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A framework for the study of householders' engagement with low-carbon energy demand practices in dwellings with grid-connected photovoltaic energy systems

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A framework for the study of householders' engagement with low-carbon energy demand practices in dwellings with grid-connected photovoltaic energy systems

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Abstract.

Introduction: This paper introduces a framework to assess householders' interaction with grid-connected photovoltaic (PV) systems in domestic buildings, in an attempt to research the question *To what extent the engagement of occupants in energy demand management practices is relevant for the operational CO_2 emissions reductions in dwellings with on-grid PV systems?* The focus is placed on identifying the engagement with low-carbon operation practices and its relevance for final CO_2 emissions from electricity consumption. Specifically, PV electricity self-consumption and energy conservation practices are studied. To this extent, the research builds on i) the energy services approach and ii) the social practices approach to domestic energy demand. The context of owner-occupied houses which have been retrofitted with PV installations in South Wales, UK is taken as an example. ***Methods:*** After a brief conceptual review on domestic energy demand, a mixed-methods framework for the study of householders' engagement with low-carbon energy demand practices is presented, comprising three key aspects: a) the conditions for the practices to occur, b) frequency with which householders enact the practices, and c) the estimation of final operational CO_2 emissions performance. ***Results:*** As part of ongoing research work, a framework to study households' engagement with low-carbon energy demand practices in buildings with grid-connected PV technology is proposed; focusing on the obtention of a socio-technical lecture to complement other sources of in-use assessment data. ***Conclusions:*** Besides single case-studies, the framework has potential applications in recognising and grouping households' engagement profiles. In this way, it is suggested that the framework might facilitate the analysis when extensive assessments are needed; such as in public policy evaluation or demand response studies. ***Grant Support:*** This work is funded by CONICYT PFCHA/DOCTORADO BECAS CHILE/2018 - 72180375.

1. Introduction

To what extent is the engagement of occupants relevant to the operational carbon emissions reductions in dwellings with on-grid photovoltaic (PV) systems? This study aims to contribute to the conceptual and methodological debate underpinning the response of this question.

To put the problem in context, let us highlight that as part of the 2015 Paris agreement, 132 developed countries ratified their commitment to reduce the built environments' CO_2 emissions. Among them, 49 have committed to implementing renewable energies in their built environment emissions mitigation plans [1]. Considering the decreasing costs of implementing renewable energies [2], and particularly photovoltaic panels, whose implementation costs have decreased by 82% during the 2010-19 period [3,p.12] it is possible to argue that their implementation in existing dwellings for energy or low carbon retrofit purposes will continue to be a global trend during the next decade.

In contrast to most countries' recent adoption of distributed microgeneration, the rollout of domestic PV installations in the UK started around a decade ago. This decade of experience represents a major learning opportunity for developing countries and those which are now starting to implement policies Nevertheless, one of the questions that the research community has raised during this period, and currently remain as an open debate is the uncertain role of householders for the maximisation of PV systems' outcomes, in terms of reducing CO_2 emissions [4–9]. The paper addresses this problem through the development of a socio-technical framework for the study of householders' engagement. In this way, the framework responds to UN Sustainable Development Goal 77: 'Affordable and clean energy', target 7.2. 'Increase substantially the share of renewable energy in the global energy mix' [10].

2. Materials and Methods

First, section 3 of this paper presents a brief critical analysis of the main conceptual elements associated to domestic energy demand is developed, through the discussion of ideas from the Energy Services Approach (ESA) and the Social Practices Theory (SPT), to end with the introduction of a conceptual framework. Secondly, the paper proposes in section 4 a set of mixed-methods parameters and techniques for the research of householders' engagement with low-carbon energy practices in the context of prosuming dwellings.

