A similar approach is used to calculate typical solar gain per square meter of each of the four orientations of the window surfaces. Internal gain and ventilation loss are calculated during simulations for each thermal zone of the reference model and are then parameterized according to square meters of total floor surfaces.

The simulation series yields a set of values (in kWh/m^2) that indicate the total annual amount of energy loss and gain per square meter of either wall surface, window surface or floor surface. These values, multiplied by the geometrical extension of walls, windows and floors of a building give the annual energy demand of that building according to the general formula:

$$Q_{H,nd} = (Q_{H,tr} + Q_{H,ve}) - \eta_{H,gn} (Q_{in} + Q_{sol})$$

where $Q_{H,nd}$ is energy loss due to transmission, $Q_{H,ve}$ is energy loss due to ventilation, Q_{in} is internal gain and Q_{sol} solar gain. The utilization factor ($\eta_{H,gn}$) has been assumed as 0.80, taking into account the typical dynamic behavior of buildings.

The table in Figure 6 summarizes all the values generated by energy simulations - each value has been calculated for each construction period, in total we have a table of 196 loss and gain values in kWh/m^2 - and describes the geometric elements used for parametrizing energy loss or gain of the building.

The formula in Figure 7 represents the final simulation running in the GIS environment, which combines the typical energy demand of each individual building with the corresponding geometric parameters.

The main output of the IDEE approach is information about the energy demand of buildings mapped at city level, for each individual building. It is worth noting that energy demand was calculated using dynamic building energy simulation procedures. This allows determining annual heating and cooling energy requirements and peak power demand for heating and cooling.

Knowing annual heating energy requirements is useful for planning retrofitting measures and policies, while peak demand, combined with annual requirements, is indispensable information for planning energy network systems. On this aspect, a further development of the IDEE project in the future will be its integration with "Rivus". It is an open-source software which implements a «linear mixed-integer optimization model for urban energy infrastructure» (Dorfner, 2016) to assess energy network construction/extension scenarios based on input about available commodities, energy conversion processes, basic demand and peaks during daytime, costs and demand areas.

