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# A tale of Sustainability and Equity: defining a *safe operating space* for households' energy vulnerability.

Federico Martellozzo[1]

**Abstract**
The demand for natural resources to sustain human activities has dramatically increased in recent decades; as a consequence, we have potentially reached peak oil, poisoned much of the remaining natural ecosystem, and irreversibly compromised the atmosphere. The consequences of the increased anthropogenic pressure on the natural environment have forced us to confront the paradoxical coexistence of two factors required to sustain the development of a growing population: the need to access a larger natural resource base and the need to increase resilience by alleviating human pressure on the natural environment. Thus, limiting energy consumption, or increasing consumption efficiency, is a matter of urgent concern in decelerating the anthropogenic depauperation of the natural environment. Policy making has often interpreted this problem within a technical-reductionist framework. This mainstream perspective has led to neglect issues pertaining resilience and justice thus creating a fertile ground for the appearance of new forms of poverty, which affect not solely developing countries but also the western world. This study focuses in particular on fuel poverty, and its aims are threefold: revitalize the critics to the implicit unsustainable and inequitable principles conveyed through the technical-reductionist approach; elaborate an alternative methodological framework based on equitable and sustainable paradigms; discuss how this can support policy makers in identifying relevant areas for public intervention.

*Keywords: energy vulnerability; Ile-de-France, sustainability, equitable development, spatial justice, energy needs.*

## 1. Introduction

The consumption of natural resources, particularly in urban areas, is a matter of increasing concern (Lorimer 2012; Lambin *et al.* 2001; Rockström *et al.* 2009; Calvert 2015). This problem is exacerbated by continual global population growth, which is projected at up to 9 billion in the near future, coupled with an accelerated rural-to-urban migration (UN 2014). Because natural resource exploitation is crucial to sustain human activities, the consequential environmental burden caused by the increased anthropogenic pressure is an issue that cannot be neglected (Foley *et al.* 2005; Grimm *et al.* 2008; Steffen *et al.* 2007, Gamlen 2014).
This aspect of human/environment interaction could be characterized as a paradox: on the one hand, there is an increasing demand for natural resources to support humanity, and on the other hand, there is a need to improve the Earth's resilience by alleviating the anthropogenic pressure on the natural environment. Many cohorts advocate that the depletion of the natural environment has gone well beyond what our planet can take and that the regenerative capabilities of the Earth's ecosystems cannot match the rate at which resources are exhausted (Rockström *et al.* 2009)[i]. Therefore, addressing the mitigation of the burden of human activities on the environment is a crucial problem for

[1]University of Florence. Dept. of Economics and Management. Via delle Pandette 9, 50127 Florence, Italy.

the persistence of many species (including humans) and for the protection of many ecosystems (Lambin and Meyfroidt 2011; Smith *et al.* 2010).
Furthermore, this study aims at contributing to the recently revitalized discourse of "energy geographies" (enunciated by Calvert in 2015), discussing in particular the theoretical rationale that often frames and juxtaposes the reduction of energy consumption with the improvement in consumption efficiency. Accordingly, the methodological framework described in this study can be characterized as aiming to bridge "*socio-spatial theory to better understand the energy-society relationship*" with "*spatial decision-support for energy planning and technology implementation*" (Calvert 2015).

### 1.1 Theoretical background

Environmental impact reduction is typically defined as improving a system's efficiency, which, in theory, implies a reduction in the total resources consumed and diminished pressure on the natural environment. The rationale underlying this technical-reductionist approach (Weichselgartner and Kelman 2014) has often caused policy makers to establish pre-set goals to seek a mere amelioration of performance (e.g., the Kyoto Protocol, the Millennium Development Goals, Horizon 2020, etc.). As a result, scientific research has substantially privileged the practical development of applications capable of achieving these goals through technical innovations (Park *et al.* 2009; Battisti 2009). Although this type of research is extremely useful (e.g., Walker R. *et al.* 2014), it fails to consider important aspects of the problem beyond technical challenges, which may result in a fallacious broader framework (Wood 2007). In fact, preventively investigating whether the established goals are achievable or not, what negative impact may be produced by the blind adoption of such implementation, and whether the magnitude of the proposed intervention's expected results is sufficient to yield significant effects is as crucial (Hertwich, 2005; Greening 2000) as increasing technical efficiency *per se*. In other words, the leading paradigm of efficiency-driven implementation primarily targets audacious decreases in the level of resources consumed. Thus, this rationale mainly promotes an optimization of the "consumption mechanism" *per se* and disregards an investigation into how to achieve a more comprehensive amelioration of the system as a whole. As a consequence, the focus on resource rationalization is habitually neglected and questions such as the following are seldom contemplated: Who is consuming? For what purpose? What is the amount of resources "wasted"? Is that consumption necessary? What is the amount of resources necessary to satisfy a specific need? Answering these questions is important, especially as we realize that our world is finite and resources are not limitless (Rockström *et al.* 2009). Therefore, the implementation of studies based on the latter paradigm becomes fundamental because it does not aim solely at increasing the "mileage per gallon" of human activities, but it also focuses on the entire consumption system, helps determine whether an inefficient waste of resources can be avoided (Pachauri 2004; Jones H. & Jones P. 2007). Thus, theoretically framing *fuel poverty* in terms of energy services and energy needs is functional to the elaboration of methodological approaches to investigate *energy vulnerability*, which "allow for a more explicit focus on the geographic aspects of domestic energy deprivation" (Bouzarovski and Petrova 2015; Pachauri *et al.* 2004). The previously mentioned paradigmatic shift implicitly fosters the idea that consumers are not exclusively considered an ensemble of separate entities but (also) as different elements within the same system; following this line of thought will facilitate the elaboration of a rationalization framework built upon sustainable and equitable criteria (Pachauri and Spreng 2004).