3. Shaping an analytical framework to assess occupants' engagement

3.1. The problem: Undesired outcomes of energy demand

As an essential part of life within buildings, people demand energy to obtain energy services, through the direct or indirect operation of devices or systems. In this process, each instance of energy demand involves the transformation of the energy *potential to do work* into actual work or a different form of energy which is useful to people at a specific moment. In this way, behind every instance of energy demand, there are a set of core elements that can be, at least theoretically, identified and measured. Namely, the base elements involved in the transformation of energy are an *energy input*, a *device or system* which performs the transformation, the *desired output* which can be understood as a provided energy service, an *operator* deciding aspects such as the intensity and duration of the instance, and an *undesired outcome*, as displayed on ***Figure 1***.

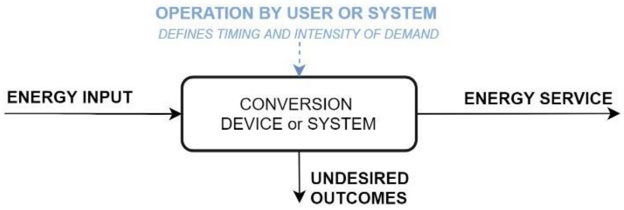

Figure 1- Base elements of the conversion of energy into energy services

As Marshall [11] explains, the conversion of an energy input into a usable energy service is just one stage of a broader energy system chain [12,13], which can be represented in a sequence of 4 different but connected systems: The energy production system, distribution system, usage system and the human activity system [11]. The last of these directly resulting in the energy demand in dwellings (Figure 2).

The processes of obtention, transport, conversion and distribution of energy deliver this demand but also cause a series of undesired outcomes, which range from energy losses to a wide variety of environmental impacts. Determining the sum of undesired outcomes of every instance of energy demand is virtually impossible, let alone the impracticality of such a task. Nevertheless, specific aspects of the undesired outcomes can be identified, tracked, and measured. For the case of electricity demand, the most common, and allegedly the most relevant, parameter to measure undesired environmental outcomes is carbon intensity: the CO_2 equivalent emissions per consumed kWh.

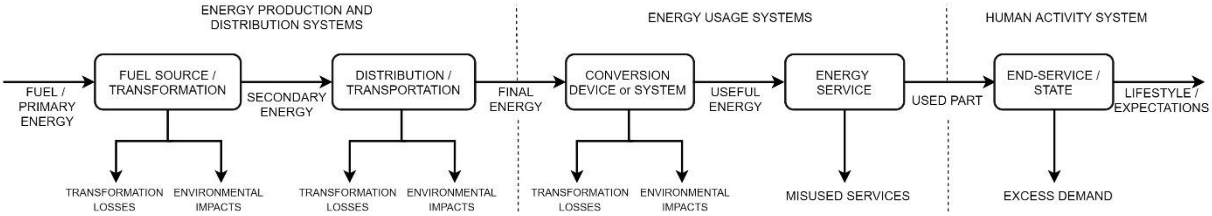

Figure 2 – Energy system chain with undesired outputs (Author, based on Marshall [11])

3.2. The context of the problem: Energy services demand in dwellings

Energy services are conventionally understood as the desired outcome of the demanded energy, "things like warmth, motion, mechanical power or process heat (…)" [14p.23]. Nevertheless, recent conceptualisations have incorporated social factors into the definition, recognising that there is an intentionality behind the energy transformation which lies beyond the obtention of energy services. In this way of thinking, Fell [15] has proposed that "Energy services are those functions performed using energy which means to obtain or facilitate desired end services or states" [15, p.137]. The notion of end-services has similarly been described as 'meta-services' [16] or 'concepts of service' [17]. These conceptualisations have in common that they allow differentiating clearly between the end-service, which is an expected situation defined by the householders; and the actual energy service, which is the outcome of the operation of the device or system. Hence, according to these approaches, energy services are just a mean to obtain desired states or end-services, which are, in turn, a reflection of what householders expect and desire from their dwellings.

