Energy vulnerable households: observing energetic consumption versus estimating potential energetic demand

Federico Martellozzo, Samuel Mermet

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Federico Martellozzo[*], *Samuel Mermet*[**]

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1. *Introduction*

Natural resources' consumption – especially in built up densely populated areas – has recently raised a renewed attention (Lambin *et al.*, 2001; Rockström *et al.*, 2009): on the one hand, world population is expected to exceed the 9 billion bar by 2050; on the other hand, we are witnessing a migration trend from rural to urban areas which has reached an alarming magnitude. Furthermore, it seems not to be stopping anytime soon (UN, 2010). So, since human development is strongly dependent on the exploitation of natural resources (Foley *et al.*, 2005), the environmental pressure caused by the depletion of natural resources is an issue of growing concern (Steffen *et al.*, 2007; Grimm *et al.*, 2008).

This paradoxical aspect of human development could be exemplified as the juxtaposition of two major trends: the growing need for natural resources to support human activities, versus the necessity to reduce the anthropogenic pressure on the natural environment in order to make Earth's resilience able to renew the natural resources' base, which is impoverished by the anthropogenic pressure itself. In fact, it is estimated that human-driven pressure has already exceeded what our planet can afford in many "domains" of the Earth system (Rockström *et al.*, 2009). Some authors report that, globally, land-use competition is getting harsher, more radical and compromising future landuse in a crucial way (Meyfroid, Lambin, 2011; Smith *et al.*, 2010).

One of the paradigms through which the reduction of environmental impact has often been fostered is based on the rationalization of the system of consumption through efficiency improvement. Thus, demand is theoretically reduced (if rebound effect is not considered) and therefore human pressure on the natural environment is finally relieved. Policy makers have often interpreted and translated this paradigm with a simple performance improvement which frequently brought to a priori establish

[*] Rome, Sapienza University of Rome, Italy.
[**] Paris, Université Paris Est, France.

several goals (i.e. the Kyoto Protocol, the Millennium Development Goals, Horizon 2020, etc.). Hence, research often focused on the development of applications capable of achieving these goals through a scientific, technical or social progress (Park *et al.*, 2009; Battisti, 2009).

This type of research is extremely important, but it seldom considers whether the pre-set goal is achievable without having a negative impact on the current life quality/style, or if the magnitude of the proposed intervention is sufficient to produce sensible results, or else if such efficiency improvement is free from rebound effects (Hertwich, 2005; Greening, 2000). So, the implementation of the system is frequently seen only as a mere decrease of consumption per unit, hence, it is designed to obtain a simple reduction of the amount of resources used (best efficiency). Conversely, what it is not considered is: which is the minimum level of resources that is needed to satisfy a specific need? This is a very useful piece of information that could facilitate an equitable human development, such as expressed in the fundamental principles endorsed at the international meeting in Rio in 1992.

Besides, especially in urban areas, electric usage increased substantially in the last decades, and it is now a crucial part of everyday life. Hence a new form of poverty has been observed and investigated which is the so called "fuel poverty" (but, in our opinion "energy vulnerability" might be a better fit). This issue has been somehow extensively explored, and there are already multiple definition of it. For example, in UK the standard for a household to be considered fuel poor is when it allocates more than 10% of its revenue to maintain thermal comfort within the house (Liddell *et al.*, 2012); while in French literature (Beslay *et al.*, 2010), even if a specific revenue's threshold has never been officially fixed, fuel poverty is often associated not exclusively with in-dwelling consumption for energy related needs but also with mobility, especially commuting. In both cases fuel poverty is investigated as a function of revenue.

This study proposes a paradigm shift which starts from the investigation of the minimum amount of energy needed (Qes) to meet a variety of "fundamental" needs, in order to better identify the area for public intervention that can potentially lead to sensible results. This study exclusively focuses on the energy consumption at the household level. Therefore, the presented model aims at establishing a baseline of Qes for each kind of family, according to its geographic and socio-demographic profile. This paper describes the general assumptions onto which the proposed model is built, the input data and the kind of output that are possible to obtain. Moreover, results from a specific case report (Ile-de-France) are presented and preliminary accuracy is tested. Finally, we offer an interpretation of some preliminary analysis to explain loco-regional differences and suggest possible intervention criteria.

