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Energy behaviours as promoters of energy efficiency: An integrative modelling approach

PhD Thesis in Sustainable Energy Systems supervised by Professor Carlos Alberto Henggeler de Carvalho Antunes and Professor Nelson Amadeu Dias Martins, submitted to the Department of Mechanical Engineering, Faculty of Sciences and Technology of the University of Coimbra

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in the context of the Energy for Sustainability Initiative of the University of Coimbra and MIT-Portugal Program

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ABSTRACT

Energy behaviours are an important underexploited resource in the context of promoting end-use energy efficiency in the residential sector. The potential of energy savings due to behaviours is usually neglected, albeit being as high as those from technological solutions. In addition, energy behaviours are also increasingly recognised as a key factor to foster higher levels of energy efficiency during the transition to smart grids. However, addressing the multidimensional nature of energy behaviours is a complex task and more effective behaviour change interventions and energy efficiency policies grounded on comprehensive approaches are required.

This thesis explores the influence of energy behaviours on end-use energy efficiency in the residential sector, as a contribution to a better understanding of this relation and the design of more effective behavioural change interventions and energy efficiency policies. Energy behaviours comprise several dimensions (e.g., usage, investment, maintenance and provision of energy resources) and are influenced by multiple variables of the personal, contextual, and technological domains. Being a complex topic, energy behaviours require the development of multidisciplinary and tailored interventions where the different energy stakeholders are involved. An integrative multidisciplinary modelling approach of the influence of energy behaviours on energy consumption is developed through the combination of methods and techniques from engineering, the social sciences and humanities, including the qualitative and quantitative dimensions of behaviours, namely the impacts on energy consumption. Behavioural adaptations during the transition to smart grids are also explored and real-world case studies are utilised to generate contextualised understanding.

Energy behaviours may significantly impact households' energy consumption. Simulations have estimated a savings potential of 72% when comparing primary energy consumption of the inefficient and efficient households. Investment energy behaviours have a higher savings potential than usage behaviours, and the behavioural savings potential per energy service is proportional to the energy consumption breakdown.

Energy behaviours also shape and are shaped by the transition to smart(er) grids and strategies aimed at enabling behavioural adaptations are needed. Behavioural adaptations comprise the increasingly active participation in the liberalised energy market, the adoption of smart grid technologies, the adaptation of household routines to shift demand and acceptance of direct load control performed by the utilities. Different strategies are required to facilitate these adaptations,

such as: (i) improving market regulation; (ii) previously assessing households' activities and usage behaviours; (iii) prioritising actions already embedded in households' daily routines; (iv) not interfering with households' activities while ensuring an override option; and (v) improving energy services, trust and information provided to end-users.

In conclusion, integrative modelling approaches contribute to properly address the influence of energy behaviours on energy consumption and design more effective behavioural change interventions and energy efficiency policies.

Keywords:

Energy behaviours, behavioural change, energy efficiency, modelling, energy policy, smart grids, demand response

RESUMO

Os comportamentos associados ao uso da energia são um recurso importante na promoção da eficiência energética no setor residencial, sendo também cada vez mais reconhecidos como um fator chave a considerar na transição para as redes elétricas inteligentes. As poupanças devidas a práticas comportamentais têm sido negligenciadas apesar de serem potencialmente tão significativas quanto as das soluções tecnológicas. Porém, por envolverem diferentes dimensões, os comportamentos no uso de energia são um tema complexo que requer programas de mudança comportamental e políticas energéticas mais eficazes.

Esta tese aborda a influência dos comportamentos relacionados com o uso da energia na promoção da eficiência energética no setor residencial, de modo a contribuir para a compreensão desta relação e, assim, contribuir para o planeamento de programas de mudança comportamental e políticas energéticas mais eficazes. Uma vez que os comportamentos no uso da energia envolvem diferentes dimensões (ex. uso, aquisição, manutenção, provisão de recursos energéticos) e são influenciados por diversas variáveis do domínio pessoal, tecnológico e de contexto, estamos perante uma temática complexa que requer abordagens multidisciplinares desenhadas à medida de cada situação, com o envolvimento das diversas partes interessadas. Neste trabalho, através da combinação de diferentes metodologias e ferramentas de engenharia, das ciências sociais e humanidades, é desenvolvida uma abordagem multidisciplinar de modelação dos comportamentos no uso da energia, incluindo a dimensão qualitativa e quantitativa dos comportamentos, como o consumo energético. São também exploradas as adaptações comportamentais que podem ocorrer na transição para as redes elétricas inteligentes e utilizados estudos de caso para contextualizar a metodologia desenvolvida.

O comportamento dos utilizadores finais tem um impacto muito significativo no consumo energético doméstico. Os resultados demonstraram que é possível poupar cerca de 72% do consumo de energia primária de um agregado familiar se, por comparação com um perfil ineficiente, forem adotadas as práticas mais eficientes. A troca de equipamentos é a dimensão comportamental com maior impacto no consumo energético, comparativamente as práticas de uso. Por outro lado, o potencial de poupança é maior nos serviços de energia com maior consumo energético.

A transição para redes elétricas mais “inteligentes” é um processo gradual que condiciona e é condicionado por alterações comportamentais, como a participação crescente no mercado liberalizado de energia, a adoção de tecnologias “inteligentes”, a alteração das rotinas dos agregados familiares para ajustar o consumo a períodos tarifários mais baratos e a aceitação do controlo de

cargas pelas empresas fornecedoras de eletricidade. De modo a facilitar estas alterações são necessárias diferentes estratégias, tais como: i) melhorar a regulação do mercado de energia; ii) avaliar previamente as práticas comportamentais dos agregados familiares; iii) dar prioridade a práticas já incorporadas nas rotinas desses agregados; iv) não interferir com as atividades das famílias, assegurando que mantêm o controlo sobre os seus equipamentos; v) melhorar os serviços de energia, a informação disponibilizada e a confiança entre consumidores e fornecedores de eletricidade.

Em conclusão, o recurso a abordagens de modelação integradoras de diversas áreas do conhecimento contribui para melhor avaliar as diversas dimensões dos comportamentos no uso da energia e, assim, planear programas de mudança comportamental e políticas de promoção da eficiência energética mais eficazes.

Palavras-chave

Comportamentos, mudança comportamental, uso da energia, eficiência energética, modelação, política energética, redes inteligentes

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ABBREVIATIONS

ABC – Attitude-behaviour-external conditions

BEPS – Building Energy Performance Simulation

CATWOE – Customers, Actors, Transformation, *Weltanschauung*, Owner, Environmental constraints

CO₂ – Carbon dioxide

COP – Coefficient of performance

CVRMSE – Coefficient of variation of root mean square error

ERSE – Energy Services Regulatory Authority

ESCOs – Energy service companies

EU – European Union

GHG – Greenhouse gases

GNP – Gross National Product

HDD – Heating degree days

HVAC – Heating, ventilation and air conditioning

ICT – Information and communication technologies

IRR – Internal rate of return

IEA – International Energy Agency

LED – Light Emitting Diode

MBE – Mean bias error

NGOs – Nongovernmental organisations

PPEC – Plan for the Promotion of End-Use Energy Efficiency

PTEM – Physical-technical-economic model

RCCTE – Portuguese regulation on the thermal characteristics of buildings

R&D – Research and development

T – Temperature

TOE – Tonne of oil equivalent

TBP – Theory of planned behaviour

TRA – Theory of reasoned action

VBN – Value-belief-norm

XPS – Extruded polystyrene insulation board

I INTRODUCTION ⁱ

I.1 BACKGROUND AND MOTIVATION

Recent environmental, economic and energy security trends point to major challenges: energy related carbon dioxide emissions reached an historic peak, the global economy remains in a fragile state, and energy demand continues to increase (OECD/IEA, 2012). From 1990 to 2005 the global final energy consumption increased by 23% while the associated carbon dioxide emissions rose by 25%, and the International Energy Agency (IEA) acknowledged that without decisive action energy related carbon dioxide emissions will more than double by 2050 (OECD/IEA, 2008b). These trends emphasise the need to redesign the global energy system, and low-carbon energy technologies such as renewable energy sources, new transport solutions and energy efficiency will require widespread deployment in order to achieve the carbon dioxide emissions goals (OECD/IEA, 2011c).

Energy efficiency is recognised by the European Union (EU) as the most cost-effective and fastest way to increase security of supply and to tackle climate change (EC, 2012b). It also contributes to reduce the investments in energy infrastructures, lower fossil fuels dependency, increase economic growth and job creation, develop industrial competitiveness, and improve consumers' welfare by reducing both local air pollution and consumers' energy bills (Taylor *et al.*, 2010). However, although energy efficiency levels have improved in the last years, both the IEA and the EU assume that there is still a significant untapped energy efficiency potential, namely in the building sector (OECD/IEA, 2012). This potential in residential buildings is estimated up to 27% and 63% by the EU and the IEA respectively, exclusively associated with infrastructural and equipment investments (CEC, 2006; OECD/IEA, 2011b, 2012).

Common strategies to improve energy efficiency in buildings include upgrading the buildings envelope, incorporating more energy efficient technologies for heating, cooling and ventilation systems, using high efficiency lighting, appliances and equipment, and low carbon technologies, such as renewable energy sources (OECD/IEA, 2012). Energy consumption in buildings is highly influenced by local climates and cultures, but it also depends to a great extent on individual users (OECD/IEA, 2008a). Indeed, people's behaviour is a major determinant of energy use in buildings and the

ⁱ This chapter is partially based on [Lopes, M. A. R., Antunes, C. H., & Martins, N. (2012). Energy behaviours as promoters of energy efficiency: A 21st century review. *Renewable and Sustainable Energy Reviews*, 16 (6), 4095-4104. doi: 10.1016/j.rser.2012.03.034]

potential of energy savings due to behaviours are usually neglected, albeit being referred to be as significant as those from technological solutions (Ürge-Vorsatz *et al.*, 2009; Jonsson *et al.*, 2010). As the EU acknowledges, one reason may be associated with the difficulty of quantifying behavioural savings and therefore this dimension is not habitually considered (EC, 2010e). Even though behaviours are recognised as a barrier in the promotion of energy efficiency (Pelenur and Cruickshank, 2012), there is still a critical lack of characterisation and systematisation of how behaviours influence it and how may leverage energy policies (Levine *et al.*, 2007).

Several interventions have been implemented in the last decades to promote more efficient energy behaviours, comprising antecedent, consequence and structural approaches (Abrahamse *et al.*, 2005; Han *et al.*, 2013). Considerable investments have been supporting these interventions, but recent assessments revealed they have been ineffective in achieving enduring and more efficient energy behaviours, and therefore substantial improvements are needed to increase their effectiveness (Gynther *et al.*, 2011; EEA, 2013). In particular, when designing interventions users' profiles and their personal and social context should be considered, as well as targeting specific behaviours instead of focusing on the potential instruments of change *per se* (which has been the common practice), while reinforcing the theoretical background of interventions. Hence, there is a need for more effective behaviour change interventions grounded on structured approaches of energy behaviours.

Furthermore, energy behaviours are going to face future challenges during the ongoing transformation of electric grids into more intelligent power grids (smart grids). Smart grids will provide a novel technological context and will change the customer-utility relationships raising significant challenges to users and energy behaviours. It is expected smart grids will increase energy awareness levels and encourage more efficient energy behaviours (Darby, 2010; EC, 2011; Wissner, 2011). Although behavioural research in this context is still in its beginning, there is an increasing recognition of the importance of end-users' behaviour role in smart grid contexts (Torriti *et al.*, 2010). Accordingly, understanding and foreseeing potential behavioural challenges is crucial for facilitating the transition to smart grids.

1.2 ENERGY BEHAVIOURS: A CHALLENGING TOPIC

Addressing energy behaviours is a complex task since they hold multiple dimensions. Energy behaviours are observed acts leading to energy consumption and include **investment**, **maintenance**, and **usage behaviours** as well as the **management and provision of energy resources** (Table 1).

Table 1 – Energy behaviours categories

CATEGORIES	DESCRIPTION OF BEHAVIOURS
Investment	Actions involved in the purchase of new equipment. They are also commonly designated as <i>efficiency behaviours</i> (Black <i>et al.</i> , 1985; Gardner and Stern, 2002; Breukers <i>et al.</i> , 2011; Karlin <i>et al.</i> , 2014).
Maintenance	Actions involved in the repair, maintenance and improvement of energy consuming equipment, including the building (Van Raaij and Verhallen, 1983).
Usage	Day-to-day actions of usage of buildings and equipment therein installed that may be characterised by the frequency, duration, and intensity. Usage behaviours decreasing the use of energy and contributing to achieve energy savings are also usually designated as <i>curtailment</i> or <i>conservation behaviours</i> (Black <i>et al.</i> , 1985; Gardner and Stern, 2002; Breukers <i>et al.</i> , 2011; Ehrhardt-Martinez <i>et al.</i> , 2011; Kok <i>et al.</i> , 2011; Karlin <i>et al.</i> , 2014).
Management and provision of energy resources	Actions involved in the planning or time shifting of energy usage, generation of energy through local renewable resources, and storage or trading self-produced electricity, which is increasingly important in smart(er) grid contexts (Geelen <i>et al.</i> , 2013).

Although the terms energy efficiency and energy conservation are often utilised in energy behaviours research (Abrahamse *et al.*, 2005; Barr *et al.*, 2005; Nässén and Holmberg, 2009; Ek and Söderholm, 2010; Maréchal, 2010; Nair *et al.*, 2010; Stephenson *et al.*, 2010; Gynther *et al.*, 2011; Martinsson *et al.*, 2011), some authors argue the term energy efficiency should not be used when referring to energy behaviours since it denotes the adoption of specific technologies reducing the overall energy consumption without changing the relevant behaviours (Oikonomou *et al.*, 2009). Instead, the term energy conservation is often recommended. In this work the strict energy efficiency definition of reducing the final energy consumed while achieving the maximum level of energy services possible is adopted. Energy efficiency may not be fully achieved only by the change of technologies, but also by the way they are used, which is related to energy behaviours (Lopes *et al.*, 2012b). Accordingly, the term **energy efficiency** will be used in an energy behaviour context and **‘more efficient energy behaviours’** indicate an increase of behavioural actions reducing the final energy consumption.

Increasing energy efficiency by adjusting energy behaviours to more efficient patterns requires targeting which specific behaviours to adjust (e.g., investment, usage, maintenance, or management of energy resources) and a comprehensive understanding of the factors leading to their activation.

In general, energy behaviours are shaped by personal and contextual factors and different research disciplines address them through distinct, yet complementary, approaches (Lopes *et al.*, 2012b; Moezzi and Janda, 2014). While the social sciences and humanities concentrate on exploring the personal and contextual factors leading to the activation of energy behaviours, engineering and more technological approaches focus on energy consumption as a result of the technical characteristics of equipment and buildings. Economics considers individuals to be totally rational, maximising utility and minimising cost in daily actions. However, behavioural economics recognises that during decision processes individuals may have information processing limitations and use heuristics and other information simplification processes. Psychology focuses on the individual perspective, identifying personal determinants (e.g., intentions, attitudes, norms, beliefs, values) or contextual influences to explain or predict energy behaviours. In turn, sociology and other social studies see energy behaviours as the result of the social context and not a consequence of individual decisions. In these disciplines, energy behaviours are considered to be a result of the social organisation in which individuals live such as social rules, lifestyles, standards or practices.

Regardless the unquestionable value of each perspective and the recent focus given by the European Environment Agency to the social practice approach (EEA, 2013), any single perspective becomes limited in addressing the different dimensions of energy behaviours by neglecting other disciplinary visions (Virkki-Hatakka *et al.*, 2013). The creative combination of different disciplines through integrative research is then required to develop comprehensive approaches to the understanding of energy behaviours and promotion of end-use energy efficiency in more effective interventions (Stern, 2014).

1.3 ENERGY EFFICIENCY IN PORTUGAL RESIDENTIAL SECTOR

Portugal's economic context, energy system, and retail electricity market are in transition. These contextual factors make it an interesting location for studying current and potential energy behaviours.

Economically, Portugal has been facing a downturn period, with a negative yearly variation of the GNP from 2011 to 2013 (FFMS, 2015) and an increase of unemployment which reached a rate of 16.2% in 2013 (Pordata, 2015).

Some energy system changes in Portugal have been relatively rapid. In 2010/11, a charging network for electric vehicles was implemented with 1,300 smart charging stations accessible to end-users throughout the country (MOBI.E, 2010). Wind turbines and solar panels have spread gradually across the Portuguese landscape, and in 2013 renewable energy sources contributed 53% of overall electricity production (DGEG, 2014b). Smart grid technologies, however, have been implemented at a slower pace. In the last decade several pilot programmes have been implemented by utilities using smart meters and energy management systems, ranging from simple in-house feedback displays to programmable systems endowed with actuation on loads. The largest smart grid program in Portugal is the InovGrid project (<http://www.inovcity.pt/en/Pages/homepage.aspx>). Initially reaching 32,000 end-users in the municipality of Évora, further development is expected in seven additional regions with the installation of 100,000 smart meters (EC, 2014), which represents an approximate national penetration rate of 2%. However, Portugal has not yet decided in favour of a large-scale smart meter roll-out, thus impairing the European Commission's 80% target penetration rate by 2020 (EC, 2014). As a consequence, demand response programmes and direct load control activities have only had an experimental basis with limited results.

The liberalised retail energy market has been progressively opened to energy intensive activities such as the industry and services since 1995, but it was only opened to small end-users, as residences, in 2006. Since then residential customers have had the option of leaving the regulated market and joining the liberalised market by choosing another supplier. Electricity in the regulated market has been supplied to residential end-users by one provider: the "last resource" company approved by the national energy authority (General Directorate of Energy and Geology). In the liberalised market, approximately ten different companies, accredited by the Energy Services Regulatory Authority (ERSE), are currently operating. As in other countries, Portuguese residential customers have been sluggish about switching suppliers. After eight years of opportunity, only 74% of residential electricity

customers have switched to the liberalised energy market (ERSE, 2015). Customers in both the regulated and liberalised markets may choose among flat, dual or three period time-of-use tariffs. However, there is a financial stimulus to change to the liberalised market. Those who remain in the regulated market are subject to tariff increases by the energy regulator on a quarterly basis. Moreover, early indications were that customers would be obliged to change at the end of a designated transition period. This transition period was recently altered by the government and the regulated market is expected to end by 2017 (ERSE, 2015).

Whatever the cause - the recent economic restrictions and/or the increase of energy prices - Portuguese energy household consumption has diminished in recent years. The households' average primary energy consumption has decreased 17% from 2004 to 2013, moving from 0.82 to 0.67 toe/household.yearⁱⁱ (excluding vehicles) (DGEG, 2015). Nonetheless, the residential sector currently represents 17% of end-use energy being the third most energy intensive sector, after transports and industry (DGEG, 2014a). Considering the different uses of energy in households, kitchens have the highest weight in primary energy consumption, accounting for over one third (39%), followed by water heating (23%), space heating (22%), appliances (11%), lighting (4%) and space cooling (1%) (INE and DGEG, 2011). Electricity is the main commodity utilised by households (43% of their overall energy consumption) which, in average, have an yearly consumption of 3,700 kWh per household: 41% in the kitchen; 33% on appliances; 14% in lighting; 9% in space heating; and 3% in water heating and space cooling (INE and DGEG, 2011).

The adoption of energy efficient appliances by the families has also been performed gradually as a result of energy efficiency policies. 54% of electrical appliances owned by households have, at least, an energy label of "A", and although inefficient light bulbs (such as incandescent) may still be found at 81% of the Portuguese homes, 68% already own fluorescent light bulbs and 3% installed LEDs (INE and DGEG, 2011). The adoption of decentralised renewable energy sources is also an ongoing process, with 2% of the households already using solar thermal systems to heat water (INE and DGEG, 2011), and 0.2% to produce electricity through the use of micro-generation systems (MEE, 2014).

The Energy Performance of Buildings Directive provided the context for improving energy efficiency of the housing stock. Most residential buildings are relatively old (in 2010, 71% were more than 30 years old) and have low insulation levels (in the same year 79% had no insulation in the exterior wall,

ⁱⁱ Tonne of oil equivalent per household per year.

83% had no insulation in the roof, and 71% had simple glazed windows) (INE and DGEG, 2011). Nevertheless, in 2015 around 3.5% of the total housing stock has, at least, an energy performance of “B-” (ADENE, 2015).

Accordingly, this is an important moment to assess current energy behaviours of Portuguese end-users and consider their potential for engagement in energy efficiency initiatives and participation in the emerging smart grid context, as a contribution to the design of more effective energy efficiency policies.

1.4 OBJECTIVES AND RESEARCH QUESTIONS

Energy behaviours represent a significant untapped potential for end-use energy efficiency in buildings and are deemed to play an increasingly relevant role during the ongoing transformation of electric grids into smart(er) grids. This thesis aims to explore energy behaviours as a catalyser of energy efficiency in the residential sector, contributing to the design of more effective behavioural change interventions and energy efficiency policies. By exploring the use of different research methods and techniques, both quantitative and qualitative, pertaining to different disciplines, this work also aims to contribute to the development of integrative research methodologies.

Three main research questions were formulated:

RQ #1. How to incorporate energy behaviours complexity into the design of more effective behaviour change interventions in the framework of energy efficiency policies?

RQ #2. How much energy savings potential in residential buildings can be achieved by promoting more efficient end-use energy behaviours?

RQ #3. What energy behavioural changes are brought by the emerging smart grid and how to facilitate behavioural adaptations?

I.5 STATE OF THE ART

This section reviews the literature on energy behaviours, namely concerning: (i) the current research on energy behaviours, (ii) modelling approaches of energy behaviours, (iii) behavioural savings potential, and (iv) the role of energy behaviours in smart(er) grids.

I.5.1 ENERGY BEHAVIOURS RESEARCH

Most of the recent research on energy behaviours in residential buildings has been essentially focused on establishing behavioural determinants of energy use and developing field experiments to test instruments for promoting more efficient energy behaviours (Table 2).

Table 2 – An overview of energy behaviour research published after 2000

ENERGY BEHAVIOURAL DIMENSIONS		EXAMPLES OF PUBLICATIONS
Behavioural determinants of energy use	Psychological and contextual determinants	(Sardianou, 2007; Crosbie, 2008; Owens and Drifill, 2008; Steg, 2008; Abrahamse and Steg, 2009; Wall and Crosbie, 2009; Cayla <i>et al.</i> , 2011; Gadenne <i>et al.</i> , 2011; Martinsson <i>et al.</i> , 2011; Yun and Steemers, 2011; Kang <i>et al.</i> , 2012; Pelenur and Cruickshank, 2012; Urban and Ščasný, 2012; Yohanis, 2012; Hayn <i>et al.</i> , 2014; Levie <i>et al.</i> , 2014; Lillemo, 2014; Ohler and Billger, 2014; Aguirre-Bielschowsky <i>et al.</i> , 2015; Beunder and Groot, 2015; Burger <i>et al.</i> , 2015; Frederiks <i>et al.</i> , 2015; Longhi, 2015; Pothitou <i>et al.</i> , 2015; Selvefors <i>et al.</i> , 2015; Winther and Wilhite, 2015; Yang <i>et al.</i> , 2015)
	Habits and socio-economic determinants	(Barr <i>et al.</i> , 2005; Maréchal, 2010; Nair <i>et al.</i> , 2010; Wenshun <i>et al.</i> , 2011; Zhao <i>et al.</i> , 2012; Langevin <i>et al.</i> , 2013; Pothitou <i>et al.</i> , 2014; Jones and Lomas, 2015)
Instruments for behavioural change	Review of behavioural change interventions and programmes	(Abrahamse <i>et al.</i> , 2005; Steg and Vlek, 2009; Gynther <i>et al.</i> , 2011; Han <i>et al.</i> , 2013)
	Feedback (e.g., tailored information, goal setting, in-home displays, web platforms, more sophisticated interfaces)	(Ueno <i>et al.</i> , 2006; Abrahamse <i>et al.</i> , 2007; Wood and Newborough, 2007b; Wood and Newborough, 2007a; Burgess and Nye, 2008; Fischer, 2008; Ek and Söderholm, 2010; Hargreaves <i>et al.</i> , 2010; Palm, 2010; Willis <i>et al.</i> , 2010; Karjalainen, 2011; Bonino <i>et al.</i> , 2012; Chen <i>et al.</i> , 2012; Jain <i>et al.</i> , 2012; Vassileva <i>et al.</i> , 2012; Hargreaves <i>et al.</i> , 2013; McKerracher and Torriti, 2013; Wilson <i>et al.</i> , 2015)
	Other (e.g., awareness, knowledge, engagement)	(Lindén <i>et al.</i> , 2006; Gyberg and Palm, 2009; Kok <i>et al.</i> , 2011; Bull <i>et al.</i> , 2015)
Quantification of behavioural impacts on energy consumption	Behavioural change interventions	(Dietz <i>et al.</i> , 2009; Ouyang and Hokao, 2009; Ürge-Vorsatz <i>et al.</i> , 2009; de Almeida <i>et al.</i> , 2011; Gynther <i>et al.</i> , 2011; Kyrö <i>et al.</i> , 2011; Leighty and Meier, 2011)
	Rebound and prebound effects	(Nässén and Holmberg, 2009; Hens <i>et al.</i> , 2010; Sunikka-Blank and Galvin, 2012; Winther and Wilhite, 2015) (Thomas and Azevedo, 2013; Galvin, 2014; Ghosh and Blackhurst, 2014; Schleich <i>et al.</i> , 2014; Orea <i>et al.</i> , 2015)

While being dominated by the environmental psychology discipline, this field of research has, in general, explored the influence of **behavioural determinants** such as attitudes, beliefs, social norms, awareness, knowledge, information, habits, income, and context on energy use. This dimension will be further developed in the next section.

Based on the common agreement that behavioural changes are required to increase energy efficiency levels, several **behavioural change strategies** have also been developed and tested over the years, namely antecedent, consequence and structural strategies (Abrahamse *et al.*, 2005; Han *et al.*, 2013). Antecedent strategies focus on changing factors preceding behaviours (e.g., information, demonstration, training, one-to-one engagement, free products, labelling, commitment and goal setting). Consequence strategies aim to change the results following behaviours, based on the assumption that positive outcomes will promote more efficient energy behaviours. They comprise feedback, providing information on energy consumption, and rewards. Structural strategies aim to change contextual conditions to facilitate behaviour changes and include financial incentives and disincentives (e.g., subsidies, taxes, bonuses, rewards and penalties) and regulatory instruments (e.g., laws and rules, agreements, regulated versus dynamic energy pricing) (EEA, 2013). Experience has shown the effectiveness of interventions increases with a preliminary clear identification of the barriers to behaviour change, targeting specific behaviours and combining the most effective strategies according to pre-identified behaviour profiles (Abrahamse *et al.*, 2005; Gynther *et al.*, 2011).

Feedback mechanisms have been one of the most studied behavioural change strategies. Feedback consists in providing information on energy consumption and is seen as an essential strategy to re-materialise energy consumption, contributing to raise awareness and encouraging individuals to have more efficient energy behaviours (Burgess and Nye, 2008; Fischer, 2008; Hargreaves *et al.*, 2010). Although the literature has identified successful feedback features (e.g., capturing the consumers' attention, drawing a close link between specific actions and their effects, presenting costs over a period of time, appliance-specific breakdown, historical comparison, and using computerised and interactive tools), one the most important conclusions is that there is not the perfect feedback for everybody and feedback should be tailored according to the characteristics of each group (Abrahamse *et al.*, 2007; Fischer, 2008; Gynther *et al.*, 2011).

Finally, behavioural research also comprises the **quantification of the behavioural impact on energy consumption**, either originated due to specific behavioural change strategies, or estimated using modelling tools (this approach will be further developed in the next section). An important line of

research explores the gap between expected and actual energy consumption, which is usually identified as the rebound – when consumption is higher than expected (Nässén and Holmberg, 2009; Hens *et al.*, 2010; Thomas and Azevedo, 2013; Galvin, 2014; Ghosh and Blackhurst, 2014; Schleich *et al.*, 2014; Orea *et al.*, 2015; Winther and Wilhite, 2015), or the prebound effect – when consumption is lower than expected (Sunikka-Blank and Galvin, 2012).

1.5.2 ENERGY BEHAVIOURS MODELLING

Modelling is a central tool to modern science, management and policy making, guiding judgement and supporting problem solving (Moezzi and Lutzenhiser, 2010; Jefferson, 2014; Moezzi and Janda, 2014). In energy efficiency studies, modelling is usually employed for forecasting energy demand, predicting the adoption of new technologies or estimating the impacts of energy efficiency programmes (Taylor *et al.*, 2014). Energy behaviours, in particular, have been modelled using a variety of different techniques, depending on the objectives and the disciplines. For the purpose of this review, three categories on energy behaviour models are defined that attempt to accurately illustrate the multidisciplinary literature published under this topic (Figure 1):

- a. **Energy behaviour frameworks** that are interpretative and explanatory approaches of energy behaviours;
- b. **Energy modelling** that comprises quantitative models aiming at estimating energy consumption;
- c. **Energy behaviour modelling** that integrates both qualitative and quantitative approaches used for forecasting behaviours.

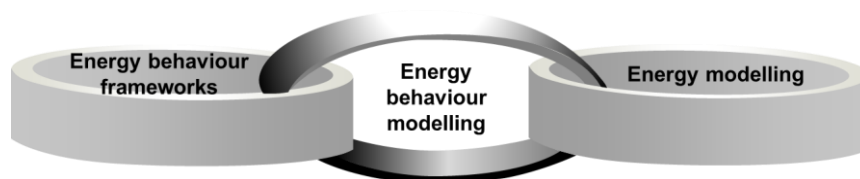


Figure 1 – Categorisation of energy behaviour models

1.5.2.1 Energy behaviour frameworks

This section reviews the structuring frameworks and energy usage behaviour determinants that provide the foundation for energy behaviour research, which is summarised in Table 3.

The **physical-technical-economic model (PTEM)** has dominated engineering research on energy use. According to this model, users are seen as merely occupants of buildings whose behaviours are secondary to energy efficiency and therefore their patterns of energy and equipment use are statistically assumed (Lutzenhiser, 1993). Nevertheless, this model considers behaviours to play a significant role in long-term energy use mainly due to the expectation of investment in more efficient building equipment and systems. Hence, this model practically neglects the influence of energy behaviours on energy use adopting a narrow perspective of energy efficiency exclusively associated with energy investment behaviours.