In these terms, the ESA allows for interpreting that a non-energy service can replace an energy service if a person's or household's expected end-service allows it [15,18]. As Morley [16] argues, an end-service is a desired state or satisfaction parameter, but it is not fixed or predefined. The range of demanded end-services and their respective set-points can change through time depending on people's changing conditions and possibilities [19], as well as on their changing expectations [16,18]. Hence, for a specific person or household, the accessibility to energy services would continuously influence the satisfaction standard of the end-services, making it increasingly difficult, if not impossible, to understand the processes of energy demand and the social processes that trigger them independently. This idea echoes the argument that the technical regime is continuously affecting the different aspects of the social regime and vice-versa [20].

This argumentation leads us to the broad debate of sufficiency in energy demand, which, as developed by Darby [21], moves further into the realm of normative discussion through the questioning of how much is enough? We are not going to delve in that debate here since it has been covered extensively elsewhere and determining how much energy or services demand are enough is not the goal of this paper. Nevertheless, it must be recognised from this debate that it sets a path to look further from what the technical systems do into what occupants do towards the achievement of the decarbonisation goals.

3.3. Searching for solutions: Operational CO_2 emissions reduction strategies and measures in residential buildings

3.3.1. CO_2 emissions reduction Strategies

The literature on the topic suggests three types of strategies to reduce CO_2 emissions during the operational stage of residential buildings. Foxell [22p.117], based on Bordass ideas discuses that these strategies are: 1) To reduce energy demand, 2) improve the efficiency of the energy demand, and 3) to decarbonise the energy supply. Similarly, these strategies match the three categories of actions recognised by Aelenei and Aelenei [23] for the design of zero energy buildings: 1) Passive, 2)Energy efficient, and 3) Renewable energies; and the "three dimensions" of energy transitions proposed by Kowsary and Zerriffi [24]: 1) Energy service demand, 2) conversion technology, and 3) energy carrier. Ultimately, the problem has also been analysed at the policy scale by Drummond and Ekins [25], reaching the argument that the three domains of change towards decarbonisation of residential energy use are 1) satisficing, 2) optimising, and 3) transformation. From the common viewpoint behind these different approaches to the problem, it can be argued that in the context of energy transitions efficiency is not a goal in itself, as usually considered, but instead just one more path to achieve the objective of CO_2 emissions reduction.

Following these ideas and the energy services conceptual framework, it is proposed that there are three main parameters that determine the CO_2 emissions during a building's operation: 1) the **intensity of energy services demand**, 2) the dwelling's active and passive systems **energy efficiency**, and 3) the **CO_2 intensity of the energy supply**. From this standpoint, the next section looks at the relation between energy services demand efficiency and intensity through the contrast of what the physical systems can do and what the householders do and expect from the first.

3.3.2. Energy services demand intensity and efficiency

Since the energy intensity of a system is the arithmetic opposite of its efficiency, reductions in intensity must have the same effect than increases in efficiency towards the reduction of energy demand, while achieving the same level of desired output. If we conceptualise a dwelling as an energy use system whose outputs are end-services, the *energy efficiency of the system* will be conditioned by the physical characteristics of the dwelling, aspects such as the quantity, type and efficiency of appliances and active systems, and such as the formal and material characteristics of the building's envelope. On the other hand, the *intensity of the system* will be conditioned by the outputs expected by its occupants (the set-point or expected standard of end-services). These can be understood, respectively, as the energy usage system and the human activity system introduced by Marshall [11] and depicted in fig 2.

Both systems are, nevertheless, mutually interdependent and define a domestic scale socio-technical environment. In the one hand, householders might change the conditions of the physical system, for example through the opening of the dwelling's windows and hence temporally reducing its overall insulation capacity; Or through the incorporation of new energy demanding devices. In the other hand, the conditions of the physical system influence the householders' desires and expectations from it. The fact of having a more efficient central heating system at home will likely influence the householders expected set-point for heating [26,27]. Therefore, both the increase of efficiency and the reduction of the intensity of energy demand are paths to energy demand reduction and form part of the same equation (fig 3a).

