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Mohamed Belmaaziz, Gianluca Cadoni. MODELLING ENERGY CONSUMPTION IN RESIDENTIAL SECTOR: A REVIEW OF EXISTING TECHNIQUES AND PROPOSITION OF AN APPROACH BASED ON THE EXPLOITATION OF A GIS TOOL. 42st IAHS WORLD CONGRESS The housing for the dignity of mankind, Apr 2018, Napoli, Italy. <hal-03601928>

HAL Id: hal-03601928

<https://hal.science/hal-03601928v1>

Submitted on 8 Mar 2022

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MODELLING ENERGY CONSUMPTION IN RESIDENTIAL SECTOR: A REVIEW OF EXISTING TECHNIQUES AND PROPOSITION OF AN APPROACH BASED ON THE EXPLOITATION OF A GIS TOOL

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Keywords: Residential buildings, georeferenced atlas, multi-scale approach, GIS.

Abstract *Residential sector is responsible for nearly 30% of the total final energy consumption in France. In order to analyse the potential of this sector to contribute towards reducing this important part of energy consumption, it is necessary to have detailed knowledge about residential building stocks characteristics. However, these characteristics are complex to define precisely because the housing stock is heterogeneous (construction period, housing types, influence of the urban context, heating modes, occupancy status, etc.).*

On the basis of a review of existing modelling techniques (bottom-up and top-down), the aim of this paper is to propose an approach based on the available spatial data exploitation by using GIS tool. By integrating the residential buildings in their urban context, this approach is used to elaborate a georeferenced atlas of energy saving of upgrade houses. In order to massify energy improvement of residential existing buildings, this atlas, planned to be integrated into the future territorial energy renovation platforms. It will offer a social, financial and energy knowledge at different scales of the territory.

1. INTRODUCTION

Environmental concerns growing, depletion of fossil resources and increasing energy consumption lead to make the improving energy efficiency in buildings a priority. In France, the residential buildings represent about 33.4 million houses which include 27.8 million principal residences. This sector is responsible for nearly 30% of the total final energy consumption. A large part of these housing (56%) was built before the first thermal regulation in 1975 and it is responsible about 59% of this energy consumption [1].

Considering the slow turnover of the French housing stock (1%) and the low pace of energy efficient retrofits, it will not be possible to reduce significantly the important part of energy consumption in this sector while the national objective fixes the part of reduction at 38% by 2020. In order to improve the performance of the residential existing buildings, it is necessary to have detailed data that enable to understand and analyse consumption characteristics in a large territory. The assessment of the potential energy-savings will allow to identify precisely the priority areas concerned by renovation and therefore guide environment policy measures.

If thermal modelling for energy assessment at single building level is relatively manageable, a territorial approach to analyse energy consumption in a large scale is complex. This complexity is due to the heterogeneity of the housing stock (according to the age of constructions), the types of housing (individual or collective, private or public, already renovated or not, in urban or rural areas), materials that compose the envelope, building shape, orientation, urban context, heating modes, occupation status (intermittent or permanent) and occupant behaviour. At this scale, analysis describe the building stock for future energy-savings measures depends of availability, reliability and precision of theses input data.

In order to explore residential housing sector at national, regional or local level and assist the strategies able to reduce energy consumption, different macro-scale studies were realized in recent years. On the basis of a review of various modelling approaches, the objective of this paper is to present a methodology based on the exploitation of GIS tool implemented in ATRE¹ (energy renovation atlas) research project framework. Financed by ADEME, this project consists to achieve a georeferenced atlas able to identify the potential energy-saving at different scale levels. This atlas, planned to be integrated into the future territorial platforms of energy renovation, will offer to public or private actors, a social, financial and energy knowledge of the territory. The approach used is based on pooling and sharing data concerning residential buildings in their urban context.

The first section presents advantages and limits of existing modelling techniques. The second one is focused on the description of a new method developed in ATRE project.