In turn, mainstream **neoclassical economics** regards energy end-users as fully rational, which means that they are expected to behave rationally and maximise utility given budget constraints at each instant (Lutzenhiser, 1992; Wilson and Dowlatabadi, 2007). However, there is strong evidence of behavioural inconsistencies mainly due to the limits that users face when processing complex and large amounts of information, usually encompassed under the designation **bounded rationality** according to Simon's works (Simon, 1972). One example is the **time inconsistency** that occurs when individuals make different decisions with different underlying discount rates in different situations (Gillingham *et al.*, 2009). When needing to process large amounts of information individuals also tend to simplify tasks by employing a wide range of **heuristics** (or simplification rules), such as affect heuristic, representativeness or availability heuristics (Slovic *et al.*, 2002). Further, individuals tend to **frame** decisions according to the way the decision problem is presented to them or even **anchoring** their decisions on predetermined information in order to assist information processing.

Table 3 – Disciplinary frameworks on usage energy behaviours

AREA OF RESEARCH	FRAMEWORK	DESCRIPTION	BEHAVIOUR DETERMINANTS	EXAMPLES OF PUBLICATIONS
Engineering	Physical-technical-economic model (PTEM)	Usage behaviours are assumed and users are expected to invest in more energy efficient equipment.	Financial ability	(de Almeida <i>et al.</i> , 2011; Beal <i>et al.</i> , 2012; Virote and Neves-Silva, 2012)
Micro economy	Utility maximisation and rationality	Behaviours are fully rational and users' preferences are perfectly ordered.	Utility maximisation	(Galarraga <i>et al.</i> , 2011; Ward <i>et al.</i> , 2011; Bull, 2012; Reynolds <i>et al.</i> , 2012; Reynolds <i>et al.</i> , 2015)
Behavioural economics	Prospect theory	Individuals tend to anchor on certain types of information and assess decisions against gains and losses.		
	Bounded rationality and heuristic decision making	Users face limitations when processing large amounts of information and simplify it using heuristics.	Utility maximisation weighted by information and heuristics.	(McCalley, 2006; Steg, 2008; Ek and Söderholm, 2010; Klotz, 2011; Streimikiene and Volochovic, 2011; Giraudet <i>et al.</i> , 2012)
	Time inconsistency	Depending on the situation, individuals make different decisions with different discount rates associated.		
Social and cognitive psychology	Theory of reasoned action (TRA)	Behaviours are a result of intentions, attitudes, beliefs and norms.	Intentions, attitudes, beliefs, subjective norms and normative beliefs	
	Theory of planned behaviour (TPB)	Beyond intentions, attitudes and subjective norms, behaviour is also conditioned by conditions and resources reflected in Perceived Behaviour Control.	Intentions, attitudes, subjective norms, resources (time, skills, money, etc.)	(Barr <i>et al.</i> , 2005; Thøgersen, 2006; Abrahamse and Steg, 2009; Thøgersen and Grønhøj, 2010; Gadenne <i>et al.</i> , 2011; Kok <i>et al.</i> , 2011; Ozaki and Sevastyanova, 2011; Sütterlin <i>et al.</i> , 2011)
	Cognitive dissonance	Behaviour results from a consistency process between knowledge, attitudes and actions.	Knowledge, attitudes and actions	
	Self-regulation	Behaviour is self-influenced and regulated.	Goal-directed behaviour, goals, self-efficacy, outcome expectations, rules and norms	
Social and environmental psychology	Value-belief-norm (VBN)	Behaviours are the result of personal and social norms, beliefs and values.	Personal and social norms, beliefs and values	(Black <i>et al.</i> , 1985; Stern, 2000; Sardianou, 2007; Steg and Vlek, 2009; Ek and Söderholm, 2010; Thøgersen and Grønhøj, 2010; Cayla <i>et al.</i> , 2011; Gadenne <i>et al.</i> , 2011; Martinsson <i>et al.</i> , 2011; Santin, 2011; Mills and Schleich, 2012; Urban and Ščasný, 2012; Han <i>et al.</i> , 2013; Hori <i>et al.</i> , 2013)
	Attitude-behaviour-external conditions (ABC)	Behaviours are generated due to attitudes when external conditions are favourable.	Attitudes, external conditions	
Sociology	Classical sociology	Behaviours are the result of social rules and standards.	Social rules and standards	
	Cultural theories	Behaviours are the result of lifestyles (material culture and cultural practices of groups).	Lifestyles	(Lutzenhiser, 1992; Stephenson <i>et al.</i> , 2010; Strengers, 2012; Sweeney <i>et al.</i> , 2013; Stephenson <i>et al.</i> , 2015)
	Social practices	Energy behaviours result from the social organisation of the household.	Social organisation	

In **social and cognitive psychology** specific models of attitude and belief-based behaviour models try to explain the relationship between cognition and action, namely the theory of reasoned action, the theory of planned behaviour, the cognitive dissonance and self-efficacy (Wilson and Dowlatabadi, 2007). The **theory of reasoned action (TRA)** assume behaviours to be a result of individuals' intentions to act that are influenced by a pre-existent attitudinal disposition (attitude towards the behaviour itself) and a social, or normative, factor (subjective norms about the behaviour) (Fishbein and Ajzen, 1975). According to this theory, intentions are a function of certain beliefs linking an object to some attributes and the attitudes towards behaviour resulting from the integration between expectation and the evaluation of attributes. Beliefs are also built from a continuous evaluation of behaviour outcomes. Although there is no consensual definition of attitudes, Fishbein and Ajzen (1975) describe them as "a learned predisposition to respond in a consistently favourable or unfavourable manner with respect to a given object" which have an evaluative and affective nature. In fact, affect (individual's feelings towards an object) is classically viewed as one important component of attitudes (Bagozzi *et al.*, 2002). In turn, subjective norms are normative pressures resulting from the beliefs (normative) that individuals think that they should, or not, perform certain behaviour. An individual's subjective norm is viewed as a potential determinant of his/her intention to perform behaviours.

The **theory of planned behaviour (TBP)** is built from the theory of reasoned action, also considering intentions as the central motivation factor when predicting behaviours but adding an ability dimension, the behavioural control (Ajzen, 1991). The stronger the intention to engage in a particular behaviour the more likely should its performance be, assuming that at some point in time the subject inspected his/her beliefs and expectations and formed a conscious intention to engage in the behaviour, thus activating this intention in the appropriate performance context. However, behaviours also depend on other factors such as the availability of necessary opportunities and resources to perform them. All together these factors represent individuals' effective control over behaviours that the theory considers at the subjective level, the **perceived behavioural control**. Also, according to the **theory of cognitive dissonance** individuals struggle to be coherent and try to reduce their internal inconsistencies between knowledge, attitudes, and actions, thus progressively having more consistent and consonant behaviours (Fishbein and Ajzen, 1975). Finally, the social cognitive theory of **self-regulation** assumes human behaviour to be continuously motivated and regulated through self-influence (Bandura, 1991). This process may be operated through self-monitoring of one's behaviour, its determinants and its effects, the judgement (cognitive and affective assessment) of one's behaviour relatively to personal standards and environmental circumstances, and effective

self-reaction. Being one of the most important processes of self-regulation, self-efficacy addresses individuals' beliefs about their capabilities to exercise control over their own level of functioning or over events that affect their lives. Self-efficacy may help determining whether an individual attempts and persists with a given task and is influenced by past experience, the learning from observation of role models, and perceived skills. The self-regulation framework is particularly relevant when addressing behaviours involved in monitoring energy consumption. In fact, experience has shown that increasing self-efficacy by setting achievable goals and providing feedback contributes to improve energy efficiency levels (Wilson and Dowlatabadi, 2007).

Another field of psychology research, social and environmental psychology, has highlighted constructs based on values, attitudes and norms in order to explain environmental behaviours, and in particular, energy behaviours (Black *et al.*, 1985; Stern, 2000; Thøgersen and Ölander, 2002; Poortinga *et al.*, 2004; Abrahamse and Steg, 2009). The **value-belief-norm (VBN) theory** proposes a causality relationship between the personality (values), specific beliefs about the consequences and responsibilities of particular actions, attitudes and personal and social norms (Wilson and Dowlatabadi, 2007). The basis for VBN is the activation norm theory of altruism through which altruistic behaviours occur in response to personal moral norms activated when individuals have two types of beliefs: their actions may pose consequences to others (awareness of adverse consequences); and they feel responsible for causing or preventing these consequences (ascription of responsibility) (Schwartz, 1977; Stern, 2000; Ibtissem, 2010). The VBN theory modified the activation norm theory to include altruistic values towards both humans (e.g., freedom, honesty, social power) and the biosphere (e.g., protecting the environment, unity with nature) (Schwartz, 1994; Thøgersen and Ölander, 2002; Wilson and Dowlatabadi, 2007). According to these theories, for new norms and considerations to enter the decision-making process a conscious decision needs to be taken during a process called norm activation that may happen, for example, due to a conflict between norms.

The previous theories do not acknowledge contextual factors and often fail to adequately explain energy behaviours when they involve high-effort, high-cost and high-involvement decisions (Wilson and Dowlatabadi, 2007). Hence, social psychology research gave a step further and incorporated contextual variables. In **attitude-behaviour-external conditions (ABC) theory** attitudes lead to behaviours only if contextual variables (physical, financial, legal, or social) provide either incentives or disincentives (Stern, 2000; Wilson and Dowlatabadi, 2007). According to this theory, the influence of attitudinal factors will be more relevant in contexts that facilitate behaviours.

Going beyond the individual perspective of energy behaviours, social studies such as sociology and anthropology argue that energy use is not a consequence of individual decisions but results from the social context (Moezzi and Lutzenhiser, 2010). Needs, attitudes and expectations are not individual in nature but are part of a complex relationship between social norms and relations, technologies, infrastructures and institutions (Wilson and Dowlatabadi, 2007). In **classical sociology** for example, the individual behaviour is a product of social rules and standards (Wilk, 2002). Individuals tend to behave in order to maintain themselves within the boundaries of social groups which they relate to. Developing this perspective, **cultural theories** focus on the group rather than the individual. As an illustration, the Cultural Model of Household Energy Consumption (Lutzenhiser, 1992) suggests that energy use is the result of the intertwined relation of the material culture and the cultural practices of groups, what is often called status, lifestyle or standards of living.

Another perspective within the social sciences views energy as a means to provide useful services that enable normal and socially acceptable activities to be carried out as part of the daily life (Wilhite, 2008; Strengers, 2012). As a result, energy use becomes a reflection of the social organisation of the household (or other social unit) in which rules, practices and routines are embedded. For instance, the **social practice perspective** sees individuals as performers of practices, and beliefs, attitudes and values arising from these practices (and being cultivated within) rather than individuals (Strengers, 2012). This approach also shifts the focus from individuals and technologies to a more holistic view encompassing understandings, infra-structures, technologies, knowledge and rules that are reproduced through daily routines (Shove and Walker, 2010).

In summary, energy behaviours are complex and influenced by a broad range of variables from different frameworks. Accordingly, integrative approaches are needed to provide a comprehensive understanding of energy usage behaviours, including the social, economic, technological, institutional, infrastructural and individual dimensions of energy behaviours, as well as their complex relations (Keirstead, 2006; Kowsari and Zerriffi, 2011; Lopes *et al.*, 2012b).

1.5.2.2 Energy modelling

Energy modelling may be used to estimate energy consumption in the residential sector supporting energy policy decisions or backing up engineering related activities (e.g., simulation of technology use, thermal behaviour of buildings). Comprehensive reviews on the techniques utilised for modelling energy consumption have been recently published (Swan and Ugursal, 2009; Kavgic *et al.*, 2010; Suganthi and Samuel, 2012).

In general, energy models may be grouped into top-down and bottom-up approaches (Table 4). **Top-down** approaches estimate long-term trends on residential energy consumption primarily for macro supply analysis, based on aggregated and widely available historical energy consumption information and input variables (e.g. gross domestic product, employment rates, price indices, climatic conditions, housing construction/demolition rates, income, estimates of appliance ownership). They consider the residential sector as a system and do not distinguish individual energy consumption uses. These models comprise econometric, technological and combined techniques. While econometric top-down models seek to establish the connection between energy use and economic variables, the technological approach focusses on other factors, such as the housing stock characteristics, appliances ownership, technological and structural trends.

In contrast, **bottom-up** approaches employ as input data the energy consumption of individual end-uses, individual buildings, or groups of buildings and extrapolate this information to represent the region or country based on the representative weight of the modelled sample. Bottom-up models include statistical and engineering methods. Based on historical information, the statistical methods use regression analysis to attribute energy consumption to particular end-uses and then estimate the energy consumption of dwellings that are representative of the residential stock. The engineering techniques are used to explicitly estimate energy consumption of end-uses based on detailed descriptions of a representative set of buildings. For instance, they combine building physical variables, such as the efficiency of space heating systems and their characteristics, the areas of the different dwelling elements along with their thermal characteristics, internal temperatures and heating patterns, ventilation rates, energy consumption of appliances, number of occupants, and external temperatures, to estimate the energy consumption of a representative sample of buildings.

Table 4 – An overview of recent energy modelling research

ENERGY MODELLING	EXAMPLES OF PUBLICATIONS
Top-down approaches	(Filippini and Hunt, 2012; Song <i>et al.</i> , 2012; Blázquez <i>et al.</i> , 2013; Oliveira and Rebelatto, 2015)
Bottom-up approaches	(Al-Mumin <i>et al.</i> , 2003; Isaksson and Karlsson, 2006; Andersen <i>et al.</i> , 2009; Hoes <i>et al.</i> , 2009; Santin <i>et al.</i> , 2009; Toftum <i>et al.</i> , 2009; Jian <i>et al.</i> , 2010; Richardson <i>et al.</i> , 2010; Roetzel <i>et al.</i> , 2010; Gago <i>et al.</i> , 2011; Pino and Herde, 2011; Santin, 2011; Stamminger, 2011; Theodoridou <i>et al.</i> , 2011; Yun and Steemers, 2011; Chingcuanco and Miller, 2012; Fehrenbach <i>et al.</i> , 2014; Fumo and Rafe Biswas, 2015; McKenna <i>et al.</i> , 2015; Wahlström and Hårsman, 2015)

While top-down approaches are referred to allowing for long term forecasting using simple, aggregated, and widely available information, they lack detail regarding the energy consumption of individual uses and therefore miss to identify key areas for energy efficiency improvement. Furthermore, by relying on historical data they fail to adequately model discontinuities due to advances in technology. On the contrary, bottom-up approaches estimate energy end-uses, although using different techniques (statistical ones determine typical uses and engineering ones use simulations). Bottom-up statistical models require large samples and engineering models are computationally intensive. Hence, these approaches have strengths and weaknesses when modelling energy consumption that must be considered when designing an energy modelling research.

These models also fail to adequately deal with socio-technical influences on energy consumption, specifically behavioural ones. For example, how households use domestic appliances or how they react to changes in the dwelling as a result of energy performance measures. Nonetheless, specific micro-scale engineering models consider to some extent the influence of occupants' behaviour on the buildings thermal behaviour and energy consumption.

1.5.2.3 Energy behaviours modelling

Although there is a vast research on energy behaviours, integrative modelling approaches of energy behaviours have had limited development. Integrative models are inclusive and flexible, considering all relevant aspects of energy behaviours while finding a balance among disciplines, and may be used by practitioners and policy makers to both theoretical and practical purposes (Keirstead, 2006).

In the last three decades multidisciplinary perspectives tackling energy behaviours in the residential sector have been developed by several authors in an effort of integration (Dholakia *et al.*, 1983; Van Raaij and Verhallen, 1983; Hitchcock, 1993; Haas *et al.*, 1998; Wilk, 2002; Keirstead, 2006; Kowsari and Zerriffi, 2011; Han *et al.*, 2013). These models provided multiple insights on energy behaviours but their level of detail, scale and approach differed substantially reflecting the different authors' backgrounds, disciplinary influences and study motivations. However, these models had a static perspective of energy behaviours, losing the intrinsic dynamic dimension of behaviours. In fact, energy behaviours do change over time and hence modelling approaches should pursue this dynamic dimension. More recently, some authors have explored this dynamic dimension by using system dynamics modelling (Elias, 2008; Motawa and Oladokun, 2015).

An additional line of research integrates both qualitative and quantitative dimensions of energy behaviours by combining users' activities and habits with energy consumption patterns, through diary approaches (Widén *et al.*, 2009; Richardson *et al.*, 2010; Hiller, 2015). Profiles are generated from a comparison between a detailed data set on the time everyday households' activities are performed and electricity measurements, and different activity patterns are identified and connected to different categories. This modelling technique generates individualised load profiles, for each family member, instead of using the household as the smallest analysis unit. It has a great potential to provide insights on how everyday activities contribute to energy use. However, it is based on a very time and resource consuming information process, which consists in written time diaries that are usually inexistent and difficult to obtain.

A more quantitative approach on energy behaviour modelling consists of extracting energy consumption patterns through data mining techniques in order to establish energy use profiles and distinguish among energy behaviours (Seem, 2005; Yu *et al.*, 2011; Yu *et al.*, 2013). This approach compares residential samples with similar characteristics such as climate, building characteristics, energy services, and search for different patterns of energy consumption only explainable by distinct occupants' behaviour. It enables the savings establishment and estimative associated with different behavioural profiles. However, it requires an extremely large amount of detailed building-related

data which is typically very complex to collect. Besides that, there is no guarantee that issues other than the behavioural ones are not embedded into energy consumption data, such as, for example, dwellings retrofitting effects.

The latest promising developments in energy behaviour modelling are multidisciplinary approaches exploring the causal chain of energy behaviours and connecting the behavioural drivers to energy consumption through modelling tools. A systematic representation of energy behaviours activation chain was recently developed to promote behavioural integration in buildings energy performance simulations (Hong *et al.*, 2015). In addition, the Brahms environment (Business Redesign Agent-Based Holistic Modelling System) was utilised as a modelling tool to integrate occupants' behaviours, the physical and thermal performance of the building, the energy consumption of the different appliances, and the outdoor environment (Kashif *et al.*, 2013).

1.5.3 POTENTIAL SAVINGS OF ENERGY BEHAVIOURS

Traditionally, behavioural savings potential in the residential sector is quantified in the context of **energy efficiency interventions** developed in real-world contexts (Table 5). Overall, behavioural change interventions usually originate savings up to 20%, but values may differ up to 100% between different studies and contexts (Lopes *et al.*, 2012b). Taking Europe as an example, the most effective interventions included feedback, energy audits, community-based initiatives and the combination of multiple strategies, all originating savings from 5% to 20% (EEA, 2013). However, these results may not be transferable since they have been produced in the context of interventions with different characteristics (e.g., location, typology, scope, scale and energy policy context). As a result, there are severe limitations to generalise energy savings resulting from behavioural interventions which has been limiting the research in this field (Ürge-Vorsatz *et al.*, 2009). Furthermore, interventions usually combine behaviour changes with equipment replacement, therefore making impossible the specific quantification of the behavioural component through this approach.

Table 5 – Behavioural savings in the residential sector estimated using behavioural interventions

APPROACHES		ENERGY SAVINGS AND EMISSIONS	REGION	PUBLICATIONS
Review	Meta-analysis of information-based energy conservation experiments. Studies from 1975 to 2012.	Up to 7.4% of electricity consumption.	World	(Delmas <i>et al.</i> , 2013)
	Review of non-technological factors influence on energy consumption and carbon emissions in buildings.	Approximately 29% of the projected baseline emissions by 2020 can be avoided.	World	(Ürge-Vorsatz <i>et al.</i> , 2009)
	Review on 100 behavioural intervention projects on 11 European countries.	Savings potentials may reach 20%.	Europe	(Gynther <i>et al.</i> , 2011)
Feedback	Review on 12 utility pilot programs using in-house displays.	Electricity savings range from 7% without an electricity prepayment system, to 14% with that scheme.	USA, Japan	(Faruqui <i>et al.</i> , 2010b)
	Review study on feedback interventions.	Electricity savings range from 1.1% to over 20%. Usual savings are between 5 and 12%.	USA, Japan, Europe	(Fischer, 2008)
	Internet-based tool combined with a loyalty program	Energy efficiency levels improved by 10%.	France	(Guerassimoff and Thomas)
	Internet-based tool combined with tailored information, goal setting, and tailored feedback.	Up to 5.1% energy savings.	The Netherlands	(Abrahamse <i>et al.</i> , 2007)
	On-line residential energy consumption information system.	Up to 9% reduction in electricity consumption.	Japan	(Ueno <i>et al.</i> , 2006)
Other strategies	Replacement of appliances by most efficient ones and reducing the stand-by consumption. Sample: 1,300 households in 12 countries.	Up to 50% of electricity savings.	Europe	(de Almeida <i>et al.</i> , 2011)
	Energy-saving education strategy in 124 households.	More than 10% electricity use.	China	(Ouyang and Hokao, 2009)
	Use of available technologies and non-business travel actions combined.	123 Mton carbon/year within 10 years representing 20% of residential buildings direct emissions or 7.4% of USA emissions.	USA	(Dietz <i>et al.</i> , 2009)

In the modelling arena, research has also been using data mining techniques to estimate the behavioural savings potential in the residential sector. For example, an energy saving potential due to behaviours was estimated to reach almost 2 GJ *per capita* per year in Japan (Yu *et al.*, 2011; Yu *et al.*, 2013). However, this approach is limited by the demanding conditions of data monitoring.

Building Energy Performance Simulation (BEPS) tools have been increasingly utilised to estimate the potential savings associated with occupants' behaviour in the residential sector. This line of research has been focused on specific energy services mostly related with thermal comfort, such as heating, ventilation and lighting (Table 6). The most commonly explored behavioural dimensions include occupancy, set points, schedule and heated area, ventilation and lighting practices, and use of blinds. Overall, significant potential savings ranging up to 88% have been estimated through the use of

dynamic modelling strategies, illustrating the potential key role occupants' behaviour may play in contributing to reduce residential energy consumption. However, research has been limited by using BEPS tools to only explore energy services mostly related with thermal comfort, and no other energy services utilised within the residential environment (Nguyen and Aiello, 2013). BEPS tools have also been combined with neural networks to assess the potential impact of peer influence on energy consumption, estimating potential savings of 31% (Xu et al., 2012).

Table 6 – Potential behavioural savings in the residential sector, estimated through building energy performance simulation tools

PUBLICATIONS	(Ben and Steemers, 2014)	(Bonte et al., 2014)	(Xu et al., 2013)	(Al-Mumin et al., 2003)	(de Meester et al., 2013)	(Martinaitis et al., 2015)
BEHAVIOURAL DIMENSIONS						
Occupancy schedules	X				X	X
Set point temperatures	X	X	X	X	X	
Heating schedule	X					
Heated area					X	
Ventilation practices	X	X	X			
Lighting practices		X		X		
Use of blinds		X				
RANGE OF SAVINGS	Up to 50%	Up to 88%	Up to 18%	Up to 39%	Up to 40%	Up to 21%
MODELLING SOFTWARE	Env.Solutions	TRNSYS17	DOE2	ENERWIN	TAS	EnergyPlus / DesignBuilder

Regardless the encouraging potential savings results estimated by modelling techniques, effective savings in the real-world are not only influenced by the effectiveness of behavioural change interventions, but also by potential **rebound effects** which may cancel energy efficiency improvements. At the household level, three different rebound effects due to energy efficiency improvements are often distinguished (Nässén and Holmberg, 2009): (1) reduction of the marginal cost of energy services which may result in energy consumption increase; (2) savings can be used by the household for increasing the consumption of goods and services; and a macro effect (3) reduction in energy demand may lower fuel prices which in turn may induce households to increase their energy consumption. Total rebound effects have been estimated around 5-13% for electricity efficiency improvements (Ghosh and Blackhurst, 2014), 6% for lighting improvements (Schleich et al., 2014), 15-25% for space cooling and heating improvements (Thomas and Azevedo, 2013), and 9% and 14% for behavioural changes using electric appliances and heating, respectively (Nässén and Holmberg, 2009). Although the rebound effects for the overall residential sector in the US was

estimated in the range of 56-80% (Orea et al., 2015), in the EU this value was estimated to be much lower (18.3%) (Galvin, 2014).

In summary, occupants' energy behaviours may significantly impact residential energy consumption therefore playing an important role in residential energy efficiency. Although effective savings are ultimately influenced by real-world constraints and limitations such as the rebound effects, integrative modelling approaches of energy behaviours are important tools to provide information to support problem solving in real-world energy contexts (Lopes *et al.*, 2015).

1.5.4 THE ROLE OF BEHAVIOURS IN SMART(ER) GRIDS

In simple terms, smart(er) grids are electricity networks that can automatically monitor energy flows and adjust to changes in energy supply and demand accordingly through advanced Information and Communication Technologies (ICT) (EC, 2011).

Most research about smart grids is mainly focused on the technological components but a growing number of studies have explored them from a socio-technical point of view (Table 7). The role of energy behaviours in the context of smart(er) grids is gaining increasing recognition by both policy makers and researchers (Torriti *et al.*, 2010). Literature in this area is diverse and includes social, behavioural, and socio-technical perspectives, focusing on impacts to end-users, critical factors of innovation adoption, and behavioural adaptations.

Table 7 – Smart grids literature exploring a behavioural perspective

SMART GRID COMPONENTS	EXAMPLES OF PUBLICATIONS
The system as a whole	(Chassin, 2010; Honebein, 2010; Clastres, 2011; Lineweber, 2011; Mah <i>et al.</i> , 2012; Wolsink, 2012; Gangale <i>et al.</i> , 2013; Geelen <i>et al.</i> , 2013; Verbong <i>et al.</i> , 2013; Leijten <i>et al.</i> , 2014; Muench <i>et al.</i> , 2014)
Advanced metering infrastructure, enabling technologies and feedback	(Darby, 2010; Honebein, 2010; Martiskainen and Coburn, 2010; Depuru <i>et al.</i> , 2011; Bonino <i>et al.</i> , 2012; Krishnamurti <i>et al.</i> , 2012; McKenna <i>et al.</i> , 2012; Paetz <i>et al.</i> , 2012; Vassileva <i>et al.</i> , 2012; Balta-Ozkan <i>et al.</i> , 2013; Gerpott and Paukert, 2013; Hargreaves <i>et al.</i> , 2013; Ivanov <i>et al.</i> , 2013; Karjalainen, 2013; Pelenur and Cruickshank, 2013; Schleich <i>et al.</i> , 2013; Vine <i>et al.</i> , 2013; Guerreiro <i>et al.</i> , 2015)
Demand response	(Alexander, 2010; Faruqi and Sergici, 2010; Greening, 2010; Jackson, 2010; Allcott, 2011; Bartusch <i>et al.</i> , 2011; Gyamfi and Krumdieck, 2011; Kim and Shcherbakova, 2011; Olmos <i>et al.</i> , 2011; Rowlands and Furst, 2011; Darby and McKenna, 2012; Strengers, 2012; Thorsnes <i>et al.</i> , 2012; Torriti, 2012; Dütschke and Paetz, 2013; Faruqi <i>et al.</i> , 2013; He <i>et al.</i> , 2013; Goulden <i>et al.</i> , 2014)
Decentralised small-scale renewable energy sources	(Keirstead, 2007; Scarpa and Willis, 2010; Bergman and Eyre, 2011; Sardanou and Genoudi, 2013; Yun and Lee, 2015)

In general, residential end-users accept “**smarter**” technologies and support related investments, but they are also uncertain about their social and individual benefits (Lineweber, 2011; Mah *et al.*, 2012; Dütschke and Paetz, 2013). Therefore, improving communication to residential end-users on the benefits of “smarter” technologies is a key aspect for their deployment (Darby, 2010; Lineweber, 2011). Recent studies also found smart home technologies are adopted or rejected depending not only on their price, savings, and payback, but also on their convenience, ecological footprint, transparency and data privacy, the sense of control they provide, and other design attributes (Paetz *et al.*, 2012; Balta-Ozkan *et al.*, 2013).

At the core of smart(er) grids, **smart meters** have an essential role to end-users. The literature shows that end-users generally support smart meters deployment, but also that they often overestimate the benefits and abilities of this technology. For example, they may confuse smart meters with in-house displays or other enabling equipment, thus expecting meters to deliver immediate savings and provide appliance-level feedback about electricity use (which would only be possible when complemented with in-house displays) (Krishnamurti *et al.*, 2012). In fact, in-house displays are important tools to re-materialise energy consumption, contributing to increased energy awareness, although not being sufficient to create enduring efficient energy behaviours (Pelenur and Cruickshank, 2013). Furthermore, end-users perceive smart meters as potentially compromising their privacy and reducing their level of control over electricity usage (Krishnamurti *et al.*, 2012). In effect, data privacy and security issues associated with the exposure of end-users’ information, habits and behaviours extracted from electricity monitoring data are the most cited key challenges in smart metering deployment (McDaniel and McLaughlin, 2009; Martiskainen and Coburn, 2010; Clastres, 2011; Olmos *et al.*, 2011; Darby and McKenna, 2012; Giordano and Fulli, 2012; Krishnamurti *et al.*, 2012; Verbong *et al.*, 2013). Positive willingness-to-pay for smart meters was found to be associated with trust in the protection of personal smart metering data, intention to change energy behaviours, and, less importantly, potential energy savings and environmental awareness (Gerpott and Paukert, 2013).

Factors influencing end-users’ enrolment in **demand response programmes** and dynamic pricing schemes cited in the literature include: end-user’s level of electricity literacy (e.g., consumption and electricity market) which may be impaired by the “invisibility” of electricity; the complexity of demand response programmes, dynamic tariffs and contracts; the upfront cost of technologies when compared to savings and financial incentives; the effort required to seek dynamic pricing information and reprogram electric appliances accordingly; end-users’ risk aversion; savings expectations and perception of equitable distribution of benefits between the utilities and end-users; and the inertia

associated with behavioural change, in particular, habits (Alexander, 2010; Chassin, 2010; Faruqui *et al.*, 2010a; Gyamfi and Krumdieck, 2011; Kim and Shcherbakova, 2011; Darby and McKenna, 2012; Paetz *et al.*, 2012; Dütschke and Paetz, 2013; He *et al.*, 2013). End-users do respond to dynamic pricing and change how they use electricity, but the magnitude of the response varies depending on several factors, such as their perception of demand response programmes, willingness to enrol, incentives, dynamic pricing structure, presence of enabling technologies and feedback systems, and the social context (Faruqui *et al.*, 2010a; Faruqui and Sergici, 2010; Allcott, 2011; Bartusch *et al.*, 2011; Darby and McKenna, 2012; Thorsnes *et al.*, 2012; Dütschke and Paetz, 2013; Faruqui *et al.*, 2013; Nyborg and Røpke, 2013). In particular, the response is stronger when more sophisticated enabling technologies are utilised to support end-users' actions and decisions, specifically those integrating large volumes of information and automatically reprogramming appliances based on price information (Chassin, 2010; Faruqui *et al.*, 2010a; Clastres, 2011; Darby and McKenna, 2012; Ivanov *et al.*, 2013). A crucial factor is end-users' willingness to leave decisions to these devices. End-users often mistrust full automation and prefer controllable levels of automation (Karjalainen, 2013). Further, they accept these technologies as long as they do not interfere with their daily routines (Paetz *et al.*, 2012). Therefore, the way technologies are embedded in end-users' daily practices (domestication) is considered very important (Shove and Walker, 2010; Verbong *et al.*, 2013). Accordingly, attention should be focused on end-users, their energy behaviours, daily routines and the social context in which they live, particularly since changes in social practices may offset energy efficiency benefits brought by "smarter" technologies (Shove and Walker, 2010; Strengers, 2012; Verbong *et al.*, 2013).