Energy-based needs and, consequently, energy consumption have increased substantially in recent decades, thus causing the emergence of new forms of poverty such as fuel poverty. Fuel poverty has been observed in many countries, and multiple definitions already exist (Walker R. *et al.* 2014; Pachauri and Spreng 2011) (Pa. For example, in the United Kingdom according to the Warm Homes and Energy Conservation Act "a person is to be regarded as living in *fuel poverty* if he is a member of a household living on a lower income in a home which cannot be kept warm at reasonable cost". Hence, households are usually considered to be fuel poor when they would need to spend more than 10% of total revenue to maintain an adequate thermal comfort in their dwelling (Liddell *et al.* 2012.). In France (Beslay *et al.* 2010), fuel poverty also factors in the energy demand necessary to support mobility needs (e.g., professional mobility). Although a specific ratio of the revenue to serve as a threshold is not officially fixed, the one used in the UK is often considered a reference point. In both cases, fuel poverty is conceptualized as a function of revenue as it has often been considered a fundamental variable to model and forecast the energy demand of a population (CERTU 2011). As a consequence, in order to discern the proportion of fuel poor population modelling and survey efforts more often than not consider current monetary expenditures rather than potential energy needs (CERTU 2011, Hills 2012, Moore 2012). However, modelling energy needs and defining fuel poverty thresholds independently from the level of revenue makes it possible to avoid the implicit unsustainable and unequitable criteria on which this rationale is based. In fact, according to this reasoning, a person with access to an unlimited level of wealth (i.e., an extremely rich individual) can hypothetically dispose of an infinite amount of resources without being considered energetically vulnerable, which is unsustainable because resources are not infinite. On the other extreme, an extremely poor person who does not have access to revenue, an individual who cannot allocate resources to satisfy energy-based needs, will also not be considered fuel poor. This second case is particularly worrisome because beyond being simply unequitable, it leads to severe health risks (Jones P. *et al.* 2007, Liddell *et al.* 2012).

### 1.2 Methodological rationale

This study proposes a paradigm shift in the investigation of fuel poverty. The funding pillar is the assessment of the *minimum amount of energy needed to satisfy a set of "fundamental" needs*[ii] (henceforth called *Qes*), as opposed to the conventional estimate of energy demand; the former is modelled in an independent fashion from the level of revenue, thus avoiding unsustainable and unequitable criteria while addressing fuel poverty. In this research, we focus on energy consumption at the household level. A suggested framework is developed to determine the *Qes* for each single household corresponding to an identical set of needs according to the geographic and socio-demographic profile of each household. This paper describes the general assumptions from which the proposed model is built, the input data and the types of outputs that are possible to obtain. Moreover, the results from a specific case report (Ile-de-France) are presented, preliminary accuracy is tested, and a methodological framework for *energy vulnerability* investigation is discussed. The described paradigmatic shift and the proposed framework for energy vulnerability constitute a rationale based on equitable and sustainable criteria. We believe this theoretical and methodological effort will lead to an improved understanding of energy consumption dynamics and urban poverty. Consequently, the benefit that this framework represents for the implementation of adequately informed policies targeting sustainability and equitable social development are discussed.

## 2. Methods and data

The goal of the modelling effort described in this research is to estimate "potential" quantities based on "realistic" hypotheses and not to mimic "real" consumption patterns. Thus, the concept of "potential" aims at defining a potentially achievable target reduction, which constitutes the baseline for a plausible comparative investigation of energy vulnerability (Martellozzo et al. 2014).

This study characterizes this "potential" as the estimate of the energy demand sufficient to fulfil a set of *a priori* established necessities (*Qes*). In other words, *Qes* answers the following question: What is the minimum amount of energy that is needed to satisfy a set of basic needs? These needs are equal among all subjects populating our case study and essentially consist of two types. The first type of need involves the energy required within the dwelling; it includes maintaining an adequate thermal comfort in the place where a household lives and sanitizing water (both variables are elicited by the energy performance of the dwelling, i.e., EPC) as well as the energy needed to run some basic appliances ($Qes_{Ab}$). $Qes_{Ab}$ is discussed in paragraph 2.1. The second type of energy-related need that is included in the estimate of *Qes* is the energy needed to satisfy professional mobility ($Qes_{Mob}$). The part of the model dealing with $Qes_{Mob}$ calculates the energy that employed people spend to commute from/to their work location according to the type of transport used (all variables are explicit in the data from the National French Census. INSEE 2008). $Qes_{Mob}$ is discussed in paragraph 2.2.

To our best knowledge, this study is the first attempt to investigate "potential" energy demand for both in-dwelling needs and professional mobility at the same time and at the same scale for an identical set of subjects. In fact, several studies have modelled energy demand, although not in terms of "potential", both for heating and commuting, and several frameworks have been proposed; however, the two dimensions are typically distinguished and separated, producing outputs at different scales and (sometimes) for different subjects (CERTU 2011).

Conversely, the framework hereby proposed, although a distinct part of the model is dedicated to each dimension, uses an identical area of investigation, set of subjects and scale of inputs for both $Qes_{Ab}$ and $Qes_{Mob}$ estimates, and it assumes that *Qes* is the sum of the two. Therefore, the results are coherent both spatially and in terms of population. Hence, $Qes_{Ab}$ and $Qes_{Mob}$ can either be combined to investigate total *Qes* or utilized separately to observe socio-regional discrepancies arising from the distinct patterns of the two dimensions (see Supplementary materials for a figure of the model workflow).

