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Effectively reducing energy demand in the residential sector: A multidisciplinary approach

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Abstract

Energy behaviours are recognised as being of paramount importance to energy efficiency policies aimed at reducing energy demand. Tackling energy behaviours is a complex and challenging task since they: encompass multiple dimensions (e.g., usage, investment, comfort, security, provision of energy resources); are influenced by personal, social, economic, material and technological contexts; are a topic of common interest but uncoordinated action of different energy stakeholders promoting energy efficiency, thus making the design of effective programmes and policies more demanding. This work proposes a multidisciplinary approach to assess the influence of energy behaviours on residential energy consumption to support the design of an energy efficiency programme held in Portugal. Methods and techniques from engineering, social sciences and psychology were combined in a systemic manner to assess the qualitative and quantitative influence of behaviours on energy usage and identify the most relevant factors that should be addressed to effectively reduce residential energy consumption. An experimental setup of 128 households was used as case study. Household's electricity consumption was monitored using smart meters and web-based surveys, which enabled to assess environmental, material and technological, economic, social and personal variables. System modelling enabled to explore the influence of behaviours in the energy consumption activation chain and integrate the contribution of different variables. Results not only confirmed the key role of energy behaviours, but also enabled to rank variables according to their quantitative impact on energy consumption, thus supporting the need of multidisciplinary approaches to design programs and policies aimed at reducing energy demand.

Introduction

Energy efficiency is recognised by the International Energy Agency (IEA) as the main contributor to demand-side interventions leading to greenhouse gases (GHG) reductions (OECD/IEA, 2016). In order to reach the -2 ºC reduction target, the IEA has selected energy efficiency measures based on proven policies and technologies as effective tools with a rapid impact on energy demand. For the residential sector these measures include minimum energy performance standards for lighting, appliances, heating and cooling equipment and building insulation levels. However, the IEA also indicated behavioural changes as a key factor to reduce energy demand while meeting consumer needs and comfort requirements.

In the residential sector, energy demand is determined by the environmental conditions (e.g., climate, location), physical characteristics of the building, appliances ownership and usage, indoor environmental quality, social and economic context, but also by the households' socio-demographic characteristics, activities and behaviours (Bedir et al., 2013; Jones and Lomas, 2016; Kavousian et al., 2013; Yu et al., 2011). Energy demand strongly depends on the energy services utilised, and diverse factors may impact them differently. Overall, the physical characteristics of the buildings are usually indicated to have a greater influence on energy demand when compared to other factors such as occupants' behaviour (Kavousian et al., 2013). For example, (Santin et al., 2009) estimated that 42 % of residential electricity consumption is determined by the building characteristics while only 5 % is due to occupants' characteristics and behaviours. However, this result contradicts previous research stating that the potential of energy savings due to behaviours may be as significant as those from technological solutions (Ürge-Vorsatz et al., 2009). In fact, occupants' behaviour are recognised as a major determinant of energy use in buildings but its specific quantitative impact on energy demand is often ignored due to the challenges of quantification (EC, 2010). Therefore, developing methodologies to quantify energy behaviours' influence on residential energy consumption is crucial to support the design of effective programmes and policies.

Literature overview and objectives

Different approaches have been developed to estimate energy behaviours' influence on residential energy demand. Traditional lines of research have concentrated on the behavioural savings materialised through real-world interventions that promote changes in end-users' behaviour. Depending on the specific context of each intervention, values differ from 20–100 % (Delmas et al., 2013; Gynther et al., 2011). However, since savings are context specific and interventions have often combined different dimensions (e.g., equipment replacement jointly with behavioural changes) the specific behavioural savings have been difficult to establish and replicate.

A recent approach uses computational modelling, namely building energy performance simulations, to assess occupants' behavioural savings potential in the residential sector. It is mostly focused on thermal (heating, cooling and ventilation) and lighting comfort (Lopes et al., 2016b). Behavioural dimensions commonly explored are occupancy, set points of thermostats, schedule and heated area, ventilation and lighting practices and use of blinds, and results indicate that potential behavioural savings range from 18 % to 88 %. Recognising that the diversity of activities performed within the household on a daily basis also influences residential energy consumption, efforts have been developed to expand modelling beyond the comfort dimension and include other energy consuming services (Hong et al., 2015a; Hong et al., 2015b; Kashif et al., 2013). Nevertheless, comprehensive modelling approaches integrating expertise from different disciplines are still referred to have had limited development (Nguyen & Aiello, 2013).

Taking advantage of technological developments enabling the availability of large quantities of energy monitoring data, data mining techniques have been used to estimate the behavioural impact on energy consumption. In this approach, residential samples with similar features such as climate, building characteristics, energy services are compared and distinctive patterns of energy consumption are identified and associated with different occupants' behaviours. A behavioural savings potential in Japan was estimated to reach almost 0,56 MWh/person/year using this approach (7% of electricity consumption per capita) (Yu, et al., 2011; Yu, Fung, & Haghighat, 2013).