We believe that the heretofore described paradigm shift and the model proposed could be helpful in many sectors of public intervention and could bring several benefits such as: avoid some of the problems due to setting a priori targets, encourage policies that while aiming at social development could also serve to reduce environmental impact per se, support sustainable and equitable human growth, foster reduction of new forms of poverty – such as energy vulnerability, which has been defined an emerging problem of our time (Walker, Day, 2012) –, and separate the concept of energy vulnerability from the level of wealth.

2. *Theoretical contextualization*

The methodological approach and the model developed for this study are inspired by what has already been described by Haberman *et al.* (2012) to estimate the urban agriculture potential in Montréal. This research is based on universal principles of sustainability and equity, which were expressed and approved at the Rio Earth Summit in 1992; afterward, they were agreed in the United Nations Framework Convention on Climate Change (UNFCCC). This framework contained two fundamental principles:

- Despite the inevitable scientific uncertainties about climate change and its consequences, adopting a precautionary approach focused on reducing greenhouse gases emissions is imperative.
- The acknowledgment that there should be a convergence of national greenhouse emission levels based on the principle of equal rights. The right to use the energy, or to produce greenhouse gases, or to use the natural environment capacity to absorb pollutants should be exercised multilaterally and equally.

In recent years, the first principle was corroborated by scientific evidences underlying the relationship between human activity and environmental impact (Rockström, 2009; Lambin, 2001), if not from a climatic point of view – on which the debate is still harsh (Hoffman, 2011) – certainly in regards of the environmental impact. Therefore, the first principle may be replaced by sustainability.

QES has been calculated for a set of needs defined uniformly for all individuals; nevertheless, the amount of energy actually varies according to socio-demographic and geographic characteristics of each family. Contrary to what is experienced by other modelling approaches (Penot-Antoniou, Tetu, 2010) in this study the income is not considered; in fact, although family income is useful to determine the energy poverty threshold (Devaliére, 2012; Price *et al.*, 2007), it does not affect QES. For example, the minimum energy needed to properly heat a house, or the energy required to go from point A to point B, varies according to the type of energy used and depending on the energetic performance of the equipment (home/transport), but the "minimum energy demand" needed to satisfy each need does not depend on income and it is the same among different consumers. Furthermore, through building the analysis on the QES measure the concept of "those who earn more can consume more" is avoided; which is quite peculiar since this concept is implicitly unfair and unsustainable and it is in contradiction with the fundamental principles that inspired this research.

3. *Methods and data*

The initial input data come from the French National Household Census (INSEE, 2008) and the House Energy Performance mapping (EPC) developed by the Institute d'Amènagement et d'Urbanisme (IAU, 2012). The domestic energetic needs considered are: hot water sanitation, heating, cooking, and the energy consumption for major electronic appliances. These needs may be defined as a function of the energy performance of equipment, the people number, the type of energy used, and the type of housing:

$$QesAb = EPC * S * Te + \lambda * Np \qquad [1]$$

Where:

- *QesAb* is the home consumption *QES*.
- *EPC* is the index of energy performance.
- *S* is the surface area of the dwelling.
- *Te* is the type of energy (different fuels have different energy yields).
- λ is the energy consumption index (ICE) which varies as a function of the number of people (*Np*) within the household elaborated by the CTCU (CTCU, 2013).
- *Np* is the number of persons who are in the family.

The energy requirement related to mobility refers exclusively to professional mobility; therefore the energy required for commuting has been calculated as a function of the path that minimizes at most the travel time between two specific points in space (origin = residence, destination = place of work) with the type of transport preferred by each individual as specified in the National Census. In other words, for each element of the dataset the fastest path to commute from home to work has been retrieved; consequently, the energy associated to cover this trip was calculated according to the type of transport used and multiplied by the number of working days per year.

It can be expressed as:

$$QesMob = f(d, Mt, Wd) \qquad [2]$$

Where:

- QESMOB is professional mobility QES; it is calculated for each family member who has a job.
- *d* is the chosen path considering the actual transport offering (public transport or private vehicle).
- *Mt* is the selected transport; each *Mt* may represent a combination of different types of transport (train, metro, bus, suburban, city bus, tram, car, motorcycle).

- *Wd* is the number of days during which the journey home-work-home is done. This depends on the type of job as specified in the National Census and by a research conducted at the DARES institution (DARES, 2005).