One of the most important and expected **behavioural adaptations** is the shifting of end-users from a passive role as consumers of electricity to a more active role as co-providers (Geelen *et al.*, 2013). From this perspective, in addition to using electricity, end-users would be involved in the management of energy resources, such as planning or shifting their electricity usage according to their needs and the economic incentives provided, producing electricity through renewable resources, and storing or trading self-produced electricity (EC, 2012b; Giordano and Fulli, 2012; Foxon, 2013; Soares *et al.*, 2014a). In this new context, end-users are expected to adopt new roles, new responsibilities and power relationships within the electricity system, thus becoming "energy citizens as opposed to merely economic actors" (Bergman and Eyre, 2011). This change of roles requires a greater involvement of agents in the energy system and higher levels of trust and confidence between end-users and utilities (Honebein *et al.*, 2011; Gangale *et al.*, 2013). This is a major challenge to both utilities and end-users, and would require innovative solutions to trigger this

change and guide end-users through it (Honebein *et al.*, 2011; Gangale *et al.*, 2013; Geelen *et al.*, 2013). For instance, recent smart grid projects in Europe revealed that in the process of turning end-users into more active players in the energy system providing information is important, but it is also essential to activate behavioural adaptations through tailored and diversified strategies based on end-users' segmentation according to attitudes, motivations towards energy usage, and values (EU, 2013; Gangale *et al.*, 2013). Furthermore, these projects also stressed the need for changing how electricity is perceived by end-users while building a trusting relationship between end-users and energy providers. However, end-users' behaviours and perceptions during this transition will concurrently be influenced by the social construction of smart(er) grids, in particular their governance models, institutional issues, socio-cultural dynamics, rules, roles performed by energy actors and the organisation of the power system (Wolsink, 2012; Verbong *et al.*, 2013). Accordingly, further empirical social research is fundamental to the successful co-evolution of technology and behaviours, thus enabling the potential of smart grids to foster end-users' active engagement (Geelen *et al.*, 2013). It also fits within the developing area of research on 'social potential' to enable energy transitions (Janda, 2014; Moezzi and Janda, 2014).

To summarise, the (socio-)technological transition towards smart(er) grids is an on-going process requiring (and producing) adaptive behaviour by end-users. Although "smarter" technologies facilitate end-users' decisions and daily routines by providing real-time information and/or control functions, their adoption will strongly depend on the technical characteristics and functionalities of these technologies. "Smarter" technologies also enable influencing electricity demand to more efficient patterns, but this is limited by end-users' daily routines and energy behaviours. However, the deployment of smart grids goes beyond the adoption and domestication of "smarter" technologies, and requires end-users to be more involved in the energy system and in the management of energy resources. This review also unveiled key factors significantly influencing end-users' enrolment, namely communication and information issues, privacy and control concerns, and mainly trust and confidence in utilities. Capturing end-users' perceptions and preferences on "smarter" technologies and the management of energy resources is therefore central to unfolding the potential of smart grids.

I.6 THESIS CONTRIBUTION

As the literature review revealed, energy behaviours are a complex topic usually addressed from different disciplinary perspectives. While the social sciences and humanities try to interpret and explain energy behaviours with a qualitative approach, engineering is mainly focused on quantifying and predicting energy consumption patterns. Regardless the unquestionable value of each perspective, their results are limited and fall short to fully address the complexity of energy behaviours. Moreover, there is a need for more effective real-world behaviour change interventions and incisive energy policies grounded on comprehensive approaches of energy behaviours.

Accordingly, this thesis adds to the state of the art by presenting an integrative modelling approach of energy behaviours in the residential sector. This work contributes to the characterisation and systematisation of end-use energy behaviours as promoters of energy efficiency, estimating the behavioural impact on energy consumption in residential buildings. It also contributes to foreseeing energy behaviours changes during the transition to smart(er) grids. This thesis aims at supporting the design of more effective behavioural change interventions and energy policies, either at a national and European scale, being particular important for energy stakeholders, such as governments, regulators, utilities, energy service companies, energy agencies and consumer associations.

The proposed approach integrates different disciplinary frameworks, namely the personal and contextual dimensions of psychology and sociology and the technical approaches of engineering, combining several modelling techniques, such as problem structuring methods, system analysis, building performance simulations, and statistical analysis. Real-world cases are studied to generate contextualised understanding. This thesis was developed in a multidisciplinary context, where researchers from engineering, the social sciences and humanities provided the support for the technological and behavioural dimensions of the studied problem.

I.7 OUTLINE OF THE THESIS

This thesis is organised in five major chapters:

Chapter 1

This chapter provides the context, motivation, state of the art, and main objectives and contributions of this work. The research is developed in the framework of energy efficiency in buildings; energy behaviours are explored as a challenging topic; the trends of energy efficiency in the Portuguese residential sector are illustrated to demonstrate the suitability of the development of this work in this context; and the state of the art is presented, which focus on recent research on energy behaviours, modelling approaches of energy behaviours, quantification of the behavioural savings potential, and the role of energy behaviours in smart(er) grids.

Chapter 2

This chapter presents the integrative modelling approach developed to establish the influence of energy behaviours on energy consumption and the results of a real-world case study. Different perspectives are explored using problem structuring methods; specific interests are made explicit to minimise the potential bias; the activation chain from usage energy behaviours to energy consumption is characterised and modelled; and contextualised understanding from a case study provides the validation for the methodology developed.

Chapter 3

This chapter provides a quantification of the behavioural impact on buildings energy consumption. A comprehensive approach is developed using building energy performance simulation tools; results are presented, including energy consumption of the reference scenario, the potential of behavioural savings is assessed, the influence of different variables is explored, and an economic assessment is performed; and building energy performance simulations are discussed as tools to explore the behavioural dimension.

Chapter 4

This chapter provides an assessment of end-users' behavioural adaptations to the smart(er) grid. Current behavioural adaptations are explored, as well as their preferences for adopting enabling technologies in the future; factors influencing these behavioural adaptations are analysed and strategies aimed at enabling these adaptations are proposed for future research.

Chapter 5

In this chapter the innovative contributions of this work are discussed, the answers to the research questions are summarised and future research is outlined.

2 MODELLING THE INFLUENCE OF ENERGY BEHAVIOURS ON ENERGY USE ⁱⁱⁱ

2.1 INTRODUCTION

Modelling is particularly important when addressing complex issues such as energy behaviours, since it enables structuring relevant knowledge and unveiling hidden relationships thus promoting targeting the problem at hand more effectively. In this sense, modelling may be firstly used as a tool for enriching the comprehension of an issue and secondly for simulation and optimisation purposes. Often utilised in such situations, problem structuring methods support the resolution of complex problems usually involving multiple stakeholders, different perspectives and interests, and uncertainties (Rosenhead and Mingers, 2001).

In real-world problems, employing a single method is not usually the most effective approach and the combination of methods is often utilised to address the different dimensions of a problematic situation (Mingers, 2001). For example, soft systems methodology helps to unveil the different visions of the stakeholders and build a consensus on an issue (Ackermann, 2012), while cognitive mapping may be used to represent those visions in a graphical way thus facilitating communication (Eden and Ackermann, 2001; Özesmi and Özesmi, 2004) and system dynamics to understand the problem dynamics over time (Sterman, 2000). To the author knowledge, these methods have had a limited use to address energy behaviours (Elias, 2008; Motawa and Oladokun, 2015), and they were more frequently applied to tackle energy efficiency problems (Neves *et al.*, 2004; Elias, 2008; Armenia *et al.*, 2009; Neves *et al.*, 2009; Jetter and Schweinfort, 2011; Yucel and Pruyt, 2011).

In this chapter, modelling is utilised as a structuring approach of multidisciplinary knowledge to establish the qualitative and quantitative influence of usage energy behaviours on energy consumption. Different modelling techniques are combined to explore various perspectives of the impact of usage energy behaviours on energy consumption, as a basis for the development of real-world behavioural change interventions. This work is exclusively focused on the usage dimension of households' energy behaviours and combines different disciplinary frameworks in the modelling process, namely the personal and contextual dimensions of psychology and sociology and the technical approaches of engineering. Furthermore, by exploring the use of different research

ⁱⁱⁱ This chapter is partially based on [Lopes, M., Antunes, C. H., & Martins, N. (2015). Towards more effective behavioural interventions: an integrative modelling approach to residential energy consumption. *Energy Research and Social Science*, 7 (0), 84-98. doi: 10.1016/j.erss.2015.03.004]

methods and techniques (both quantitative and qualitative) of several disciplines, this work also aims to contribute to the development of integrative research methodologies and answer to the following research questions referred to by Sovacool (2014a, 2014b):

“- How can the benefits of ‘human-centred’ research methods be best coupled with quantitative forms of data collection and analysis?

- Human-centred, as well as ‘mixed’ research methods, tend to be more complex (difficult to fit in a box), expensive, and subjective than others – how can they be improved?

- How can researchers minimise bias – their own and that of their subjects – when doing research?

- Are some disciplinary methods simply incompatible with an interdisciplinary approach?” (Sovacool, 2014b, 2014a).

It further aims at contributing to facilitate knowledge and information transfer between experts from different areas to practitioners and policy makers (Fri and Savitz, 2014), thus promoting more effective behaviour change interventions and energy efficiency policies.

This chapter is divided in four sections. Section 2.2 describes the methodology developed to explore the influence of energy behaviours on energy use. Section 2.3 presents and discusses the main results obtained, and section 2.4 summarises the main conclusions.

2.2 METHODOLOGY

When addressing a complex issue, selecting the tools to use is ultimately a decision influenced by the nature of the problem, limitations of time, resources and competences, reflecting the individual researcher and team skills, experience, values and personality (Mingers, 2001).

This study has been developed from 2011 to 2015 and comprised three stages (Figure 2):

- I. Assessment of the socio-political, material and personal context;
- II. Action and generation of contextualised understanding;
- III. Transference to practice and policy making.

At each stage, methods and techniques from different methodologies were combined to develop activities and involve the different agents. It is, however, worthwhile to mention that methods were in some circumstances implemented just to the extent required by the characteristics of the actual situation to be dealt with. Specific components of problem structuring methods were carefully chosen to enrich and develop the comprehension of the problem and the appreciation stage, while complying with the respective paradigm (Schultz and Hatch, 1996; Mingers and Brocklesby, 1997). Nevertheless, the overall methodology developed conforms with the generic constitutive definition of problem structuring methods (Yearworth and White, 2014), namely by embodying a systematic way to contribute to the improvement of the problematic (and messy) situation under analysis, using a systemic approach, creatively combining elements of problem structuring methods, acknowledging different worldviews, involving interactive and iterative processes, recognising the stakeholders as insiders of the problem and the own limits of the approach.

STAGE	ACTIVITIES	METHODS & TECHNIQUES	AGENTS INVOLVED
Assessment of the political, social, material and personal context ↓	A. Identification of stakeholders, their roles and collection of visions	Literature review Workshops, interviews, meetings Problem structuring tools - soft systems methodology: expression of the problem situation using workshops and rich pictures	Multidisciplinary research team, scientific community, energy agencies, utilities, regulator, energy service companies, environmental NGOs
	B. Focusing the problem and the system	Problem structuring tools - soft systems methodology: CATWOE analysis	Multidisciplinary research team
	C. Integration of different perspectives	Conceptual modelling: cognitive mapping and system dynamics	Multidisciplinary research team
Action and generation of contextualised understanding ↓	D. Design and implementation of the field actions	Meetings, negotiations, written agreements & contracts Electricity consumption monitoring (smart metering), energy behaviours characterisation (self-reported surveys)	Multidisciplinary research team, practitioners: energy agencies, energy service company
	E. Collection of data and analysis of results	Load diagram characterisation (indices of electricity consumption) Integration of quantitative and qualitative data in a common database Statistical analysis (e.g., descriptive and multivariate analysis)	Multidisciplinary research team, practitioners: energy agencies, energy service company
Transference to practice and policy making	F. Dissemination and recommendations to practitioners and policy makers	Meetings, workshops, conferences, publications	Multidisciplinary research team, scientific community, energy agencies, utilities, regulator, energy service companies, environmental NGOs

Figure 2 – Methodology used to develop this study

A. Identification of stakeholders, their roles and collection of visions

The first step consisted in identifying the stakeholders, their roles and collecting their visions on the complex situation. Different techniques were utilised, depending on the agents, with special emphasis on problem structuring methods specially designed to explore and elicit different points of view, such as the first stage of soft systems methodology (Rosenhead and Mingers, 2001). Special attention was paid to clarify energy behaviours, their role in the energy consumption activation chain, all the factors influencing this relationship as well as strategies to promote more efficient energy behaviours and the roles of energy stakeholders. The role, interests and points of view of the energy stakeholders (e.g., the scientific community, energy service companies, utilities, energy regulator, energy agencies, non-governmental organisations, society in general) were unveiled using interviews, meetings and workshops. In particular, the perspective of the scientific community has been further enriched through an extensive literature review in peer-reviewed journals and direct

involvement of experts from different disciplines. Furthermore, the particular visions of residential users were indirectly collected using surveys. The energy stakeholders' role on energy behaviours was incorporated into a rich-picture making their interests explicit and enabling a clarification of roles, which contributes to minimise the potential research bias (section 2.3.1). Information regarding the influence of energy behaviours on energy consumption was incorporated into the conceptual modelling stage.

B. Focusing the problem and the system

After collecting the different perspectives, a "CATWOE" analysis was used to elicit and clarify the underlying system of this study, the specific agents involved, their interests and roles. Following the soft systems methodology, and complementarily to the rich picture, the use of the "CATWOE" analysis (i.e., *Customers, Actors, Transformation, Weltanschauung* or world view, *Owner*, and *Environmental constraints*) helps focusing and characterising a complex problem, while clarifying the different interests and views of the stakeholders involved (Ackermann, 2012). Particularly in this study in which different agents were involved, the use of this technique enabled to focus the underlying system and made the roles of the different agents involved explicit, thus contributing to minimising potential bias associated (including the researchers'). This analysis is explored in section 2.3.2.

C. Integration of different perspectives

The last step of the assessment stage consisted in the integration of the multidisciplinary knowledge. Conceptual modelling was utilised to explore the influence of energy behaviours on energy consumption and to integrate the contribution of variables pertaining to different disciplinary domains. Both static (cognitive maps) and dynamic representations (causal diagrams) were used. Cognitive maps were structured around the chain of actions leading to energy consumption. Different levels of detail were developed: from a more aggregated version that provided an overall perception of the relationships to a more disaggregated and detailed version where quantifiable variables were made explicit. Although cognitive mapping usually reflects actions required to change the situation in a positive way (Eden and Ackermann, 2001), in this work they were used to increase the comprehension on the topic and therefore the energy consumption activation chain was the main focus. Causal loop diagrams from system dynamics (Sterman, 2000) were used to explore the

dynamic dimension of this system. For simplification purposes, only a small part of the dynamic dimension is presented. The modelling process was implemented through an iterative improvement process until the conceptual model was accepted as consensual within the multidisciplinary research team. The proposed conceptual model is explored in section 2.3.3.

D. Design and implementation of the field actions

The first stage of generating contextualised understanding began with the design of *in-situ* activities. The agents involved in this study (two energy agencies, an energy service company, and residential consumers) were engaged through formal and informal strategies, namely meetings and written agreements to establish interests, tasks and data confidentiality issues. This study was designed to potentiate synergies with other on-going initiatives to use resources more efficiently while ensuring proper data gathering conditions (e.g., electricity monitoring equipment, access to households), which allowed overcoming some of the most common limitations of energy behaviour research. The objectives of the energy agencies, the energy service company, and the author of this work and the associated research team were thoroughly made compatible (e.g., concerning the timeframe and milestones) to minimise the impacts of this study on the residential sample, which involved a total of 450 households living in Portugal.

Household's energy consumption was monitored at the utility meter level using a smart meter (<http://www.cloogy.com/en/>) with a time step of 15 minutes. From the tools commonly used in the social sciences (Crosbie, 2006), web-based surveys were chosen due to their resilience characteristics and since they minimise the households' disturbance (one example is available at <http://www.ces.uc.pt/inqueritos/sintra>). One 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, behavioural personal determinants (Table 8 and Table 28 in appendix). Variables were selected taking into consideration their recognised importance in the literature and the challenges when collecting field data.

Table 8 – Structure and design of the survey developed

COMPONENTS	DESCRIPTION
Socio-demographic variables	Respondent (e.g., gender, age, marital status, education level, professional activity, employment status). Household composition, dwelling ownership.
Activities	Time spent at home, schedule of energy intensive activities (e.g., cleaning and washing).
Building characteristics	Type, size, age, thermal comfort perception.
Physical environment	Climate characterised through location (e.g., postal code).
Energy resources and services	Electricity supply conditions, ownership of technologies based on renewable energy sources, ownership of several home appliances including their efficiency class.
Energy behaviours	Frequency of performing behaviours such as turning appliances off to avoid waste consumption, eliminating stand-by consumption, use of passive strategies to control thermal comfort or lighting, efficient use of appliances, adjusting settings of appliances, using dual time tariffs, controlling and monitoring energy consumption, purchasing efficient appliances.
Personal determinants	Beliefs on energy savings (responsibility, consequences to the environment and the economy) and energy literacy (advantages of energy efficiency), adapted from (Black <i>et al.</i> , 1985). Willingness to monitor and save energy.
Influence of economic crisis on energy behaviours	Identification of energy behaviours which have changed: use of appliances, reading the electricity bill and the meter, change of the electricity contract (power, tariff), shifting appliances to cheaper periods, buying efficient equipment, home improvements, use of renewable energy sources. Identification of motives for not changing (limitations to change such as need and effort).

E. Collection of data and analysis of results

The final step in generating contextualised understanding consisted in analysing the collected data. Although the initial dimension of the sample was 450 households, only 128 were selected for this phase since they complied with data quality criteria (e.g., minimum of nine months of electricity monitoring and simultaneously answering the full survey).

For each household, and based on electricity monitoring data, specific indices were determined allowing the characterisation of electricity consumption (e.g., daily average consumption, minimum and maximum power, ratios between average and maximum and minimum power, seasonal consumption). These electricity consumption indices were integrated with the answers of the survey in a database and analysed using statistical analysis (IBM® SPSS® Statistics v.22 software). Firstly, a frequency analysis was performed, followed by association measures between variables (e.g., correlations). Variables from the survey were reduced and synthesised through factor analysis and combined to provide the model dimensions. Finally, multiple regression analyses were performed to test the adequacy of the model and assess the contribution of usage energy behaviours to energy consumption. Section 2.3.4 presents a summary of these analyses.

F. Dissemination and recommendations to practitioners and policy makers

Dissemination ensures knowledge and experience exchange with practitioners and policy makers. Different methods were used according to the profile of each stakeholder, such as meetings, workshops, conferences and publications. Although represented as the last stage of the process, dissemination has occurred continuously.

2.3 RESULTS AND DISCUSSION

This section presents and discusses the main results of this study namely concerning the perspective of different stakeholders, the underlying system definition, the conceptual model, and contextualised understanding from a case study.

2.3.1 THE INFLUENCE OF ENERGY BEHAVIOURS ON ENERGY EFFICIENCY AS PERCEIVED BY ENERGY STAKEHOLDERS

As it is often the case in real-world situations, there are several agents interested and involved in the topic of the influence of energy behaviours on energy efficiency, such as governments, regulators, governmental and energy agencies, utilities, energy service companies (ESCOs), manufacturers, retailers, consumer associations, environmental non-governmental agencies, the scientific community, and the society as a whole.

Figure 3 depicts a rich-picture with the energy stakeholders' role in energy behaviours, which illustrates the context in which this study was developed. A rich picture provides a visual representation of most important relationships between the agents in a problematic situation under analysis (Checkland, 2001). Following the European Union policies, the Portuguese government defines energy efficiency policies, regulations and efficiency goals. Both governmental agencies and the energy system regulator implement these policies. Energy utilities have recently been diversifying their offerings of energy services. ESCOs are also focused on selling energy services using technological solutions incorporating smart devices. Non-governmental associations represent consumers' interests and benefit from a trusted relation with them, while manufacturers and retailers develop their activities following regulations in general with no particular concern on energy efficiency. The scientific community carries out research and transfers knowledge on energy efficiency and behaviours, whose results are disseminated within the community and policy makers and practitioners in general.

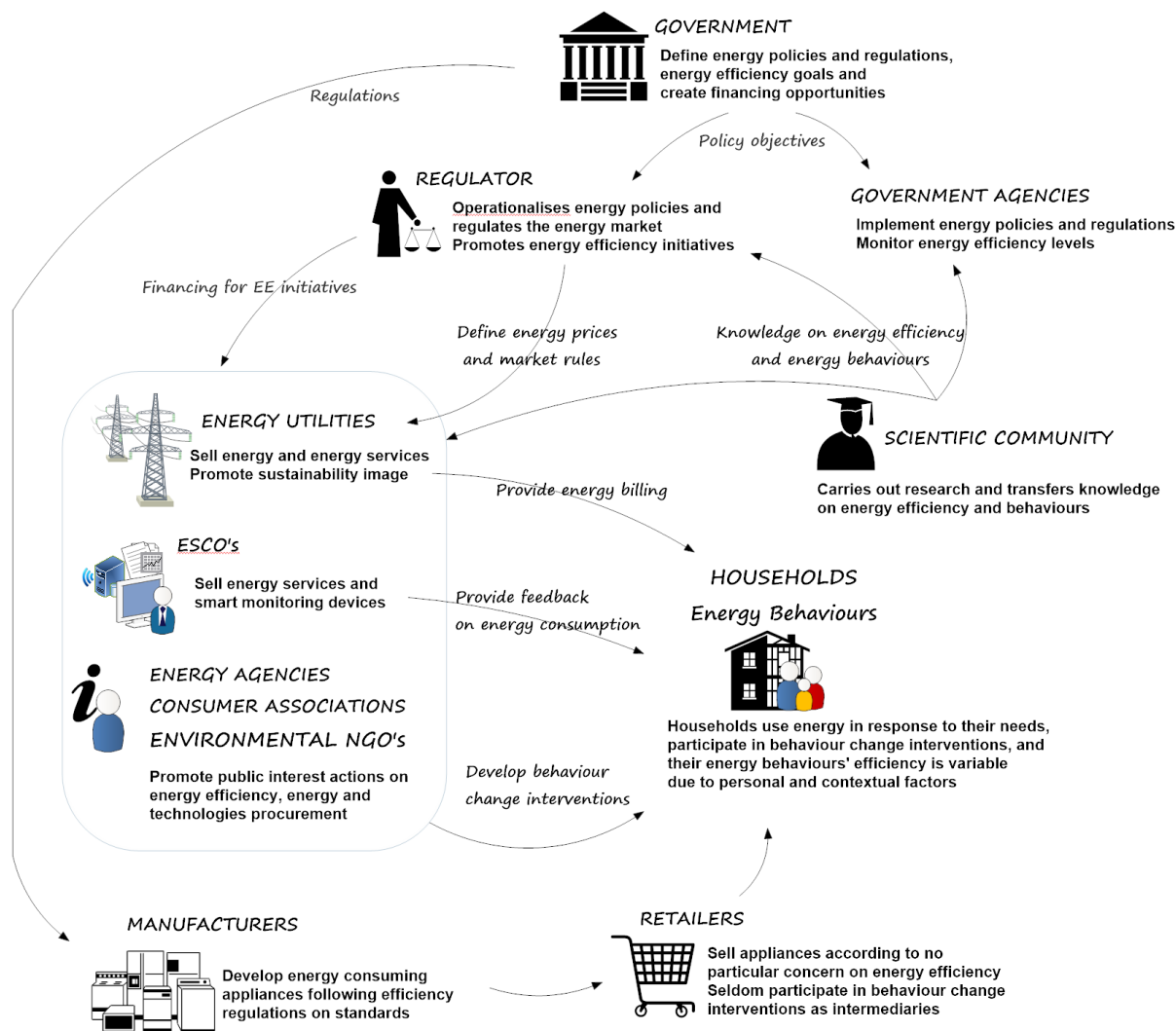


Figure 3 – A rich-picture displaying the energy stakeholders’ role in energy behaviours

In Portugal, behaviour change interventions have traditionally been promoted by energy agencies through the support of the Intelligent Energy Europe programme (<http://ec.europa.eu/energy/intelligent/>), but recent energy efficiency policies created financing opportunities for behavioural change interventions. Hence, since 2007 the national energy regulator is promoting the most important funding initiative in energy efficiency (Plan for the Promotion of End-Use Energy Efficiency, PPEC) (ERSE, 2011). It aims at promoting more efficient behaviours when using electricity and the adoption of more efficient equipment. Energy stakeholders have been using this mechanism to promote behaviour change interventions despite, in some cases, their apparent conflicting interests (e.g., energy utilities, whose main aim is to maximise profits through selling energy) or overlapping of roles (e.g., the national governmental energy agency, responsible for the implementation of policies, also benefits from this financing mechanism). This created an

environment of competition, but also of cooperation among energy stakeholders leading to the development of innovative behaviour change initiatives. In addition, these real-world interventions provide an excellent opportunity and context for cooperation and knowledge dissemination among the scientific community, practitioners and policy makers, in which this thesis is positioned.

All the stakeholders involved in the workshops and meetings held during this work recognised the influence of energy behaviours on energy end-use and their importance on energy efficiency. Their interest and visions on energy behaviours were not only influenced by their educational backgrounds and professional affiliations, as discussed by (Virkki-Hatakka *et al.*, 2013), but also by the Portuguese context. Energy efficiency was identified as a complex topic to end-users and energy literacy was emphasised as a key factor to the improvement of end-use energy efficiency. Re-materialising energy consumption, associating it with daily actions through the use of smart technologies, and simplifying the language used in communication and feedback tools (e.g. awareness campaigns, billing, in-house displays) were consensual strategies pointed out by energy agencies, energy service companies and utilities. However, some of the stakeholders (e.g., utilities, regulator, and governmental agencies) considered energy efficiency as a minor concern to households due to the small weight energy bills represented in the household monthly expenses, and consequently potential savings associated with energy behaviours are small when compared to infrastructural or equipment improvement costs. Further factors hampering more efficient energy behaviours included the disinformation originated by the multiplicity of stakeholders interacting with the households and communicating on energy efficiency (Figure 3). Better coordination between stakeholders and, in some situations, information delivered by reliable and trusted interveners was indicated as crucial to improve end-use energy efficiency. Moreover, the specific context of changes in the energy market, in which this thesis was conducted, was pointed out to be substantially influencing energy behaviours. Although the liberalised retail energy market was open to the residential sector in 2006, a decision of forcing residential consumers to entering the liberalised market was made in July 2012. Since this date residential consumers have been encouraged to change their energy suppliers through numerous campaigns, not only improving end-users' energy literacy but also creating a social awareness on the topic (Lopes *et al.*, 2014). Other behaviour change strategies mentioned by the stakeholders comprised structural (e.g., regulation, prices), antecedent (e.g., proximity, gamification) and consequence strategies (e.g., peer comparison, financial rewards). One interesting perspective unveiled during this process was the opportunity of transforming traditional energy services into more sophisticated services to the households, in some way similarly to the evolution of communication services. Behavioural change interventions were also indicated by the stakeholders

to be sometimes limited in their scope and impacts due to their small scale. Nevertheless, and regardless this limitation, the stakeholders were consensual to recognise behaviour change interventions as crucial steps towards more efficient energy behaviours.

In summary, energy stakeholders recognised the role and the challenges associated with energy behaviours and energy efficiency, being involved in the process of fostering higher levels of end-use energy efficiency. Considering their different roles, all energy stakeholders are relevant to the development of more effective behaviour change interventions. Yet, better coordination among them and the design of integrative approaches will contribute to maximise the full potential of behavioural interventions.

2.3.2 THE SYSTEM: THE PLAYERS, THEIR ROLES AND THE PRACTICAL CHALLENGES

In the process of developing this integrative approach on energy behaviours, a “CATWOE” analysis was used to elicit the underlying system, the specific agents involved, their interests and roles, in order to minimise the potential bias.

The underlying **system** of this study is defined as *a system to combine disciplinary perspectives on energy behaviours to foster more effective interventions and energy efficiency policies*. According to the “CATWOE” analysis, the relevant components of this system are:

- **Customers** – As the target of interventions, residential users are the main customers of this study. Indirectly, society as a whole also benefits from promoting end-use energy efficiency thus making it an indirect customer. Agents promoting these interventions, which have been ineffective in achieving enduring behaviour changes (e.g., utilities, energy service companies, manufacturers, energy agencies, consumer associations, environmental non-governmental organisations), are intermediaries in this process and for this reason they are also considered customers. In this study, two regional energy agencies and an energy service company are directly involved as clients being promoters of behaviour change interventions. These agents provided access to households and to energy monitoring data.
- **Actors** - The author of this study. Her motivation in developing this work arose from consulting experience in energy efficiency, research on end-use energy efficiency (http://www.uc.pt/en/org/inescc/Projects/energy_box), and the R&D work leading to this thesis in Sustainable Energy Systems developed in a multidisciplinary environment (<http://www.uc.pt/en/efs/about/phd>). Also cooperating in this study, a research team

composed of researchers from the social sciences and humanities (e.g., psychology and sociology) and engineering (e.g., energy systems and decision aid) provided support to the planning, modelling, implementation and analysis of results.