2. A REVIEW OF MACRO-SCALE ENERGY APPROACHES AND MODELLING TECHNIQUES

The studies carried out on the reducing of energy consumption in existing housing proceeds

¹ ATRE is a research project financed by ADEME (French Agency for the Development and the Mastery of the Energy) in the framework of call of project entitled "Vers des bâtiments responsables à l'horizon 2020".

according to various approaches that depend on the desired objectives and refer to investigation scale and modelling strategies. At a micro-scale (housing or building), assessing the energy performance aims to sensitize homeowners and leads to undertake thermal retrofitting. Even if the spatial resolution allows fine modelling because of input data precision and employed diagnosis tools, this individually approach, those conduct to adopt investment measures to improve the energy efficiency, remains limited. Their effect is insufficient because it cannot be expanding to whole housing stock. Identify potential energy savings in order to massify improving performance in the residential sector imposes to change scale analysis and explore stock housing in a large territory.

Swan and Ugursal [2] have identified two categories of approaches usable for modelling residential sector energy consumption in macro-scale: “top-down” and “bottom-up”. Both of these modelling approaches benefits and limitations are detailed by Kavgica and al. [3]. The top-down technique is based on the exploitation of national, regional or local energy consumption data (available for example from energy distribution network operators). These models are qualified as econometric when they allow analysing the inter-relationships between the energy use and macroeconomic indicators (energy prices, employment rates, gross domestic product). They can also include other parameters such as climatic conditions, projections of future housing construction and demolition rates. The technological top-down models are another kind of technique permeating to predict the influence of technical concerns such as future technological evolution and structural changes on the energy consumption. Even if these techniques can be useful for evaluate specific policy measures in macro-scale, the global data generated can toughly be disaggregated and assigned to lower levels such as building.

The bottom-up technique includes models which exploit an extensive data inputs from a less level to aggregate them to higher resolution scales. In the basis of energy consumption end-uses knowledge of housing, group or type of houses, it is possible to extrapolate data for analysing the stock in a large territory. Two distinct methods enable to estimate consumption according to this approach. The first one, so-called "statistics", consists of using data from real estimates on the energy consumed by housing samples. Ideally, data from energy suppliers could be a source of information, but at this scale, these data are unavailable or, when they exist, are often confidential.

The “engineering” model is another method used when the consumption modelling of housing is based on physics building calculation approach. Generally, these models use thermodynamic simulations (heat transfer functions) and need information such as the geometric characteristics and thermal properties of the existing envelope (walls, floor, roof, windows, doors, and thermal bridges), the power of the technical equipment, the occupant behaviour as well as climatic data. Unlike the top-down approach, engineering models require an important amount of technical data with high level of precision. However they give fairly accurate results.

Modelling the complexity and the diversity of residential building stock involve to group buildings by classes according to some parameters such as their size and age. On the basis

of national classification and by using engineering models, many studies are carried out to estimate the energy consumption of a single or a sample representative buildings. Statistical data about the structure of the stock combined to empirical relationships allow to scaled-up the energy results to represent energy behaviour on a territory. This is the case of work carried by Tobias L. and al. [4] which uses the nomenclature classification established in the framework of the European projects TABULA² and EPISCOPE³ for study energy consumption of residential buildings in various countries. Synthetically average buildings representing each type among the 40 identified serve to establish standard energy balances. By integrating hypotheses of renovations, global estimates were obtained by multiplying the unit consumptions by the number of dwellings of each type composing the national stock.

However, even though the calculations at building scale ensure accurate results, this aggregation of knowledge to higher scale levels (districts, municipalities, regions) leads to affect the estimation accuracy. The precision depends to the representativeness of the sample and the influence of the contextual urban factors that are not being considered.

More accurately estimates can be done with engineering models if the calculations are made “building by building”. This approach assumes a detailed knowledge of each residential building which composes the stock studied. This is the case of the bottom-up methodology solution proposed by ENERTER⁴ model used to describe French building stock. Modelling is based on the classification of the stock by representativeness types and the calculation process includes the population census data for each building individually (physical properties of each building and their energy use, occupation, adjoining building, etc.). The model allows to explore the energy assessment and economic perspective of the renovation at IRIS⁵ level in municipalities studied to achieving the target "Factor 4".

Even if this kind of building engineering models may be considered a useful tool to guide efficient and rational implementation of energy policy, it remains limited when it comes to target localized actions at lower than the IRIS spatial resolution (district or urban island mesh). Furthermore, calculations energy balances do not take into account urban context which is important for accurate estimations.

3. PROPOSITION OF APPROACH BASED ON GIS TOOL

Different existing methods are able to model the energy behaviour of residential building stocks at urban area or in a large territory. At this scale, the detail level of inputs data determines the quality of energy estimation demand. Among these methods, the bottom-up physics method

² Typology Approach for Building Stock Energy Assessment.