Statistical analysis is also often utilised to assess the influence of different variables such as climate, building attributes, appliances ownership and household characteristics on residential energy consumption. Information from surveys or building energy certificates is integrated with smart meter data and statistical techniques applied to extract energy demand determinants (Table 1). In addition to the limitations commonly referred to in the literature associated with the studies using these techniques (e.g., limited set of explanatory variables, low-resolution energy consumption data, no distinction of load features) (Kavousian et al., 2013), most studies have not included the influence of end-users' energy behaviours[1] as determinants of energy consumption. Or, when including behavioural dimensions, these were very limited, only focusing on the household socio-demographic attributes, partial attitudes towards environmentally-friendly practices, and a narrow scope of energy behaviours that influence energy consumption in the residential setting. Nevertheless, this approach remains the only one enabling the integration of variables that address the different dimensions influencing energy demand.

Moreover, as one of the most important factors shaping energy demand, energy behaviours are a complex and challenging topic, since they incorporate multiple dimensions (e.g., usage, maintenance, investment, auto-control and monitoring, provision of energy resources) and are influenced by personal, social, economic, material and technological contexts (Lopes et al., 2012). The combination of different disciplines through integrative research is then necessary to effectively exploit the influence of energy behaviours on energy demand (Stern, 2014).

This paper proposes a multidisciplinary approach combining methods and techniques from engineering, social sciences and psychology to assess the qualitative and quantitative influence of behaviours on energy usage and identify the most relevant factors that should be addressed to effectively reduce residential energy demand. This approach was developed under the scope of an energy efficiency programme held in Portugal.

Methods

A bottom-up multidisciplinary strategy is proposed to assess the qualitative and quantitative influence of energy behaviours on residential electricity usage. The approach involved three stages: (1) design of the energy consumption conceptual model; (2) electricity consumption and behaviours monitoring; and (3) integration of information and statistical analysis.

Conceptual modelling through cognitive maps was used to explore the chain of actions leading to energy consumption where the contribution of variables from different disciplinary fields was integrated.

Household's electricity consumption was monitored at the meter level using a smart meter (http://www.cloogy.com/en/) with a time step of 15 minutes during the period of one year. Specific electricity consumption indexes were determined to characterise electricity consumption (e.g., daily average consumption, minimum and maximum power, ratios between average and maximum and minimum power, seasonal electricity consumption).

From the tools commonly used in social sciences (Crosbie, 2006), web-based surveys were chosen due to their resilience

1. Energy behaviours are end-users' actions that lead to energy consumption (Lopes et al. 2012).

Table 1. Overview of statistical studies considering behaviour and household characteristics as determinants to explain residential energy consumption.

Case study	Considered behaviour and household characteristics	Established impacts on energy demand	Reference
15,000 households, The Netherlands (2000)	Presence of people at home, respondents age, households size and income, dwelling ownership, and temperature set points	42 % of the variation in energy use was originated by building characteristics while only 5 % was due to occupant behaviour and household characteristics.	(Santin et al., 2009)
323 households, The Netherlands (2008)	Household characteristics: education, presence at home, age groups Appliances use: laundry, dishwasher and tumble dryer, washing temperature set points, number and duration of showers, ventilation	Household characteristics and appliances use explained 58 % of the variance in electricity consumption.	(Bedir et al., 2013)
76,770 households, Sweden (2009/10)	Households size and income, age (head of the family), presence of children, ethnic background, ownership of "green" car, preference for the environmentalist party	Building characteristics had a higher impact on energy use associated with heating and cooling, while the households' socio-economic characteristics had a greater influence on electricity usage for lighting and appliances. Savings potential was estimated as 15 % of energy consumption (3,757 kWh/year/dwelling) and was related to the dwelling attributes and the outdoor temperature.	(Wahlström and Hårsman, 2015)
1,628 households, USA (2010)	Number of occupants, age of the household, number of pets, purchasing E-Star appliances, energy behaviours (energy conscious use of thermostat settings and turning lights off when not in use), attitudes of occupants towards energy consumption	Weather, location and floor area were the most important determinants, explaining 55–65 % of the variability in electricity consumption. The number of refrigerators and entertainment devices were strongly associated with daily minimum consumption, while the number of occupants and high-consumption appliances were associated with maximum daily consumption.	(Kavousian et al., 2013)
845 households, UK (2011/12)	Number of occupants, age, income, tenure, gender, employment status, sick or disabled persons, length residency, appliances use (weekly usage of oven/grill/hob), attitudes toward environmentally-friendly lifestyle, energy behaviours (turning lights off when not in use, boiling just the amount of water needed, standby, laundry temperature)	Appliance ownership and use, including lighting, explained 34 % of variability in electricity consumption, while socio-demographic variables only explained about 21 %. Self-reported energy behaviours, opinions about climate change and 'green lifestyle' were negligible. A combined model, encompassing all predictors, explained 39 % of variability in electricity consumption.	(Huebner et al., 2016)

characteristics and minimisation of households' disturbance. A survey was developed for characterising the conceptual model dimensions, namely: the socio-demographic context of the household, their activities, energy resources and services utilised, building characteristics, physical environment, current energy behaviours and recent behavioural adaptations, and behavioural personal factors selected among the constructs usually used in the psychology field (e.g., intentions, attitudes, norms, beliefs, literacy and values) (Table 2). Variables were selected taking into consideration their recognised importance in the literature. A specific set of 26 behaviours related with electricity usage was selected as being the most relevant to be characterised in the Portuguese context (Table 3). Questions used a 5-point Likert scale when assessing variables in relation to frequency and agreement.