- **Transformation process** - Disciplinary views of energy behaviours are limited in addressing the multidimensionality influence of energy behaviours on energy consumption. There is a need for a more holistic vision, built upon disciplinary approaches, which will provide an integrative perspective of the effects of energy behaviours on energy consumption. Accordingly, the transformation may be formulated as follows: *[input]* single disciplinary behavioural intervention \xrightarrow{T} *[output]* integrative behavioural intervention.
- **Weltanschauung** (*world view*) – A comprehensive vision of the influence of energy behaviours on energy consumption, built upon disciplinary approaches, maximises the effectiveness of energy behaviour change interventions and promotes further end-use energy efficiency.
- **Owner** – From a perspective of energy efficiency initiatives, financing and promoters such as political agencies and regulators that may not adequately acknowledge comprehensive approaches, or the promoters of energy behaviour change programmes not using integrative approaches as a common practice, are both considered owners of this intervention. Furthermore, since this study is also developed in a research context, and from this specific point of view, the scientific community also plays a role as owner of this intervention since it is able to restrict either the publication of this work or the development of the PhD project.
- **Environmental constraints** - Limited resources to support the development of this approach (e.g., financing, time, cooperation of the stakeholders).

Although real-world behaviour change interventions involving energy stakeholders are considered a valued asset when researching the impact of energy behaviours on energy efficiency, in this case it raised intrinsic challenges, such as: reconciling all players' specific and different interests, roles and visions; engaging households in behaviour change actions in particular in a context without a consolidated tradition in this field (such as the Portuguese reality); and dealing with the players' reduced engagement as the restrictive economic context evolved. Tackling these challenges involved designing this work to be flexible, constantly adapting, and using multidisciplinary and adaptive tools and skills (e.g., negotiation, communication, integration of information).

2.3.3 CONCEPTUAL MODEL: FROM USAGE ENERGY BEHAVIOURS TO ENERGY CONSUMPTION

As a result of daily activities and processes, households feel needs whose satisfaction leads to the activation of **usage energy behaviours** in order to provide for energy services (heating, cooling, lighting or electrical appliances powering) (Figure 4). Energy resources (e.g., electricity, gas, fuel) enable energy services. Several factors influence these relations, such as environmental (e.g., physical and socio-economic environment), structural (e.g., building and equipment characteristics), contextual (e.g., household socio-demographic characteristics, activities) and personal factors (e.g., values, attitudes) (Figure 5).

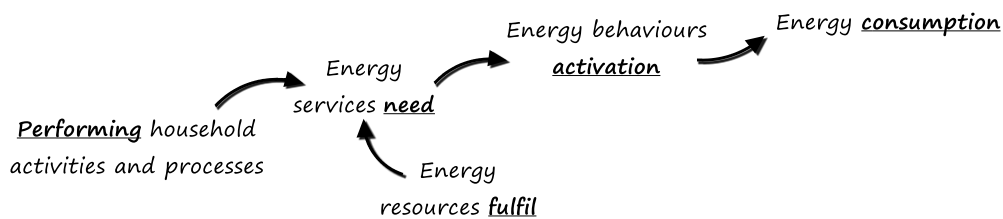


Figure 4 – Energy consumption activation chain

People’s daily activities are very diverse and comprise, in general, gainful work and study, domestic work, meals, personal care, travel, free time and sleep (EC, 2004). Most of these activities are performed at home and involve several processes that activate energy services (some of them energy intensive), such as food preparation, dish washing, cleaning, laundry, watching television, or even reading. These activities and processes are influenced by the socio-economic environment (e.g., financial constraints) and the household socio-demographic characteristics (e.g., composition, stage of life, level of education, income, professional activity, dwelling ownership) and practices (e.g., time spent at home, lifestyle) (Cayla *et al.*, 2011; Hori *et al.*, 2013).

The need for energy services is also influenced by the physical environment and the building characteristics. Climate directly affects the level of energy services required to achieve a comfortable indoor temperature and solar exposure influences both the thermal and the lighting comfort (OECD/IEA and AFD, 2008). In fact, a considerable amount of energy is consumed for space heating in residential buildings, which reached in 2008 in the EU-15 a share of 67% of household energy use (EEA, 2008). Two major building characteristics influence the magnitude by which energy services are activated, thus leading to more or less energy consumption: the dwelling size and its energy performance. The bigger the dwelling the larger the area to be cooled or heated, more lighting power is required and more appliances need to be powered, thus leading to a greater need of energy

services. The building energy performance directly influences the indoor comfort perception thus determining the level of energy services required. The most important parameters affecting the building energy performance are the thermo-physical properties of the building envelope, which is directly related to the level of insulation and the passive architectural features such as orientation, the building form and optical characteristics that influence natural lighting (OECD/IEA and AFD, 2008).

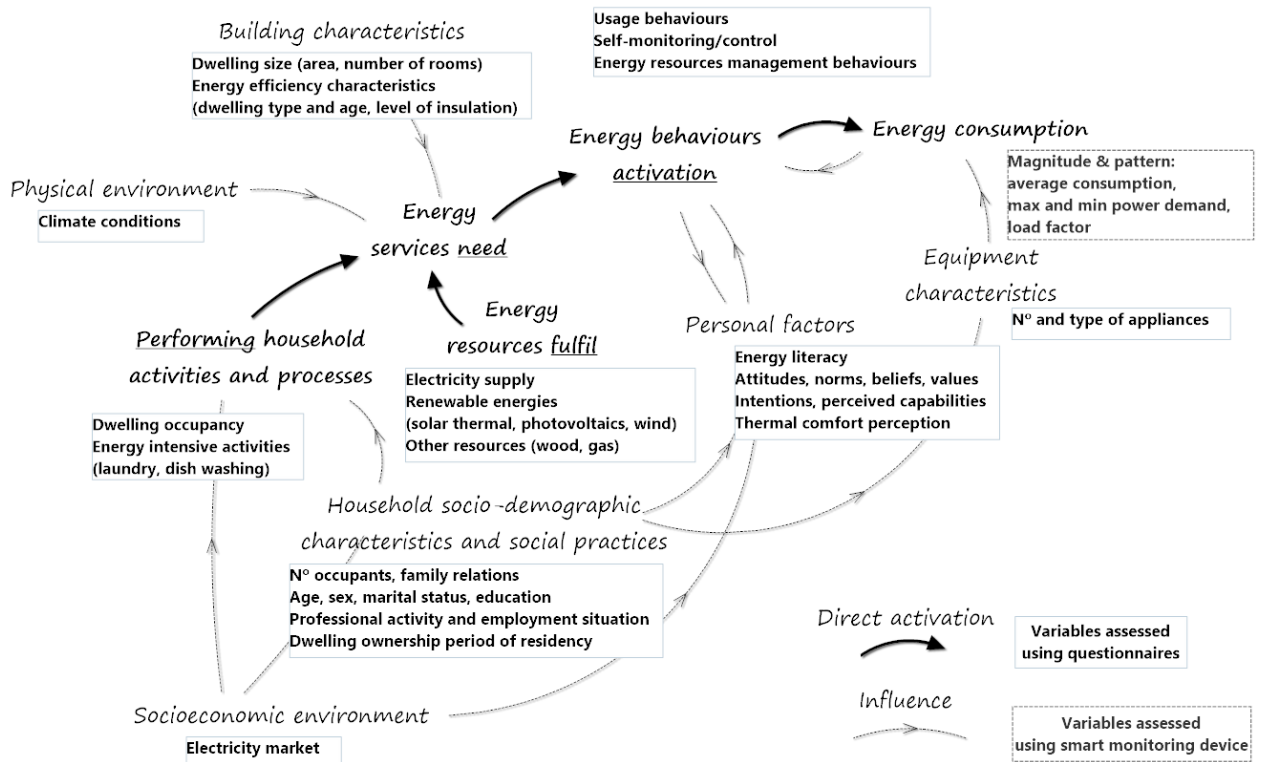


Figure 5 – Disaggregated factors influencing the energy consumption activation chain with the identification of the variables assessed

While the activation of energy services may be set in motion due to the need itself, processes shaping the efficiency of energy behaviours or the magnitude of that activation may be influenced by personal factors (e.g., habits, intentions, attitudes, norms, beliefs, concerns, self-regulation mechanisms, perceived capabilities) (Fishbein and Ajzen, 1975; Ajzen, 1991; Bandura, 1991; Schwartz, 1994; Stern, 2000; Bagozzi *et al.*, 2002; Thøgersen and Ölander, 2002). These personal factors may also influence, and be influenced by, the household’s socio-demographic characteristics, processes and activities. For example, an increased concern on energy efficiency may lead to a change of habits and activities and to a replacement of existing processes by others which are less energy intensive, or to the reduction of their frequency or magnitude.

Existing energy consuming equipment influences the level of energy use in two opposite ways. The number of energy consuming equipment increases the magnitude of the required energy services and consequently the level of energy use, but the increase of their energy efficiency level reduces the amount of energy required to perform energy services. Recent statistics have shown that regardless of the improvements on energy efficiency standards of appliances, energy demand has substantially increased in the residential sector due to the rapid growth of ownership and quantity of electricity consuming devices (OECD/IEA, 2008b), thus demonstrating the predominance of the effect of the increase of the number of appliances over their energy efficiency. Moreover, the rebound effect associated with a more efficient use of energy may lead to an increase in energy consumption (Nässén and Holmberg, 2009; Hens *et al.*, 2010; Winther and Wilhite, 2015).

At a broader level, the socio-economic environment also influences the household's socio-demographic characteristics and their capability of performing household activities and processes. It may also influence the system of personal factors. For example, a favourable economic context increases the household financial ability and therefore its capacity to diversify and intensify the household's needs for energy services thus increasing their energy demand (the reverse of this effect is nowadays being felt in some European countries due to the economic constraints). In turn, the increase of energy prices creates a higher expenditure with energy, which although reducing available resources also promotes further energy awareness among households thus favouring more efficient energy behaviours.

A further component of this model comprises its dynamic dimension. Cognitive mapping represents systems at one point in time, neglecting the time lag associated with each effect (Park and Kim, 1995; Özesmi and Özesmi, 2004). Hence, it becomes a limited modelling tool in situations whose dynamics over time is relevant, such as the influence of energy behaviours on energy efficiency. A *system dynamics* approach was used to explore this dimension. As an example, Figure 6 illustrates a "zoom" made into the influence of the socio-economic environment on energy behaviours. In general, the improvement of energy awareness and literacy levels created by bill increases, behaviour change programmes or energy efficiency policies reinforce some of the personal determinants promoting end-use energy efficiency. Social pressure may also activate personal determinants (e.g., social norms) towards more efficient energy behaviours. One important dimension included in this diagram is the *rebound effect*. The activation of more efficient energy behaviours contributes to reduce energy use, leading to a reduction of energy expenditure and to an increase of the household's financial ability. However, this often originates an increase in the level/number of energy consuming

The residential sample (N=128) is geographically located in Portuguese urban areas. Families live mostly in owned apartments (80.5%) of medium size (70.3% possess two or three bedrooms) (Table 9). In average, each family is constituted by 1.7 adults ($\sigma=0.8$) and 0.9 children ($\sigma=1.1$). Average electricity consumption is about 10.8 kWh/day ($\sigma=5.5$), similar to the national average consumption of 10.1 kWh (INE and DGEG, 2011). The ownership of appliances is generally higher than national rates (laundry machine 83.9%, dishwasher 91.7%, tumble dryer 32.9%, air conditioning system 15.6%, and electric water heater 7.8%)^{iv}. Respondents of the survey are mainly men (68.5%) with an average age of 37.5 years old ($\sigma=8.7$). Most respondents are highly educated (85.4% has a higher education degree, which contrasts with the national average value of 19%), is currently employed (85.5%) and is married (69.7%).

Table 9 – Characteristics of the residential sample (N=128)

DIMENSIONS	VARIABLES	LEVEL	
Building	Typology	Apartment	88.3 %
		Villa	11.7 %
	Size	Less than 2 bedrooms	7.1 %
		2 or 3 bedrooms	70.3 %
		More than 3 bedrooms	22.6 %
Energy use	Average electricity consumption	10.8 kWh/day	
Electrical equipment	Ownership	Laundry machine	83.9 %
		Dishwasher	91.7 %
		Tumble dryer	32.9 %
		Air conditioning system	15.6 %
		Electric water heater	7.8 %
Household	Number	Adults	1.7, $\sigma=0.8$
		Children	0.9, $\sigma=1.1$
Respondents	Gender	Female	31.5 %
		Male	68.5 %
	Age	< 36	49.2 %
		36 - 45	35.5 %
		46 - 55	8.9 %
	Education level	> 55	6.5 %
		No university degree	14.6 %
	Marital status	University degree	85.4 %
		Single	23.0 %
	Professional activity	Married	69.7 %
Divorced or widower		7.3 %	
Working		85.5 %	
	Non-working (student, retired, unemployed)	14.5 %	

^{iv} National statistics indicate the following ownership rates: laundry machine 91%, dishwasher 41%, tumble dryer 19%, air conditioning system 7%, electric water heater 3% (INE and DGEG, 2011).

The model dimensions were characterised using a list of 15 variables reduced from the original set. While factor analysis was used to reduce information on energy behaviours and behaviour determinants, the remaining variables were transformed and combined to characterise the intended dimensions (Figure 7). Factor analysis of self-reported energy behaviours enabled identifying three main factors in the studied sample (Table 10):

- (1) **daily behaviours** (e.g., efficient use of appliances, avoiding waste and stand-by consumption, and passive strategies to control thermal comfort and lighting);
- (2) **specific know-how based** (adjustment of appliance settings and shifting activities to benefit from dual time-of-use tariffs and reduce costs); and
- (3) **information based** (investment in efficient appliances, auto-control and monitoring of energy use).

Factor analysis of personal determinants comprising intentions - from Unified Theory of Acceptance and Use of Technology (Venkatesh *et al.*, 2003) - and beliefs enabled reducing this information to two factors associated with the *influence of social image* and *consequences to lifestyle*. In summary, variables characterising the model dimensions comprise: energy consumption (*daily average electricity consumption*), energy services (*weatherising need, energy intensive appliances, efficient equipment and use of renewable energy sources*), household characteristics (*stage of life*), activities and processes (*time spent at home, weekly washes*), energy behaviours (*daily behaviours, based on specific know-how and information*), behaviour personal determinants (*influence of social image and consequences to lifestyle, values and energy literacy*), and the socio-economic environment (*influence of the economic crisis*).

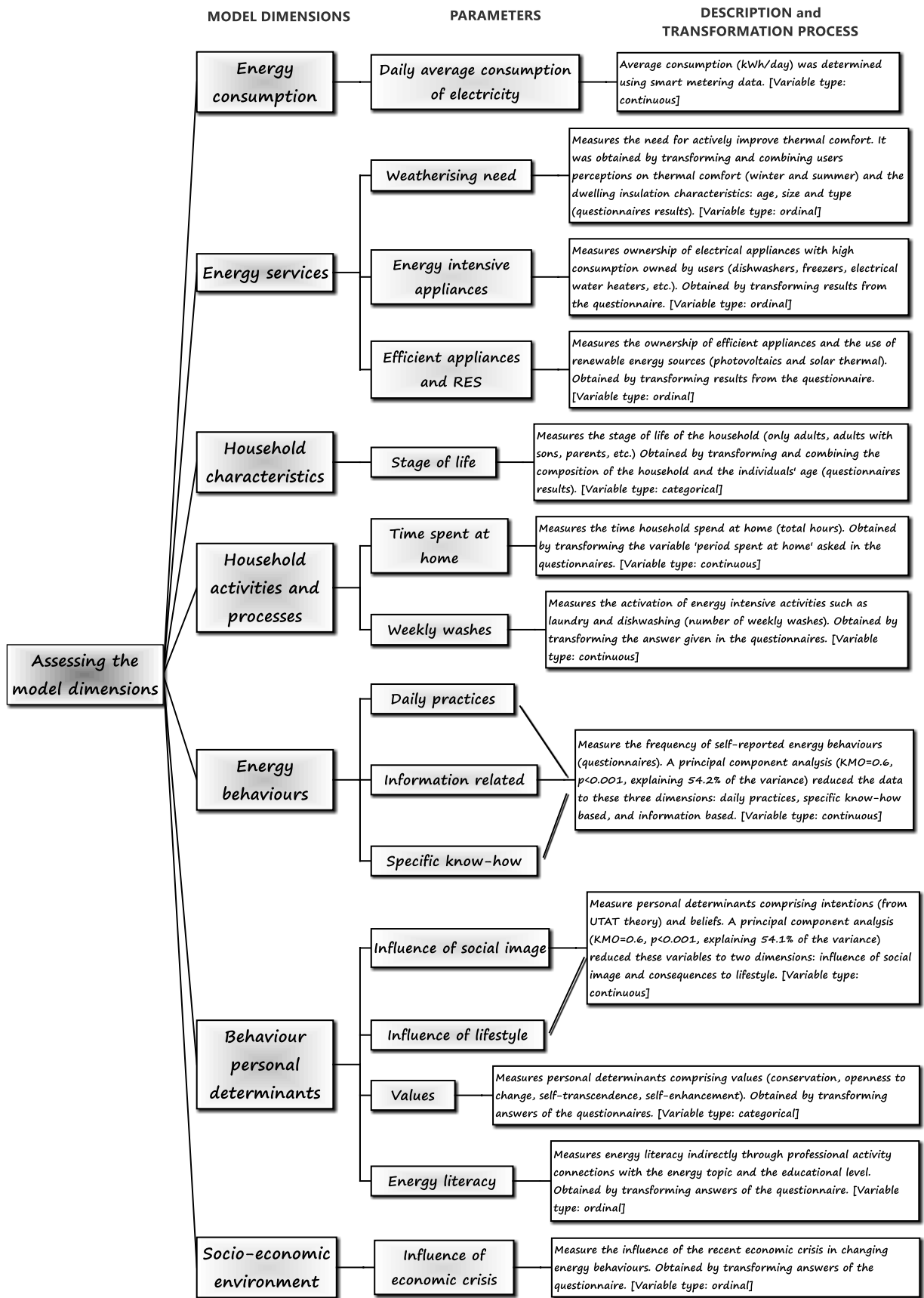


Figure 7 – Integration of variables during the assessment of the model dimensions

Table 10 – Relation between the factors emerged from the factor analysis, the measured self-reported energy behaviours and the respective categories

FACTOR	SELF-REPORTED ENERGY BEHAVIOURS	CATEGORY
Daily behaviours	Turning appliances off to avoid waste consumption (e.g., turning off the lights in empty rooms; turning TV off when nobody is watching it; turning water heating system off when in holidays)	Usage
	Eliminating stand-by consumption (e.g., turning appliances off using central plugs to avoid stand-by consumptions; turning appliances off directly on the switch to avoid stand-by consumption)	
	Use of passive strategies to control thermal comfort or lighting (e.g., using sun light in the rooms; insulating windows and doors; in the summer, closing the curtains/blinds during the day, and opening the windows during the night; in the winter, leaving curtains/blinds open during the day and closing them during the night; keeping doors and windows closed when they are being warmed or cooled; turning heating/cooling equipment on only in occupied rooms)	
	Efficient use of appliances (e.g., turning the dishwasher on only when it is full; using the washing machine at low temperature programmes; using dishwasher with eco programmes; turning the washing machine on only when it is full; ironing in long periods, instead of short ones; not opening and closing the fridge door very often; leaving the fridge door open for the less time needed)	
Specific know-how based	Settings adjustment (e.g., adjust acclimatisation temperature according to the season: summer 23-24°C, winter 18-20°C; regulating the fridge temperature according to the season)	Usage
	Use of dual time-of-use tariffs (e.g., using a timer to schedule water heating; turning the washing machine/dryer on during the cheapest periods; using cumulative heaters to benefit from cheaper electricity consumption periods)	
Information based	Auto-control and monitoring (e.g., talking with the dwelling occupants about electricity consumption and savings; reading the electricity bill; providing the meter readings to the electricity supplier)	Usage
	Investment in efficient appliances (e.g., buying more energy efficient equipment)	Investment

Literature acknowledges as the most important determinants of residential electricity consumption factors such as the climate, the dwelling and the household's characteristics, and appliances ownership and use, in particular energy intensive ones (Sanquist *et al.*, 2012; Bedir *et al.*, 2013; Kavousian *et al.*, 2013). In this case study, significant correlations were found between *daily average electricity consumption* and the following parameters of the model: *weekly washes*, *stage of life*, *weatherising need*, *specific know-how*, *energy intensive appliances*, and *consequences to lifestyle* (Table 11).

Table 11 – Significant correlations established between the model parameters and *daily average electricity consumption*

MODEL PARAMETERS	r
Weekly washes	0.61***
Specific know-how	-0.45***
Weatherising need	0.46***
Stage of life	0.54***
Energy intensive appliances	0.22**
Consequences to lifestyle	-0.20**

Table notes: r – Pearson regression coefficient, **p<0.05, ***p<0.001

Using the 15 synthesised variables of the model, a multiple regression analysis yielded a solution accounting for approximately 60% of the variance of the sample's daily average electricity consumption (Table 12, model 1). The best predictors of *daily average electricity consumption* include different dimensions of the conceptual model: energy services (*weatherising need*, B=3.14), followed by energy behaviours (*specific know-how*, B=-1.85), household activities (*weekly washes*, B=0.56) and their characteristics (*stage of life*, B=0.24). The specific technical dimension associated with energy behaviours embedded in the variable *specific know-how* revealed to be significantly contributing to the reduction of electricity consumption. Further exploring the compound variable *weatherising need* in predicting daily average electricity consumption (Table 12, model 2), the *insulation level* of the dwelling (B=5.92) appears as statistically significant revealing a greater prediction ability than the *perception of the thermal comfort* or the *size of the dwelling* (also embedded in *weatherising need*). In this particular case, this variable measures the poorness of the insulation and not its quality (B>0). The variable *energy intensive appliances* (B=0.05) also emerges as statistically relevant. The behavioural dimension maintains its prediction significance (*specific know-how*, B=-2.10). Regardless these significant results, this complementary model accounts for a lower variance of the sample's electricity consumption (40%) than the main model (Table 12, model 1).

Table 12 – Regression models for predicting *daily average electricity consumption*

DEPENDENT VARIABLE	MODEL	B	STD. ERROR	BETA	ADJ. R ²	OBSERVATIONS
Daily average electricity consumption	(Constant)	4.03	0.94	-	0.6**	Stepwise method, collinearity statistics VIF<5 and tolerance close to 1
	Weekly washes	0.56	0.14	0.38***		
	1 Specific know-how	-1.85	0.48	-0.30***		
	Weatherising need	3.14	0.89	0.28***		
	Stage of life	0.24	0.10	0.22**		
	(Constant)	3.31	1.95	-	0.4**	
	Stage of life	0.40	0.10	0.36***		
	2 Specific know-how	-2.10	0.51	-3.51***		
	Insulation level*	5.92	2.77	0.18**		
	Energy intensive appliances	0.05	0.02	0.18**		

Table notes: Adj. R² – Adjusted multiple determination coefficient, B – Partial regression coefficient, Beta – Standardised regression coefficient, VIF – Variance inflation factor, * Parameter originally embedded in "weatherising need", **p<0.05, ***p<0.001

When exploring the specific influence of the size of the household^y through further regression analysis, predicting models account for lower variances of *per capita daily average electricity consumption* (only 30%) (Table 13). As previously, two complementary analysis are performed, the first one using the original variables (model 3) and the second one exploring the compound variable *weatherising need* (model 4). It is interesting to note that the calibration of the model against the size of the household highlights the influence of the same variables as predictors of *per capita daily average electricity consumption* as previously: energy behaviours (*specific know-how*, B=-1.18), household characteristics (*stage of life*, B=-0.25) and energy services (*weatherising need*, B=1.49). Further developing the influence of *weatherising need* components on predicting *per capita daily average electricity consumption*, this dimension loses statistical significance in the resulting model, while a behaviour personal determinant (*value self-enhancement*, B=-3.33) emerges as significant. Moreover, according to these results, *daily average electricity consumption* is reduced with increased *specific know-how*, *stage of life* and the *value of self-enhancement*.

Table 13 – Regression models for predicting *per capita daily average electricity consumption*

DEPENDENT VARIABLE	MODEL	B	STD. ERROR	BETA	ADJ. R ²	OBSERVATIONS	
<i>Per capita daily average electricity consumption</i>	(Constant)	5.71	0.61	-			
	3	Specific know-how	-1.18	0.36	-0.35***	0.3**	
	Stage of life	-0.25	0.06	-0.41***			
	Weatherising need	1.49	0.66	0.24**		Stepwise method, collinearity statistics VIF<5 and tolerance close to 1	
	(Constant)	5.57	0.87	-			
	Weekly washes <i>per capita</i>	0.69	0.18	0.35***			
	4	Stage of life	-0.23	0.06	-0.35***		0.3**
	Specific know-how	-0.18	0.33	-0.33**			
	Value self-enhancement	-3.33	1.51	0.20**			

Table notes: Adj. R² – Adjusted multiple determination coefficient, B – Partial regression coefficient, Beta – Standardised regression coefficient, VIF – Variance inflation factor, * Parameter originally embedded in “weatherising need”, **p<0.05, ***p<0.001

For this particular case study, these results confirm the quantitative significant impact of different dimensions on electricity consumption, such as energy services, household activities and their characteristics, and more importantly, usage energy behaviours. The specific conceptual model for the case study is displayed in Figure 8 (following Table 12, model 1). According to these results, behavioural change actions integrated in this work were focused on both structural and behavioural strategies, namely by promoting a better insulation of the dwellings, providing specific and technical

^y Both electricity consumption and weekly washes are normalised to *per capita* values.

information and encouraging specific usage energy behaviours (e.g., settings adjustment, more efficient use of washing appliances).

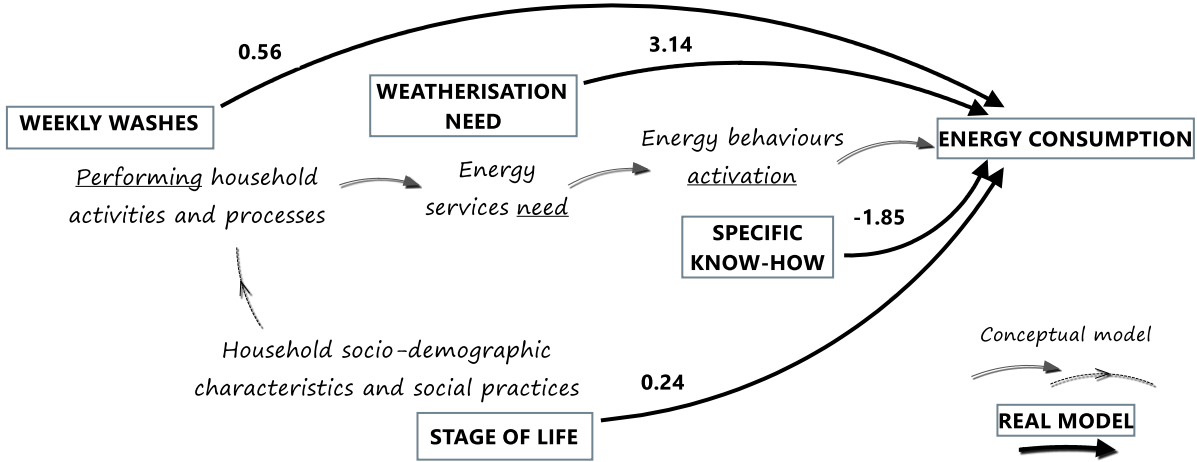


Figure 8 – Specific conceptual and real models for the case study

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 derived from the conceptual model and may emerge as relevant in samples with different characteristics. These results contribute to illustrate the need for considering an integrative perspective, while unveiling the important role of usage energy behaviours when addressing energy efficiency in the residential sector.

2.4 CONCLUSIONS

The role of energy behaviours in energy efficiency is gaining increasing recognition and more effective behaviour change interventions should be designed in the framework of sound energy efficiency policies. Tackling energy behaviours is however a complex and challenging task since they hold multiple dimensions, which require to be addressed using complementary disciplinary perspectives. The combination of these different views through integrative research is needed to develop comprehensive approaches to the understanding of energy behaviours and promotion of adequate end-use energy efficiency actions and programmes.

An integrative intervention to explore the qualitative and quantitative influence of usage energy behaviours on energy consumption was developed through an innovative combination of modelling techniques. The use of problem structuring methods enabled the comprehension and characterisation of the problem from various perspectives, the identification of the best methods and techniques to be utilised and their integration into a unified and coherent methodology, while facilitating the communication and the involvement of different stakeholders. Problem structuring methods also made explicit the underlying system, the stakeholders' roles, visions and positioning (including the researchers') thus enabling reducing the associated bias. Although this study did not aim at reconciling the stakeholders' different visions towards a common one, future developments of this thesis will include this dimension. Yet, all the dimensions of the generic constitutive definition of problem structuring methods were properly established: improvement activity, systemic approach, adaptation/creativity, methodological lessons, worldviews, messiness, interactive/iterative, subjectivity, limits. Also from a methodological perspective, the approach developed enabled to integrate both qualitative (e.g., behaviours characterisation) and quantitative information (e.g., energy monitoring data). Accordingly, problem structuring methods revealed to be pertinent tools to be utilised in complex human-centred energy research, such as energy behaviours, by enabling the development of tailored methodologies. However, in voluntary multi-agent contexts (Franco, 2006), in which an intrinsic lack of authority exists, problem structuring methods may offer limited results in promoting mutual accommodations, overcoming individual interests and coping with scarcity of resources at stake to lead to more effective actions.

Results from this study confirmed the statistical significant influence of the impact of usage energy behaviours on energy consumption. Furthermore, it also confirmed the impact on energy consumption of variables associated with different dimensions, thus supporting the need for considering an integrative perspective when addressing residential energy efficiency. In the case

study analysed, energy efficiency increases by promoting both structural actions and energy behaviours, namely a better insulation of the dwellings (which reduces energy consumption by a factor of 3.14) and encouraging specific usage energy behaviours (e.g., settings adjustment and efficient use of washing appliances, which reduce energy consumption by a factor of 1.85 and 0.56, respectively). However, these recommendations are case specific and may not be generalised since the sample under study is not representative of the overall population. This should be taken into account in future developments of this work.

More effective energy efficiency intervention policies addressing energy behaviours in the residential sector should involve the different energy stakeholders (e.g., regulators, governmental and energy agencies, utilities, energy service companies, consumer associations, scientific community), while ensuring their adequate coordination, since they play important and complementary roles. The development of behaviour change interventions in real-world contexts should also anticipate challenges such as uncertainty and constant changes (e.g., resources availability, stakeholders' involvement) and be designed to be flexible, adaptive and comprise important skills such as communication, negotiation, and integration of information.