³ Energy Performance Indicator Tracking Schemes for the Continuous Optimisation of Refurbishment Processes in European Housing Stocks.

⁴ ENERTER is an energy model developed by Énergie Demain society. It is used for calculation of energy consumption.

⁵ The IRIS is a level of most detailed geographical statistics is available in France from the 1999 general population census. It contains approximately 2000 inhabitants.

“building by building” can be considered as greater accuracy approach but it depends to detailed data availability at low scale. From this observation, we propose in this paper a methodology which exploits the potentialities offered by Geographic Information System (GIS) to estimate energy balances at different scale levels. Indeed, since GIS is not only intended to produce a map, it is possible to exploit its ability to manage spatial data and to produce geometric parameters (area, number of floors, height, volume, etc.) necessary for energy calculations. These parameters can be enriched or crossed with other data (such as the age of the building, envelope components, climate) to estimate energy consumption and forecasting demand.

This methodology is developed and implemented in the framework of ATRE research project. It is based on bottom-up physics technique. By using existing databases and a GIS tool, the objective is to create processing procedures in order to produce a multi-scalar atlas of energetic renovation.

3.1 Available data and methodology developed

A representative typology to characterise residential building stock is necessary to identify archetypes in a studied area. In order to achieve this task, a GIS tool is used to treat databases collected.

The most important data sources available at lower scale are the BD TOPO produced by IGN⁶ and the tax assessor database provided by DGFIP⁷. The first one contains geometrical data geo-localized and desegregated by building. Every building block is represented as a polygon with information about his height and his altimetry. The second database corresponds to data gathered, treated and structured by CEREMA⁸ from the complex taxation files of government. Among the different data collection, this database contains information about age, dwelling number and habitable area aggregate at the parcel.

For creating a building energy model, the tasks developed can be summarized into the following steps (figure 1):

- building archetype classification
- characterisation of geometric inputs
- modelling energy heat balance

⁶ French National Geographic Institute.

⁷ The Public Finances Directorate General in France.

⁸ French expertise public centre of risks, environment, mobility and planning.