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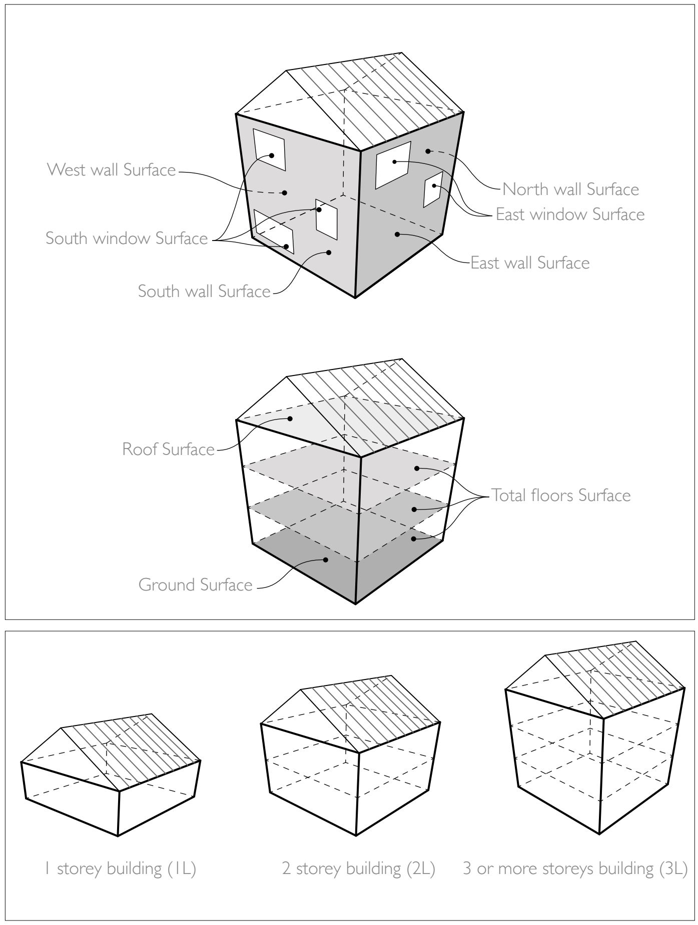
	Parametrization surface	Variabile name
Transmission loss: $Q_{H,tr}$	Ground Surface (1 storey buildings)	$Q_{H,tr}(S_G)1l$
	Ground Surface (2 storeys buildings)	$Q_{H,tr}(S_G)2l$
	Ground Surface (3 or more storeys buildings)	$Q_{H,tr}(S_G)3l$
	Roof Surface (1 storey buildings)	$Q_{H,tr}(S_R)1l$
	Roof Surface (2 storeys buildings)	$Q_{H,tr}(S_R)2l$
	Roof Surface (3 or more storeys buildings)	$Q_{H,tr}(S_R)3l$
	East wall Surface (1 storey buildings)	$Q_{H,tr}(S_E)1l$
	East wall Surface (2 storeys buildings)	$Q_{H,tr}(S_E)2l$
	East wall Surface (3 or more storeys buildings)	$Q_{H,tr}(S_E)3l$
	North wall Surface (1 storey buildings)	$Q_{H,tr}(S_N)1l$
	North wall Surface (2 storeys buildings)	$Q_{H,tr}(S_N)2l$
	North wall Surface (3 or more storeys buildings)	$Q_{H,tr}(S_N)3l$
	West wall Surface (1 storey buildings)	$Q_{H,tr}(S_W)1l$
	West wall Surface (2 storeys buildings)	$Q_{H,tr}(S_W)2l$
	West wall Surface (3 or more storeys buildings)	$Q_{H,tr}(S_W)3l$
	South wall Surface (1 storey buildings)	$Q_{H,tr}(S_S)1l$
	South wall Surface (2 storeys buildings)	$Q_{H,tr}(S_S)2l$
	South wall Surface (3 or more storeys buildings)	$Q_{H,tr}(S_S)3l$
	East windows Surface	$Q_{H,tr}(S_{WE})$
	Nord windows Surface	$Q_{H,tr}(S_{WN})$
	West windows Surface	$Q_{H,tr}(S_{WW})$
	Sud windows Surface	$Q_{H,tr}(S_{WS})$
Ventilation loss: $Q_{H,ve}$	Total floors Surface	$Q_{H,ve}(S_{TF})$
Internal gain: Q_{in}	Total floors Surface	$Q_{in}(S_{TF})$
Solar gain: Q_{sol}	East windows Surface	$Q_{sol}(S_{WE})$
	Nord windows Surface	$Q_{sol}(S_{WN})$
	West windows Surfac	$Q_{sol}(S_{WW})$
	South windows Surface	$Q_{sol}(S_{WS})$



06 | Parameters produced by Energy Dynamic Simulation

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$$Q_{H,nd} = (Q_{H,tr} + Q_{H,ve}) - \eta_{H,gn}\,(Q_{in} + Q_{sol})$$

$$Q_{H,tr} = (Q_{H,tr}(S_G)\varkappa l \cdot BuildingArea) + (Q_{H,tr}(S_R)\varkappa l \cdot BuildingArea) + (Q_{H,tr}(S_E)\varkappa l \cdot LossSurfaceArea\_E) + (Q_{H,tr}(S_N)\varkappa l \cdot LossSurfaceArea\_N) + (Q_{H,tr}(S_W)\varkappa l \cdot LossSurfaceArea\_W) + (Q_{H,tr}(S_S)\varkappa l \cdot LossSurfaceArea\_S) + (Q_{H,tr}(S_{WE}) \cdot WindowArea\_E) + (Q_{H,tr}(S_{WN}) \cdot WindowArea\_N) + (Q_{H,tr}(S_{WW}) \cdot WindowArea\_W) + (Q_{H,tr}(S_{WS}) \cdot WindowArea\_S)$$

$$Q_{H,VE} = Q_{H,ve}(S_{TF}) \cdot TotalFloorsSurfaceArea$$

$$Q_{in} = Q_{in}(S_{TF}) \cdot TotalFloorsSurfaceArea$$

$$Q_{sol} = (Q_{sol}(S_{WE}) \cdot WindowArea\_E) + (Q_{sol}(S_{WN}) \cdot WindowArea\_N) + (Q_{sol}(S_{WW}) \cdot WindowArea\_W) + (Q_{sol}(S_{WS}) \cdot WindowArea\_S)$$

07 | Formula utilized in the GIS environment to calculate the annual heating energy demand for each building; the formula merges energetic data of the Dynamic Energy Simulations (Figure 6) with geometric data of buildings (Figure 5)

Results, Implications and Impact

The first part of the project, concerning UEb methodology and tools and their application in the test case of Feltre, is already concluded. Project results and impacts can be assessed according to the three elements that characterize Smart Cities indicated in the Research and Experimentation paragraph.