3 ESTIMATING THE BEHAVIOURAL SAVINGS POTENTIAL ^{vi}

3.1 INTRODUCTION

Buildings are one of the largest energy consumers, with a share of 32% of global energy use (OECD/IEA, 2012). European buildings were responsible for 41% of end-use energy consumption and for 36% of CO₂ emissions in 2010 (EC, 2012c), turning this into a key sector to achieve greenhouse gases (GHG) emissions targets. Both the IEA and the EU assume that a large portion of energy efficiency improvements in buildings still remains unexploited (CEC, 2006; OECD/IEA and AFD, 2008; OECD/IEA, 2012). This potential in residential buildings, which is exclusively associated with infrastructural and equipment investments, is estimated up to 27% and to 63%, by the EU and the IEA respectively (CEC, 2006; OECD/IEA, 2011b, 2012).

Energy use in residential buildings is not only determined by climate, building characteristics and operations, energy services and indoor environmental quality, social and economic context, but also by occupants' characteristics, activities and behaviours (Yu et al., 2011). Occupants' behaviours are a major determinant of energy use in residential buildings and their role in energy efficiency is recognised by energy policies such as the European Directive on Energy Efficiency (EU, 2012). However, the potential of energy savings due to behaviours is frequently far from being adequately exploited, albeit being referred as significant as those from technological solutions (Ürge-Vorsatz *et al.*, 2009; Jonsson *et al.*, 2010). As the EU acknowledges, the reason may be linked with the difficulty of quantifying behavioural savings and therefore, this dimension is not commonly considered (EC, 2010e). Nevertheless, research on energy behaviours indicate behavioural savings potential may reach 20%, although values differ up to 100% between different studies and situations (Lopes *et al.*, 2012b).

Traditionally, behavioural savings potential has been estimated in the context of energy efficiency interventions that are developed in real-world contexts. Recent research has been using modelling strategies for estimating this potential, such as data mining techniques. Building energy performance simulation (BEPS) tools have also been increasingly utilised, but this line of research has been essentially centred on specific behavioural dimensions associated with thermal and lighting comfort,

^{vi} This chapter is partially based on [Lopes, M.A.R., Antunes, C. H., Reis, A., & Martins, N. Estimating behavioural savings in dwellings using Building Energy Performance Simulations. *Building Research and Information* [In print]]

without addressing the diversity of household activities influencing energy demand. The literature has also highlighted the need for the development of multidisciplinary integrative modelling approaches that consider the broad range of households' daily activities as tools to support the development of behavioural change interventions (Nguyen and Aiello, 2013; Lopes *et al.*, 2015). Moreover, in the Portuguese energy policy context, adequate methods using bottom-up strategies are needed to provide more accurate assessments of the behavioural impact on energy consumption.

Accordingly, in this chapter a bottom-up comprehensive modelling approach of energy behaviours in the residential environment is presented as a tool to estimate the behavioural impact of households on energy consumption. It uses BEPS tools to explore the behavioural w thus supporting more effective energy policies.

This chapter is divided in four sections. Section 3.2 describes the methods used to estimate the behavioural savings potential. Section 3.3 presents and discusses the main results obtained, and section 3.4 summarises the main conclusions.

3.2 METHODS

A bottom-up strategy is proposed to estimate the behavioural savings potential of a specific segment of Portuguese urban households. The approach involves five stages and is briefly described as follows: (1) design of the household activity model; (2) energy consumption modelling; (3) validation; (4) design of energy behaviours profiles; and (5) estimate of behavioural savings potential (Figure 9).



Figure 9 – Methodology developed to estimate behavioural savings potential

A. Design of the household activity model

In the last decade there has been a trend of reduction in size of Portuguese families, which in 2014 reached the average of 2.6 individuals per household (Pordata and INE, 2015a). Although households are still mostly composed by a couple with children (35.8%), families composed by a couple with no children have increased at an average rate of 2.4% per year, and one parent family at 2.9% per year (Pordata and INE, 2015c). Moreover, the birth rate has continuously decreased (Pordata and INE, 2015b). Hence, for simplification purposes, a household profile was established to represent a family composed by a working couple with a school-age child, representing approximately 30% of Portuguese households.

Based on the time use survey of Portuguese households (INE, 1999; Lopes and Coelho, 2002) a schedule of home activities occurring during a regular working week was established. The main activities considered were: sleeping time (in general, from 11 p.m. to 7 a.m.); personal and family care time; home care activities; making and having meals (e.g., breakfast, lunch, dinner); time at (or going to) work/school; leisure time at home (e.g., watching television, listening to music); and some work developed at home (e.g., through computer usage) (Figure 10). A period of nine hours each working day is considered to be spent at work, school or in transit between home-work (INE, 1999; Lopes and Coelho, 2002), and a leisure time outdoors during the weekend is also considered. Overlapping between activities may also occur and therefore the schedule is globally indicative. Holidays were also considered according to the family profile (e.g., compatible with school breaks) and the traditional national holidays.

Time	Weekday	Saturday	Sunday	
00:00	Sleeping	Sleeping	Sleeping	
01:00				
02:00				
03:00				
04:00				
05:00				
06:00				
07:00	Personal care & Meals	Personal care & Meals	Personal care & Meals	
08:00				
09:00	Home & family care			Home & family care
10:00				
11:00				
12:00	Meals			
13:00	Home & family care, leisure			
14:00				
15:00				
16:00	Work at home, leisure			
17:00				
18:00	Home & family care			
19:00	Meals	Meals	Meals	
20:00	Home & family care, leisure, sleeping	Home & family care, work at home, leisure, sleeping	Home & family care, work at home, leisure, sleeping	
21:00				
22:00	Sleeping	Sleeping	Sleeping	
23:00				

Figure 10 – Illustrative schedule of home activities during a regular working week

B. Energy consumption modelling

Energy consumption and potential savings are directly related with households' activities and occupants' energy behaviours. Energy consumption is the result of the activation chain beginning with the household's activities and needs that lead to the use of energy services, such as heating, cooling, lighting and electrical appliances powering (Lopes et al., 2015). Based on this rationale, a set of energy services was inferred and the resultant energy consumption profile was estimated using BEPS tools, namely the Energy plus/Design-Builder® software (version 8.1). This tool was chosen for its characteristics, such as being user-friendly and widely used in building design or including specific models for energy flows (Tindale, 2004; Tronchin and Fabbri, 2008; Fumo *et al.*, 2010).

The following set of energy services was established: lighting, leisure and entertainment, work at home, food refrigeration, cooking, dishwashing, home care activities such as vacuuming and ironing, laundry, clothes drying, space heating and cooling, and water heating (Table 14, Figure 11). Only energy consuming activities performed at home are within the scope of this work, mobility is not considered.

The reference location was chosen for its mild climate characteristics both in the winter and the summer to minimise climate influence (Sines, located at south Portugal, with a mild Atlantic climate, average temperature in the summer below 20°C, and heating degree days of 1,150 °C.days) (MOPTC, 2006). The influence of climate was also assessed through the change of location to alternatives that have more demanding climatic conditions in the winter and in the summer. Hence, according to the climatic zones of the national regulation of energy performance of buildings, Bragança was chosen for having a colder climate in winter (heating degree days of 2,850 °C/day) and Beja for having a warmer climate in the summer (average temperature above 22°C) than the reference location (MOPTC, 2006).

The reference building characteristics were established to represent an average Portuguese urban apartment which accounts for 47% of the total dwellings (INE and DGEG, 2011). This subset of dwellings has an average area of 96 m² and is inhabited by an average of 2.6 individuals (INE and DGEG, 2011). Hence, a virtual test cell (single room, quadrangular) with 100 m² representing an apartment located at an intermediate floor (between adiabatic floors) of a multistage building was considered. It was assumed that the thermal characteristics of the external walls were in accordance with the former national regulation on energy certification of buildings, RCCTE (MOPTC, 2006) (Table 15). It was also considered one window per façade (centrally located), with 15% of the floor area size, and with double glazed and simple aluminium frame (no thermal break).

Table 14 – Energy services need, activation and energy consumption profile

ENERGY SERVICE	NEED	ACTIVATION	ENERGY CONSUMPTION PROFILE
Artificial lighting	Provides luminance to support daily activities, complementarily to natural light. In Portuguese households it is supported by incandescent lamps (81% households), fluorescent lamps (78%), halogen lamps (22%), and LED (3%). ^[1]	When the family is at home and natural lighting provides less than 250 lux. ^[2]	A simultaneity factor is considered for the use of artificial lighting. $P_{max}=600\text{ W}$ ^[1] and the normalised load diagram is shown in Figure 11.
Leisure and entertainment	Watching TV, playing or listening to music are deeply incorporated in daily routines of families (ownership rates: TV 100%, Wi Fi 36%, DVD player 47%, radio 41%) ^[1] , and are usually performed after home and family care periods, meals, work time, and before sleeping ^[3] .	Weekday: after dinner Weekend: in the afternoon and evening	A simultaneity factor is considered for the use of TV, Wi-Fi, and DVD player. $P_{max}=160\text{ W}^*$ and the normalised load diagram is shown in Figure 11.
Working at home	Active households often work at home during the weekend ^[3] , namely qualified professions, using a computer (ownership rate: 59%) ^[1] .	Saturday afternoon and Sunday evening.	A simultaneity factor is assumed for the use of laptop, router, and printer. $P_{max}=160\text{ W}^*$ and the normalised load diagram is shown in Figure 11.
Refrigeration of food	Supports nourishment and cooking and it is widely used in households (ownership rates: refrigerator with a small freezing area 58%, combined fridge and freezer 38%, and freezer 48%) ^[1] .	Continuous, assumed to be provided by a combined fridge and freezer.	$P_{max}=240\text{ W}^*$ and the normalised load diagram is shown in Figure 11.
Cooking	In Portuguese households it is supported by several appliances: microwave (ownership rate of 82%), stove and oven (66%), plate (36%), and exhausting system (66%) ^[1] .	Every morning (breakfast), evening (dinner) and Saturday's lunch.	A simultaneity factor is considered for the use of microwave, stove, oven and exhausting system. $P_{max}=2,880\text{ W}^*$ and the normalised load diagram is shown in Figure 11.
Dishwashing	It is often made by a dishwasher (ownership rate of 41%) ^[1] .	4 X per week ^[4] 3 during the week and 1 during the weekend.	$P_{max}=2,340\text{ W}^*$ and the normalised load diagram is shown in Figure 11.
Home care activities	Home care activities such as vacuuming and ironing are often performed in households (ownership of vacuum cleaner 75% and of iron 92%) ^[1] .	1 X per week, Saturday morning.	A simultaneity factor is considered for the use of vacuum cleaner and iron. $P_{max}=2,508\text{ W}^*$ and the normalised load diagram is shown in Figure 11.
Laundry	Using a laundry machine is a deeply embedded practice (ownership rate of 91%) ^[1] .	4 X per week ⁵ Week: 2X low Temp. Weekend: 2X high Temp.	$P_{max}=1,920\text{ W}^*$ and the normalised load diagram is shown in Figure 11.
Clothes drying	Results from laundry and is performed with and without a tumble dryer (ownership of 19%) ^[1] , depending on the climate ^[5] .	Winter: 2 X per week Summer: never ^[5]	$P_{max}=2,308\text{ W}^*$ and the normalised load diagram is shown in Figure 11.
Climatisation: heating, cooling and ventilation	Improves the thermal comfort indoors and is needed depending on the climate, building insulation and the activities performed. While heating is often performed using independent heaters (61% ownership rate), HVAC systems (7%) and open fireplaces (24%), cooling is mostly performed using fans (70%) and HVAC equipment (26%) ^[1] .	HVAC ON when the family is at home. Set point temperatures established by the Portuguese regulation on buildings certification ^[6] .	Determined by Design Builder® software according to predefined set point temperatures, the local climate, and the coefficient of performance.
Heating water	Hot water is mostly used in daily hygiene, cooking and home care activities and in Portuguese households water is heated mostly using gas (90%) and only 4% uses electricity ^[1] .	Daily basis, <i>per capita</i> consumption is 40 l/(person.day) ^[6] , delivered at 37.5°C *.	Energy consumption profile is determined by the Design Builder® software according to predefined set point temperatures, consumption and performance.

Table notes: P_{max} - Peak power, ^[1] (INE and DGEG, 2011), ^[2] (CIE, 2002), ^[3] (INE, 1999; Lopes and Coelho, 2002), ^[4] (Stamminger, 2011), ^[5] (Schmitz and Stamminger, 2014), ^[6] (MOPTC, 2006), * Obtained from energy audits.

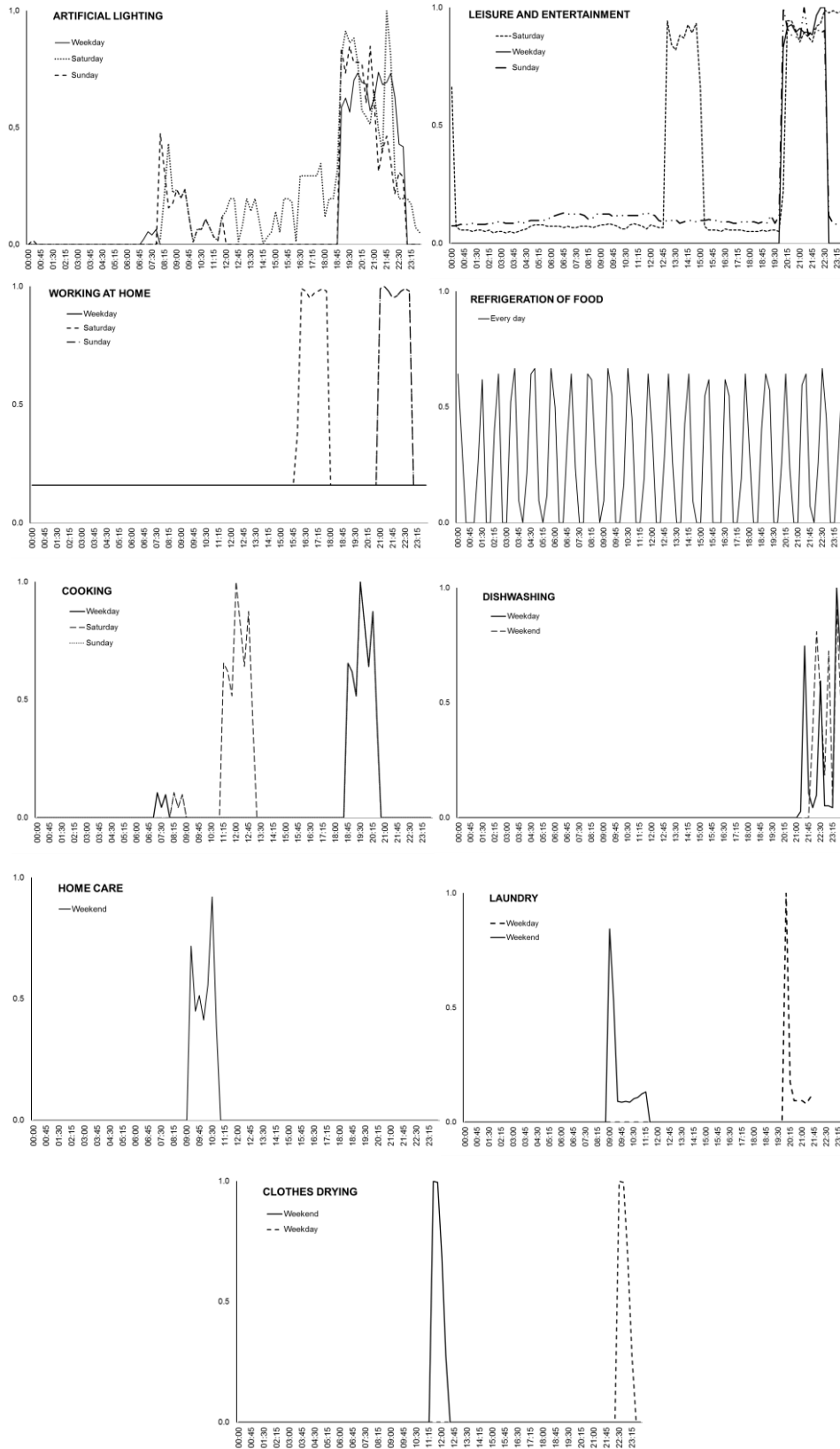
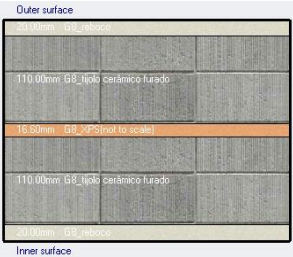
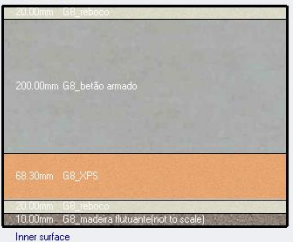


Figure 11 – Normalised load diagrams of several energy services (obtained through energy audits)

Table 15 – Assumed building envelope characteristics

SURFACE	MATERIAL	U (W/m ² .°C)	STRUCTURE
External walls	Plaster (20.0 mm) Hollow bricks (110 mm) XPS (Sines and Beja 16.6 mm; Bragança 37.7mm) Hollow bricks (110 mm) Plaster (20 mm)	Sines and Beja: 0.7 Bragança: 0.5	
Floor	Plaster (20 mm) Reinforced concrete (200 mm) XPS (68.3 mm) Plaster (20 mm) Floating wood (10 mm)	Adiabatic	
Windows	Double glazing (6mm / 6mm air) Simple aluminium frame with no thermal break No shading Total solar transmission coefficient: 0.7	3.094	

C. Validation

A reverse process was used to validate the household energy consumption model. Using an energy monitoring dataset of 128 real urban households previously studied, 20 cases were selected according to the: type of dwelling (apartment); size ($\approx 100\text{m}^2$); year of construction (built after 2000); composition of the family (one/two parents, and one child); similar location and appliances ownership. Energy consumption data was obtained using a smart meter (<http://www.cloogy.com/en/>) placed at the utility meter level, with a monitoring time step of 15 minutes. The measured monthly energy consumption from the 20 cases was compared with the energy consumption model obtained through BEPS (Figure 12). Adjustments to the BEPS model assumptions were performed during the calibration process. A final mean bias error (MBE) of 0.5% and a coefficient of variation of root mean square error of 9% (CVRMSE) were obtained between the measured and the monthly energy consumption of the model final version, thus complying with the calibration acceptance criteria for building energy performance models (Coakley *et al.*, 2014).

Nevertheless, it should be taken into account that the model calibration has only been conducted at the aggregate monthly energy consumption, and not at the energy services level, which limits the generalisation of results that may be extracted.

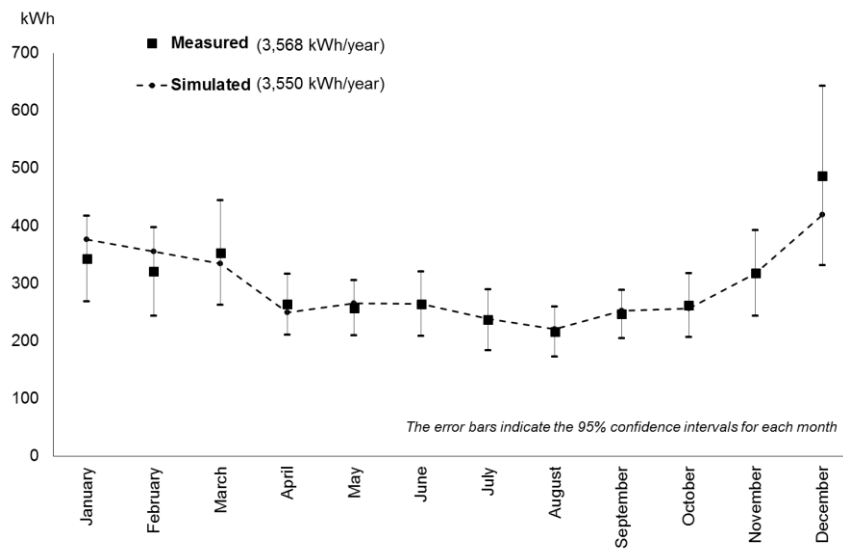


Figure 12 – Measured (N=20) and simulated monthly energy consumption

D. Design of behavioural profiles

Three hypothetical behavioural profiles (efficient, reference, inefficient) were established as a function of a set of parameters reflecting different energy behaviours when utilising energy services at home. Two main categories of energy behaviours are considered: investment (I) and usage (U). While usage energy behaviours refer to the day-to-day usage of equipment, investment energy behaviours involve the replacement of an equipment by a more efficient one (Lopes *et al.*, 2015). For each energy service and behavioural category, the considered behavioural profiles (efficient, reference and inefficient) were characterised (Table 16). While the reference profile corresponds to the one considered in the energy consumption modelling stage, the efficient profile combines the most efficient available technologies and efficient usage energy behaviours, and the inefficient profile combines less efficient available technologies and inefficient usage energy behaviours.

Assumptions about efficient and inefficient profiles were based on regulations, statistics, published results and energy audits performed in the residential environment, and although they have not been calibrated using real-world samples, it is considered they fairly represent real Portuguese households. These profiles were also designed to comply with health and wellbeing criteria. The difference of one degree in heating and cooling set points relatively to the reference profile does not change thermal comfort according to Fanger's PMV (Predicted Mean Vote) model (Charles, 2003), and if it would possibly change it, then comfort could be very easily restored through a small change

of clothing. Moreover, lighting settings are in accordance with the European Standard EN 12464-1 for indoor working places, since the minimum luminance assumed is required by this norm in activities that are also performed in a residential environment (e.g., cooking, dressing, personal care, cleaning) (CIE, 2002).

E. Estimate of the behavioural savings potential

Occupants' energy behaviours may range from more efficient to more inefficient. Instead of predicting all behavioural settings or using probabilistic methods (e.g., Monte Carlo methods), this approach follows a boundary analysis by assuming hypothetical scenarios where the combination of all efficient energy behaviours originates an efficient profile and the combination of all inefficient energy behaviours creates an inefficient profile, which leads to theoretical minimum and maximum energy consumption scenarios, respectively. The potential of behavioural energy savings will then be given by the difference of energy consumptions between the reference, efficient and inefficient profiles. However, it must be emphasised that the upper and lower bounds correspond to hypothetical scenarios and have not been validated using real-world samples.

The potential of energy savings is estimated on a yearly basis. The contribution of usage and investment behaviours and the influence of energy services to savings are also estimated. The influence of climate in behavioural savings potential associated with heating and cooling needs is also assessed through the change of location to two other cities with different climatic characteristics (Bragança and Beja).

As assessment of investment behaviours is performed considering common economic selection criteria of energy efficiency measures, such as the initial expenditure, net present value, payback and internal rate of return (IRR) (Fleiter *et al.*, 2012; ERSE, 2013a).

Table 16 – Occupant’s behaviour profiling assumptions

ENERGY SERVICE	BEHAVIOURS CATEGORY	OCCUPANT’S BEHAVIOUR PROFILES		
		REFERENCE	INEFFICIENT	EFFICIENT
Lighting	I	$P_{ref}=600\text{ W}$ ^[1]	All light bulbs are incandescent +38% of P_{ref}	All light bulbs are LED -86% of P_{ref}
	U	ON when natural luminance lower than 250 lux ^[2]	ON when natural luminance lower than 300 lux	ON when natural luminance lower than 200 lux
Leisure	I	$P_{ref}=160\text{ W}$, Energy label A *	Energy label D *, +100% P_{ref} ^[3]	Energy label A+++, -57% P_{ref} ^[3]
	U	Stand-by during the weekend ^[4]	Stand-by all week, +28% E_{ref} *	No stand-by, -15% E_{ref} *
Working home	I	$P_{ref}=160\text{ W}$ * Notebook A, standards 2014 **	Integrated desktop computer +68% P_{ref} ^[5]	Notebook A, standards 2016 -25% P_{ref} ^[5]
	U	No stand-by ^[4] , web router always on **	Sleep mode between usages, web router always on, +7% E_{ref} *	No stand-by, web router off when not used, -82% E_{ref} *
Refrigeration of food	I	$P_{ref}=240\text{ W}$, Energy label A *	Energy label C ^[6] , +36% P_{ref} ^[7]	Energy label A+++, -48% P_{ref} ^[7]
	U	Regular usage and set points defined by the manufacturer.	Set-point less 1°C standard, users often open the door +28 E_{ref} ^[8]	Cool and ventilated spot, good maintenance practices -10% E_{ref} ^[8]
Cooking	I	$P_{ref}=2,880\text{ W}$, Energy label A *	Energy label D**, +49% P_{ref} ^[9]	Energy label A+++, -45% P_{ref} ^[9]
	U	Regular usage	Opening the oven for more than 10 seconds, +8% E_{ref} ^[8]	Turning off 15 min before end -7% E_{ref} *
Dishwashing	I	$P_{ref}=2,340\text{ W}$, Energy label A *	Energy label D ^[10] , +27% P_{ref} ^[11]	Energy label A+++, -21% P_{ref} ^[11]
	U	2X ECO and 2 high temperature / week **	Always high temperature +8% E_{ref} *	Always ECO, -8% E_{ref} *
Home care	I	$P_{ref}=2,508\text{ W}$, Energy label A *	Energy label D**, +43% P_{ref} ^[12]	Energy label A+++, -64% P_{ref} ^[12]
	U	Regular usage	Turning off 15 min after ending +10% E_{ref} *	Turning off 15 min before ending, -10% E_{ref} *
Laundry	I	$P_{ref}=1,920\text{ W}$, Energy label A *	Energy label D ^[6] , +28% P_{ref} ^[13]	Energy label A+++, -22% P_{ref} ^[13]
	U	2X Regular and 2 high temperature / week **	Always high temperature +4% P_{ref} *	Always regular temperature -4 P_{ref} *
Clothes drying	I	$P_{ref}=2,308\text{ W}$, Energy label A *	Energy label D ^[6] , +31% P_{ref} ^[14]	Energy label A+++, -43% P_{ref} ^[14]
	U	Winter: tumble dryer 2X /week Summer: outside	Always: tumble dryer 4X /week +300% E_{ref} *	Winter: tumble dryer 1X /week Summer: outside, -50% E_{ref} *
Climatisation	I	COP=3 ^[15]	COP=1 **	COP=3.61 **
	U	ON when the family is at home. Heating set point: 20°C, cooling set point: 25°C ^[15] and ON only 1h/day **	Heating set point: 21°C ** Cooling set point: 24°C **	Heating set point: 19°C ** Cooling set point: 26°C **
Heating water	I	Natural gas boiler ^[16] , $\eta=0.85$	Electric heating system** $\eta=0.95$	Flat plate solar collectors (sun 60% of the time) complemented by the reference technology. **
	U	Hot water consumption 40 l/(person.day) ^[15] , delivered at T=40°C *	Same consumption, T=40°C **	Same consumption, T=35°C **

Table notes: I – Investment; U – Usage; P_{ref} - Reference power; E_{ref} - Energy consumption for P_{ref} ; ^[1] (INE and DGEG, 2011); ^[2] (CIE, 2002); ^[3] (EC, 2010d); ^[4] 45% of the Portuguese households have stand-by consumption, but only 10% is associated with computer usage (INE and DGEG, 2011); ^[5] (EC, 2013b); ^[6] Ownership rate of 15% (INE and DGEG, 2011); ^[7] (EC, 2010b); ^[8] (IPS *et al.*, 2012); ^[9] (EC, 2013a); ^[10] Ownership rate of 12% (INE and DGEG, 2011); ^[11] (EC, 2010a); ^[12] (EC, 2013c); ^[13] (EC, 2010c); ^[14] (EC, 2012a); ^[15] (MOPTC, 2006); ^[16] Ownership rate of 85% (INE and DGEG, 2011); * Obtained from energy audits; ** Assumed.

3.3 RESULTS AND DISCUSSION

This section provides an analysis of building energy performance simulation results, including primary energy consumption breakdown for the reference household, behavioural savings potential, and the influence of climate, thermal comfort and personal care practices on the savings potential.

3.3.1 ENERGY CONSUMPTION OF THE REFERENCE PROFILE

Simulations have estimated the annual primary energy consumption^{vii} of the reference household to be 113 kWh/(year.m²) which originates the emission of 0.8 tCO₂e/(year.m²). Energy consumption breakdown shows powering appliances as the most energy intensive service, holding a share of 50% of the total primary energy consumption, followed by water heating (22%), climatisation (space heating 15% and cooling 8%) and lighting (5%) (Figure 13). Although the calibration of the model has not been performed at the energy services level and results obtained at this level of detail are limited, it must be noted that these results are similar to the energy breakdown of an average Portuguese household (appliances in the kitchen 39%, other appliances 11%, space heating 22% and cooling 1%, water heating 23%, and lighting 4%) (INE and DGEG, 2011).

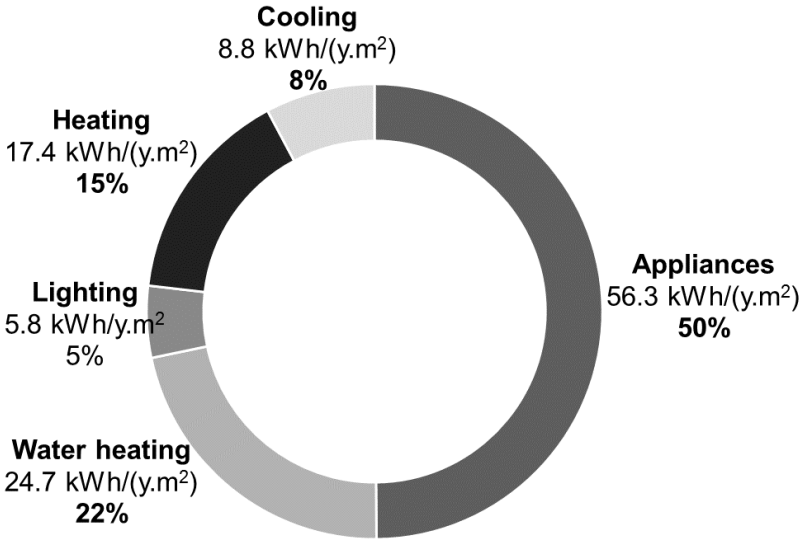


Figure 13 – Primary energy consumption breakdown of the reference household

^{vii} Energy consumption is expressed in primary energy units (primary factors applied: electricity 2.5; all fossil fuels 1) (MEI, 2008).