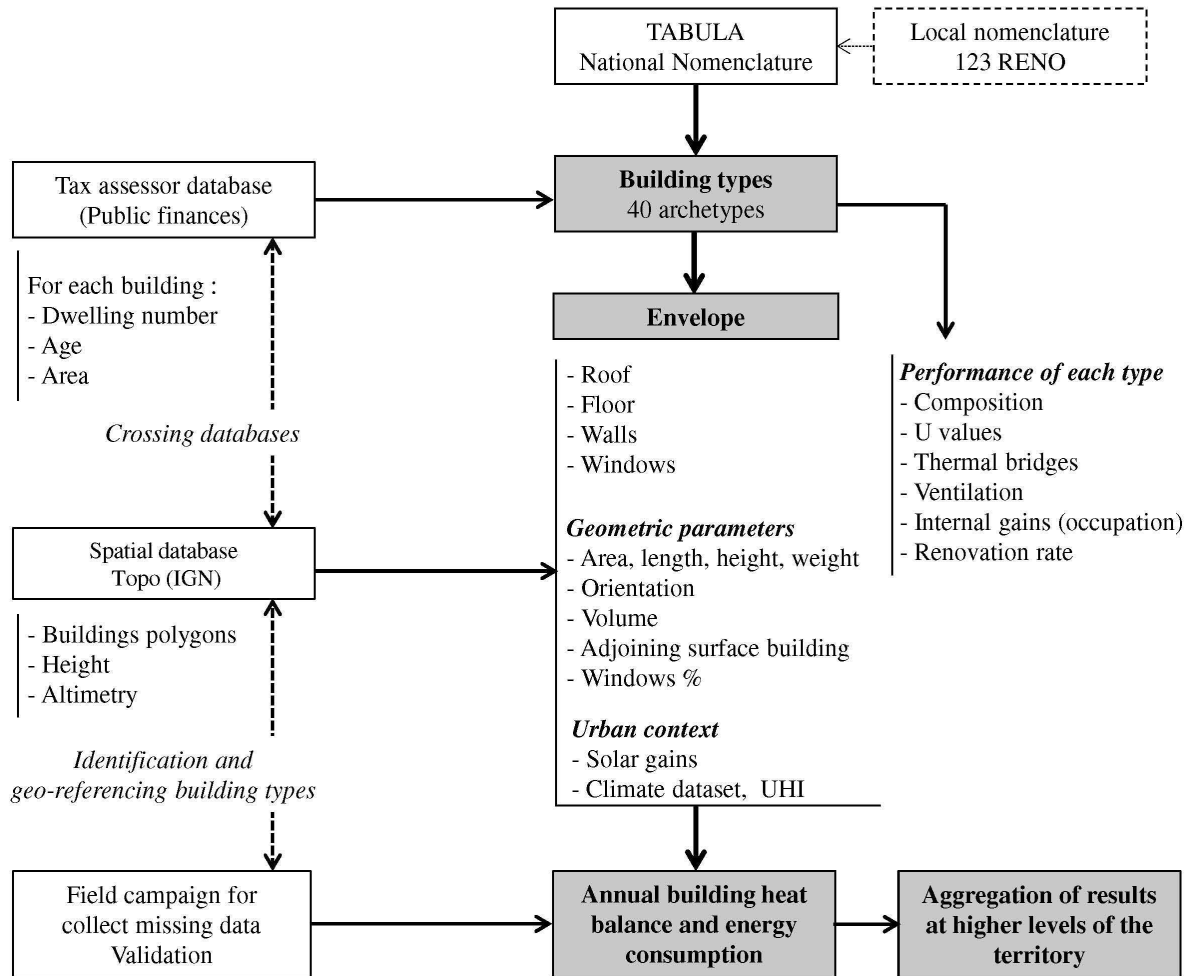


Figure 1. Schematic representation describe the methodology considered at the different stages of treatment (inputs data and outputs produced).

3.2 Building classification by typology

Most part of residential buildings nomenclature abstract national or regional stock into archetypes. The classification of buildings typologies is defined by categories of housing, (individual or collective) and refers to representative periods of construction. These periods depend on historical evolutions of construction technologies and thermal regulation. Generally, classifications cross families and periods in order to define all types of housing.

TABULA European nomenclature groups buildings according their categories, age and size [9]. This classification (table 1) is based on a matrix formed by 4 families and 10 periods for a total of 40 buildings types; families are: Single Family House (SFH), Terraced House (TH), Multi-family House (less than 10 dwellings) (MFH) and Apartment Block (more than 10 dwellings) (AB).

Table 1. TABULA nomenclature based on harmonised classification structure by period and grouped by categories corresponding to French residential building stock.

Stock building categories	Representative age bands considered									
	1	2	3	4	5	6	7	8	9	10
Single family house (SFH)	< 1915	1915	1949	1968	1975	1982	1990	2000	2006	> 2012
Terraced house (TH)		-	-	-	-	-	-	-	-	
Multi-family house (MFH)		1948	1967	1974	1981	1989	1999	2005	2012	
Apartment block (AB)										

The TABULA nomenclature was chosen to be used in the framework of ATRE project because it is an exhaustive national classification. It is also adapted to be implemented in GIS utilities. The spatial data can be crossed with information about age and size in order to assign TABULA archetypes for all residential buildings composing the stock. Processing procedures were developed to harmonise the information structure of spatial database of IGN with DGFIP data.

At this stage of treatment each building is identified by an archetype. Our approach considers an archetype as a theoretical model representing thermal characteristics (composition of envelope, U-values, thermal bridges, opening ratio by facade, ventilation rate, etc.). For more accuracy in defining these characteristics we use a knowledge resulting out of a 123 Reno⁹ local classification which takes into account the regional constructive specifications.

3.3 Characterisation of geometric inputs data

Building geometry description is necessary to estimate energy heat balance. The envelope geometrical characteristics can be extracted from the information of building entities present in the BD TOPO spatial data. Based on height, altimetry and perimeter of building, it is possible to determine areas exchange with exterior environment. Some treatments procedures were developed to evaluate the areas of different components composing the envelope. They consist to desegregate building information at facade level. This step allows to:

- identify adjoining building surfaces and deduct their area from the envelope area exchange
- precise the orientation of each elevation to calculate solar gains
- evaluate the area of external walls, roof and floor and volume for heat losses calculation

Unlike physic approaches, which they consider a global opening rate for the total envelope as a simplification, another procedure has been developed in order to classify the elevations (principal, secondary and blind elevation) and attribute opening rate. This classification is built by considering some specific criteria relative to the archetypes. For example, in the dense urban context, mostly old buildings are characterised by one principal elevation facing the street with opening rate greater than the secondary facade facing courtyard. Despite the fact that this parameter is necessary to evaluate solar gains for accurate heat energy balance, implemented for each archetype, the advantage of this automatically procedure consists to gather important

⁹ 123 Reno is a local classification of residential buildings developed for Provence territory [6].

data without field work.