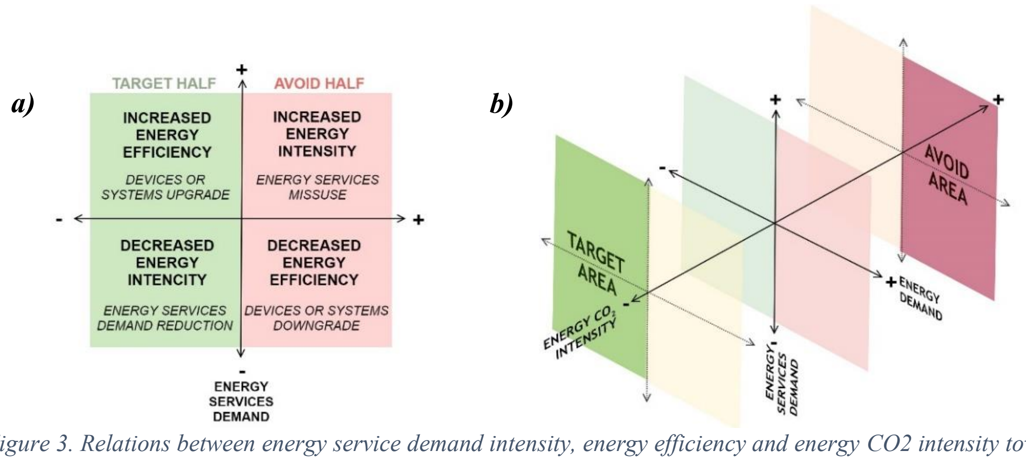

Figure 3. Relations between energy service demand intensity, energy efficiency and energy CO2 intensity towards the decarbonisation of domestic energy demand (Fig. source: author, based on [22], [23], [24] and [25])

However, as it has been highlighted in the precedent section, energy demand reduction, either through changes in efficiency or intensity, is not the only strategy to reduce final CO_2 emissions, since the final undesired outcomes are determined not only by the amount of demanded energy but also by the type of final energy being consumed (Figure 3b).

3.3.3. CO_2 intensity of the energy supply

As discussed before, the main parameter to measure the intensity of CO_2 emissions of the electricity consumed at a dwelling is CO_2g/kWh. This parameter is, nevertheless, highly variable depending on the mix of fuels being used in the energy system at every single moment. Similarly, the energy production of domestic PV energy systems is also highly variable depending on the time of the day due to the changing level of radiation received on the panels. Therefore, the householders do not have direct control over the CO_2 intensity of the electricity they use, but they do have the possibility to manage their demand in order to *shift* or *shave* their peak demand. *Demand shifting* refers to demanding energy at different time frames, in order to maximise the demand when the CO_2 intensity is lower. *Demand peak shaving* refers to minimise simultaneous consumption at any single moment to avoid peaks of power demand [5]. If a PV energy system is present, the CO_2 intensity of the demanded energy will be significatively affected by the energy generation times of the PV system. These two situations can help to reduce the amount of emission directly (Figure 4a). A theoretical reduction of CO_2 emissions can also be considered to occur in the form of a 'balance' of emissions between demanded and injected at different times [28] (Figure 4b), since in grid-connected energy systems the electricity that is not directly consumed on-site at the moment of its generation is injected to the energy grid.