3.3.2 BEHAVIOURAL SAVINGS POTENTIAL

Simulations show occupants' energy behaviours may significantly impact households' primary energy consumption (Table 17, Figure 14). While the hypothetical efficient profile consumes less 34% energy than the reference household (-38.8 kWh/(y.m²)), the inefficient profile consumes 131% more (+148.0 kWh/(y.m²)). An inefficient household may consume as much primary energy as 3.5 households with efficient energy behaviours. However, future improvements of this work should consider validating these profiles with real-world samples so a more accurate estimate of the behavioural impact on energy consumption is performed.

Table 17 – Primary energy consumption of the different household profiles [kWh/(y.m²)]

ENERGY SERVICES	BEHAVIOURAL PROFILES		
	EFFICIENT	REFERENCE	INEFFICIENT
Appliances	46.8	56.3	99.9
Water heating	8.8	24.7	61.4
Lighting	0.8	5.8	8.0
Heating	12.8	17.4	55.5
Cooling	5.0	8.8	36.2
TOTAL	74.2	113.0	261.0

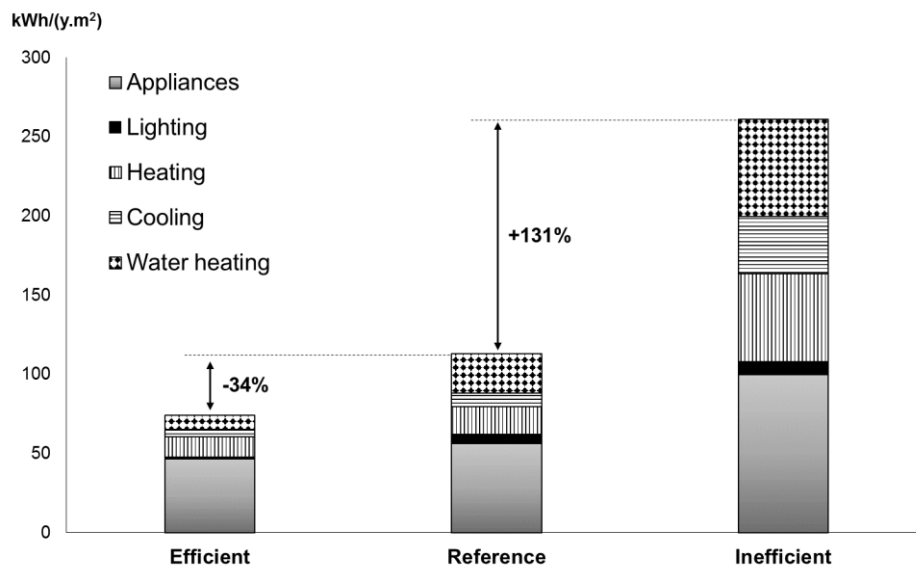


Figure 14 – Behavioural impact on end-use energy consumption

Although savings potential is apparently higher than that indicated in the reviewed literature (Al-Mumin *et al.*, 2003; de Meester *et al.*, 2013; Xu *et al.*, 2013; Ben and Steemers, 2014; Bonte *et al.*, 2014), the results are not comparable. Firstly, energy services considered in this work are different

and broader than in other studies which are only focused on heating, cooling, ventilation and lighting. Secondly, assumptions on behavioural dimensions are different and the energy behaviours considered are of distinct nature (e.g., usage versus investment). For example, when comparing our assumptions on lighting and climatisation with Martinaitis et.al.'s (2015), both studies explore usage behaviours (e.g., set points, luminance thresholds), but this approach also explores investment behaviours such as the alteration of technologies, which is not considered by them. Thirdly, energy units are different, due to the fact that most studies estimate final energy consumption whereas this work and Martinaitis et al.'s (2015) both estimate primary energy consumption.

Simulations also illustrate that energy behaviours may significantly impact primary energy consumption of each energy service, particularly of space cooling and heating, and water heating (Figure 15). Behavioural savings potential per energy service is proportional to the energy breakdown. Powering appliances has the highest behavioural savings potential, since it has the largest difference between the efficient and inefficient profiles (53.1 kWh/(y.m²)), followed by water heating (52.6 kWh/(y.m²)), space heating (42.6 kWh/(y.m²)) and cooling (31.2 kWh/(y.m²)). Lighting presents the lowest behavioural savings potential (7.2 kWh/(y.m²)), despite having the highest ratio between the efficient and inefficient profiles. However, due reservations are needed since the model calibration was not performed at the energy services level, therefore limiting these results.

Nevertheless, the present results reinforce the need for real-world behavioural change interventions to previously assess households' energy behaviours and quantify energy consumption breakdown, in order to maximise potential savings.

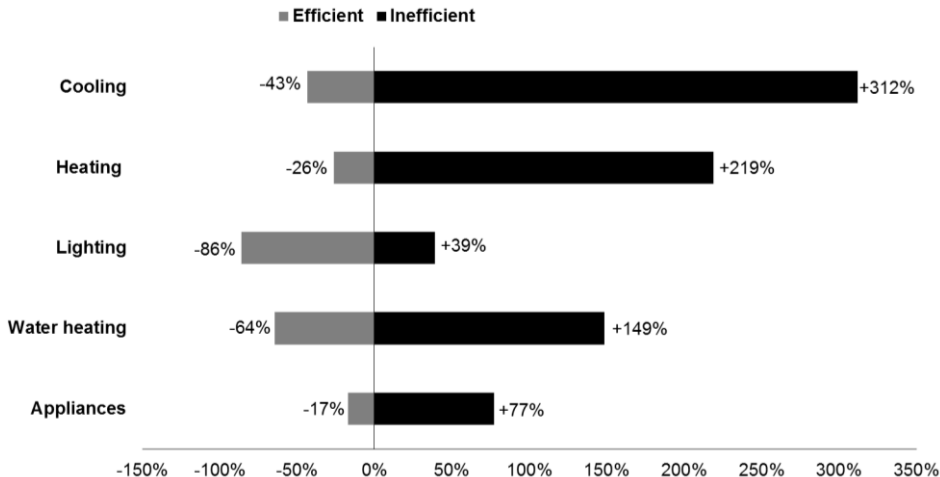


Figure 15 – Behavioural impact on the reference household primary energy consumption, per energy service

When comparing usage and investment energy behaviours, simulations show investment behaviours may have the highest impact on potential savings. Efficient investment energy behaviours may save up to 39% of primary energy consumption of the reference household, while inefficient investment energy behaviours may almost double (+97%) the reference energy consumption (Figure 16). Usage energy behaviours may also have a noteworthy impact on energy consumption of the reference household, from -16% to +17% with efficient or inefficient usage profiles, respectively.

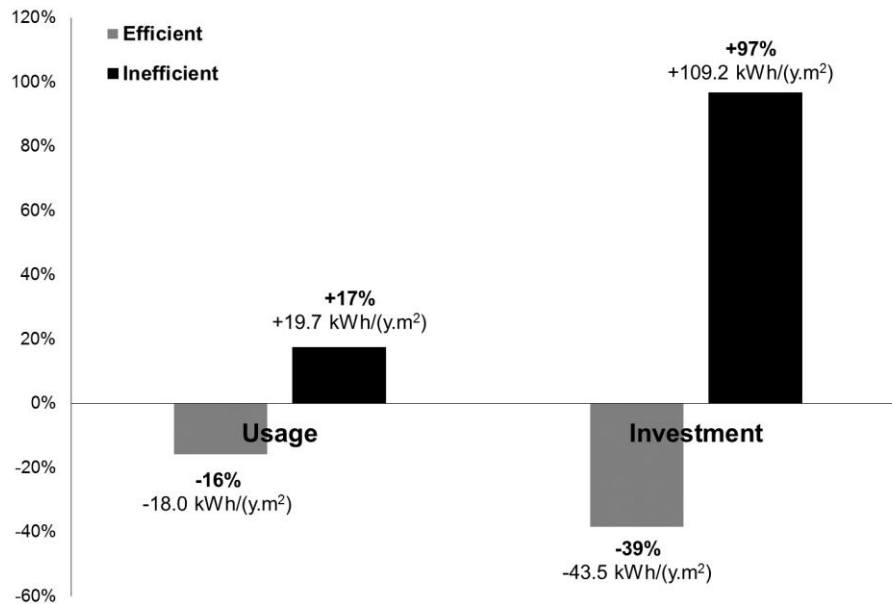


Figure 16 – Impact of efficient/inefficient usage and investment energy behaviours on primary energy consumption of the reference household

Even though a significant behavioural savings potential associated with both usage and investment energy behaviours was estimated by simulations, experience has shown the challenge of promoting more efficient energy behaviours and materialising savings in the real-world. In fact, a recent assessment of behaviour change interventions revealed they have been ineffective in achieving enduring efficient energy behaviours (Gynther *et al.*, 2011; EEA, 2013). Moreover, effective savings are also influenced by potential rebound effects which may cancel energy efficiency improvements. Direct and indirect rebound effects for the residential sector in Portugal have been estimated by Galvin (2014) to be as much as 38.1%, which may cancel part of the estimated behavioural savings.

3.3.3 INFLUENCE OF CLIMATE, THERMAL COMFORT AND PERSONAL CARE PRACTICES

When moving to other locations, the energy consumption of the reference profile changes accordingly to the climatic characteristics (Table 18). For example, while moving to Bragança where heating degree days (HDD) more than doubles leads to an increase of 121% in space heating consumption, moving to Beja (where the average temperature in the summer is higher than 22°C) just increased space cooling by 4%. However, the change of location maintains a similar ratio between energy consumption resulting from efficient/inefficient energy behaviours when compared with the reference profile. While inefficient energy behaviours increase space heating consumption of the reference household by more than 3 times ($\approx 200\%$) in both Sines (mild climate) and Bragança (colder climate), they increase cooling energy consumption by more than 4 times. In turn, efficient energy behaviours decrease heating energy consumption by 19-26% and cooling energy consumption by 41-43%, depending on the location. These results provide a clear indication that behavioural influence on energy consumption is independent of local climates. Although this may seem counterintuitive, it is justified by the changes in the model assumptions, in particular the thermal characteristics of the building envelope which are imposed by the Energy Performance of Buildings Directive (Sines and Beja have a heat transfer coefficient of 0.7 W/m².°C and Bragança of 0.5 W/m².°C) (Table 15).

Table 18 – Impact of efficient/inefficient energy behaviours on space heating/cooling consumption in distinct climatic characteristics

Energy service	Location	Climate characteristics ^[1]	Behavioural profile		
			Reference	Efficient	Inefficient
Heating	Sines	Mild: HDD= 1,150 °C.days Average T _{summer} <20°C	17.4 kWh/(y.m ²)	-26.1%	+219.0%
	Bragança	Colder: HDD= 2,850 °C.day	38.5 kWh/y.m ²	-19.3%	+199.1%
Cooling	Sines	Mild: HDD= 1,150 °C.days Average T _{summer} <20°C	8.8 kWh/(y.m ²)	-43.2%	+311.9%
	Beja	Warmer: Average T _{summer} >22°C	9.1 kWh/(y.m ²)	-41.2%	+313.0%

Table notes: ^[1] (MOPTC, 2006)

It was assumed in the present model that heating and cooling services automatically deliver standard comfort temperatures established by the Energy Performance of Buildings Directive (MOPTC, 2006), which is a common practice by households with young children (such as the reference profile). However, it is known that some segments of the Portuguese population neither use the automatic mode of air-conditioning systems nor follow standard set points (Lopes *et al.*, submitted). Instead,

households often switch the air-conditioning temporarily on (or for short periods of time) for either heating or cooling a room, with higher (or lower in the case of cooling) temperatures than the standard set points. While these two alternative methods for operating air-conditioning systems are very different, they can result in the same overall energy consumption. For example, when setting the heating system to 5°C higher than the reference set point it would only take four hours to reach the reference consumption. However, these behaviours have different consequences to the power demand and the overall energy system efficiency, since setting higher temperatures for short periods of time may generate peak loads.

The model also shows that energy behaviours may significantly impact energy consumption when heating water. For instance, when simulating a 2.5°C variation in the delivered water temperature, a 10% variation is generated in the primary energy consumption of this service. In addition, a variation of 50% in the time spent on personal care practices such as showering may have an impact in the same proportion on the energy consumption of this energy service. An inefficient household having longer showers (+50% of the time) may consume almost 4 times more energy (+273%) than the reference profile. In turn, an efficient household that reduces their shower period by 50% and uses water saving shower-heads may save almost twice as much energy (-91%) when heating water than the reference household.

3.3.4 ASSESSMENT OF INVESTMENT BEHAVIOURS

Although the previous results have shown a significant savings potential associated with energy behaviours in the residential sector, it is important to complement this analysis by assessing proposed investment behaviours using common economic criteria utilised in the appraisal of energy efficiency measures (Fleiter *et al.*, 2012; ERSE, 2013a). Both the reference and inefficient households were assessed with regard to an upgrade to the efficient profile.

The total initial investment was estimated at 7,580 Euro (Table 19). Since the savings margin was higher in the inefficient household than in the reference profile, economic criteria of proposed efficiency measures had better results in this case.

Overall, the payback period of each investment may be categorised from medium (2-4 years) to very long (>8 years) (Fleiter *et al.*, 2012). Only the upgrade of the lighting (for both profiles) and the climatization systems for the inefficient household meet the threshold of three years usually utilised in the assessment of energy efficiency measures (Fleiter *et al.*, 2012). The remaining investments

have higher payback periods, therefore making them less interesting from this criterion point of view.

Most investments have negative internal rates of return. Only three investments have positive values but with low to medium rates: the upgrade of the oven (IRR=11%) and of the climatization system (IRR=29%) in the case of the inefficient household; and the upgrade of the lighting system to LEDs in both profiles (IRR=15% and 5% for the inefficient and reference profiles, respectively).

Table 19 – Economic assessment of investment behaviours

Energy service	Technology	Useful life ^[1] [years]	Initial expenditure ^[2]	Net present value ^[3]		Payback ^[4] [years]		Internal rate of return ^[5]
				Ref→Ef	Ineff→Ef	Ref→Ef	Ineff→Ef	Ineff→Ef
Laundry	Laundry machine A+++	12	310 €	106 €	404 €	45	20	<0
Clothes drying	Tumble dryer A+++	12	1,200 €	-281 €	483 €	126	39	<0
Dishwashing	Dishwasher A+++	12	480 €	238 €	309 €	39	31	<0
Food refrigeration	Combined fridge and freezer A+++	15	470 €	1,212 €	2,056 €	14	8	<0
Cooking	Oven A+	12	700 €	2,802 €	5,675 €	9	4	11%
Leisure	Television A++	12	600 €	353 €	1,386 €	36	13	<0
Weatherising	Heat pump A+++	20	1,070 €	604 €	13,584 €	49	3	29%
Cleaning	Vacuum cleaner A	12	100 €	307 €	495 €	11	7	<0
Working home	Notebook	5	600 €	-238 €	327 €	62	17	<0
Lighting	LED	20	100 €	1,418 €	1,865 €	3	2	15%
Heating water	Flat plate solar collectors	20	1,950 €	3,629 €	8,918 €	21	8	<0
TOTAL			7,580 €					

Table notes: ^[1] (ERSE, 2013a); ^[2] Reference prices of technologies were taken from main retailers; ^[3] Net present value was determined according to the Consumption Efficiency Promotion Plan Rules (ERSE, 2013a) and comprised social benefits assessment (e.g., avoided cost of electricity supply and of CO₂ emissions, 0.0962€/kWh and 0.88€/kWh respectively) and a discount rate of 5%; ^[4] Payback was determined considering the cost of electricity as being 0.1602€/kWh, corresponding to one of the most common profiles of residential users (low voltage, simple tariff, contracted power of 6.9kW); ^[5] Internal rate of return was determined for half the useful life.

From a social point of view, the net present value is positive for all energy efficiency upgrades with the exception of the replacement of the tumble dryer and the notebook for the reference household, thus complying of the social test of the rules of the Plan for the Promotion of End-Use Energy Efficiency (ERSE, 2013a).

In short, if households behave rationally and follow strict economic criteria it is less likely they upgrade their appliances in the short-term and unfold potential savings. Although technology development over time tends to improve these criteria by reducing initial investment, the positive results of the social test justify the use of public funding for promoting behavioural changes in the scope of energy efficiency policies.

3.3.5 BEHAVIOURAL CHALLENGES IN BUILDING DYNAMIC MODELLING

Building dynamic simulations have been traditionally utilised to optimise buildings design and to improve their energy performance without a proper integration of occupants' behaviour, which led in some situations to inaccurate expectations of buildings energy performance (IEA, 2014). Yet, due to the characteristics of BEPS tools, such as being progressively user-friendly and widely used in building design or including specific models for energy flows (Tindale, 2004; Tronchin and Fabbri, 2008; Fumo *et al.*, 2010), they have become relevant tools to assess the behavioural impacts on energy consumption of the different energy services utilised by households. Nevertheless, these tools present some limitations when exploring the behavioural dimension, such as neither include behavioural parameters nor have adequate approaches to deal with occupants' behaviour uncertainty.

Future developments of building dynamic simulation tools are then required to facilitate the modelling of the different dimensions of occupants' energy behaviours (e.g., usage, investment, maintenance) and the multiple factors influencing the energy consumption activation chain (e.g., household characteristics and activities, energy behaviours, and personal profiles) (Lopes *et al.*, 2015). Further improvements are also necessary to incorporate specific savings according to energy behaviours, household profiles and energy performance of different appliances. Stochastic modelling (e.g., Monte Carlo methods) may also be incorporated to model behavioural variability and uncertainty. The integration of the behavioural dimension in BEPS tools may suggest forms of energy behaviours that, if changed in a real-world context, may lead to energy savings.

3.4 CONCLUSIONS

An integrative (both quantitative and qualitative) modelling approach of energy behaviours in the residential environment was presented in this chapter. Complementing existing literature, this approach has estimated the behavioural savings potential associated to different categories of energy behaviours (e.g., investment and usage) when using the various energy services in daily household activities (e.g., powering appliances, water heating, space heating and cooling, lighting). This approach enabled a thorough comprehension of the potential influence of household activities on energy consumption, while structuring the modelling process and facilitating the identification of saving opportunities. By combining expertise from engineering with the social sciences, this work also contributed to the development of a comprehensive, yet quantitative, modelling approach of occupants' energy behaviours in buildings, as recommended by the International Energy Agency (IEA, 2014).

Building energy performance simulations (using the Energy plus/Design-Builder® software) have estimated a significant behavioural savings potential associated with both usage and investment energy behaviours which may be materialised if energy behaviours are changed to more efficient patterns in the real-world. Results also showed that investment energy behaviours have a higher savings potential than usage behaviours, and that behavioural savings potential per energy service is proportional to the energy consumption breakdown. These findings suggest the need for real-world behavioural change interventions to previously assess households' energy behaviours and quantify energy consumption breakdown in order to maximise potential savings.

Even though a significant behavioural savings potential was estimated through the modelling approach herein developed, behavioural savings are known to be difficult to achieve in the real-world, which is confirmed by a reduced efficacy of behavioural change interventions (Gynther *et al.*, 2011; EEA, 2013). Effective savings may also become just a part of potential savings due to rebound effects (Galvin, 2014). Furthermore, results are somehow limited by the lack of validation of the behavioural profiles. Although the reference profile has been calibrated using a real-world sample, both efficient and inefficient profiles are hypothetical. Future improvements of this work should validate these profiles with real-world samples so a more accurate estimate of the behavioural impact on energy consumption is performed. Social sciences techniques such as surveys and interviews may be utilised in this process. Nevertheless, despite the limitations of the proposed modelling approach, it may be easily adapted and replicated in other segments of the population or other situations such as the non-residential setting.

Building energy performance simulations have shown to be stimulating approaches to be used when estimating the behavioural savings potential. However, existing BEPS tools, such as the Energy plus/Design-Builder® software, require further improvements to adequately incorporate the complexity of behavioural dimensions. In particular, this can be achieved by considering the different dimensions of occupants' energy behaviours (e.g., usage, investment, maintenance) and the multiple factors influencing the energy consumption activation chain (e.g., household characteristics and activities). Moreover, stochastic modelling techniques can be used to model behavioural variability and uncertainty.

In summary, estimating the potential savings associated with different energy behaviours is most important for a more effective design of behaviour change interventions. It enables focusing on behavioural actions that may maximise energy savings, but also contributes to empower households by providing them with detailed information on how their individual actions may impact energy consumption.

4 BEHAVIOURAL POTENTIAL TO FACILITATE THE SMART(ER) GRID ^{viii}

4.1 INTRODUCTION

The decarbonisation of the economy is an indispensable step towards sustainability, and the electric power industry is a critical part of this process. The evolution towards smart(er) grids is expected to enable the large-scale integration of low-carbon technologies, such as decentralised renewable resources, storage technologies, electric vehicles, and controllable demand along with conventional power generation, delivering power more efficiently and reliably (Hledik, 2009; EC, 2011; OECD/IEA, 2011c). Furthermore, smart(er) grids and associated technologies are foreseen to enable end-users to have greater management ability over their electricity consumption and to actively participate in the electricity market (EU, 2013).

Smart(er) grids are electricity networks that have been upgraded with information and communication technologies to monitor and manage the transmission of electricity from all generation sources to meet the varying electricity demand of end-users (EU, 2011; OECD/IEA, 2011c). In the generation, transmission and distribution sectors, the intelligence of the system relies on the use of advanced real-time monitoring systems, automated operation and power control tools optimising equipment use, mitigating disturbances through self-healing, improving reliability and stability, and avoiding blackouts, thus enabling a more efficient utilisation and management of the grid (OECD/IEA, 2011c). At the core of smart grids, the advanced metering infrastructure links end-users with the distribution network, allowing two-way communication between the utility and the meter. This infrastructure enables remote access to the meter for operational purposes (e.g., disconnect/reconnect users, send out alarms in case of problems), and provides access to real-time information on the electricity consumption of each end-user (Hledik, 2009; McDaniel and McLaughlin, 2009; OECD/IEA, 2011c; Wissner, 2011). While suppliers can use this information to establish energy consumption profiles and operate the network more efficiently, end-users can also benefit by managing their energy consumption patterns and changing to more efficient, differently timed, or less consumptive behaviours (EC, 2011; Wissner, 2011). The smart(er) grid infrastructure

^{viii} This chapter is partially based on [Lopes, M.A.R., Antunes, C. H., Janda, K. B., Peixoto, P., & Martins, N. 2016. The potential of energy behaviours in a smart(er) grid: Policy implications from a Portuguese exploratory study. *Energy Policy*, 90, 233-245. doi: 10.1016/j.enpol.2015.12.014]

may therefore increase energy awareness levels and significantly change customer-utility relationships (Darby, 2010; Wissner, 2011).

From the utility perspective, the technological context provided by smart(er) grids also offers an important opportunity to influence the final use of electricity to achieve changes in demand, which will improve the power grid operational performance (OECD/IEA, 2008a). For many years this demand flexibility has been promoted by electricity suppliers through centralised demand response and demand-side management activities (OECD/IEA, 2008a). It has since evolved to decentralised actions where market-based time-of-use financial incentives play a crucial role, particularly in the context of liberalised electricity markets (OECD/IEA, 2008a; Gyamfi and Krumdieck, 2011; Kim and Shcherbakova, 2011). Generically designated as demand response, these actions involve shifting demand from one time period to another, reducing demand through more efficient end-uses (including curtailment), and changing the supplier in response to price and product offerings (OECD/IEA, 2008a). For example, smart thermostats may automatically change air conditioning settings, and appliances may be temporarily turned off (e.g., electric water heaters) or their working cycle shifted (e.g., washing machines) when the electricity price exceeds a pre-specified threshold (Hledik, 2009; Faruqi *et al.*, 2010a). Furthermore, smart(er) grids are also expected to facilitate the large-scale penetration of decentralised small-scale renewable energy sources, storage technologies and electric vehicles (Hledik, 2009; OECD/IEA, 2011c; Wissner, 2011).

However, deciding whether to use, store or sell electricity back to the grid in the face of dynamic variables such as the price of electricity, weather conditions, comfort requirements, and electricity availability from decentralised renewable sources, is a very challenging decision process for small end-users thus requiring some form of automated support (Livengood and Larson, 2009; Chassin, 2010; Lopes *et al.*, 2012a; Soares *et al.*, 2014a). Technologies that provide this kind of support are considered “enabling technologies” and include advanced metering, automatic control devices, in-house communication and energy management systems and displays. The deployment of enabling technologies to provide cost-effective, real-time metering information, verification and control capabilities is essential to support small end-users in their daily decisions (OECD/IEA, 2011a). However, it is also anticipated that end-users will play an increasingly active role in the management of the electric power supply and demand (Giordano and Fulli, 2012; Foxon, 2013). Indeed, end-users are expected to shift from a passive role as consumers of electricity to an active role as co-providers in which, besides using electricity, they are involved in the management of energy resources (Geelen *et al.*, 2013). This further shift brings a novel dimension to energy behaviours, traditionally only focused on investment, maintenance and usage behaviours (Van Raaij and Verhallen, 1983), and to

their contribution in promoting energy efficiency. Understanding and foreseeing these changes and the behaviours' role and challenges in smart(er) grids is therefore crucial for developing energy behavioural interventions for facilitating the transition to smart grids.

Most research about demand response is designed using fictive circumstances to provide general estimates of technical and economic potential (Mohsenian-Rad *et al.*, 2010; Pedrasa *et al.*, 2010; Du and Lu, 2011; Zehir and Bagriyanik, 2012; Soares *et al.*, 2014b; Haoa *et al.*, 2015). Research is also based on studying pilot projects with small non-representative samples (Gangale *et al.*, 2013). In contrast, this study uses empirical research methods to explore the behavioural potential. This study is therefore necessarily located in a specific time and place, and assesses the willingness of people rather than the ability of things. It characterises current energy behaviours and considers future behavioural adaptations of end-users to the smart(er) grid through a web survey performed in July 2013 in Portugal to a representative sample of a specific segment of the population. It also explores end-users preferences towards enabling technologies, thus contributing to empowering end-users as co-providers in smart(er) grids, as recommended by Geleen *et.al.* (2013).

This work was developed in the context of a multidisciplinary project developing a demand responsive energy management system - the Energy Box - to be used to control, manage, and optimise both smart grid technologies and home electricity use (http://www.uc.pt/en/org/inescc/Projects/energy_box). This system aims to autonomously coordinate and optimise electricity management for small end-users, including storage and selling back to the grid (Livengood and Larson, 2009; Chassin, 2010; Lopes *et al.*, 2012a). For this purpose, users' preferences need to be properly understood and addressed, including constraints associated with household activities, the use and shifting of domestic loads, local renewable generation and electric vehicles.

In this chapter end-users' current behavioural adaptations, as well as their preferences for adopting enabling technologies in the future, such as the demand-responsive energy management system mentioned above, are discussed. Factors influencing these behavioural adaptations are analysed and strategies aimed at enabling these adaptations proposed for future research.

This chapter is divided in four sections. Section 4.2 describes the methods used to estimate the behavioural potential in smart(er) grids. Section 4.3 presents and discusses the results obtained, and section 4.4 summarises the conclusions.

4.2 METHODS

This section discusses how current and potential behaviours were studied, the empirical research process, and the design of the survey instrument.

4.2.1 STUDYING BEHAVIOURS

Studying energy behaviours is a complex task since they hold multiple dimensions. For the purpose of this work, energy behaviours are considered to be observable acts related to energy consumption and include investment, maintenance, and usage behaviours (Van Raaij and Verhallen, 1983). **Investment behaviours** involve the purchase of new equipment; **maintenance behaviours** involve the repair, maintenance and improvement of energy consuming equipment; and **usage behaviours** refer to the day-to-day utilisation of buildings and equipment. In the context of smart(er) grids, energy behaviours also comprise actions required to **manage energy resources** (e.g., leading to producing electricity through mini/microgeneration or storing electricity in electric vehicles) (Geelen *et al.*, 2013).

Research on residential energy consumption may use qualitative tools such as surveys, interviews, focus groups or other form of survey-based methods collecting data on end-users' behaviour (Crosbie, 2006). There are limitations to using surveys for assessing behaviours, since real-life conduct can diverge considerably from statements made in answering a survey (Gangale *et al.*, 2013). Moreover, a household's future response to imagined situations and technologies is difficult to assess through an a priori standardised survey. Survey questions also unavoidably produce framing (Van de Velde *et al.*, 2010) or anchoring (Slovic *et al.*, 2002) effects which limit both the shape of respondents' answers as well as the conclusions that can be reliably drawn from them. Despite these limitations, surveys are a common tool used in research exploring both existing and hypothetical scenarios, such as the willingness-to-pay (Hansla, 2011). They reach a large number of respondents in a short amount of time, are a familiar tool, and are less intrusive than other exploratory methods. For these reasons, a web-based survey was selected as the main research method.

4.2.2 SURVEY SAMPLE, DELIVERY AND RESPONSES

In 2013, the percentage of Portuguese residents with a higher education degree represented 15% of the overall population (Pordata and INE, 2015a). In the same year, the total number of higher education teaching staff in Portugal was estimated to be 33,582 people (Pordata, 2014), and the full set of potential respondents covered about 24% of this population segment. The use of this sample limits the extrapolation of these results to the overall population. Nevertheless, studying this sample provides a vision of a relevant population segment, i.e. typical “early adopters” on the diffusion curve of technological innovations (Rogers, 2003).

This population segment has an income level above the national average, and wide-ranging access to the internet (mobile and at home). Literate groups are assumed to have a higher savings potential than the average citizen, more likely acknowledge the importance of energy efficiency, more receptive to smart grids and associated technologies, and thus more willing to participate in a research on this topic. These characteristics also contributed to improve the rate of answers since web-based surveys possess a low rate of answers in less educated samples (Divard, 2013). The survey was presented to participants through e-mail and a web platform to facilitate respondents’ participation (since they use e-mail and web on a daily basis) and to minimise data treatment errors.

The survey was performed during June and July 2013 to a sample of 8,000 professionals from higher education institutions (mostly composed of university faculty) through e-mail contacts and further expanded through a snowball strategy. Hence, it is not possible to estimate the final number of professionals reached. A total of 1,612 answered surveys were received (circa 20% response rate). Surveys lacking more than 5% of answers were eliminated, making a total of 1,084 surveys analysed. Results were treated using descriptive statistics and questions lacking more than 5% of answers were not considered (such as the case of the assessment of the willingness to accept the control of some appliances: clothes dryer, air conditioning system and water heating system).