Regarding "Participatory Approaches", mapping of city energy behavior information from PPGIS promoted a transparent and collaborative process, allowing us to integrate more traditional approaches in the final decision, such as public meetings and surveys on focus groups. With citizens participating in the process, more informed decisions can be made, and awareness of environmental issues is enhanced (Monteiro et. al. 2018). This blended participatory approach (mixing traditional meeting with online platform) is commonly used in some initiatives promoted by the municipal government (*Casa dei beni comuni* and *Feltre Rinnova*) aimed at encouraging participatory planning and common actions for renewing heating systems in houses.

As for "Better Planning", the mapping of building-specific energy demand at city level has been used by the municipal authorities to better tune the City SEAP and as background information to prepare retrofitting plans for public buildings and preliminary plans for the construction of a mini district heating system.

"Intelligent use of Information and Communication Technologies" has been a key aspect of the whole project evidenced by the project output and results. On the other hand, the application of this work methodology in the territory demonstrated that proper and extensive use of ICT can help municipal authorities to become more efficient and effective.

Limits of the Research, Future Development and Conclusion

The experience acquired in Feltre teaches us that it is fundamental to build a user-friendly, easy replicable and updatable system in order to produce effective UBEMs.

In striving to achieve these goals, common pitfalls are mostly related to complexity in data retrieving and integration, as well as in difficulties to implement replicable tools and procedures. Therefore, the IDEE strategy is based on large-scale datasets (even though less detailed and up-to-date) and standardized procedures to provide end-users with an easy-to-use "toolkit" for processing data.

In a sense, the main limitations of the IDEE strategy are related to the above-mentioned assumptions. Census data have been used because of their large-scale homogeneity; unfortunately, they are not available (due to privacy regulations) for details about single buildings, so some calculation parameters must be statistically estimated. For this reason, a further step of the project will be to update and improve the quality of the City Sensing model. Some automatic procedures are needed to process new survey information and data sources such as a questionnaire addressed to householders, construction license databases and other detailed data about building characteristics.

The UEb project represents an important step in the project development process and the IDEE approach intends to overcome some of its shortcomings in defining a scalable methodology. In this ongoing research process, the UEb dataset will be used to validate the results of IDEE simulations and set-up corrective parameters.

The last step to be implemented will be a pilot based on Rivus software to support energy network scenario assessment. One of the actual weaknesses of Rivus regards the availability of a detailed enough dataset about energy demand: to develop a scenario, only the building's area is used to estimate energy demand. The IDEE output dataset - which contains detailed information about energy demands for each single building - will feed information into the Rivus database that will finally be transformed into a web-oriented application aimed at improving decision-making processes for the benefit of experts and administrators.

To conclude, the aim of our research project is to develop approaches, tools and methodologies that can contribute to optimizing the management of resource use for buildings. The IDEE project is not a point of arrival but a concrete opportunity to extend the international network started up with UEb and continue conducting research on energy efficiency issues in urban areas. The methodologies and tools implemented with these activities will remain publicly available to researchers, experts, administrators and citizens who intend to develop services in the framework of the European Pathways to Smart Cities.

ACKNOWLEDGMENTS OF VALUE

Valter Bonan
Local authority on participatory democracy, energy and environment of the City of Feltre

The City of Feltre Administration has given its support and full contribution to the UEb and IDEE projects. These projects succeeded in combining research, innovation and experimentation with concrete potentialities and opportunities to reduce consumption by improving territorial energy efficiency. The process activated, and the quality of the research applied to the city context, had the merit of making recognizable, and implicitly consolidating, the possible virtuous relations of reciprocity and mutuality between research activities and management and participatory planning - which is one of the objectives of the City of Feltre. It is no coincidence that the portal developed for the project - already connected to our public ICT systems and portals - has produced a concrete urban analysis and is now a strategic support system to be used in drafting the SEAP plan and monitoring its results. On the other hand, the innovative survey models of UEb and IDEE methodologies, the related databases and intuitive methods of browsing and displaying information have disseminated new knowledge and increased awareness among the population, previously difficult to attain without such an instrument.

NOTES

[1] www.urbanenergyweb.eu

[2] www.interreg-idee.eu

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