The analysed area is the Ile-de-France region, and the scale of inputs is at the household level. Because the set of needs from which *Qes* is based is defined uniformly for all subjects populating the dataset (households living in Ile-de-France), the *Qes* of each household actually varies according to its socio-demographic and geographic characteristics. As opposed to what has been done in antecedent modelling studies (Penot - Antoniou and Tetu 2010; CERTU 2011), this study does not use the level of wealth that a household can dispose of (e.g., income, revenue), which is a variable typically used to first model energy consumption and then to determine a threshold for fuel poverty (Devaliére 2012; Waddams Price *et al.* 2007). This is because *Qes* was (intentionally) defined in an independent fashion from revenue. In fact, the energy theoretically needed to properly heat a house is not influenced by the income of the occupants but rather by physical properties, construction characteristics (determining the energy performance of the dwelling) and the type of energy used. Similarly, the energy required to fulfil professional mobility is greatly influenced by the mode of transport used and by the path chosen to go from point A to point B, but the revenue of the commuter does not influence the amount. In other words, the "minimum amount of energy necessary to satisfy energy-based needs" in both domains is influenced by the energy performance of the equipment (home/transport), whereas the level of wealth of the subject is not relevant to assess *Qes* [iii]. This definition of *Qes* was intentionally conceived to avoid the unsustainable and unequitable concept of "who earns more can consume more", which underlies the emergence of new forms of poverty and also implicitly leads to unsustainable development paths (Walker G. and Day R. 2012).
In the following paragraphs, the plausible assumptions from which the modelling framework is built are described. As mentioned, these are exclusively based on socio-demographic and geographic variables of each household, and the economic profile is not considered. However, knowing the estimates for *Qes* in energetic units (KWh) and the mix of sources utilized, it is also possible to convert *Qes* from energetic values to monetary values. Both types of results are given and are further discussed in paragraphs 3 and 4 of the Results and Discussion sections.

### 2.1 $Qes_{Ab}$ : "In-dwelling" minimum energy demand

The first part of the analysis addresses the assessment of the energy needed to satisfy a set of in-dwelling necessities, such as sanitized water production, maintenance of thermal comfort, and the energy consumption of basic electronic appliances. Estimates of the energy required to satisfy these needs depend greatly on the number of people, the type of energy used, the energy performance and the size of the dwelling.
The variables used to model $Qes_{Ab}$ are extracted from the French National Household Census (INSEE, 2008) and from the online repository "Visieu Energie" developed by the *Institute d'Amènagement et d'Urbanisme* (IAU 2005)[iv]. From the first dataset, we obtained all variables related to the demographic profile of each household (e.g., number of people) and the characteristics of the dwelling (type, location, date of construction, size, type of energy used, etc.). From the dataset developed by the AIU, we extracted a spatially explicit cartography for the energy performance (EPC) of each dwelling grouped by type and age of construction. Then, we spatially joined this with the household census

dataset to assign each household an EPC value based on the combined correspondence of construction characteristics and geographical location of the dwelling (see SM2).

## 2.2 Minimum energy demand for "professional mobility" ($Qes_{Mob}$)

The energy amount necessary to satisfy mobility-related needs takes into account only professional mobility; thus, it reflects the energy needed to commute from home to work and from work to home. The *Qes* required for commuting is calculated as a function of the path that minimizes the travel time between two specific points in space (origin = residence; destination = place of work) for the type of transport of choice (which is elicited in the data input). In other words, for each commuter in the dataset, the fastest path to travel from home to work was identified from a spatially explicit infrastructure network reproducing all of the means of transport available in Ile-de-France; consequently, the energy to cover the trip was calculated according to the type of transport used and multiplied by the number of working days per year[v]. The potential energy consumption associated with professional mobility was calculated on a road network including all public transport alternatives and all of the driveable roads accessible with a private car; furthermore, the amount of greenhouse gas emissions and the monetary cost associated with each commuting trip was also derived. The coefficients regarding the energetic consumption per kilometre and per passenger in public transport as well as the average speed for each type of transport commonly used in France were taken from data developed by the *Régie Autonome des Transports Parisiens* (RATP 2010). These values were used as regulating criteria for the route-finding network analysis (see SM3).

By integrating the two procedures described above, it was possible to estimate the total *Qes* for each household residing in the study area (see SF1 in SM1). Moreover, the monetary value associated with total *Qes* for each household was calculated according to the type and price of energy used (EUROSTAT 2010). In fact, the output table is a dataset that shows the forecasted potential *Qes*, the corresponding price that should be paid, and the amount of greenhouse gas emission associated with the hypothetical consumption for each household. Furthermore, *Qes* was also normalized by the number of people composing each household to derive the $Qes_{Mob}$ and $Qes_{Ab}$ *per capita* for each household. The validity of the obtained results is discussed in the next section.

## 3. Results

The first part of this section investigates the validity of the proposed model in portraying *Qes* and how *Qes* differs from real consumption observations or modelled predictions (e.g., Walker *et al.* 2014, CERTU 2011). The second part demonstrates how the output of the proposed model can be utilized to identify loco-regional differences arising from the consumption patterns investigated and how these differences can be crucial in supporting informed policy making and planning. The third part of this section presents a framework for fuel vulnerability investigation analogous to models involving more general concepts of poverty.

### 3.1 Empirical evidence of robustness and validity of the methodological framework

To investigate whether the model is capable of reproducing realistic results, the estimated *Qes* was compared with a dataset of observed energy consumption for the same year and for the same population developed by IAU[vi] (IAU 2005) (fig. 1). The outcomes of this comparison are encouraging and represent a preliminary step forward in assessing the robustness of the proposed model. The scatterplot of the two dimensions (fig. 1) shows that the datasets are likely correlated; the linear regression coefficient is quite high (~ 0.9 $R^2$, fig. 2), thus revealing significant covariance of the two datasets. Moreover, it is important to note that estimates of *Qes* are persistently less than actual consumption; which is perfectly meaningful given that *Qes* represents a hypothetical optimization baseline for energy consumption that minimizes waste but satisfies the "fundamental" needs elicited in the model (thus implicitly mimicking a perfectly rational and informed behaviour).