4.2.3 SURVEY DESIGN

The survey included 44 questions using mainly a closed format, but open questions were also included. As shown in Table 20 and Table 29 (in appendix), the survey covered basic socio-demographic and geographic variables, then asked respondents about current behaviours and possible future behavioural adaptations to the smart grid and associated technologies.

Current behaviour questions addressed a range of energy behaviours, energy beliefs and literacy, participation in the liberalised electricity market, the effects of the economic crisis on energy behaviours, and the adoption of smart grid technologies. In this work current energy behaviours were characterised using a selected list of self-reported energy usage behaviours (e.g., lighting, use of appliances, thermal comfort), investment, control and monitoring behaviours. Respondents were asked to assess the frequency usage energy behaviours were performed in the household in the last year. Questions used a 5-point Likert scale when assessing variables relatively to frequency, importance, availability, flexibility, probability and agreement.

Preferences concerning hypothetical smart grid technologies, demand shifting, and direct load control were assessed for a future “smart(er) grid” scenario. The complexity associated with this scenario was simplified in the survey since the smart grid topic is still unfamiliar for the majority of end-users. Hence the “smart grid” expression was not presented to respondents and, as an alternative, they were presented with a hypothetical future scenario of dynamic pricing of electricity (having an hourly variation) (Table 20 and Table 29 in the appendix).

Table 20 – Survey structure and design developed for assessing behavioural adaptations to smart(er) grids

COMPONENTS	DESCRIPTION	
Socio-demographic characteristics	Gender, age, marital status, education level, professional activity, employment status.	
Geographical location	Postal code identification.	
Current Energy Behaviours	Energy behaviours	Frequency of performing specific behaviours such as: efficient use of lighting and appliances; characterisation of the current use of air conditioning system; investment in efficient equipment; use of passive techniques to improve thermal comfort; shifting appliances to cheaper periods; monitoring electricity consumption; involvement of the household.
	Beliefs and literacy	Beliefs on energy savings (responsibility, consequences to the environment and the economy) and energy literacy (advantages of energy efficiency), adapted from (Black <i>et al.</i> , 1985).
	Influence of economic crisis on energy behaviours	Identification of energy behaviours which have changed: use of appliances, reading the electricity bill and the meter, change of the electricity contract (power, tariff), shifting appliances to cheaper periods, buying efficient equipment, home improvements, use of renewable energy sources. Identification of motives for not changing (limitations to change such as need and effort).
	Participation in the liberalised retail energy market	Change of the energy supplier and associated motives, knowledge of dissemination campaigns on this topic.
	Current adoption of smart grid technologies	Use of electricity monitoring and controlling devices, controlled appliances. Adoption of hybrid or electric vehicles and small generation systems based on renewable energy sources.
	Behavioural Potential	Adoption of hypothetical smart grid technologies
Flexibility for demand shifting and change the household routines		Willingness to change the time-of-use of electrical appliances, factors involved in this decision (e.g., savings, environment, being at home, electricity supply, energy services provision, and interference with home activities).
Willingness to accept load control		Willingness to accept direct load control performed by the utility, both in the present context and in a hypothetical smart grid scenario (namely dynamic electricity pricing). Decision factors involved (e.g., damaging equipment, override, savings, privacy, trust, information, guarantees, interference with home activities, environment, energy supply), types of control and preferred appliances (laundry machine, dishwasher, tumble dryer, and water heating system).

4.3 RESULTS AND DISCUSSION

This section provides an analysis of the survey results, including relevant socio-demographic variables, current behaviours, and hypothetical future behaviours.

4.3.1 SOCIO-DEMOGRAPHIC CHARACTERISTICS

The respondents (N=1,084) had an average age of 46.87 years ($\sigma=9.53$)^{ix}, 55.4% were men and 43.6% women. The majority of the respondents were highly educated (97.7% had a higher education degree, which contrasts with the national value of 15.0%), 93.1% were employed in highly qualified professions (e.g., teaching staff) and 72.6% married. The sample was geographically spread in the country, with 17.3% from the north, 53.0% from the centre region, 26.2% from the Lisbon urban area, and the remaining 3.5% from the south region and islands. The composition of respondents' household was not characterised, which constitutes a limitation of this study. However, considering the respondents' age, marital status and income, it is expected families to be composed by two adults with the possibility of having small children^x.

4.3.2 CURRENT ENERGY BEHAVIOURS

This section characterises current energy behaviours found in the survey, including frequent behaviours, literacy and beliefs, effects of the current economic context, participation in the liberalised energy market, and adoption of existing smart grid-related technologies.

4.3.2.1 Frequent behaviours

Results show households frequently engage in twelve different energy usage, control, and investment behaviours. Answers to these questions used a Likert scale with 1="never" and 5="always". Across all respondents and behaviours, the results show a mean of 4.65, corresponding to a very frequent practice (Table 21). There are, however, two less frequent energy behaviours: providing meter readings to the utility and buying more efficient equipment. 76.0% of respondents stated they read the electricity bill "frequently or even "always". However, they rarely provide meter readings to the electricity supplier (32.6%). According to the Directive 2009/72/EC, 80% of end-users

^{ix} The average age of the Portuguese population in the last census (2011) was 41.83 years old (INE, 2013).

^x The average composition of a Portuguese household in 2013 was 2.6 individuals (Pordata and INE, 2015a).

are expected to be equipped with smart metering systems by 2020 (EC, 2009). The majority of Portuguese end-users still possess meters requiring manual readings (either performed by the utility technicians or end-users) to enable more accurate billing. Reasons may be associated with a potential lack of time to perform this task, reduced level of importance attributed to it, or disinterest since it is performed by the utility at least once a year. These and other motives should be assessed in future developments of this work.

A principal component analysis of self-reported behaviours enabled reducing energy behaviours to four dimensions explaining 52.1% of the variance^{xi}: avoiding waste and stand-by consumption; improving thermal comfort by taking advantage of passive strategies; auto control and monitoring; and reducing energy costs (e.g., shifting demand to take advantage of dual time-of-use tariffs).

Table 21 – Characterisation of energy behaviours (1=“non-applicable”, 2=“never” to 6=“always”)

CATEGORY	SELF-REPORTED ENERGY BEHAVIOURS	MEAN	σ
Usage	Switching off the lights in empty rooms	5.59	0.58
	Keeping doors and windows closed when they are being warmed or cooled	5.39	1.01
	Switching off TV when nobody is watching it	5.22	0.85
	Switching on heating/cooling equipment only on occupied rooms	5.26	1.23
	Switching off appliances directly on the switch to avoid stand-by consumption	4.70	1.24
	Insulating windows and doors	4.69	1.42
	Switching off appliances using central plugs to avoid stand-by consumptions	4.30	1.41
	Switching on washing machine/dryer during the cheapest periods	4.13	1.98
Control and monitoring	Reading the electricity bill	5.11	1.08
	Talking with the dwelling occupants about electricity consumption and savings	4.02	1.53
	Providing the meter readings to the electricity supplier	3.60	1.54
Investment	Buying more energy efficient equipment	3.78	2.20

4.3.2.2 Literacy and beliefs

When assessing energy behaviour determinants such as energy literacy and beliefs, results show respondents have a general positive perception about saving electricity and are aware of its importance to the economy (83.9% stated “totally agree” or “agree”), the power grid management (72.9%) and the environment (97.4%) (Table 22). They also recognise their own responsibility in this process (92.8%) and consider saving electricity to be compatible with their daily lives, neither disrupting home activities nor generating inconvenience (56.7% stated “disagree” and “totally

^{xi} Varimax rotation with Kaiser Normalisation, KMO=0.7, Bartlett's test of sphericity $p < 0.001$, Alfa of Cronbach ≥ 0.5

disagree” to disrupting the household daily activities; 62.5% to spend too much time performing these activities).

A principal component analysis of energy behaviour determinants enabled reducing them to two dimensions explaining 50.9%^{xii} of the variance: potential impacts on the daily life and recognition of their own responsibility.

Table 22 – Assessment of personal determinants on saving electricity (1=“totally disagree” to 5=“totally agree”)

DETERMINANTS	SAVING ELECTRICITY...	MEAN	σ
Energy literacy	...improves the environment	4.64	0.56
	...contributes to energy security by minimising energy imports	4.38	0.71
	...improves the national economy	4.23	0.83
	...improves the power grid management	3.98	0.81
Beliefs	... is a societal obligation	4.54	0.68
	...represents economic advantages to the household	4.38	0.62
	...begins with my example	4.37	0.72
	...is a consumer responsibility	4.12	0.81
	...disrupts household daily activities	2.50	0.98
	...spends too much of my time	2.30	0.93
	...implies a lifestyle with reduced comfort	2.20	0.94
	...creates more disturbance than it generates benefits	2.06	0.86

4.3.2.3 Current economic context

Since this study has been developed during a particular context of enduring economic downturn, the survey asked respondents to consider this effect on their energy behaviours.

The majority of the respondents (56.9%) stated they have not changed the way of using electricity in their households due to this economic context. The main reason given was related with their beliefs of already saving as much electricity as possible. This motive, also found by previous studies (Gouveia *et al.*, 2011), may be invoked by a gap on specific information on how to save energy and increase energy efficiency levels. It further may be due to the inertia of changing behaviour.

The remaining 43.1% of respondents stated they did make changes to their electricity use due to the economic context. Specific energy behaviour changes comprised: curtailment actions (72.8%); shifting the use of electricity to cheaper periods (42.6%); investing in more efficient appliances

^{xii} Varimax rotation with Kaiser Normalisation, KMO=0.9, Bartlett's test of sphericity $p < 0.001$, Alfa of Cronbach ≥ 0.5

(34.7%); reading the electricity bill or the meter (31.0%); altering the contract to change the electricity tariff (18.6%) and contracting a lower power value^{xiii} (8.4%); adopting renewable energy resources (7.7%); and making home improvements (4.7%) (Figure 17). Curtailment actions consisted in a general effort to reduce the use of appliances, although they were not specified. Other measures indicated by respondents in the open format questions included switching energy suppliers, switching fuels, using enabling technologies (such as in-house displays and programming devices) and implementing passive actions to promote thermal comfort.

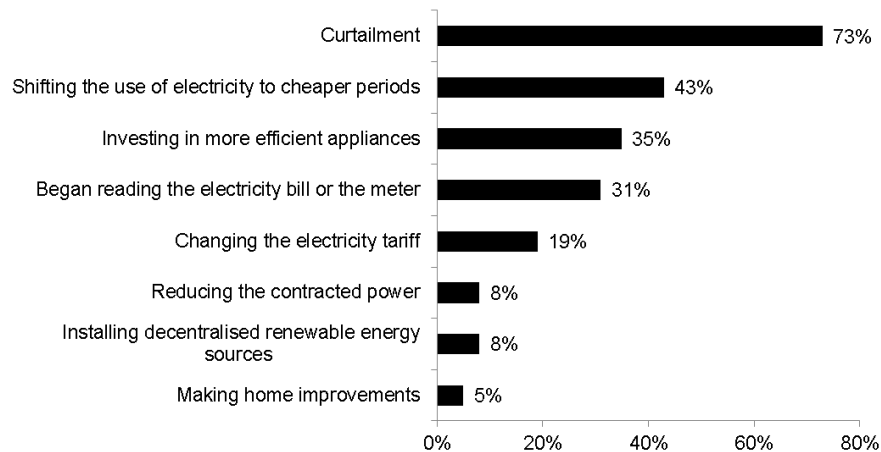


Figure 17 – Energy behaviours changes due to the economic crisis

End-users are mainly performing curtailment to reduce consumption, but they are also implementing efficiency measures to use electricity in a more rational way (e.g., investing in more energy efficient appliances, optimising their energy supply contracts, shifting electricity use to cheaper periods). Solutions requiring larger investments such as the adoption of local renewable energy sources or home improvements are implemented in a lower scale, probably due to financial restrictions. Although it is not possible to estimate the level of savings associated with these behavioural adaptations, these results are in consonance with Portuguese energy statistics indicating a reduction of 17% of the households' primary energy consumption from 2004 to 2013 (DGEG, 2015).

^{xiii} In the Portuguese residential sector low voltage electricity may be supplied through eight power levels ranging from 3.45 to 20.7 kVA. Very often consumers contract a higher value than they need, which constitutes an opportunity for economic savings.

4.3.2.4 Participation in the liberalised energy market

Enrolling in the liberalised energy market constitutes an indication of end-users' awareness of energy supply activities.

In July 2013^{xiv}, 33.5% of the survey respondents had enrolled in the liberalised energy market. Compared with the national enrolment rate at the same time, 46% (ERSE, 2013b), this shows that respondents were roughly 25% less likely to join the liberalised energy market than the average population.

The main barriers invoked by respondents who have not enrolled in the liberalised retail energy market (61.9%) to justify their inaction comprised the lack of information (stated by 40.5% of respondents), inexistence of motivating prices (33.5%), satisfaction with the prevailing supply conditions (23.7%), lack of trust in the energy suppliers (14.8%), peer influence (7.2%), and unawareness of the liberalised energy market (4.8%) (Figure 18). Even though 77.9% were aware of the dissemination campaign implemented by the national consumers association, only 6.8% of those joined the liberalised market under this campaign.

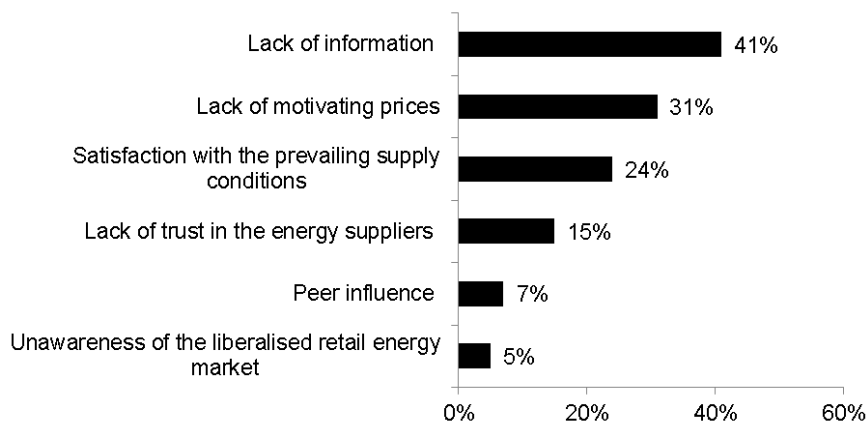


Figure 18 – Barriers for not joining the liberalised retail energy market

In fact, although the majority of the respondents (95.2%) was aware of the mandatory need of changing into the liberalised market - a more recent national wide study refers a similar value, 93% (Accenture, 2014) - 40.5% referred the lack of information as a barrier. Savings was indicated as the second motive. Although this was not further explored in this study, a recent research referred

^{xiv} Period of implementation of the survey.

Portuguese consumers to be dissatisfied with the price of energy, also indicating competitive offers as being one of the main motivations to adhering to the liberalised market (Accenture, 2014). Trust was pointed out as the third reason, which is in accordance with previous research on the need of changing the relationship between consumers and utilities, particularly emphasising trust and credibility (Darby, 2010; Gangale *et al.*, 2013). However, a more active role in the energy market consists not only in leaving the regulated energy tariffs and contracting energy within the liberalised market, but also in frequently changing the energy supplier in face of competitive offers. Recent assessments have revealed Portuguese consumers have not yet internalised this practice since only 3% of residential consumers within the liberalised market have changed their energy suppliers more than once (Accenture, 2014).

Future improvements of this work should also assess other influencing factors for enrolling in the liberalised energy market and switching energy suppliers, such as the availability of time to study different offers (particularly in working segments of the population), the level of detail of information provided to end-users and how much competitive offers should be to promote the enrolment or the change of energy suppliers.

4.3.2.5 Adoption of smart grid technologies

The transition to smart grids also comprises the increasing adoption by end-users of technologies such as demand-responsive enabling technologies, electric vehicles and local micro-generation. This work evaluated the adoption of electricity monitoring devices, controlling functions of appliances or specific devices to shifting demand, adoption of electric vehicles and micro-generation (e.g., micro wind turbine or photovoltaics).

Results revealed that only 7.0% of respondents used electricity monitoring devices (e.g., in-house displays) despite being particularly aware of their energy consumption (76.0% of them stated to read the electricity bill “frequently” or “always”).

28.7% currently use time-of-use controlling functions on their appliances (e.g., programming or time-delaying). The most frequently controlled appliance is the laundry machine (by 15.4%), followed by the dishwasher (12.0%), the electric heating system (9.4%), the water heating system (5.8%), and to a lesser extent the tumble dryer (3.2%) and the air conditioning system (1.9%) (Figure 19). These results are similar to Stamminger and Anstett (2013) findings, where one third of their sample used the start-time delay function of their appliances. However, the results of this study were influenced by the ownership rate of appliances and their technical functionality, which were not characterised

in this survey. National statistics indicate the following appliance ownership rates: laundry machine 91%, dishwasher 41%, tumble dryer 19%, air conditioning system 7%, electric water heater 3% (INE and DGEG, 2011). Hence, appliances ownership must be considered when assessing the potential for adopting demand-responsive enabling technologies. Nevertheless, these results illustrate that almost one third of respondents already plan their electricity usage and shift it when appropriate to benefit financially from different existing time-of-use electricity tariffs.

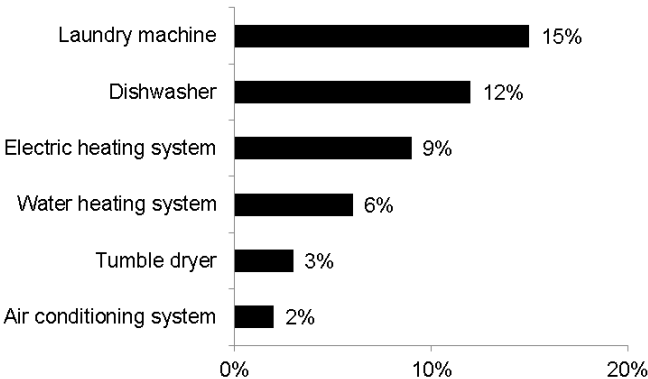


Figure 19 – Appliances controlled by respondents

Only 3.0% of respondents were both consumers and producers of electricity (prosumers). However, this value is 15 times higher than the national rate of 0.2% (MEE, 2014). Similarly, 3.1% also owned an electric or hybrid vehicle, a value at least 30 times higher than the national ownership rate of less than 0.1% (MEE, 2014). This may be due to the higher income levels and environmental awareness of this population segment.

4.3.3 FACILITATING FUTURE BEHAVIOURAL ADAPTATIONS

In face of the on-going evolution of the energy system into smart(er) grids, end-users are expected to enrol into this dynamics, adapt to this new socio-technological context and change their regular behaviours. In the previous section, this study assessed respondents’ existing energy behaviours. This section considers their willingness to adopt hypothetical smart grid technologies, in particular an energy management system like the “Energy Box”, shift demand and adapt household’s routines, and accept load control actions performed by the utility.

4.3.3.1 Adopting an “Energy Box”

When facing a future hypothetical scenario with an hourly change of the electricity price, 71.0% of respondents stated they would be willing to purchase an automated control device - such as the Energy Box - to help them control their electricity use.

A number of factors would, however, influence this purchase (Table 23). Respondents indicated it was “very” to “extremely important” that the device would cause no damage to appliances (95.3%), save energy and reduce energy costs (93.9%). They also wanted to have full control of the device (87.9% stated to be “very important” and “extremely important”), expected it would be easy to install and use (80.7%), have a low cost of acquisition (82%), provide useful information (86.9%), and have a friendly user interface (74.4%). Less importance was attributed to the design (aesthetics) factor (only 18.4% of respondents stated to be “very important” and “extremely important”). These results further detail factors for adopting smart home devices previously explored by Paetz et al. (2012).

Table 23 – Assessment of factors influencing the potential purchasing of an “Energy Box” (1=“not important” to 5=“extremely important”)

INFLUENCING FACTORS	MEAN	σ
Causing no damages to appliances	4.70	0.57
Saving electricity and reducing costs	4.54	0.62
Full control of the device	4.46	0.73
Low cost of acquisition	4.36	0.78
Quality of the information	4.35	0.73
Trust in the technology	4.34	0.72
Easiness of installation & configuration	4.22	0.79
Easiness of use	4.20	0.81
Portfolio of functionalities	4.10	0.79
Friendly interface	4.10	0.82
Design	2.63	1.05

Respondents were also asked to assess the importance of potential functionalities of this device (Table 24). All the functional options provided were considered at least “very important”: real time information on consumption and cost (64.9%) and on control of appliances (67.1%); turning appliances off (78.8%); eliminating stand-by consumption (70.2%); and automated programming to shift consumption (73.7%) and to save electricity (73.6%). Preferred functionalities were mainly focused on maximising savings rather than feedback features, which should be considered in the development of the “Energy Box”.

Table 24 – Assessment of functionalities of an “Energy Box” (1=“not important” to 5=“extremely important”)

FUNCTIONALITIES	MEAN	σ
Turning off appliances	4.19	0.91
Automated shifting of appliances to cheaper periods	4.07	0.93
Automated programming to save electricity	4.03	0.95
Eliminating stand-by consumption	3.97	0.98
Feedback on load control	3.94	0.93
Real time feedback on electricity savings	3.90	0.94

Given the equivalent level of importance given to both purchase decisions and functionalities, future research should consider alternative methods to elicit preferences to improve discrimination (e.g., ranking, limiting options), bearing in mind the limitations when capturing preferences pertaining to future scenarios. Nevertheless, results showed a positive predisposition towards “smarter” technologies, particularly in a context of dynamic pricing, which reinforces previous research (Krishnamurti *et al.*, 2012; Paetz *et al.*, 2012), while unveiled specific preferences that are essential for designing user-friendly enabling devices and empowering end-users’ interaction with the smart energy system.

4.3.3.2 Willingness to shift demand and adapt household routines

Shifting electricity demand from one period to another is at the centre of demand response programmes and smart(er) grids contexts. But changing demand in time may involve shifting household activities and their routines. Although the majority of the smart grid literature assumes end-users as rational individuals who will change their electricity usage given the adequate economic incentives, this study explored other decision factors influencing whether end-users are willing, or not, to shift their household routines.

When asked about their willingness to change the time-of-use of their appliances, 68.1% of respondents stated they would be available to perform that change, even without any direct benefit (this value increased to 78% when considering those who already shift appliances use). For example, this percentage was much higher (98%) in a German study in which savings were generated (Stamminger and Anstett, 2013).

The shifting potential of six specific appliances was considered: the laundry machine, the tumble dryer, the dishwasher, the electric water heater, the air conditioning system and electrical heaters (Soares *et al.*, 2014b). Only the willingness to shift the laundry machine and the dishwasher could be analysed, since the other appliances had missing responses rates above 5%. The potential to shift

the time-of-use of both appliances was high: 72.1% and 75.3% of respondents stated to be “flexible” to “extremely flexible” in shifting laundry and dishwashing, respectively. This high feasibility is probably due the specific characteristics of these activities. For example, the laundry and the dishwashing can be performed at night, or when the users are away. Shifting these activities may already be embedded in the daily routines of households with a dual time-of-use tariff. Hence, during the transition to smart(er) grids demand response programmes may prioritise actions already embedded in end-users' daily lives and gradually introduce less common actions.

Although similar in some points with Stamminger and Anstett (2013) findings, the results of this study differ on the preferred appliances for demand shifting, namely relatively to the tumble dryer which was indicated as one of the main shifting appliances in Germany but does not occur in this study. Differences between ownership rates may justify these differences, thus reinforcing the role of this factor in the design of demand response programmes.

In general, most important decision factors for accepting demand shifting included electricity savings (considered at least “very important” by 91.3% of respondents), not compromising the energy service (82.8%) and environmental benefits (77.8%) (Table 25). Not interfering with the domestic activities (66.2%) and electricity security (63.7%) were considered of medium importance. The presence of the householders at home when appliances are switched on was considered the least important factor (36.8%). The motives underlying the unwillingness to shift demand also reflected the importance given to electricity savings and to not compromising neither the energy service nor households activities, although with a lower importance, which may suggest hidden motives requiring to be addressed in a future developments of this work. The presence of the householders at home when appliances are switched on was considered a more important factor for those respondents unwilling to shift their demand, thus indicating this to be a relevant factor to be considered.

Although results show demand shifting in this segment of the population to be responsive to rational economic motives such as savings, it is also strongly influenced by the compliance with households' activities and some sense of control over appliances, as well as environmental benefits and security of electricity supply. These results provide further insights on previous research, which only indicated savings, environmental benefits and comfort as the main motivational factors for demand shifting (Gangale *et al.*, 2013).

Table 25 – Decision factors influencing willingness to accept demand shifting in both groups (1=“not important” to 5=“extremely important”)

DECISION FACTORS	WILLING	UNWILLING
Electricity savings	4.55, $\sigma=0.67$	3.94, $\sigma=0.94$
Service is performed in due time	4.21, $\sigma=0.78$	3.96, $\sigma=0.94$
Environmental benefits	4.20, $\sigma=0.84$	Non applicable
Interference with households activities	3.87, $\sigma=0.95$	3.75, $\sigma=1.06$
Security of electricity supply	3.79, $\sigma=0.96$	Non applicable
Presence of household at home	3.09, $\sigma=1.20$	3.59, $\sigma=1.17$

The majority of the respondents (89.4%) stated they would change the way they use electricity in face of a future hypothetical scenario with an hourly change of the electricity price. From the list of behaviours potentially to be adopted (Table 26), they revealed preferring load shifting (considered at least “very likely” by 85.4%) and using control devices (59.8%) rather than paying attention to electricity prices (41.6%) or adopting decentralised renewable energy sources (25.3%). Only 20.9% were willing to accept load shifting performed by the utility. While attention to dynamic electricity prices may result in information overload thus leading end-users to more convenient solutions such as using enabling technologies to load shifting, they prefer maintaining their own control not allowing utilities to perform load shifting through direct load control actions. These results also suggest end-users’ preferences towards lower cost investments, rather than higher investments such as renewable energy sources.

Table 26 – Potential behaviours to be adopted in face of a future hypothetical scenario with an hourly change of the electricity price (1=“very unlikely” to 5=“very likely”)

DECISION FACTORS	MEAN	σ
Shifting loads to cheaper periods	4.29	0.75
Use of enabling technologies	3.72	0.95
Paying attention to electricity prices	3.27	1.09
Invest in decentralised renewable energy sources	2.84	1.14
Accept shifting performed by the utility	2.41	1.19

The motives invoked by 10.6% of respondents for not changing their behaviours were mostly related with the belief that the effort required to change would outweigh any potential advantages (mean 3.42, $\sigma=1.10$). This group also noted changing electricity usage had limitations associated with the household routines (mean 4.05, $\sigma=0.82$). In fact, electricity is used to provide energy services required by the household activities, and hence attention should also be paid on rethinking the household practices and activities and not only on shifting the appliances operation *per se* (Shove

and Walker, 2010). However, household activities have specific dynamics, which may constrain changes. Ultimately, there are shifting limitations imposed by the household characteristics and pattern of activities, which should be considered in demand response programmes.

Strategies aiming at facilitating the willingness to shifting energy demand should prioritise actions already embedded in end-users' daily routines and gradually introduce less common actions, while ensuring energy savings and no interference with households' activities. A previous detailed understanding of households' activities and energy behaviours, appliances ownership and assessment of shifting potential is paramount. In this population segment enabling technologies may facilitate this process as far as end-users maintain the control over control actions. This is important information to the design and development of enabling technologies such as the "Energy Box".

Future developments of this work should consider other exploratory tools (e.g., open format questions and interviews) to unveil hidden factors associated with shifting demand and further explore end-users' demand shifting flexibility.

4.3.3.3 Enabling direct load control

Although direct load control performed by utilities is a typical dimension of demand response programmes in the context of smart grids in other countries (Newsham and Bowker, 2010; EU, 2013), it has had limited developments in the Portuguese context. This study explored end-users' availability to accept different load control actions performed by the utility over appliances, such as shifting their time-of-use, turning them temporarily off during more expensive tariff periods or redefining their operational settings (Soares *et al.*, 2014b).

The majority of the respondents (65.1%) was not willing to accept direct load control from the utility, even in a hypothetical future scenario of dynamic electricity pricing. Only 34.9% were willing to accept the control of their appliances by the utility. The minority of respondents willing to accept load control was more willing to accept shifting the laundry machine (mean 4.15, $\sigma=1.02$) and the dishwasher (mean 4.16, $\sigma=0.98$) than to redefine the settings of the fridge or the freezer during most expensive periods (mean 3.25, $\sigma=1.31$). Once again, already embedded practices such as shifting the laundry and the dishwashing are prioritised in favour of less common actions. It is also possible that the reduced flexibility to redefine the settings of the fridge/freezer is originated by the belief that these actions may damage refrigerated and frozen food. For utilities to travel this path, additional evidence need to be provided to assure end-users that there is no potential danger to their food from small changes to refrigeration cycles.

Both the unwilling and the willing groups considered all the decision factors provided as “very” to “extremely important” to justify their decision, although there were some differences between both groups (Table 27). While the “willing group” attributed less importance to the security of electricity supply, to the “unwilling group” the most relevant factors were the override option, privacy issues, feedback about control actions, the existence of a pre-existing agreement to perform these actions, and the potential interference with the household activities. In the latter group, the risk of damaging appliances, electricity savings and trust in the utility were less important decision factors to accept direct load control from the utility.

The interference with the private domain arises as one of the most relevant decision factors when assessing the willingness to accept load control. Although this is aligned with the prevailing literature (Krishnamurti *et al.*, 2012; Paetz *et al.*, 2012), further specific dimensions were assessed that require to be taken into account in the design of demand response programmes.

Future developments of this work may also utilise other exploratory tools to both elicit potentially compromising dimensions and motivating end-users to accept direct load control.