An overall sample composed of 450 households living in Portuguese urban areas was used as a real case study in 2013/14, from which 128 households were selected since they delivered data of sufficient quality, such as a minimum period of electricity monitoring (at least nine months) and simultaneously answering the full survey.

Data characterising electricity consumption and information from the surveys were integrated in a database and analysed using statistical analysis (IBM© SPSS© Statistics v.23 software). A frequency analysis was performed, followed by the reduction and synthesis of variables through variables combination and factor analysis. Association measures between variables (e.g., correlations) trying to unveil significant relations with electricity consumption indexes were established. Finally, multiple regression analyses were performed to test the adequacy of the model and assess the contribution of usage energy behaviours to electricity consumption.

Results and discussion

FROM DAILY LIVES TO ENERGY DEMAND: A CONCEPTUAL MODEL

Households' daily routines comprise a broad range of activities such as gainful work and/or study, domestic work, travel, meals and personal care, free time and sleep (EC, 2004). Most of these activities are performed at home and raise needs (e.g., comfort, biological, non-physical) leading individuals to act in order to

Table 2. Personal factors towards saving electricity. Adapted from (Schwartz, 1994; Venkatesh et al., 2003).

Personal determinants		Statements
Intentions to save electricity	Perceived behavioural control over savings	Electricity saving actions are compatible with our way of living; If I have the proper conditions, it will be easy to save electricity; I can induce the dwelling occupants to perform saving behaviours; We have the necessary conditions to save electricity
	Attitudes toward saving	Saving electricity is a good idea; Saving electricity is wise; I feel happy when I try to save electricity while keeping the comfort levels; Saving electricity is not boring; When I try to save electricity, it is difficult to stop doing it
	Perceived ease of saving	Saving electricity is not difficult
	Social influence to saving	It is my obligation to try saving electricity while keeping satisfying comfort levels; I want to satisfy people who are important for me when saving electricity; I'm embarrassed when I don't try to save electricity
Beliefs and literacy on saving electricity	Consequences for the environment and the economy	Saving electricity has an impact on improving the environment; Saving electricity contributes to minimise energy imports; Saving electricity facilitates the power grid management; Saving electricity improves the national economy
	Consequences for lifestyle	Saving electricity implies a lifestyle with reduced comfort; Saving electricity brings too much disturbances to my lifestyle than the benefits that generate; Saving electricity creates inconveniences to daily activities; Saving electricity has economic disadvantages
	Responsibility	Saving electricity is a consumers' responsibility; Saving electricity begins with my example; Saving electricity is community's obligation
Values	Conservation: conformity and tradition	Following society rules and norms, Accepting what others suggest without arguing; Seeing people treated with equality, Being tolerant with others; Respecting traditions and practices, Being humble and modest without calling attention
	Openness to change: self-direction and stimulation	Being independent, Being creative; Having an exciting life, Doing new and different things
	Self-transcendence: benevolence and universalism	Helping others, Worrying with the well-being of others; Worrying with nature and the environment, Respecting the planet Earth; Having a quiet and safe life, Assuring the protection of family and friends
	Self-enhancement: power, achievement and hedonism	Being successful, Being recognised by others; Influence others decisions; Having money to buy expensive goods; Having a pleasant life; Enjoy life

Table 3. Monitored energy behaviours.

Behavioural dimension	Energy service	Energy behaviours
Equipment use	**Lighting**	Turning off lights in empty rooms; Prioritising sun light
	Cleaning	Turning on the washing machine only when it is full; Turning on the dishwasher only when it is full; Using the washing machine at low temperature programmes; Using dishwasher with ECO programmes; Turning the washing machine/dryer during the cheapest periods Ironing in long periods, instead of short uses
	Entertainment	Turning off TV when nobody is watching it; Turning off appliances directly on the switch to avoid standby; Turning off appliances using central plugs to avoid standby
	Food refrigeration	Regulating the fridge temperature according to the season; Not opening and closing the fridge door very often; Leaving the fridge door open for short periods of time
	Water heating	Turning off the heating water system when in holidays
Thermal comfort	**Heating & cooling**	Keeping doors and windows closed when they are being warmed/cooled; In winter, leaving curtains/blinds open during the day and closing them during the evening; In summer, closing the curtains/blinds during the day, and opening the windows during the evening; Turning on heating/cooling only in occupied rooms; Insulating windows and doors; Adjusting set points according to the season
Energy monitoring	**Auto control and monitoring**	Dialogue within the family about electricity consumption and savings; Reading the electricity bill; Providing the meter readings to the electricity supplier
Investment behaviours	**Investment**	When buying new equipment, giving priority to higher energy standards