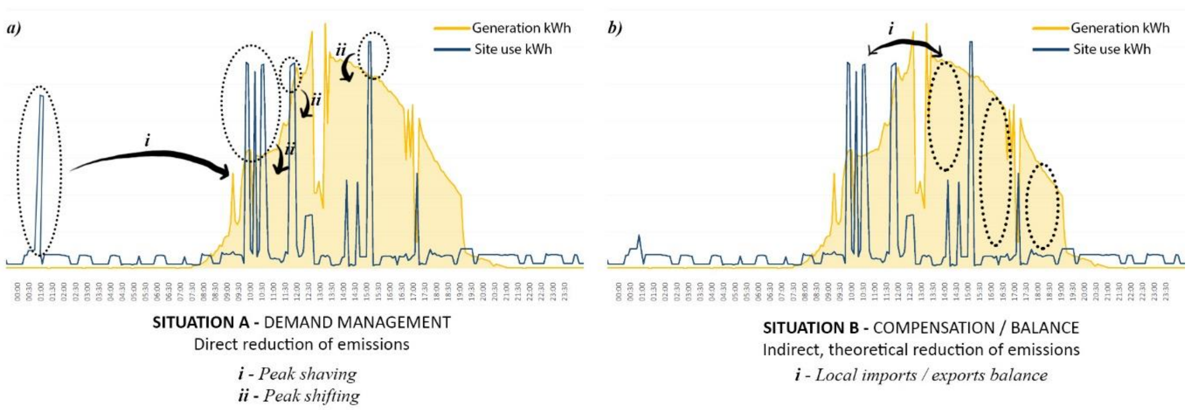

Figure 4. Approaches to intensity of energy supply reduction in dwellings with PV energy systems. a) thorough energy demand management practices (i. peak shaving, and ii. Peak shifting); and b) through imports and exports equivalent emissions balance (Fig. source: author).

Such theoretical balance or compensation of CO_2 emissions can be argued based on ‘saved’ emissions, calculated by multiplying the kWh injected and the CO2 intensity of the grid at the moment of injection. Following this approach, it is possible to estimate, theoretically, the volume of emissions that have been 'avoided' elsewhere due to the renewable energy injected to the grid [28].

3.4. Decarbonising the process of domestic energy demand

From an energy services perspective, the process of domestic energy demand can be depicted as a flow that starts when a desired end-service or state is unmet or below a minimum satisfaction parameter [18]. This argument does not try to reduce energy demand to a deterministic process. Instead, it recognises the complexity of the problem and sustains that different aspects of the process need to be analysed considering different parameters and methods, despite them being all part of the same socio-technical system. Following this framework, the measures taken to decarbonise the operation of dwellings can be classified regarding the parameters over which they act.

An interpretation of the process of residential energy demand based on the introduced concepts is presented in ***figure 5.*** In this diagram, desired end-services or states are taken as the starting condition and the desired end-point of energy-demanding instances. On the way through, the three parameters that condition the final level of CO2 emissions are highlighted, along with the three main strategies that arise from this conceptualisation: 1) reducing the **intensity of energy services demand**, 2) increasing the devices and systems **energy efficiency**, and 3) switching CO2 source to decrease the **CO_2 intensity of the energy supply**.

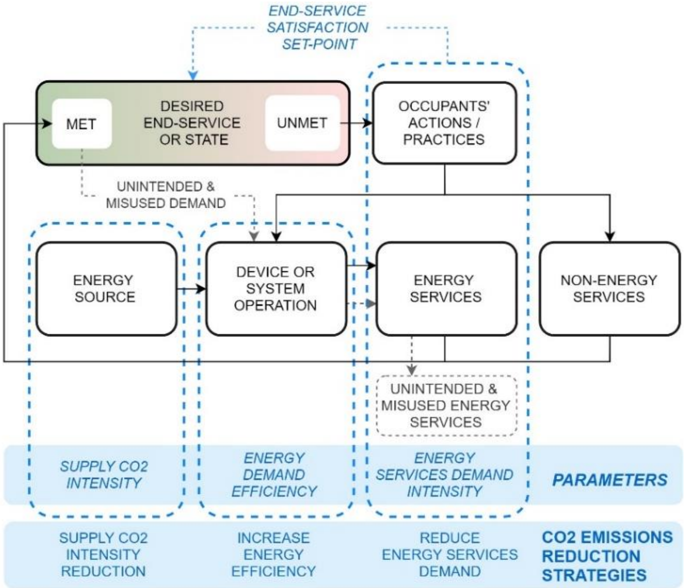

Figure 5. Residential energy demand process, from the point of view of the energy services approach. In blue, the three types of strategies and parameters for the reduction of operational CO2 emissions, and their fields of action (Fig. source: author, based on [15],[16],[18] and [22]).