In order to calculate the energy cost, it was necessary to reconstruct the entire road network of the Ile-de-France considering the real infrastructures for private use and public transport, the associated costs in terms of GHG emissions, energy required and money. The model is based on several assumptions concerning the energetic consumption per kilometre for passenger, and the average speed for each type of transport commonly used in France (RATP, 2010). This work has been done using ArcGIS Network Analyst. The network analysis consisted basically on a work of "route finding" constrained by several *a priori* determined criteria. The most important one was the travelling time. In fact for each active individual it was necessary to calculate the path to go from his home place to his work place in the least amount of time with the type of transport preferred.

By integrating the two procedures described above (Fig. 1), it was possible to estimate the total QES for each family residing in the study area, and calculate QESMOB and QESAB per capita to the highest possible spatial detail. In other words QESAB was calculated for each household, while QESMOB was calculated individually for each person having a job within a household; finally the different calculated quantities have been summed and properly averaged. Hence, estimating the monetary value associated with QES depending on the type and the price of energy used was possible (EUROSTAT, 2010).

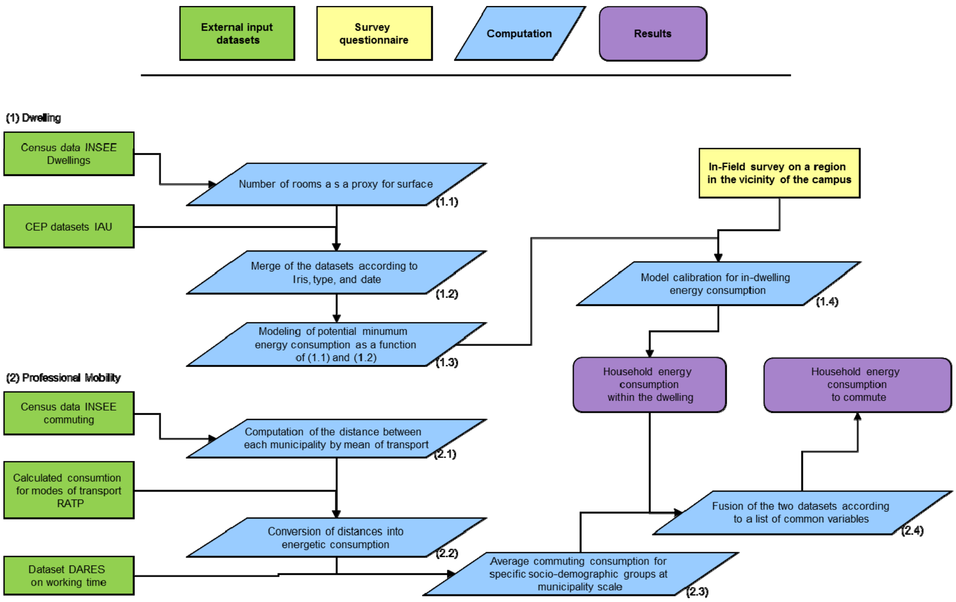

Fig. 1 – The model workflow, from data input to expected results.

Source: personal elaboration.

The model was designed together with an in-field survey meant to be used for calibration purposes. However, at this time the survey has not been carried out yet. To overcome this limitation, a preliminary accuracy analysis has been done comparing the estimated QES with a dataset of observed energetic consumption developed by IAU (IAU, 2005) for all the municipalities in Ile-de-France (Fig. 2). Results of this piece of preliminary accuracy testing are encouraging and are given in the next paragraph.

4. *Results*

One of the first thing to do when working with hypothetic forecasts and scenario-modelling is to test the validity of the hypothesis and the accuracy of the results achieved. As before mentioned, a preliminary test in this regards was performed by comparing the estimated QES with a dataset of observed energetic consumption developed by IAU, which resulted in encouraging outcomes. In fact, the coefficient of a linear regression between the two dataset resulted to be quite high (~ 0.9 R^2; Fig. 2), although our modelled QES was always sensibly (and reasonably) lower. Since the two dimensions (modelled and real) resulted to appear closely related, although having been developed with separate analysis by independent institutions from different input and through different methodologies, we can speculate that the model developed for QES estimate is robust and ground based. Furthermore, we can notice how QES is almost always sensibly lower than the observed measure by IAU, which make sense since (QES) is the potential minimum amount