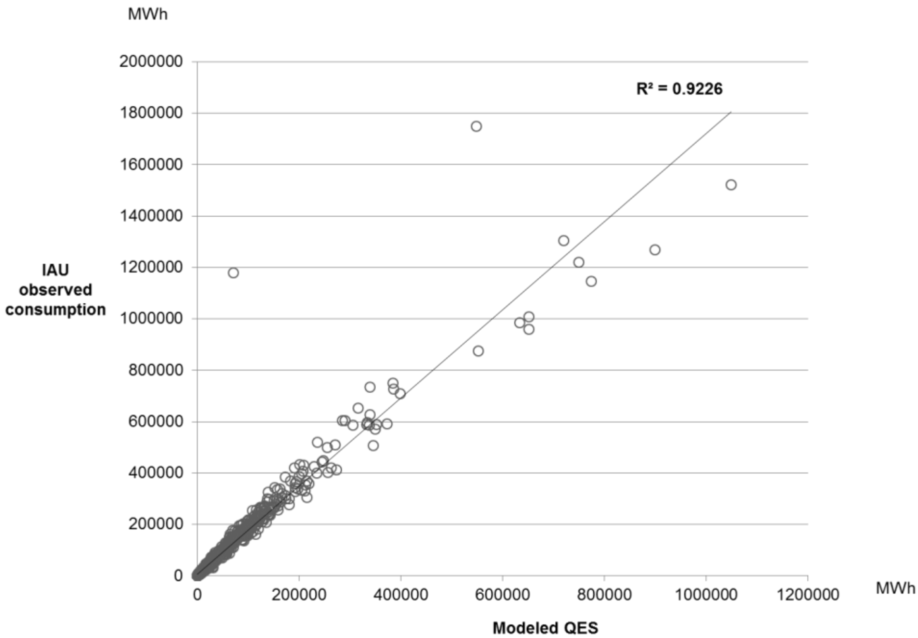


*Figure 1. Scatterplot of Qes and actual consumption data. Linear regression coefficient is ~0.9.*

Conversely, IAU observations portray the actual energy demand, which can hardly correspond to perfectly rational consumption patterns in real life. Thus, it appears reasonable that *Qes* is always less than actual consumption. Nonetheless, the two vectors, although developed by different institutions with different research frameworks, appear closely related with systematically comparable magnitudes, thus reinforcing the fact that speculation about the validity of the suggested estimates for *Qes* is justified.

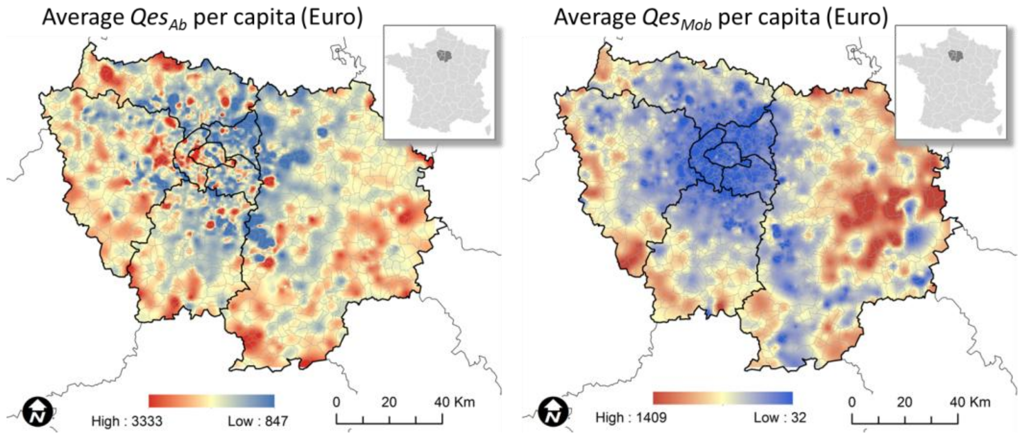


*Figure 2. Minimum amount of energy needed to meet a set of fundamental needs (Qes). Spatial distribution of average QesAb per capita (left) and average QesMob per capita (right) in Ile-de-France. Qes spatial distribution is given in monetary units (see SM4).*

### 3.2 Spatial variation of average Qes per capita

One of the outputs of the proposed methodological framework is the ability to explore the spatial variation of the investigated quantity. To this end, yearly *Qes* per capita was derived both for commuting and in-dwelling needs to map the variability of potential energy demand across space (fig. 2)[vii]. In particular, for the presented case study, which more or less coincides with the metropolitan Paris area, the investigation of $Qes_{Mob}$ per capita variability confirms the monocentric character of Ile-de-France; in fact, areas closer to the centre reveal a lower potential energy demand to satisfy commuting needs than areas further from Paris. However, $Qes_{Mob}$ clearly increases as the distance to the centre increases; the same trend can be identified for $Qes_{Ab}$ but with a more scattered pattern.

Both components of *Qes* increase when approaching the peripheral areas of Ile-de-France, although in different proportions. The lesser clarity of the monocentric spatial pattern drawn by $Qes_{Ab}$ suggests that the energy needed to satisfy professional mobility is strongly influenced by variables that decay homogenously in space, whereas the ones influencing $Qes_{Ab}$ are only partially influenced by the distance from the centre. This appears to be reasonable given that $Qes_{Ab}$ depends greatly on the characteristics of the dwelling even though commuting it is unequivocally influenced by the distance from the centre. For example, EPC is established as a function of (above all) the year of construction (based on the hypothesis that newer buildings are more efficient than older ones). Furthermore, it is also possible to observe at any given location whether $Qes_{Ab}$ or $Qes_{Mob}$ has a greater impact on total *Qes*, thus identifying which dimensions of the potential household energy demand require priority in public intervention.