At this treatment stage, an elevation has attributes (area, orientation, classification) and are referenced by an identifier number that qualifies its assignation to a building.



Figure 2. Example of elevations classification in a dense urban context and in a suburban context.

3.4 Energy modelling

Standard reference calculation procedures are implemented in GIS tool and used for determining the heat balance building by building. Starting from the principle that every building is linked to an archetype (defining his thermal characteristics) and different envelope components areas are known, the calculation consists to evaluate heat loss by transmission through the envelope. Ventilation heat loss is calculated on the basis of air change rates affiliated to building archetypes and the effective heat volume extracted from spatial database. Global heat losses are performed with climatic data set corresponding to degree-hours deducted from typical meteorological year (TMY).

$$Q_{loss} = [\sum_i A_i U_i + \sum_k l_k \psi_k + (V_h \times Q_v \times 0,34)] \times DH$$

Where:

Q_{loss}	building total heat losses (envelope and ventilation) [Wh]
A_i	area of each envelope component [m ²]
U_i	envelope component heat transfer coefficient (transmittance) [W/m ² K]
Ψ_k	linear thermal bridge heat transfer coefficient [W/mK]
l_k	linear thermal bridge length [m]
V_h	building heated volume [m ³]
Q_v	air change rate
DH	degree-hours [Kh]
0.34	air volumetric specific heat capacity coefficient [Wh/m ³ K]

Solar gains are evaluated by exploiting 2D spatial data extruded in 2,5D according to the heights of buildings and their altimetry. The geometric buildings models are exported to SketchUp tool.

T4SU¹⁰ plugin permitted to evaluate the theoretical solar irradiation during the heating season for each elevation composing a building. The modelling takes into account obstruction masks, direct and diffuse irradiations. Using solar irradiations from meteorological data, a procedure was developed in order to calculate the net solar irradiations received by elevations (figure 3).

$$Q_G = \sum_f [(Q_B \times SF) + (Q_d \times SVF)]$$

Where:

- Q_G global solar irradiations received by each elevation [Wh/m²]
- Q_B beam solar irradiations (evaluate from TMY) received by each elevation without obstruction [Wh/m²]
- SF ratio between theoretical beam solar irradiations (with obstruction) and beam solar irradiations (without obstruction) of the elevation
- Q_d diffuse solar irradiations (evaluate from TMY) receive by each elevation without obstruction [Wh/m²]
- SVF sky view factor evaluated in the centroid of each elevation



Figure 3. Example of global solar irradiations received by each elevation [Wh/m²] of building. Calculations carried out by take into account urban obstructions.

Result of solar energy received by the building is integrated in the heat balance calculations proportionally to the opening ratio of each elevation and window solar factor. Finally, the energy heat balance is performed on the basis on heat losses, solar gains and normalised internal gains.

$$Q = Q_{loss} - [(Q_G \times \tau \times sf \times A_f) + (Q_i \times A)]$$

Where:

- Q heat demand [Wh]

¹⁰ T4SU is a plugin of SketchUp developed by CRENAU research laboratory of Nantes School of Architecture in France. It is used to achieve morphological analyses in the urban fabric.

τ	opening ratio by elevation according to the building archetype
sf	opening solar factor
A_f	elevation area [m ²]
Q_i	internal gains [Wh/m ²]
A	building heated surface [m ²]



Figure 4. Example of heat balance areas obtained.

3.5 Procedures validation

In order to validate the automatic processing procedures developed to characterise buildings and envelopes, it has been decided to confront results with data gathered by campaign field. During this campaign we verify the elevation reconnaissance of face hierarchy and the building archetype assignation. This task is also an opportunity to improve quality of information about renovation undertaken in existing buildings. We complete our database with percentage of double glazed windows, presence of loggias and balconies, floor above cellar or soil, etc. These data can be used to improve archetypes knowledge.