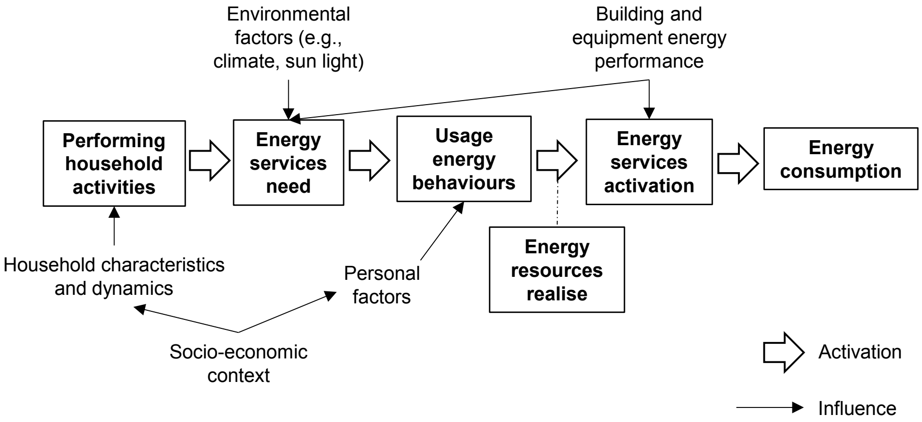

Figure 1. Simplified chain of actions and factors leading to energy consumption in the residential context.

satisfy them (Hong et al., 2015b) through the activation of energy services such as powering electrical appliances, lighting, heating and cooling. These actions are often called usage energy behaviours (Van Raaij and Verhallen, 1983). Energy consumption is then a result of energy behaviours, and not only incorporates the time when activities are performed and reflects the household dynamics, but also makes explicit the intensity of the activated energy services (Figure 1).

Household activities are influenced by the family socio-demographic characteristics and dynamics, such as its composition, stage of life, time spent at home, lifestyle, level of education, income (Abrahamse and Steg, 2009; Bedir et al., 2013; Cayla et al., 2011; Jones and Lomas, 2015). Energy services needs are influenced by external environmental factors such as the climate, which are in turn mediated by the building and equipment energy performances (Kavousian et al., 2013). In one of the focal points of the chain of actions and factors leading to energy consumption, energy behaviours may be shaped by personal factors such as intentions, attitudes, norms, beliefs, concerns, self-regulation mechanisms and perceived capabilities (Ajzen, 1991; Bagozzi et al., 2002; Bandura, 1991; Fishbein and Ajzen, 1975; Schwartz, 1994; Stern, 2000; Thøgersen and Ölander, 2002).

Although all the factors in this chain ultimately contribute to energy consumption, also in a dynamic manner, it is expected that for each specific situation different factors may be more relevant, or have higher impact, than others. Hence, in the context of energy efficiency interventions, preliminary assessments are recommended in order to determine the most relevant factors impacting energy consumption. Contextualised understanding from a real case study is presented in the next sections illustrating this point of view.

CHARACTERISATION OF THE CASE STUDY

The residential sample (N=128) was physically located in Portuguese urban areas in Coimbra and Lisbon regions. Families lived mostly in owned apartments (80.5 %) of medium/large dimension (at least 92.9 % possess two or three bedrooms) (Table 4[2]). In average, each family had 1.7 adults (SD = 0.8) and 0.9 children (SD = 1.1). Average electricity consumption was about 10.8 kWh/day (SD = 5.5), close to the national average consumption of 10.1 kWh/day (INE and DGEG, 2011). This sample had an average standby power of 0.112 kW and peak power of 6.0 kW (SD = 1.6). Appliances' ownership rate was generally higher than the national rates (INE and DGEG, 2011)[3]: laundry machine 83.9 %, dishwasher 91.7 %, tumble dryer 32.9 %, air conditioning system 15.6 %, and electric water heater 7.8 %. Renewable energy systems ownership was also above the national average: 3.1 % owned solar panels to heat water and more than 2 % owned photovoltaic panels. The respondents of the survey (the person in the household with more responsibilities in energy decisions) were mostly men (68.5 %), with an average age of 37.5 years old (SD = 8.7). Most respondents were highly educated (85.4 % had a higher education degree, which contrasted with the national average value of 19 %), employed (85.5 %) and married (69.7 %).