### 3.3 An operative framework for fuel vulnerability

As said, fuel poverty is often interpreted, modelled and observed as a function of revenue. In fact, a ratio of the level of revenue is typically used to establish a baseline, and fuel poverty is said to occur when the allocation of economic resources to satisfy energy-related needs is higher that the established baseline. On the one hand, an estimate of fuel poverty based on this sort of benchmark has the advantage of applying homogenous parameters across the area and the population considered, thus making the comparison of the different entities straightforward. On the other hand, it conveys a certain degree of arbitrariness in establishing the benchmark value.

However, this approach is highly similar to the one typically used to investigate the more general concept of poverty, in which poverty lines are determined according to revenue. In investigating poverty lines, relative measures are generally compared with absolute estimates (Sallila *et al.* 2006); the benchmark for the former is established by a comparison with the entire set of elements populating the case study, whereas the latter derives a baseline from criteria considered valid unconditionally. The literature concerning the more general concept of poverty and the methods to adequately determine a poverty line usually juxtapose the two types of estimates depending on the goal of the study; however, the median value is usually the threshold from which the baselines are derived. Nevertheless, both approaches are based upon a deterministic rationale wherein the distinction between absolute and relative depends solely on the scale of the area considered.

Analogous to what is typically developed to determine poverty lines, the same rationale can be applied to *Qes* to derive a baseline for energy vulnerability. In this regard, terminology defining a mixed approach would be preferable rather than a real distinction between absolute and relative measures. In fact, although energy-related needs do not vary from subject to subject, *Qes* was designed according to a deterministic "absolute-like" approach that is grounded in criteria considered universally valid. Moreover, context variables such as energy types and infrastructure availability differ from region to region; therefore, we believe that any attempt to frame energy vulnerability should consider the background context. Thus, a relative estimate based on *Qes* should be contextualized according to its variation within the region of interest and investigated among an appropriate set of co-subjects.

In practice, we propose that household *Qes* is determined in an absolute fashion, whereas its application to investigate energy vulnerability is framed according to relative criteria. Thus, for each household, the difference and the distance of the *Qes* per capita ($Qes\_{pc}$) from the median $Qes\_{pc}$ observed within the case study area were also calculated. According to this rationale, a positive delta indicates that household energy demand is higher than the median, suggesting that the household is more energivore (or less efficient) in satisfying the same set of necessities. Conversely, when $Qes\_{pc}$ is lower than the median, it indicates that the household fulfils its energy-related needs with a smaller amount of energy. In the first case, the distance from the $Qes\_{pc}$ baseline can be interpreted as a gradient for the susceptibility to energy vulnerability, whereas in the second case, it may indicate the likelihood of a household to be more resilient. In other words, when household $Qes\_{pc}$ is above the median, increasing the distance between the two dimensions increases the probability that the household is potentially fuel vulnerable; conversely, when household $Qes\_{pc}$ is below the median, increasing the difference identifies a more efficient household that is less prone to fuel vulnerability and consequently more inclined to resilience (fig. 3).

Figure 3 shows *Qes_pc* for all households living in an economically relevant municipality located just outside Inner Paris (Aubervilliers). On the *x* axis, *Qes_pc* is given in energy units (KWh), whereas the *y* axis features the price per capita that household would have to pay for *Qes* (in Euro) (see SM4). The majority of households fall in a portion of the graph that is below and limited by both medians; thus, using a metaphor from the Planetary Boundaries concept (Rockström *et al.* 2009), it can be considered as a "safe operating space" for potential energy demand. In fact, subjects belonging to this group can potentially outperform (in terms of efficiency) half of their neighbours to satisfy their energy needs and can also pay less than what half of them pay. Conversely, households remaining in the space above both medians are the ones likely prone to fuel poverty; the severity of their vulnerability depends on how far from the medians they fall.

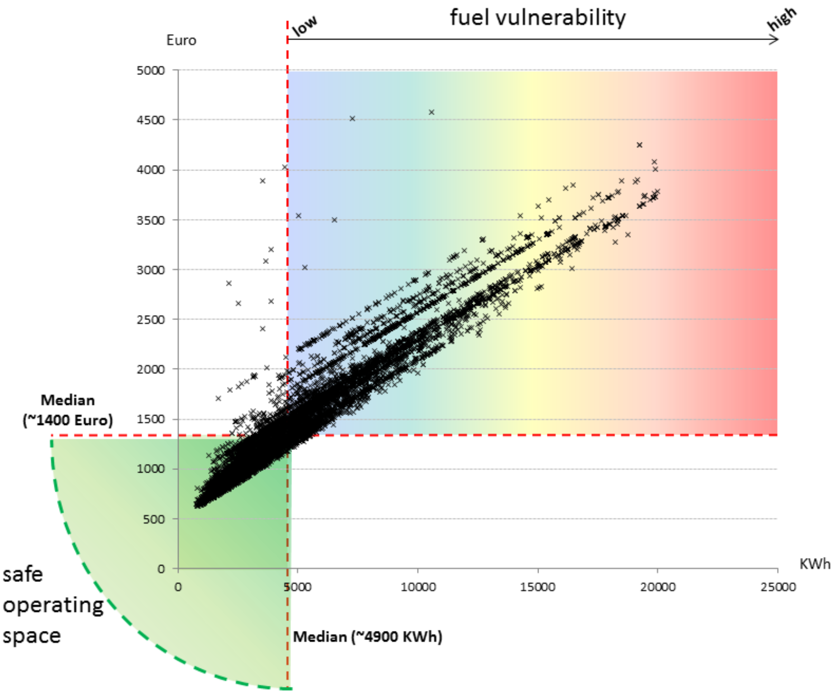


*Figure 3. Susceptibility to fuel vulnerability and "safe operating space": Scatterplot of the Qes_pc in energy units (KWh) and in monetary units (Euro) of all households living in Aubervilliers.*

Moreover, there are some households that despite not showing an extremely high *Qes*, would pay more for it than other households. This condition is highly likely to be determined by the composition of energy types used; thus, switching to less expensive sources of energy could allow them to join the "safe operating space". In other words, these people may already be prone to fuel vulnerability but they could (theoretically) easily get out of it if they could access cheaper energy; hence, public action aiming at ameliorating their condition should not neglect issues such as energy access and supply.