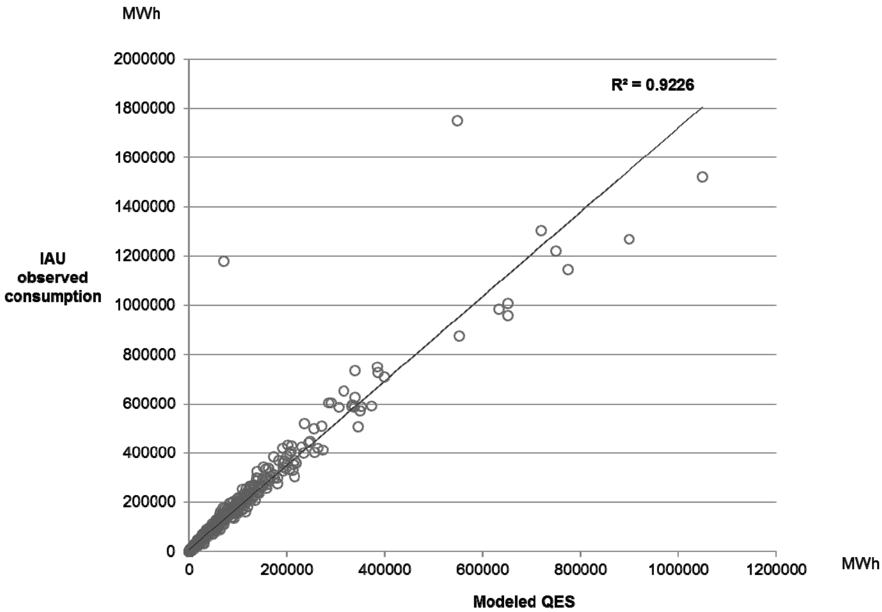

Fig. 2 – Linear regression of modelled Qes versus the observed consumption dataset developed by IAU for the same set of needs and population, aggregated at the municipality level.
Source: personal elaboration.

of energy needed, therefore it aims at defining an optimum baseline that minimizes waste; hence it represents a goal for improving energetic efficiency, which can hardly be met spontaneously in real life since social behaviour is seldom perfectly rational.

The results obtained confirm the monocentric nature of the Ile-de-France, dominated by its core represented by the city of Paris (Fig. 3).

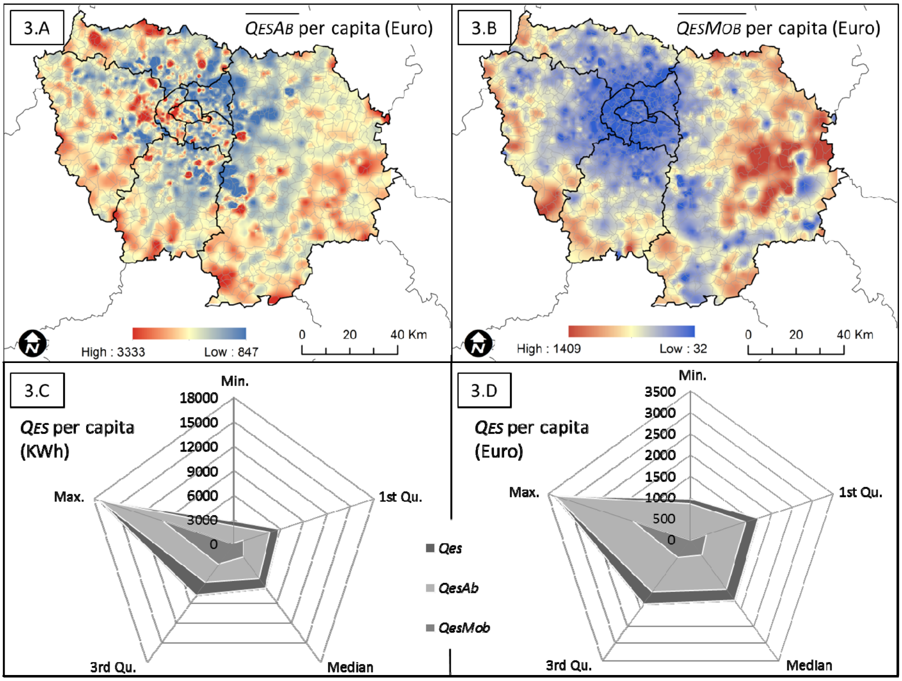

Fig. 3 – The minumim amount of resouces needed to meet a set of fundamental need (QES). Spatial distribution of average QESAB per capita (3 A) and average QESMOB per capita (3 B) in the Ile-de-France. QES statistical distribution, QESAB and QESMOB average in energy (3 C) and monetary terms (3 D).