Self-reported energy behaviours in this residential sample had an overall good performance, although opportunities of improvement still existed. Behaviours reported by the respondents to be frequently[4] performed were associated with the use of lighting and washing machines as well as investing in new equipment. Behaviours reported to be occasionally performed were associated with entertainment services and the elimination of standby consumption, cleaning practices, thermal comfort, use of the fridge, and energy monitoring and self-control. Behaviours rarely/never performed were related with the adjustment of set points of air conditioning and water heating systems in the different seasons, and voluntarily providing the meter readings to the electricity supplier. Although the Directive 2009/72/EC stated that 80 % of end-users should be equipped with smart metering systems by 2020 (EC, 2009), most Portuguese households still possess meters requiring manual readings (either performed by the utility technicians or end-users) (Lopes et al., 2016a).

Overall, the respondents had positive attitudes toward saving electricity (mean 4.9, SD = 0.3), perceived it as a personal responsibility (mean 4.6, SD = 0.6) and as being compatible with their daily lives (mean 4.0, SD = 0.7), although not having all the necessary conditions to save (mean 3.5, SD = 0.9), full control over all dwelling occupants' actions (mean 3.8, SD = 0.9)

2. Thermal comfort perception: Extremely uncomfortable to 5: Extremely comfortable.

3. National statistics indicate the following ownership rates: laundry machine 91 %, dishwasher 41 %, tumble dryer 19 %, air conditioning system 7 %, electric water heater 3 %.

4. 1: Not applicable; 2: Never to 6: Always.

Table 4. Characteristics of the residential sample (N = 128).

Category	Variables	Level		Variables	Level	
Socio-demographic	Gender	Female	31.5 %	Household composition	Adults	1.7, SD = 0.8
		Male	68.5 %		Children	0.9, SD = 1.1
	Age	< 36	49.2 %	Presence of adults at home	In the evening	93.0 %
		36–45	35.5 %		In the afternoon	24.2 %
		46–55	8.9 %		In the morning	15.6 %
		> 55	6.5 %			
	Education level	No university degree	14.6 %	Professional activity	Working	85.5 %
		University degree	85.4 %		Other	14.5 %
	Marital status	Single	23.0 %		Working for a third party	83.6 %
		Married	69.7 %		Other situation	16.4 %
		Divorced or widower	7.3 %			
Building characteristics	Typology	Apartment	88.3 %	Ownership	Owner	80.5 %
		Villa	11.7 %		Rented / other	19.5 %
	Size	Less than 2 bedrooms	7.1 %	Year of construction	After 1999	37.8 %
		2 or 3 bedrooms	70.3 %		1981–1999	22.0 %
		More than 3 bedrooms	22.6 %		1961–1980	17.3 %
					Before 1960	16.5 %
				Thermal comfort perception	In the summer	3.66, SD = 0.96
					In the winter	3.16, SD = 1.12
Energy usage	Average electricity consumption		10.8 kWh/day	Average standby power		0.112 kW
				Peak power		6.0 kW, SD = 1.6
	Owned photovoltaic panels		2.4 %	Heating water	Solar panels	3.1 %
	Ownership of efficient lighting	More than half	63.9 %		Gas boiler	86.7 %
		Half or less	36.1 %		Electric system	7.8 %
					Other	2.4 %
	Electrical equipment	Laundry machine	83.9 %	Heating& cooling systems	Oil heater	53.9 %
		Dishwasher	91.7 %		Fan heater	24.2 %
		Tumble dryer	32.9 %		Air conditioning	15.6 %
		Freezer	38.4 %		Fireplace	22.6 %
		Fridge	100.0 %		Central heating system	22.7 %
		HVAC	15.6 %			

and admitted that saving electricity could be difficult (mean 3.3, SD = 1.0). Respondents were also significantly aligned with self-transcendence values, such as benevolence and universalism (more than 50 % selected "having a quiet and safe life, assuring family and friends protection", "worrying with nature and the environment, respecting the planet Earth").

ENERGY BEHAVIOURS' IMPACT ON ENERGY CONSUMPTION: CONTEXTUALISED UNDERSTANDING

The conceptual model dimensions were characterised in the context of the case study to assess the impact of households' energy behaviours on electricity consumption.

Variables from the original set were reduced and synthesised through transformations and principal component analysis (Table 5). Variables characterising electricity consumption were reduced to two factors that represent the households' average electricity consumption and the minimum required power (KMO[5]=0,8, p<0.001[6], explaining 80.1 % of variance) (Table 9 in appendix).

Self-reported energy behaviours were grouped by category and reduced to three factors with statistical meaning within this sample (KMO = 0,6, p<0.001[6], explaining 54.2 % of the variance) (Table 10 in appendix): (1) Automatic behaviours already incorporated in the household daily routines that promote savings, which are mostly associated with turning appliances OFF, eliminating standby consumption, use of passive strategies to improve thermal and lighting comfort, and the use of cleaning appliances; (2) Behaviours requiring specific and technical know-how, typically comprising the adjustment of set points and shifting the use of appliances to make the most out of time-of-use tariffs thus reducing energy costs; (3) Information-demanding behaviours, which comprise self-control and energy consumption monitoring and buying appliances with higher energy efficiency standards, both demanding specific and tailored information. While automatic behaviours are expected to be widely adopted by the overall population, the second and third categories are actions requiring specific skills that may pertain to more literate samples such as the one studied. Hence, in different case studies other behavioural dimensions may emerge, therefore making the preliminary characterisation of energy behaviours an essential task to be performed.