Some households instead fall in the lower right quadrant, which indicates that they potentially consume a higher amount of energy but pay a cheaper price for it. The condition of these households may likely be influenced by the inefficiency of the equipment (house and/or mix of transport) they use. They do not fall in the vulnerable space only because their energy is cheaper, which can make them not resilient as well as at risk. In this case, policy makers might be more interested in trying to understand how to lower their energy demand rather than the price by improving the energy efficiency of buildings and ameliorating public transport issues.

## 4. Discussion

As a first output, the analysis described in paragraphs 3.1 and 3.2 allows policy makers to map where *Qes* is higher on average to establish a list of high-priority locations (hot spots). Moreover, the ability to distinguish which component of *Qes* has the greater impact on total *Qes* is also enabled. Hence, particularly with hot spot locations, the possibility of separating and juxtaposing the energy consumption related to professional mobility from the consumption related to in-dwelling needs will result in highlighting which of the two is the most responsible for a spike in total *Qes*. This second piece of information is particularly useful; in fact, it can suggest for any given location whether it is more urgent to invest in a project targeting an amelioration of household energy efficiency or, conversely, whether it is more beneficial to focus on empowering transport infrastructures[viii]. It is true that these figures give a picture of average *Qes* variability across space, while aggregate values are not considered. We favoured this type of analysis to highlight spatial variability and to limit the blooming effect of Paris, whose aggregate magnitude would have covered up any other relevant spatial variation. However, aggregate *Qes* can also be calculated at a different spatial aggregation to reflect the geographical potential energy demand at different scales.
From a monetary point of view, our specific case study results suggest that to tackle energy vulnerability and to improve fuel efficiency, public intervention should be more focused on the rationalization and improvement of the energy performance of the housing sector. This is because in most areas, a reduction of $Qes_{Ab}$ would have a much greater impact on total *Qes* than a reduction of the same proportion of $Qes_{Mob}$. Considering the characteristics of the case study, these findings are unsurprising. In fact, it is reasonable that $Qes_{Mob}$, is lower in areas close to the centre, which have benefited more from the recent expansion and modernization of public transport. Moreover, the fact that *Qes* is less impacted by $Qes_{Mob}$ than by $Qes_{Ab}$ is unsurprising given that Ile-de-France is considered to have exemplary public transportation offerings in terms of quality, quantity and reach. Moreover, for this specific case study, a focus on those areas representing an exception to the mono-centric model should not be neglected as it may be helpful in understanding what most influences vulnerability and thus in narrowing the options for public intervention. However, whether obtaining such a reduction in energy demand will require a proportional effort for the two different domains is an openly debated topic that has not yet been investigated, thus offering fertile ground for further development.

The framework proposed to investigate fuel vulnerability considers not solely the monetary dimension of energy vulnerability, which conveys equity, but also the amount of the potential energy demand, which builds upon sustainability. Moreover, in regards to investigating fuel vulnerability, we are sceptical about the usefulness of setting a threshold that works uniformly across space and time (e.g., the 10% for fuel poverty adopted in the UK); instead, a flexible gradient able to capture a greater range of variations is preferred. Although it is highly practical, this rationale for estimating energy vulnerability according to a flexible framework might potentially in some instances generate biased results, and this is particularly evident when the population observed is quite small. However, we believe that defining *Qes* univocally, according to principles considered universally valid and independently from revenue, should account for that possible bias. Furthermore, we recognize that the interpretive caveats related to the implementation of a fuel poverty threshold are not secondary; hence, we are aware that a *Qes* slightly off the median is likely not capturing a severe energy vulnerability situation nor can feasibly indicate a substantially different condition from a *Qes* slightly above the median. However, it is actually for this reason that we speculate that interpreting "*Qes* distance from the median" (or other baseline) as a gradient indicating the degree of susceptibility or resilience to fuel vulnerability might be more appropriate.

Nevertheless, the work hereby presented showcases how sustainability and equity are conveyed more thoroughly than in existing frameworks to investigate fuel poverty. However, how the model is built (especially $Qes_{mob}$) may raise some concerns and open up the discussion to multiple policy implication. In fact, although all the possible combinations of public and private transport are elicited in the network used in the model, the simulation of *mobility needs* is based on the assumption that commuters move with the mode of transport reported in the census. Thus, building the simulation on a different set of hypothesis could potentially lead to radically different results. A preliminary sensitivity analysis of this assumption has been performed allowing commuters to use alternatively the quickest or the least energivore mode of transport available in their vicinity to satisfy their mobility needs. From this test no significant differences arise and influence the patterns elicited in figure 2. However, some policy implications still remain unaddressed; e.g. *i)* Should households be allowed to live as far away from work as they wish and claim their commuting as a 'need' or should there be a limit on this? *ii)* Could people be encouraged to use public transport more, or be supported to move closer to where they work? *iii)* Should employers be stimulated in implementing tele-working? By the way, all these interrogatives are not the focus of this work but they represent a stimulating challenge for future policy-oriented research on this topic.

Furthermore, in addition to the approach described to investigate energy vulnerability, the methodological and theoretical framework developed for *Qes* has the potential to represent a solid foundation for further analyses related to sustainability and resilience. For example, another possible application is answering questions such as "how resilient are specific geographic regions in regard to sequestering the greenhouse gas emissions (GHG) related to *Qes*?" In fact, knowing the energy composition of each household *Qes* at any given location, it is possible to map the spatial distribution of the degree of "potential resilience" as a function of the amount of GHG that vegetation can sequester.