Field campaigns were conducted in 5 IRIS of urban area of Marseille. Areas were chosen to cover a heterogeneous urban territory. Two downtown IRIS characterized by high density (Thubaneau and Longchamp) and three suburban IRIS (Mireille-Clairval, Gasquy and Pervenches) are explored. In these areas we can find old archetypes of single family houses and apartment blocks.

Actually field campaign is in progress. First conclusions concerning the assignation of period and family conduct to assign right archetype for about 80% buildings, a part of this error depends from wrong data used.

Success of assignation of facade's hierarchy depends from density of urban area. In the downtown we obtain good results (less than 4% of error), but in suburban quarters with high presence of single family houses the results are lower (more than 10% of error). These results are encouraging future improvements of the methodology.

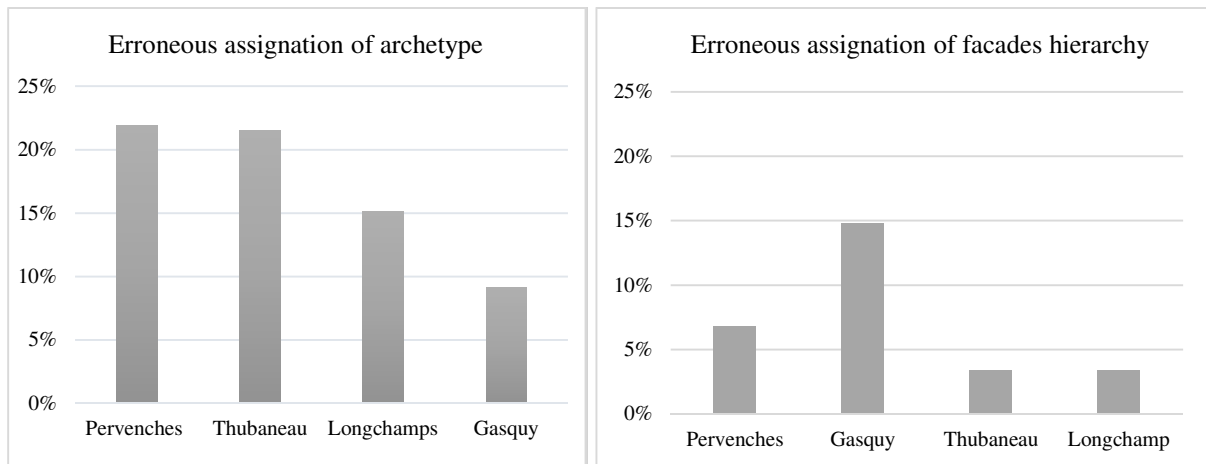


Figure 5. Results of automatic procedures validations.

4. CONCLUSIONS

The importance of energy demand of residential buildings stocks leads to implement targeted renovation policy measures based on detailed information covering different scale levels of a territory (building, district, urban area and region). Producing this knowledge depends essentially to detail level data available and the quality of modelling approach. Generally engineering bottom-up methods are built on archetypal classification and abstract the energy modelling to a sample of residential buildings. It is in this context that ATRE research project framework is carried out. Our ambition consists to develop methods allowing to exploit different residential sector databases in order to generate accuracy energy diagnosis at building scale and able to be aggregate at higher scale levels. Based on data series implementation in a GIS tool combined with physic approach, the objective is to develop automatic procedures that allows us to generate energetic atlas which can be reproducible. Similar approaches¹¹ exist but data collection is done through field campaign.

At this stage of project, the procedures developed in order to assign archetypes or to characterize geometric parameters have given promising results. Buildings that cannot be assigned to an archetype are due shortage of data. Other limits encountered concerns the elevation classification hierarchy of some buildings such as single family house elevations. Considering the weak number of building concerned, these problems can be resolved by a limited field campaign.

Since sufficient detail and urban context have considered to evaluate heat balance, the generate data conducts to accurate results. The future tasks will focus on calibration of climatic data according to urban context by using LCZ method [8]

. Some hypothesis of renovation undertake in existing housing will also contribute to improve results. Outputs produced will be crossed with socio-economic indicators.

¹¹ APUR (Atelier Parisien d'Urbanisme) have product an energetic atlas based on GIS tool. Datas were substantially collected by field campaign [7].

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