5. Kaiser-Meyer-Olkin (KMO) test (acceptable values are ≥ 0.5).
6. Bartlett's Test of Sphericity.

Table 5. Variables characterised to assess the conceptual model.

Model dimensions	Variables	Variables description and transformation process
Electricity consumption	**Average electricity consumption** (kWh/day): overall year and seasonal values, **Max, min and average power** (kW), **Standby power** (kW), **Pmed/Pmax**, **Pmin/Pmax**	Measured using a smart meter and reduced through a principal component analysis to two factors (KMO = 0,8, p<0,001[6], explaining 80,1 % of variance) (in appendix): 1. Minimum power factor 2. Average electricity consumption factor
Energy services activation	**Ownership of energy intensive appliances** associated with cleaning, food refrigeration, thermal comfort and domestic hot water	Self-reported in the survey
	Thermal comfort need for actively improving thermal comfort	Obtained through the transformation of the dwelling size, age of the building and occupants' thermal comfort perceptions, which were self-reported in the survey
Energy resources	**Ownership of decentralised renewables**: solar thermal and photovoltaic	Self-reported in the survey
Household characteristics	**Stage of life** of the household	Obtained through the transformation of the number of occupants and family bonds, which were self-reported in the survey
Household activities	**Time spent at home** (total number of hours)	Self-reported in the survey
	Weekly **use of energy intensive appliances** (number of cycles per week and duration/cycle of the laundry machine, dishwasher and tumble dryer)	Self-reported in the survey
Energy behaviours	Equipment use, thermal comfort, auto control and monitoring, and investment behaviours	Self-reported in the survey and reduced through a principal component analysis to three factors (KMO = 0,6, p<0,001[6], explaining 54,2 % of the variance) (in appendix): 1. Automatic daily behaviours 2. Behaviours requiring specific and technical know-how 3. Information-demanding behaviours
Personal factors	**Intentions to save electricity:** perceived behavioural control over savings; attitudes toward saving; perceived ease of saving; social influence to saving	Self-reported in the survey and reduced through a principal component analysis to two factors (KMO = 0,6, p<0,001[6], explaining 54,1 % of the variance) (in appendix): 1. Attitudes (responsibility, attitudes toward saving and social influence) 2. Lifestyle (household conditions to save energy)
	Personal values: conservation (conformity and tradition); openness to change (self-direction and stimulation); self-transcendence (benevolence and universalism); self-enhancement (power, achievement and hedonism)	Self-reported in the survey and indexes associated with each value dimension were calculated
	Energy literacy	Obtained through the transformation of the educational level and professional activity which were self-reported in the survey
Socio-economic context	**Behavioural changes** in the use of electricity due to the socio-economic context of constraints	Self-reported in the survey

Personal factors were also grouped by category and reduced to two factors with statistical meaning in this sample: attitudes toward saving, which are also associated with responsibility and social influence; and lifestyle, reflecting the household conditions to save energy (KMO = 0.6, p<0.001[6], explaining 63.2 % of the variance) (Table 11 in appendix).

Variables characterising the model dimensions comprised: *energy consumption* (average electricity consumption and the minimum power), *energy services activation* (weatherising need, energy intensive appliances), *energy resources* (use of renewable energy sources), *household characteristics* (stage of life), *household activities* (time spent at home, use of energy intensive appliances), *energy behaviours* (automatic behaviours, based on specific and technical know-how, and information-demanding), *personal factors* (attitudes toward saving, lifestyle), and *the influence of the socio-economic context* (e.g., economic crisis).

A preliminary association analysis unveiled statistically significant correlations between the average electricity consumption and several variables of the model (Table 6). In contrast, behaviours requiring specific/technical know-how and lifestyle (having conditions to save energy) had significant negative correlations with average household electricity consumption. These results indirectly revealed the connection between the life stage and the comfort level of the household with electricity consumption.

Multiple regression analysis was used to explore the influence of the model components on the households' electricity consumption (Table 7). Two dependent variables associated with electricity consumption were tested and the model explaining the higher percentage accounted for 60.5 % of the dependent variable *average electricity consumption factor.* The best predictors of this variable included different dimensions of the conceptual model, namely: energy services (*thermal comfort need,* B = 0.818); household activities (*weekly washes*, B = 0.112) and their characteristics (*stage of life*, B = 0.052). A second model had a similar predictive power and explained 59.1 % of the dependent variable *households' daily average electricity consumption*. Besides reinforcing the statistical importance of energy services (*thermal comfort need,* B = 3.14), household activities (*weekly washes*, B = 0.56) and households' characteristics (*stage of life*, B = 0.24), this model also unveiled the contribution of specific usage energy behaviours (*requiring specific and technical know-how*, B = -1.85) to increase average electricity consumption in this case study.