Source: personal elaboration.

In fact, both components of QES, although in different proportions, increase with increasing distance from Paris. The QESMOB average cost that each worker of families has potentially to deal with is lower towards the centre and increases in peripheral areas (Fig. 3.B). In the same way, the average QESAB per capita roughly shows the same spatial pattern, although it is less clear; in fact, there are several areas where this cost is individually very high in comparison to the surrounding areas (hot spots) (Fig. 3.A). Consequently, this indicates that QESAB is a function of other variables whose geographical tie still needs to be further explored, although it is unequivocally influenced by the distance from the centre. Nevertheless, it is also possible to observe which of the two components has the bigger impact on total QES. Generally speaking, QESMOB represents on average a portion much lower than QESAB, nevertheless they potentially belong to the same order of magnitude. This ratio (QESMOB = ~ 1/3 QESAB) applies both from the energy (in kWh; Fig. 3.C) and monetary point of view (in Euro, Fig. 3.D). Although a thorough and more detailed analysis of energy vulnerability for different type of household has not been carried out yet, we can however understand how this estimate can be proficiently used in this regard. In fact, although it is not possible through QES to define a specific threshold or proportion of revenue over which a household or an individual can be considered fuel poor, it is still possible to investigate why QES varies so much among individual that should have similar characteristics or among geographic areas that are relatively similar (i.e. see the red cluster in the outer right side of the Ile-de-France in Fig. 3.B). However, a more thorough analysis in this regards will be the object of future research.

5. *Conclusion*

From a monetary point of view, our results suggest that in order to reduce household energy vulnerability/poverty and to increase fuel efficiency, the public actors' activities should be more focused on the rationalization and improvement of the energetic performance of the housing sector. In fact, a certain reduction of QESAB would have a much greater impact on QES total, than a reduction of the same proportion of QESMOB. At the same time, they should mainly focus on those areas which represent an exception to the mono-centric model, trying to understand not only "how" to make them less vulnerable, but also "what" determines their vulnerability. However, regarding QESMOB, it is rather evident that areas close to the centre have benefited from the public transport recent expansion and modernization, although this happened at the expenses of more peripheral areas.

In addition to the application described to estimate QES and to investigate energy vulnerability, we believe that this modelling work has the potential to represent a solid base for further analyses in several closely related domains, such as, fuel poverty, sustainability, resilience etc. For example, another application is the possibility to assess the "resilience potential" as a function of CO_2 emissions related to the estimated QES, and of the potential CO_2 sequestered by the existing vegetation. In fact, knowing the different types of energy composing QES and their relative proportion, it is possible to calculate the amount of CO_2 emissions that QES is responsible for at different geographical scales (RATP, 2010). At the same time, we can get an estimate of the area covered by forest or green spaces within each administrative area using any sort of land-cover data (e.g. CLC2000, European Environment Agency). Consequently, by appropriate conversion coefficients between vegetation type and the amount of CO_2 sequestered per unit area, it is possible to estimate how potentially resilient each geographic area is in respect of the CO_2 potentially produced by QES. Although this is only an example of the sort of analysis that is possible to conduct at the aid of QES estimate, we believe it particularly important because this modelling approach allows drawing different scenarios that can find relevance in different disciplines.

Besides the benefits listed so far, we believe useful to also highlight some of the critical aspects of the proposed method. The fact that the model neglects to consider the level of income results in the impossibility of determining a specific threshold below which an individual turns out to be energetically vulnerable; in fact, while on the one hand it allows to decouple the concept of vulnerability from the concept of wealth, on the other hand revenue cannot be used as a variable to better group households in different profiles. Consequently, in order to investigate fuel poverty it is necessary to consider the QES of an individual always in comparison to the QES of the other elements populating the same socio-demographic and geographic sub-group. Furthermore, although we believe the set of assumptions taken to develop the model to be robust and valid, QES is a hypothetical measure; hence, to exactly derive how much energy could be saved, both at an aggregate or individual level, a dataset describing the real consumption is needed. However for this case report, we do not have an accurate database about the real energy consumed to satisfy the set of needs listed above that can be compared with the obtained results. This issue provides the basis for future development of the research.