In this way it is functional to the estimate of the environmental footprint of urbanites' energy needs on the landscape. In other words, it can be used to proficiently support the estimate of the amount of resources that regions would need outside of their boundaries to meet sustainable goals; which is an important aspect of urban sustainability assessment (Eaton *et al.* 2007). Although this is only an example of the sort of analysis that is possible to conduct with the aid of *Qes* estimates, we believe it particularly important because this modelling approach allows the illustration of different scenarios that can find relevance in several applications.

Besides the benefits listed thus far, we believe it is also useful to highlight some limitations of the proposed method. The fact that the model neglects to consider the level of income allows, on one hand, a decoupling of the concept of vulnerability from the concept of wealth, but on the other hand, revenue cannot be used as a variable to group households according to their socio-economic profile, and consequently it cannot be used to establish an intelligible fuel vulnerability baseline. Therefore, to investigate fuel poverty, it is necessary to consider the *Qes* of an individual (or household) in comparison to the *Qes* of the other elements populating the same region. The size and the characterization of the population chosen for the analysis then become crucial and thus represent a potential limiting factor.

Furthermore, although the assumptions made to develop the model are considered robust and valid, we have to bear in mind that *Qes* is a hypothetical measure; it aims to assess the degree of *fuel vulnerability* affecting each household in comparison with what is taken as a context (for the whole population/society of the region of interest). However, to derive exactly how much energy could be saved (at an aggregate or individual level) for an in-depth case study, *Qes* should be compared and the model should be calibrated with actual consumption data coming from observations, experiments or surveys; in other words, *Qes* can be considered as a representative and indicative model for fuel vulnerability, although its capability to represent an exhaustive framework for in-depth analysis of fuel poverty *per se* should be further investigated.

Nonetheless, when discussing issues such as energy efficiency and consumption, rebound effects can be highly important (Greening *et al.* 2000). We speculate that an analysis of those effects in this case will not be relevant to the scope of why the framework was developed. In fact, *Qes* aims to be a tool for reducing the energy required to satisfy the same set of needs for everyone and does not aim to improve the efficiency of any specific need. Hence, although our analysis does not consider risks related to the green paradox *per se*, our conclusions are not compromised by this omission.

## Conclusion

We believe that the methods outlined in this paper represent a valid means to investigate fuel vulnerability; furthermore, the paradigmatic approach on which it is founded explicitly conveys fair and sustainable principles. In fact, this research aims at being a tool to support public action for fair and resilient development. The proposed model is, to our knowledge, the first investigation to explicitly refuse to model energy vulnerability as a function of revenue and to simultaneously consider professional mobility and household needs. Moreover, it is not specific to any geographical context but can be easily applied to other case studies, which grants this tool a satisfactory flexibility.

A more detailed investigation of some sort of energy-vulnerability profile of different socio-demographic groups that is focused on characterizing the households most prone to fuel vulnerability has not yet been carried out; however, the proposed framework can be used to reach this goal. In fact, although it is not possible using *Qes* to define a specific threshold or ratio of the revenue below which a household (or an individual) can be considered fuel vulnerable, it is still possible to investigate how and why *Qes* vary among individuals having similar characteristics or among geographic areas that are relatively close. A more thorough analysis on this topic will be the subject of future research.

In conclusion, we believe this research substantially contributes to the understanding of fuel vulnerability and of the variables influencing consumption patterns; furthermore, it highlights the crucial need for more accurate and appropriate definition and measurements of such phenomena in supporting adequate and effective policies targeting sustainability and equity. Nonetheless, it represents a solid foundation for further studies aiming to promote human development built upon equitable and sustainable principles.

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## Notes:

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[i] A team of scholars led by J. Rockström and W. Steffen developed the Planetary Boundaries concept and initiated the discussion of a 2009 research agenda.

[ii] Note that the set of needs considered in this analysis is a representative subset of the basic needs related to energy, but it does not aim at being exhaustive.

[iii] For more details on the modelling framework and calculations, see SM1, SM2, SM3 and SM4.

[iv] This dataset is highly relevant as it indicates the amount of energy needed in each house to maintain thermal comfort and to provide enough hot water, according to the standards imposed by the French national law.

[v] The number of working days varies according to the type of job; our inputs are based on the findings from a study conducted at the DARES institution (DARES 2005). See SM 3.

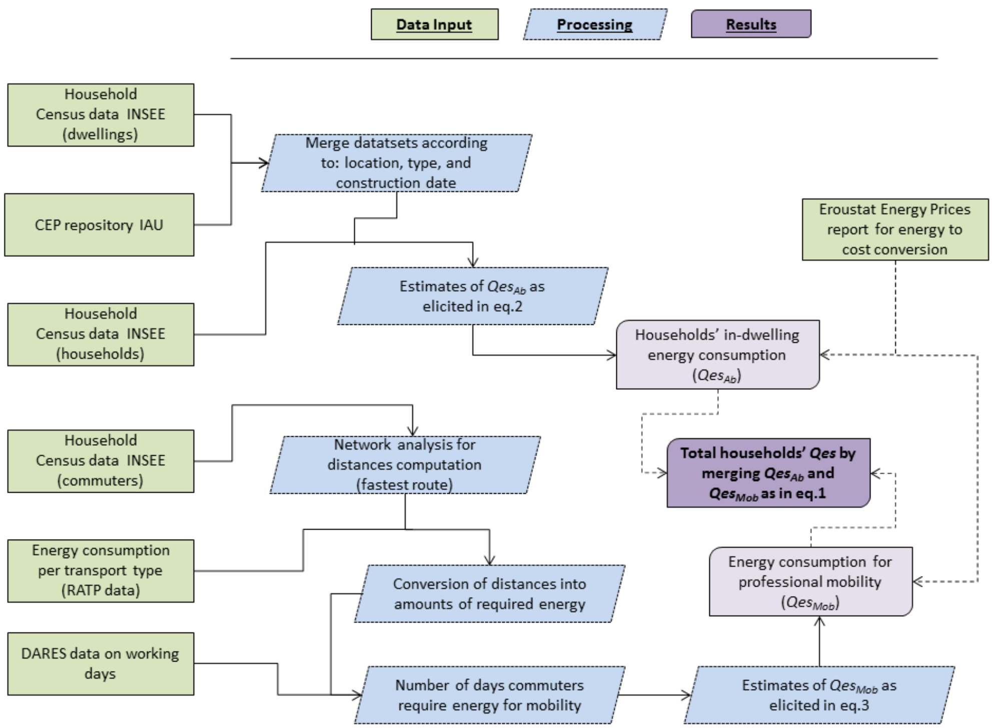
[vi] The observations of real consumption developed by IAU are aggregated at the IRIS scale; hence, *Qes* was also aggregated according to the same spatial lattice.