Since *weekly washes* are considered a direct predictor of energy consumption, multiple regression analysis was repeated and this variable excluded (Table 8). In addition to the variables already identified as relevant (e.g., *thermal comfort need*, *stage of life*, *behaviours requiring specific and technical know-how*), the ownership of energy intensive appliances and the time families spend at home emerged as relevant to explain 54.5 % daily average electricity consumption.

To summarise, these results confirm the quantitative significant impact of different dimensions of the conceptual model on households' average electricity demand, such as the household characteristics and activities, use of energy services and usage energy behaviours (e.g., requiring specific and technical know-how). For example, in this case study an increase of 1 % of *thermal comfort need* originates an increase of 3.14 % in daily average electricity consumption, while an increase of the same amount of *behaviours requiring specific and technical know-how* reduces by 1.85 % the average kWh/day. The specific conceptual model of this case study is displayed in Figure 2. According to these results, behavioural change actions aimed at reducing residential energy demand in this case study are more effective if focused on strategies that improve the insulation of buildings, provide tailored and technical information and encourage specific usage energy behaviours (e.g., settings adjustment, more efficient use of washing appliances). However, these recommendations are case specific and may not be generalised since the sample under study is not representative of the overall population.

Table 6. Correlation between the daily average electricity consumption and model variables.

Variable	Correlation
Weekly use of energy intensive appliances	r = 0.6, p<0.001
Stage of life of the household	r = 0.5, p<0.001
Ownership of appliances	r = 0.4, p<0.001
Thermal comfort need	r = 0.4, p<0.001
Behaviours requiring specific/technical know-how	r = 0.4, p<0.001
Lifestyle (conditions to save energy)	r = 0.3, p<0.05

Table 7. Regression models for predicting electricity consumption.

Dependent variable	Model	B	Std. Error	Beta	R	R^2	Adj. R^2	Observations
Average electricity consumption factor	(Constant)	-1.420	0.179	–	0.791	0.626	0.605**	Stepwise method, collinearity statistics Variance Inflation Factor <5 and tolerance close to 1.
	Weekly washes	0.112	0.027	0.426***				
	Thermal comfort need	0.818	0.234	0.313**				
	Stage of life	0.052	0.020	-0.278**				
Daily average electricity consumption	(Constant)	4.03	0.94	–	0.783	0.613	0.591**	
	Weekly washes	0.56	0.14	0.38***				
	Behaviours requiring specific and technical know-how	-1.85	0.48	-0.30***				
	Thermal comfort need	3.14	0.89	0.28***				
	Stage of life	0.24	0.10	0.22**				

*Table notes: Adj. R^2 – Adjusted multiple determination coefficient, B – Partial regression coefficient, Beta – Standardised regression coefficient, **p<0.05, ***p<0.001.*

Results also showed that in this approach it is essential to carefully select the dependent variable to be explained. For example, aggregating electricity consumption data through factor analysis reduced the detail and seasonal variability thus diminishing the importance of variables associated with thermal comfort (the partial regression coefficient B reduced from 3.14 to 0.818 when the dependent variable *daily average electricity consumption* was replaced by the *average electricity consumption factor* obtained by a principal component analysis).

Although the remaining variables of the model have not resulted as significant in this particular case study, they maintain their importance on influencing energy consumption and energy efficiency levels as resulting from the conceptual model and may emerge as important in samples with different characteristics.

Conclusions

This work proposed a multidisciplinary approach to assess the qualitative and quantitative influence of energy behaviours on electricity usage in a residential setting. A diversified set of energy behaviours was characterised and a significant connection was found between specific behavioural dimensions and electricity consumption, not only demonstrating the importance of energy behaviours influence on energy demand but also that it is fundamental to consider a diversified set of energy behaviours when designing energy efficiency measures. Furthermore, experimental results confirmed the impact of variables associated with different behavioural dimensions on energy consumption, thus supporting the need of an integrative perspective when addressing residential energy efficiency.

Table 8. Regression models for predicting electricity consumption, excluding the weekly washes.

Dependent variable	Model	B	Std. Error	Beta	R	R^2	Adj. R^2	Observations
Average electricity consumption factor	(Constant)	-1.964	9.357	–	0.784	0.614	0.585**	Stepwise method, collinearity statistics Variance Inflation Factor <5 and tolerance close to 1.
	Stage of life	0.063	0.019	0.333**				
	Thermal comfort need	0.837	0.243	0.320**				
	Ownership of energy intensive appliances	0.014	0.004	0.295**				
	Behaviours requiring specific and technical know-how	-0.266	0.125	-0.209**				
Daily average electricity consumption	(Constant)	5.642	2.200	–	0.759	0.577	0.545**	
	Stage of life	0.361	0.096	0.329***				
	Thermal comfort need	3.925	0.969	0.346***				
	Behaviours requiring specific and technical know-how	-1.967	0.504	-0.324***				
	Time spent at home	-0.45	0.186	-0.207**				
	Ownership of energy intensive appliances	0.051	0.022	0.193**				