Undoubtedly, the CO_2 emissions performance of a dwelling could also be improved by retrofitting its physical conditions of the dwelling, i.e. improving the efficiency of its active or passive systems. Nevertheless, what this study is addressing is the possibility for users to improve CO_2 emissions performance through direct occupancy measures. Therefore this framework focuses on how householder's practices in prosumer dwellings can have a direct effect over CO_2 emissions though two of the three CO_2 reduction strategies: 1) by managing the demand in order to switch to the energy sources with the lower possible CO_2 intensity, and 2) by reducing the intensity of energy services demand. In practice, when PV systems are present, this would be 1) by matching the PV generation times with the energy demand times, and 2) by energy conservation, which might be achieved either through the preference of non-energy services over energy services, though the reduction of the end-services satisfaction set point, or through the reduction of unintended and misused energy services.

3.5. A determinant of success? The relevance of practices

The emergence of the Social Practices Theory (SPT) as an approach to the domestic energy demand studies field is usually associated to a search for alternatives to the mainstream behavioural approach [29]. As highlighted by Strengers [30], SPT allows rethinking how the questions, and ultimately the solutions, are proposed for energy demand problems. Shove, Pantzar and Watson [31], argue that social practices occur by the combination of three families of elements that make them possible to be enacted. These elements are the people's competences to perform the practices, the meaning that they give to the practices and the material elements that support the realisation of these practices [29–31].

For the problem here recognised, SPT works as a bridge between the ESA and the qualitative aspects of peoples' everyday actions. Since the material elements refer to everything found in the physical world, it corresponds to the energy use system introduced in ***figure 2***. Following, meanings and competences become relevant for the understanding of the human activity system, introduced in the same diagram. Hence, while the materials component of SPT approaches gives clues about what can be done, meanings and competences are conceptualisations the analysis of how and why it is done.

In this way, considering the elements of the SPT framework, an operational definition for householders' engagement with low-carbon demand practices is proposed as *the relation between the perceived conditions necessary to perform those practices and the actual frequency with which the practices are performed.* Therefore, a household highly engaged with CO_2 reduction practices would maximise the enactment of the practices according to its existing conditions (materials, knowledge, meanings). In ***figure 6***, a list of aspects for the qualitative assessment of practices aimed to *reduce the intensity of energy services demand*, and *energy source switching* are presented.

	Reduce the intensity of energy services demand	*Energy source switching through demand time shifting*
Meanings	Moral relief Monetary savings	Moral relief Investment return opportunity
Materials	Access to non-energy services Existence of unintended demands Existence of feedback devices Existence of green tariff contracts	Existence of alternative energy source (PV) Existence of feedback devices Existence of green tariff contracts Existence of Feed-in-Tariffs
Competences	Knowledge of energy conservation measures Acceptability of lower energy intensity Knowledge of feedback device operation Understanding of climate issues Understanding of national grid peak load issues	Knowledge of system generation times Knowledge of feedback device operation Understanding of climate issues Understanding of national grid peak load Understanding of tariff rate changes

Figure 6. Some aspects observed for each of the two analysed practices among a group of case-studies in South Wales. In purple are those aspects considered critical for the practice to occur, in light blue those which could be both critical or complementary, and in light blue those considered complementary. (Fig. source: author, based on [31]).

4. A mixed-methods toolkit for the study of engagement with low-carbon energy demand practices in dwellings with grid-connected photovoltaic energy systems

A mixed-methods toolkit to research householders' engagements and its implications on final CO2 emissions is proposed in ***figure 7*** focusing on recognising key parameters and potential methods and metrics to assess the relation between occupants' engagement and final CO2 emissions performance. This is achieved by recognising **3 main assessment categories: 1)** the existence of the material **conditions for the practices** to occur, 2) the actual **frequency with which householders enact the practices (**energy conservation and electricity self-consumption), and 3) the estimation of **final operational CO_2 emissions performance**.