In conclusion, the modelling work implicitly conveys the underlying principle from which it was inspired, hence the produced results are influenced by such paradigmatic approach; as a consequence this research aims at being a tool to support public action for a sustainable and equitable development. The proposed model is rather flexible; in fact, although it is (in our opinion) the first investigation to decline the energy vulnerability as a function of mobility and domestic consumption at the same time, it is not specific to any geographical context but can be easily applied to other case studies. Furthermore it represents a solid base onto which is possible to further proficiently expand the concept of fuel poverty and build upon the paradigmatic shift proposed by the model.

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Vulnerabilità energetica familiare: osservazione dell'energia consumata contro la stima della potenziale domanda energetica

Recentemente il consumo di risorse naturali da parte dell'uomo ha raggiunto livelli inimmaginabili; conseguentemente anche la preoccupazione per il depauperamento accelerato dell'ambiente naturale è aumentata ed è divenuto un argomento di ampio interesse sociale e scientifico. Questo fenomeno viene spesso rappresentato come il conflitto tra la necessità di aumentare la base di risorse disponibili per alimentare lo sviluppo umano da un lato; e dall'altro, il bisogno di ridurre la pressione umana sull'ambiente, in quanto fattore funzionale all'accrescimento della capacità di resilienza del nostro pianeta. Molto spesso la soluzione a tale conflitto è basata sul raggiungimento di obiettivi stabiliti a priori in termini di miglioramento delle prestazioni – questo è particolarmente vero per ciò che concerne l'energia. In questo studio, tuttavia, si vuole proporre un quadro operativo differente che si distanzia dall'osservazione del consumo reale di energia, e si concentra piuttosto sulla stima di un quantitativo ipotetico necessario al soddisfacimento di una serie di bisogni specifici. Il modello qui presentato mira a servire principalmente come strumento per lo studio della vulnerabilità energetica e vuole fornire un utile strumento a supporto dell'azione pubblica in tal senso. Il lavoro di modellazione prende come unità di analisi il singolo nucleo abitativo e vuole stimare solo il fabbisogno energetico necessario per il consumo domestico e la mobilità professionale. Le osservazioni qui presentate fanno parte del progetto di ricerca *Efficacité Energétique*, finanziato dal LABEX Futurs Urbains (Ecole des Ponts ParisTech, Université Paris-Est).

Vulnérabilité énergétique des ménages: observation de l'énergie consommée contre estimation de la demande énergétique potentiel

Dernièrement, la consommation de ressources naturelles par l'homme a atteint des niveaux inimaginables. Par conséquent, la préoccupation pour l'épuisement accéléré de l'environnement a également augmenté et est devenue un sujet d'intérêt croissant pour les médias comme pour la communauté scientifique. Ce phénomène est souvent illustré comme le conflit entre la nécessité d'accroître les ressources naturelles disponibles pour soutenir le développement d'une part; et d'autre part, la réduction de la pression humaine sur l'environnement, facteur fonctionnel à une augmentation de la capacité de résilience. Très souvent, la solution pour résoudre ce conflit est basée sur la réalisation d'objectifs fixés *a priori* en termes de performance, en particulier dans le secteur de l'énergie. Dans cette étude, toutefois, un cadre opérationnel original a été mis en place, fondé non pas sur l'observation de la consommation réelle mais plutôt sur une estimation de la quantité minimale potentiellement nécessaire à la satisfaction d'un besoin spécifique. Le modèle présenté ici est destiné à servir principalement d'outil pour l'étude de la vulnérabilité énergétique, tout en fournissant des indications utiles à l'intervention publique sur ce sujet. Le travail de modélisation prend comme unité d'analyse le ménage individuel et prend en compte exclusivement les besoins en énergie pour la consommation domestique et la mobilité professionnelle. Les observations présentées ici font partie du projet de recherche *Efficacité Energétique*, financé par le Labex Futurs Urbains (Université de Paris-Est).