[vii] Results have been converted from energy units into monetary units. See paragraph 3 in Discussion section and SM4.
[viii] The information produced can inform policy makers and helps give a clearer idea of which component of the potential energy demand is higher, but it cannot indicate *per se* which kind of investment, amelioration or policy is needed.

## Appendices:
## Supplementary materials

**SM1.** The work presented herein assumes that energy consumption for each household primarily consists of the fulfilment of in-dwelling needs and professional mobility. Thus, the minimum amount of energy that a household needs ($Qes$) is represented by the minimum amount of energy necessary to satisfy both components ($Qes_{Ab}$ and $Qes_{Mob}$). The results, steps, data sources and model workflow are described in figure SF1.
Hence, $Qes$ is a function of $Qes_{Ab}$ and $Qes_{Mob}$ (eq. 1):

$$Qes = Qes_{Ab} + Qes_{Mob} \qquad [1]$$




*Supplementary Figure 1. Representation of the model workflow from inputs to outputs.*

**SM2.** The first term of equation 1 describes the in-dwelling energy demand to satisfy a set of needs; the needs considered include hot water sanitation, heating, cooking, and the energy consumption of major electronic appliances. These needs may be defined as a function of the energy performance of the dwelling, the number of people, the type of energy used, and the type of housing as shown in equation 2:

$$Qes_{Ab} = EPC * S * Te + \lambda * Np \qquad [2]$$

Where:

- $Qes_{Ab}$ is the in-dwelling consumption component of *Qes*.
- *EPC* is the index of the energy efficiency (performance) of the dwelling.
- *S* is the surface area of the dwelling.
- *Te* is the type and composition of energy (different fuels/sources have different energetic yields).
- $\lambda$ is a term expressing an energy consumption index (ICE )[viii] that varies as a function of the number of people (*Np*) within the household. This was elaborated by the CTCU (CTCU, 2013).
- *Np* is the number of persons who are in the family.

The variables expressed in equation 2 regarding households' and dwellings' characteristics are contained in the French National Household Census (INSEE, 2008), whereas the EPC values were extracted from the IAU dataset (*Institute d'Amènagement et d'Urbanisme*; IAU, 2005[viii]). Each household was assigned an EPC value according to an identical correspondence of construction characteristics and geographic location possessed by the dwelling. ICE was derived according to the CTCU model (CTCU, 2013). The cartographic product developed by the IAU is provided at the scale of IRIS (an extremely fine administrative lattice implemented in France[viii]); it represents a sufficiently detailed product because IRIS in Ile-de-France is quite small. Some scale-related bias might have been introduced in this phase; however, the sensitivity test presented in fig. 1 of the main text suggests that potential scale aggregation factors may have a negligible effect.

**SM3.** The second term in equation 2 describes the variables considered in estimating the energy need for professional mobility. The minimum amount of energy required for commuting needs can be framed as a function of (i) the path that minimizes the travel time between two specific points in space (origin = residence; destination = place of work); (ii) the chosen type(s) of transport. In other words, for each element of the dataset, the fastest path to commute from home to work was calculated. The energy associated with this trip was derived according to the type of transport used and was multiplied by the number of working days per year.

Hence, $Qes_{Mob}$ can be expressed as:

$$Qes_{Mob} = \sum_{i}^{n} (d_i * Mt_i * Wd_i^k) \qquad [2]$$

Where:

- $Qes_{Mob}$ is the component of *Qes* required to fulfil professional mobility; it is calculated for each employed family member (*n*).
- *n* is the number of employed people, and *i* is the $i^{th}$ person having a job. Thus, all variables featuring an *i* index refer exclusively to the $i^{th}$ person.
- *d* is the fastest path considering the actual transport options (public transport or private vehicle) that can allow each commuter to go from home to work.
- *Mt* is the selected mode of transport; each *Mt* may represent a combination of different types of public transport (train, metro, suburban bus, city bus, tram), or private vehicle (car, motorcycle) if the person possesses a private vehicle for commuting[viii].
- *Wd* is the number of days during which the home-work-home journey is done. This depends on the type of job (*k*) – full time/part time as specified in the National Census. The number of working days per each *k* job category was derived from the results of a study conducted at the DARES institution (DARES, 2005).

To calculate the energy cost, it was necessary to reconstruct the entire road network of 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 energy consumption per kilometre for a passenger and the average speed for each type of transport commonly used in France (RATP, 2010). This work was performed using ArcGIS Network Analyst. The network analysis consisted basically 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 home to work in the least amount of time for each type of transport (private car/public transport).

**SM 4.** By integrating the two procedures described in SM2 and SM3, it was possible to estimate the total *Qes* for each family residing in the study area. In addition, normalizing $Qes_{Mob}$ and $Qes_{Ab}$ by the *Np*, it was possible to obtain per capita estimates of $Qes_{Mob}$ and $Qes_{Ab}$ for each household. Furthermore, knowing *Te* and *Mt* and using the Eurostat Energy Price Report for 2010 (EUROSTAT, 2010), it was also possible to estimate the monetary value associated with total *Qes* as well as for $Qes_{Mob}$ and $Qes_{Ab}$ separately.