Key Parameters			Type	Possibly associated methods	Metrics
Conditions to support the practices	Meanings (specific aspects as shown in fig.6) Materials (specific aspects as shown in fig.6) Competences (specific aspects as shown in fig.6)		Qualitative	Questionnaires Interviews, focus-groups Site visits	Conceptual relations, comparable ordinal scales
Frequency of occurrence	Self-reported	Frequency of each practice Intension to perform each practice Energy services demand intensity	Quantitative / Qualitative	Ordinal questions / Interviews, focus-groups	Conceptual relations, comparable ordinal scales
	Observed	Electricity self-consumption ratio Total electricity consumption	Quantitative	Monitoring	solar hWh / total kWh kWh / time period
Operational CO2 performance parameters	Total carbon emissions CO2 intensity CO2 intensity (per person)		Quantitative	Calculated, based on monitoring and national grid carbon intensity	CO2eq.Kg CO2eq.Kg / kWh CO2eq.Kg / kWh pp

Figure 7. A mixed-methods toolkit for the assessment of householders' engagement with low-carbon energy demand practices in households with PV systems. Key parameters and possible methods are presented.

This toolkit is presented as a guideline for the elaboration of specifically tailored instruments for each group of case studies. It is proposed that performance parameters can be used to observe what is happening, while the parameters related to the SPT can give clues about how and why these results are obtained. Although the framework is intended to be used for primary data collection, some aspects will necessarily rely on external data sources; such as the CO_2 intensity of the regional or national grid at each analysed time.

It is proposed that the results obtained from the application of this framework would allow assessing dwellings' operational stage from a socio-technical and multidimensional approach to energy services demand.

5. Conclusions

Through a short literature review, this paper has addressed the main strategies towards the decarbonisation of domestic buildings (section 3.3) and has identified those that apparently remain as the most relevant in the context of prosumer dwellings with PV energy systems (section 3.4). Some of the problematics of this type of energy regime have also been discussed and through the framework of the SPT two families of practices have been recognised as relevant or future research: those that promote a *time-shift of energy services demand* and those that promote a *decrease in total demanded energy services* (section 3.5).

From the integration of both conceptual backgrounds, a mixed-methods toolkit to assess the relations between engagement with low-carbon electricity demand practices and final calculated CO_2 emissions is proposed (section 4), arguing its potential to use as a conceptual guideline for the elaboration of specific assessment tools which recognise both the CO_2 emissions performance and the socio-technical aspects that configure that result. The framework could prove relevant in the evaluation of large groups of households, where the study of the elements of the SPT can be researched through open-ended or ordinal scales questionnaires. Such an approach could facilitate the definition of analysis groups defined by the households' engagement levels, in contrast to the usually implemented demographic approaches.

The major intended contribution of the framework is to allows considering social parameter in relation to performance results in a comparable manner between different case studies. In this way, some interesting questions arise for its future application:

- To what extent the householders' self-reported engagement and practices are relevant for the final observed CO_2 emissions?
- In terms of the final CO_2 emissions, to what extent the variation of engagement in low-carbon energy demand practices is relevant if compared to variations in the grid CO_2 intensity?
- In terms of the final CO_2 emissions, to what extent the engagement in demand time-shifting practices is relevant if compared to the balance obtained from compensating emissions from demand and injection to the grid?

Currently, the framework is being applied on a mixed-methods longitudinal study of a group of PV energy prosuming households in Cardiff, Wales, in the context of the author's PhD research process. The results from this study are expected to confirm the adequacy of the toolbox in a empiric data collection processes, and should allow the author to discuss general aspects of the previously introduced research questions.

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