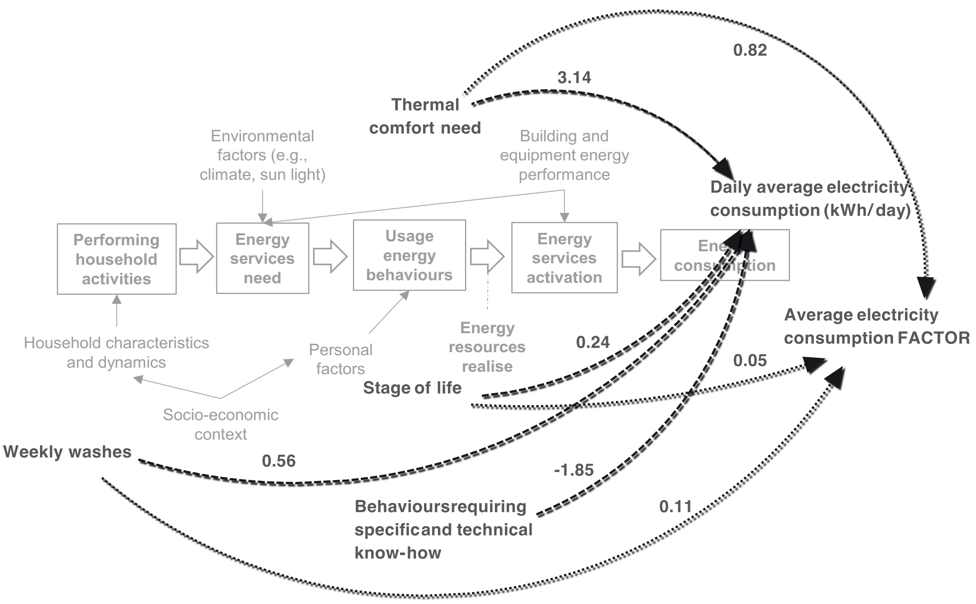

Figure 2. Specific conceptual model and real models for the case study.

Statistically significant correlations were found between the average electricity consumption and the weekly use of intensive energy consumption appliances, the stage of life of the household, the ownership of appliances and the required level of thermal comfort, revealing the significant influence of these variables on the increase of electricity consumption. In contrast, behaviours requiring specific/technical know-how and lifestyle (conditions to save energy) had significant negative correlations with household average electricity consumption demonstrating that these variables contributed to reduce electricity consumption.

Despite the important role multidisciplinary approaches such as the one presented in this work may have to contribute to reduce energy demand in the residential sector, they raise additional challenges associated with the involvement of experts and the combination of methods and techniques from different disciplines (particularly from engineering and the social sciences and humanities) and the amount of resources involved, namely to address a representative sample. Hence, future developments of this work should exploit how to make the most out of data provided by emerging technologies such as smart meters to reduce data collecting efforts.

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Appendix

Table 9. Component score coefficient matrix (rotation method: Varimax with Kaiser Normalisation).

Electricity consumption variables	Component	
	Average electricity consumption	Minimum power utilised
Standby power (kW)	0.058	0.194
Pmed (kW)	0.162	-0.050
Pmin (kW)	-0.080	0.460
Pmax (kW)	0.124	-0.064
Pmed / Pmax	0.118	0.024
Pmin / Pmax	-0.092	0.474
Daily average electricity consumption (kWh/day)	0.162	-0.050
Summer average electricity consumption (kWh/day)	0.138	-0.018
Winter average electricity consumption (kWh/day)	0.144	-0.070
Spring average electricity consumption (kWh/day)	0.145	-0.013
Autumn average electricity consumption (kWh/day)	0.125	0.005

Table 10. Component score coefficient matrix (rotation method: none).

Energy behaviours categories	Component		
	Automatic behaviours	Specific and technical know-how	Information demanding
Turning appliances OFF to avoid waste consumption	0.612	0.272	-0.131
Passive strategies to control thermal comfort or lighting	0.636	0.089	-0.086
Eliminating standby consumption	0.588	0.034	0.464
Adjusting the settings of appliances	0.457	-0.630	-0.143
Use of appliances	0.593	0.283	-0.070
Shifting the use of appliances to reduce electricity costs	0.365	-0.610	0.346
Auto-control and monitoring behaviours	0.058	0.510	0.620
Investing in efficient appliances	0.304	0.232	-0.636

Table 11. Component score coefficient matrix (rotation method: Varimax with Kaiser Normalization).

Personal determinants	**Component**	
	Attitudes toward saving	**Lifestyle (conditions to save energy)**
Perceived behavioural control over savings	0.347	0.492
Attitudes toward saving	0.443	0.395
Perceived ease of saving	-0.009	0.801
Social influence to saving	0.671	0.016
Consequences for the environment and the economy	0.783	-0.082
Consequences for lifestyle	-0.052	0.790
Responsibility	0.833	0.197