Table 27 – Decision factors influencing willingness to accept direct load control from the utility in both groups (1=“not important” to 5=“extremely important”)

DECISION FACTORS	WILLING	UNWILLING
Risk of damaging appliances	4.73, $\sigma=0.55$	3.59, $\sigma=1.21$
Electricity savings	4.69, $\sigma=0.57$	3.65, $\sigma=1.14$
Trust in the utility	4.46, $\sigma=0.73$	3.66, $\sigma=1.17$
Override option	4.54, $\sigma=0.71$	4.37, $\sigma=0.92$
Privacy issues	4.48, $\sigma=0.82$	4.45, $\sigma=0.82$
Provision of feedback (e.g., control actions, savings)	4.42, $\sigma=0.71$	4.29, $\sigma=0.91$
Pre-existing agreement and prior notice	4.35, $\sigma=0.76$	4.28, $\sigma=0.95$
Environmental benefits	4.28, $\sigma=0.82$	Non applicable
Risk of interference with household activities	4.11, $\sigma=0.11$	4.20, $\sigma=0.92$
Security of electricity supply	3.99, $\sigma=0.98$	Non applicable

Moreover, although from a technical point of view water heating and air conditioning systems are also considered interesting appliances to be controlled under load control interventions, the ownership rate of these appliances in Portugal is very low: 3% and 7%, respectively (INE and DGEG, 2011). These ownership rates significantly limit the use of these appliances in real and large-scale interventions. In addition, the way households utilise air conditioning systems may also influence load control actions and limit load control savings potential. For example, only 12.2% of the respondents owning air conditioning systems stated always keeping it turned on in a constant

temperature, while 38.6% always turned it on temporarily for cooling or heating a room. Accordingly, both appliances ownership rates and usage energy behaviours are important variables to be assessed when designing effective demand response programmes.

Similarly to demand shifting, load control programmes should also prioritise control actions over practices already embedded in households' daily lives. Unusual control actions should be previously presented and explained to end-users and gradually introduced through pilot groups, while providing detailed feedback. Furthermore, strategies to foster the willingness to accept load control should improve the building of trust between end-users and the electricity utilities (through, for example, increased transparency, personalised services, detailed contracts specifying authorised load control actions or even creating insurance policies to compensate possible damages), and providing detailed information on the control actions, both before and after controlling events. Load control actions should also be programmed not to interfere with the household usual activities, and an override option should be always provided to end-users. From the regulator perspective, rules should be established and publicised to guarantee end-users' rights and avoid potential misuse of load control.

4.4 CONCLUSIONS

The transition to smart(er) grids is an on-going process that may both shape and be shaped by end-users' energy behavioural adaptations. This study used a web-based survey to explore the potential for behavioural adaptations of a statistically representative sample of a segment of Portuguese society, highly educated and with an above average income, as a good proxy for early adopters of smart grid technologies. The results of this survey give an empirically grounded indication of how the smart(er) grid in Portugal will unfold, as well as useful insights for future research.

Enrolling in the liberalised energy market is generally considered to be essential for the deployment of demand response programmes in smart grid contexts (OECD/IEA, 2011a). Results have shown this segment had a 25% lower participation rate in the liberalised retail energy market than the national value, so from this indicator the assumption about this sample's participation in the smart(er) grid was not supported. Factors such as information, prices, satisfaction with the present supplier and trust were considered by this sample as the most important factors for not joining the liberalised energy market, but peer influence should not be neglected as well. Facilitating end-users' involvement in energy supply activities must therefore include providing detailed and tailored information on the process and consequences of changing energy suppliers, use real examples like opinion makers as case studies, offer competitive and personalised services, and regulate the market to improve transparency and end-users' protection.

During the transition to smart(er) grids it is also expected end-users increase their **adoption of smart grid technologies**, such as demand-responsive enabling technologies, electric vehicles and decentralised generation. The survey showed this market segment has a positive predisposition towards "smarter" technologies, with a significantly higher ownership rate of decentralised renewable energy sources and electric/hybrid vehicles than the national average. Moreover, they already use controlling functions of appliances or specific devices to shifting demand to benefit from cheaper electricity tariffs, and they are willing to adopt a demand responsive enabling technology to support their actions in a future dynamic pricing scenario. Hence, this population segment acknowledges the usefulness of "smarter" technologies and uses them when required to minimise energy bills. The most important decision factors influencing the adoption of these technologies comprise the safety of use, savings generated, full control, cost, feedback content, being user-friendly and the portfolio of functionalities, while the least important factor is design. The preferred functionalities are mainly facilitators of energy savings (e.g., turning off appliances, eliminating stand-by, demand shifting) and as the least preferred are the feedback on energy consumption and

load control. This difference may suggest the importance for manufacturers to develop different and complementary “smarter” technologies, such as energy management systems more focused on optimising and controlling energy consumption, and displays aimed at providing feedback to end-users.

Shifting demand will expectedly be at the centre of demand response programmes in smart grids and this particular segment self-reports performing this action frequently. Although also driven by rational economic motives such as savings, this segment is responsive to the compliance with household activities, a sense of control over the appliances, and values incorporated in contributions to society, such as environmental benefits and security of electricity supply. In this population segment enabling technologies may facilitate shifting demand as far as end-users maintain the control over shifting actions. Based on these results, facilitating the willingness to shifting energy demand should prioritise actions already embedded in end-users’ daily lives (e.g., shifting the laundry and the dishwashing) and gradually introduce less common actions, while ensuring energy savings and procedures to meet the household preferences and not interfering with their activities. When designing demand response programmes, the preliminary assessment of household’s activities and practices, usage behaviours and appliances ownership are also required to accurately evaluate the shifting potential, thus contributing to the success of the programmes. It must, however, be kept in mind that there is a limit to each household shifting potential imposed by its own living standards and dynamics.

Direct load control performed by the utilities was, in general, not accepted, even in a scenario of dynamic pricing of electricity. However, different preferences were found in terms of loads and control actions. For example, while shifting the dishwasher and the laundry machine was acceptable, controlling the freezer or the refrigerator was not. Control actions similar to those already embedded in daily routines were better accepted than unusual control actions. Other decision factors influencing the acceptance of load control were related with safety, energy savings, interference with the private domain, control, privacy, feedback and social values. Hence, strategies to facilitating load control should prioritise known and already embedded actions, regulation of load control actions, ensure override possibility to end-users, provide detailed and tailored feedback, building trust between end-users and the electricity utilities (through, for example, increased transparency, personalised services, detailed contracts specifying authorised load control actions or even creating insurance policies to compensate eventual damages), while guaranteeing effective savings.

Moreover, while this segment has an income level above the national average being able to afford “smarter” technologies, in less privileged segments of the population it is expected cost and savings to gain an increased importance. Hence, policies comprising economic incentives are therefore crucial to facilitate the adoption of “smarter” technologies by the overall population.

These results are of utmost importance for both the design and development of “smarter” technologies as enablers and facilitators of end-users’ daily lives in the smart grid (such as the “Energy Box”), as for the design of more effective demand response programmes and energy policies.

However, although the results are applicable to a particular representative segment of the Portuguese population, they are not generalizable to the overall population. Further improvements should consider expand this exploratory study to the overall Portuguese society while complementing surveys with other tools (e.g., interviews, surveys with more open format questions, conjoint analysis) to further detail decision factors, unveil hidden elements and elicit end-users’ preferences. Moreover, since the survey mainly assessed the willingness to engage into certain actions, not measuring the actions in themselves, future research should also include measures of effective actions through the partnership with on-going smart grid projects. Future research should also improve the statistical analysis by using inferential and multivariate statistics to segment groups and preferences.

Finally, this research should lay the foundation to develop an analysis framework of behavioural adaptations in smart(er) grid contexts.

5 CONCLUSION AND FUTURE WORK

5.1 CONTRIBUTIONS OF THIS WORK

Energy behaviours are presently recognised as a key factor in promoting end-use energy efficiency in the residential sector, and are also gaining special relevance during the on-going transition to smart(er) grids. However, energy behaviours are still an underexploited resource due to the lack of adequate approaches to address their complexity. In fact, energy behaviours comprise different dimensions (e.g., usage, investment, maintenance and the provision of energy resources) and are influenced by multiple variables (e.g., personal, contextual, technological, environmental).

In addition, energy behaviours are usually addressed from various disciplinary perspectives. While the social sciences and humanities use qualitative approaches and develop interpretative frameworks, more quantitative disciplines, such as engineering, focus on predicting energy consumption patterns. When utilised in an isolated manner, each discipline provides a narrow and, to some extent, incomplete vision of the potential influence of energy behaviours on energy efficiency, and falls short in providing a comprehensive explanation of this topic particularly by not quantifying the behavioural impact on energy consumption.

Recognising the need of promoting more efficient energy behaviours, behavioural change interventions have been implemented in the last decades without significant success. Often interventions have been dominated by disciplinary approaches or were mainly focused on testing instruments to promote change (e.g., feedback), often lacking a sound theoretical support as well as an adequate segmentation of energy behaviours.

Hence, this thesis explored the influence of energy behaviours on end-use energy efficiency in the residential sector, as a contribution to a better understanding of this relation and to the design of more effective behavioural change interventions and energy efficiency policies. It did not aim at neither implementing nor testing strategies to promote behavioural changes.

This work contributed to the current knowledge by developing an integrative modelling approach of energy behaviours, which combined not only different methods and perspectives from engineering, the social sciences and humanities, but also the quantitative and qualitative dimensions of energy behaviours.

In summary, this work contributed to the:

1. Characterisation and systematisation of energy behaviours as promoters of end-use energy efficiency in the residential sector;
2. Identification of most important variables pertaining to different fields of knowledge when addressing the influence of energy behaviours on energy efficiency;
3. Integrative modelling of the influence of energy behaviours on energy end-use and suitability of the proposed model to a case study;
4. Development of a comprehensive methodology for the estimate of energy behavioural savings potential using building energy performance simulation tools;
5. Preview of energy behaviour adaptations during the transition to smart(er) grids and characterisation of end-users' preferences regarding a residential demand responsive energy management system.

Furthermore, the methodologies developed and the case specific results may be straightforwardly utilised by different energy stakeholders (e.g., governments, regulators, utilities, energy services companies, energy agencies, consumer associations, scientific community) in the design of real-world behavioural change interventions and energy policies, either in a national or international context. Recognising the importance of integrating behavioural knowledge into policies, the American administration has recently approved the 'Behavioral Science Insights Policy Directive' which aims at incorporating behavioural science into governmental policies and programmes so they become more effective (House, 2015).

As a final point, this work also contributed to facilitate knowledge and information transfer between experts from different working disciplines and to the development of an integrative 'human-technology research methodology which may be replicated in other fields of knowledge.

5.2 ANSWERS TO THE RESEARCH QUESTIONS

Three research questions were initially formulated that were appropriately addressed in the previous chapters of this thesis. The responses to each one of them are summarised below.

RQ #1. How to incorporate energy behaviours complexity into the design of more effective behaviour change interventions in the framework of energy efficiency policies?

Energy behaviours is a complex topic requiring the development of multidisciplinary and tailored approaches. Effective interventions promoting the change of energy behaviours to more efficient patterns should be designed taking into consideration:

- The inclusion of an assessment stage in the framework of each specific case under study, enabling the detailed characterisation of the influence of energy behaviours on energy consumption namely regarding personal, technological, contextual and environmental factors;
- The specification of the behavioural dimension(s) to be addressed (e.g., usage, investment, maintenance, provision of energy resources), including which energy behaviours are required to be changed (e.g., use of specific appliances, thermal comfort practices, time-of-use, investment or maintenance behaviours);
- The involvement of different energy stakeholders (e.g., regulators, governmental and energy agencies, utilities, energy service companies, consumer associations, scientific community), while understanding and reconciling their different perspectives, roles and interests in the issues to be addressed;
- The involvement of experts from different disciplines into a multidisciplinary team, particularly from engineering and the social sciences and humanities;
- The tailored design of the intervention, based on a systemic approach, combining complementary methods and techniques from the different disciplines (e.g., interviews, surveys, energy monitoring, data mining, modelling) to adequately tackle the qualitative and quantitative dimensions of energy behaviours (e.g., influencing variables, energy consumption patterns);
- The choice of methodologies enabling some degree of flexibility and adaptability to face constant changes and uncertainties which are intrinsic characteristics of real-world interventions;
- The allocation of adequate material, human and financial resources.

RQ #2. How much energy savings potential in residential buildings can be achieved by promoting more efficient end-use energy behaviours?

End-users' behaviour may significantly impact energy consumption in residential buildings. The literature review unveiled that behavioural change interventions over the years have achieved effective savings up to 20%, but this value usually varies significantly depending on the strategies utilised to promote behavioural changes and on the social, political and economic context. On the other hand, behavioural savings potential is often estimated using modelling techniques to be much higher. For example, the literature review showed a potential of 88% which could be achieved solely by changing thermal comfort practices.

Using energy building performance simulations this thesis has estimated the behavioural savings potential associated with two categories of energy behaviours (e.g., investment and usage) when using the various energy services in daily household activities (e.g., powering appliances, water heating, space heating and cooling, lighting). Simulations have estimated a significant behavioural savings potential (72%) between efficient and inefficient household profiles, which may be materialised if some forms of energy behaviours change in the real-world. Results also showed that investment energy behaviours have a higher savings potential than usage behaviours, and that behavioural savings potential per energy service is proportional to the energy consumption breakdown.

Although a significant behavioural savings potential was estimated through the modelling approach, behavioural savings are known to be difficult to materialise through the implementation of real-world behavioural change interventions and are often partially cancelled by rebound effects.

An economic assessment of investment behaviours revealed that the majority of proposed energy efficiency improvements does not comply with common economic criteria, although meeting the social test of the Plan for the Promotion of End-Use Energy Efficiency, which, given the estimated savings potential, justifies the use of public funding for promoting behavioural change in the scope of energy efficiency policies.

RQ #3. What energy behavioural changes are brought by the emerging smart grid and how to facilitate these behavioural adaptations?

The transition to smart(er) grids is an on-going process that may both shape and be shaped by end-users' behavioural changes. This work has provided an empirical grounded indication of Portuguese end-users' adaptations to the smart(er) grid and useful insights for enabling these adaptations. In summary, these include:

- Participation in the liberalised energy market. Facilitating end-users' involvement in energy provision activities should comprise providing detailed and tailored information on the process and consequences of changing energy suppliers, use real examples like opinion makers as case studies, offer competitive and personalised services, and regulate the market to improve transparency and end-users protection.
- Increasing adoption of smart grid technologies, such as demand-responsive enabling technologies, electric vehicles and decentralised generation. While the features of these technologies will play a crucial role in the acceptance process, economic incentives are important to facilitate a widespread adoption by the overall population.
- Willingness to shifting demand and adapt household routines. Enabling end-users' disposal to shifting energy demand should prioritise actions already embedded in end-users' daily routines and gradually introduce less common actions, while ensuring energy savings and procedures to meet the households' preferences and not interfering with their activities. Demand response programmes should include preliminary assessment of households' activities and practices, usage behaviours and appliances ownership to accurately evaluate the shifting potential.
- Willingness to accept direct load control performed by the utilities. Strategies to facilitating load control acceptance should prioritise known and already embedded actions, regulation of load control actions, ensure override possibility to end-users, provide detailed and tailored feedback, building trust between end-users and the electricity utilities (through, for example, increased transparency, personalised services, detailed contracts specifying authorised load control actions or even creating insurance policies to compensate eventual damages), while guaranteeing effective savings.

5.3 FUTURE RESEARCH

The research process may be characterised by being a constructive approach that is creatively built with the results of the previous iterations. Accordingly, identifying future research lines is of utmost importance since it contributes to new lines of development, while enabling to overcome research constraints of the former steps.

This thesis explored energy behaviours as promoters of energy efficiency in the residential sector as a contribution to design more effective behavioural change interventions and energy efficiency policies. Future research should address three dimensions: scope of the work; methods and techniques; and representativeness of case studies.

In general, research on energy behaviours has been essentially focused on the residential sector. Although this trend is changing with recent research addressing energy behaviours in other type of buildings such as services (Zhao *et al.*, 2014; Zhuang and Wu, 2014; Nilsson *et al.*, 2015; Schakib-Ekbatan *et al.*, 2015), this is still a noteworthy unexplored line of research. The present work should be extended to small services and the energy behaviour model improved to include behavioural specificities in services, as well as existing synergies and complementarities with the residential sector. In fact, most end-users divide their daily lives between both buildings so it is important to understand which spill over effects may naturally occur or be induced to promote more efficient energy behaviours (Littleford *et al.*, 2014). Furthermore, the behavioural adaptations and challenges during the transition to smart(er) grids in services require to be further explored.

This thesis has initially characterised and systematised energy behaviours into four categories: usage, investment, maintenance and provision of energy resources. Although energy behaviours modelling has been mainly focused on usage behaviours, future research should improve the model to include the other categories of behaviour, such as investment, maintenance or the provision of energy resources. Furthermore, using the structuring approach already developed, the model may be expanded to include behavioural change strategies, therefore contributing to the development of a policy maker friendly toolkit which may be utilised in the design of behavioural change interventions and energy policies.

Future research should also proceed the multidisciplinary approach and further integrate expertise from engineering, social sciences and humanities in the improvement of a combined quantitative and qualitative energy behaviours modelling approach. One line of research should consist in integrating the present energy behaviour model with energy management optimisation, through the

modelling of the needs, activities and other determinants of energy consumption into the demand-responsive energy management system under development (Soares *et al.*, 2014a; Soares *et al.*, 2014b), as it has been illustrated by a recent study (Kashif *et al.*, 2013). Another line of research aims to improve building energy performance simulation tools to include different behavioural dimensions (e.g., usage, investment, maintenance), multiple factors influencing energy consumption activation chain (e.g., household characteristics and activities, energy behaviours, and personal profiles), specific savings according to energy behaviours, household profiles and energy performance of different appliances, and some form of stochastic modelling (e.g., Monte Carlo methods) to model behavioural variability and uncertainty. These will contribute to more accurately assess the actual behavioural impact on energy consumption and design more user-friendly buildings regarding energy consumption control. A similar strategy is under development by the International Energy Agency (IEA, 2014). The integration of the behavioural dimension in building energy performance simulation tools will also contribute to the development of a policy maker friendly planning tool of behaviour change interventions and energy policies, or even the development of a feedback and awareness tool for end-users. Following the previous lines of research, machine learning and artificial intelligence (Raza and Khosravi, 2015) may also be incorporated in the modelling process to mimic end-users' behaviour and improve the predictive dimension of the model.

While more quantitative modelling techniques may be included in the modelling process, a further use of social techniques (e.g., interviews, surveys, conjoint analysis, and script analysis) is required to support the design and validation of the modelling process, namely regarding the definition of behavioural profiles, elicitation of preferences, measurement of effective actions, and other behavioural dimensions.

Problem structuring methods should be further utilised to reconcile the different stakeholders' visions to promote the design of behavioural change interventions and energy policies, although limitations regarding the lack of authority issues require to be overcome.

Finally, future research should also consider developing empirical research using representative case studies so the results may be applicable to the overall population.

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APPENDIXES

APPENDIX I — SURVEYS DEVELOPED

Table 28 – Questions included in the survey of the behaviour change intervention

COMPONENTS	QUESTIONS
Socio-demographic characteristics	<p>Gender (F/M); Age; Marital status (single, married, divorced, widower)</p> <p>What is your education level? (none; primary school; high school; secondary school; college and university)</p> <p>What is your main activity? (professional activity; looking for the 1st job; unemployed; working-student; retired; student; no activity; no paid worker)</p> <p>What is your profession? (open answer)</p> <p>What is your current activity? (open answer)</p> <p>What is your employment situation? (working for someone else; non-paid worker; employer of less than 10 workers; employer of more than 10 workers; entrepreneur; other)</p> <p>How many persons live with you? (children until 12 years old, adolescents, adults with less than 35 years old, between 35 and 65, and more 65 years old)</p> <p>In what type of dwelling do you live in? (Owned, rented, other option).</p>
Household activities	<p>During the week, in what period are adults usually at home? (in the morning, in the afternoon, in the evening)</p> <p>For the following appliances, please provide the number of working cycles per week, the duration of each cycle and the period in which it is turned on: laundry machine, dishwasher, and tumble dryer (open answer)</p>
Building characteristics	<p>In what type of dwelling do you live in? (Apartment, villa, independent villa)</p> <p>How many bedrooms does it have? (0 to higher than 5)</p> <p>In what year was it built? (before 1960, after 1999, 1961-1980, 1981-1999, I don't know)</p> <p>How comfortable is your home during the Winter and the Summer? (Likert scale from 1 to 5, Don't know)</p>
Physical environment	<p>What is the postal code of your dwelling?</p>
Energy resources and services	<p>What is your contracted power? (3.45, 4.6, 5.75, 6.9, 10.35, 13.8, 17.25, 20.7 kVA)</p> <p>What is your electricity tariff? (Simple, dual/three tariff, don't know)</p> <p>What is your average electricity bill? (open answer)</p> <p>Do you own solar panels to heating water? Yes/no</p> <p>Do you own photovoltaic panels to produce electricity? Yes/no Do you own micro-turbine to produce electricity from wind? Yes/no</p> <p>Electricity is used for other purposes than your home? Yes/no If yes, which ones? (water pumping, agriculture, swimming pools, others)</p> <p>How many of the following appliances do you own of the following list: Laundry machine, Laundry and tumble dryer combined, Dishwashing, Tumble dryer, Freezer, Refrigerator of 1 or 2 doors (open answer)</p> <p>What systems do you use to heating and cooling your home? (oil heater, heat cumulative system, fan, air conditioning system, fireplace with heat recover system, fireplace without heat recovery, salamander, central heating system)</p> <p>What systems do you use to heating water? (electric system, gas boiler, pellets boiler, solar panels)</p> <p>Do you own efficient light bulbs? Yes/no/Don't know If yes, what their proportion in the overall lighting system of your home? (Less than half, about half, the majority, all of them)</p>

COMPONENTS	QUESTIONS
Energy behaviours	<p>How often do you perform the following actions:</p> <p>switching off the lights in empty rooms; in the summer, closing the curtains/blinds during the day, and opening the windows during the night; in the winter, leaving curtains/blinds open during the day and closing them during the night; insulating windows and doors; keeping doors and windows closed when they are being warmed or cooled; switching on heating/cooling equipment only on occupied rooms; adjust acclimatisation temperature according to the season: Summer 23-24°C; Winter 18-20°C; switching off appliances using central plugs to avoid stand-by consumptions; switching off appliances directly on the switch to avoid stand-by consumption; switching off TV when nobody is watching it; switching on washing machine/dryer during the cheapest periods; talking with the dwelling occupants about electricity consumption and savings; reading the electricity bill; providing the meter readings to the electricity supplier; buying more energy efficient equipment; regulating the fridge temperature according to the season; turning heating water system off when are in holidays; using a timer to regulate water heating; turning the dishwasher on only when it is full; using the washing machine at low temperature; programmes; using dishwasher with ECO programmes; turning the washing machine on only when it is full; ironing in long periods, instead of short uses; using cumulative heaters to benefit from cheaper electricity consumption periods</p> <p>In the next month how often do you intend to: save electricity at home, reading the meter or the electricity bill?</p>
Personal determinants	<p>Do you agree with the following statements:</p> <p>we have the necessary conditions to save electricity; if I have the proper conditions, it will be easy to save electricity; electricity saving actions are compatible with our way of living; I can induce the dwelling occupants to perform saving behaviours; saving electricity is a good idea; saving electricity is boring; when I'll try to save electricity, it will be difficult to stopping it; saving electricity it's wise; I'm happy when trying to save; electricity and keeping comfort levels; saving electricity is difficult; I'm embarrassed when I don't try to save electricity; it is my obligation to try saving electricity while keeping satisfying comfort levels; I want to satisfy people who is important for me by saving electricity; reading the electricity bill or the meter is boring; when I'll begin reading electricity; consumption, it will be difficult stopping it; reading the electricity bill or the meter is difficult;</p> <p>Do you agree with the following statements:</p> <p>"Saving electricity..." improves the environment; ...improves the national economy;...improves the power grid management;...contributes to minimise energy imports;...begins with my example;...is a society obligation;...is a consumer responsibility;...represents economic advantages to the household;...implies a lifestyle with reduced comfort;...brings too much disturbances to my lifestyle than the generated benefits;...disturbs the household daily activities;...spends too much of my time.</p> <p>From the following groups of statements, please choose the four that are most important to you:</p> <p>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; Being independent Being creative; Having an exciting life Doing new and different things; 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 family and friends protection; Being successful Being recognised by others; Influence others decisions Having money to buy expensive goods; Having a pleasant life Enjoy life</p>
Influence of economic crisis on energy behaviours	<p>Has your electricity use changed because of the current economic crisis? Yes/no.</p> <p>If yes, how? we have reduced the use of some appliances; we began reading the bill or the meter; we changed the contracted power; we changed the tariff; we began turning some equipment on during the cheapest period; we bought more efficient appliances; we improved the dwelling in order to save; we invested in renewable energy sources; other</p> <p>If no, because: we haven't yet felt the need to save electricity; we already save as much as we can; there are limitations preventing us from saving more; other</p>

Table 29 – Questions included in the survey assessing behavioural adaptations to smart(er) grids

COMPONENTS	QUESTIONS
Characterisation of the case study	<p>Socio-demographic characteristics</p> <p>Gender (F/M); Age</p> <p>Marital status (single, married, divorced, widower)</p> <p>What is your education level? (none; primary school; high school; secondary school; college and university)</p> <p>What is your main activity? (professional activity; looking for the 1st job; unemployed; working-student; retired; student; no activity; no paid worker)</p> <p>What is your profession? (open answer)</p> <p>What is your current activity? (open answer)</p> <p>What is your employment status? (working for someone else; non-paid worker; employer of less than 10 workers; employer of more than 10 workers; entrepreneur; other)</p>
	<p>Geographical location</p> <p>What is the postal code of your dwelling?</p>
	<p>Energy behaviours</p> <p>How often do you perform the following actions: switching off the lights in empty rooms; insulating windows and doors; keeping doors and windows closed when they are being warmed or cooled; switching on heating/cooling equipment only on occupied rooms; switching off appliances using central plugs to avoid stand-by consumptions; switching off appliances directly on the switch to avoid stand-by consumption; switching off TV when nobody is watching it; switching on washing machine/dryer during the cheapest periods; talking with the dwelling occupants about electricity consumption and savings; reading the electricity bill; providing the meter readings to the electricity supplier; buying more energy efficient equipment.</p>
	<p>Personal determinants</p> <p>Do you agree with the following statements: "Saving electricity..." improves the environment; ...improves the national economy;...improves the power grid management;...contributes to minimise energy imports;...begins with my example;...is a society obligation;...is a consumer responsibility;...represents economic advantages to the household;...implies a lifestyle with reduced comfort;...brings too much disturbances to my lifestyle than the generated benefits;...disturbs the household daily activities;...spends too much of my time.</p>
	<p>Influence of economic crisis on energy behaviours</p> <p>Has your electricity use changed because of the current economic crisis? Yes/no. If yes, how? we have reduced the use of some appliances; we began reading the bill or the meter; we changed the contracted power; we changed the tariff; we began turning some equipment on during the cheapest period; we bought more efficient appliances; we improved the dwelling in order to save; we invested in renewable energy sources; other If no, because: we haven't yet felt the need to save electricity; we already save as much as we can; there are limitations preventing us from saving more; other</p>
Energy behavioural adaptations during the transition to smart(er) grids	<p>Adhesion to the liberalised retail energy market</p> <p>Have you changed your electricity supplier due to the liberalised market? (If no) Why? Prices are not interesting; there is no sufficient information; my friends or family advised me not to change yet; I do not trust in energy suppliers; I did not know it was possible to change; I am satisfied with the present service. Do you know the DECO campaign "Together we pay less?" Yes/no. Have you enrolled in this campaign? Yes/no.</p>
	<p>Adoption of smart grid technologies</p> <p>Do you use any electricity monitoring device (e.g., display)? Yes/no. Do you use any control device to save electricity? Yes/no. (If yes) In which equipment? Washing machine; drying machine; dishwasher; water electric heater; air conditioning; electric heater; other. Are you a prosumer? Yes/no. Do you own an electric/hybrid vehicle? Yes/no. In hypothetical future scenario of dynamic pricing of electricity, what level of importance would you give to the functionalities of an automated device to manage electricity use? Real time information on consumption, cost and savings; information on controlled appliances; turning off stand-by; turning off appliances; automated shifting to cheaper periods; automated alteration of appliances settings to reduce electricity consumption. Would you be interested in adopting an automated device to manage your electricity use? Yes/no. (If yes) How important are the following adopting factors: trust in the technology; low cost of acquisition; level of electricity savings; user friendly; functionalities; ease of installation and configuration; quality of the feedback; design; not damaging equipment; full control over the device.</p>

COMPONENTS	QUESTIONS
<p>Flexibility for demand shifting and change the household routines</p>	<p>Would you be willing to switch your appliances on in a different schedule than the usual? Yes/no.</p> <p>(If yes) How important are the following factors? Effective electricity bill savings; environmental advantages; only if each appliance concludes the cycle at the intended hour; only if it does not interfere with the household activities; To be at home when appliances are switched on.</p> <p>(If no) How important are the following factors? Appliances must be switched on at the schedule I establish; being at home when appliances are switched on; level of electricity bill savings; guarantee appliances conclude the cycle at the intended hour; not interfering with the household activities.</p> <p>Please indicate your flexibility to change the time-of-use of the following appliances: washing machine; drying machine; dishwasher; water electric heater; air conditioning; electric heater.</p> <p><u>In hypothetical future scenario of dynamic pricing of electricity, would you admit changing the way you use electricity?</u> Yes/no</p> <p>(If yes) How likely would you adopt the following practices? I would pay attention to electricity prices at each moment; I would shift my demand to cheaper periods; I would invest in decentralised renewable energy sources; I would install automated control devices do shift my demand; I would accept load control performed by the electrical utility.</p> <p>(If no) Why? Prices variation would not significantly change the electricity bill; I do not have the possibility to significantly shift my electricity demand; I would be afraid to damage equipment; it would generate more inconveniences than advantages; I believe that scenario is a manipulation exercise by the utility.</p>
<p>Willingness to accept load control</p>	<p>Would you be willing to accept the control of some appliances by your electricity utility? Yes/no.</p> <p>(If yes) How important are the following factors? Only if needed to ensure electricity supply; only if it was established in the contract and there was a previous warning; trust in the utility; possibility to override, at any time, that control; effective electricity bill savings; environmental advantages; not interfering with the household activities; not compromising privacy; be informed of the control actions and savings generated; not damaging equipment.</p> <p>(If yes) How willing are you to accept the following control actions over these appliances: shifting to a cheaper period (washing machine; drying machine; dishwasher; water electric heater); turning off for small instants during the most expensive periods (water electric heater, fridge or freezer; air conditioning); changing the temperature set-point during the most expensive periods (water electric heater, fridge or freezer; air conditioning).</p> <p>(If no) How important are the following factors? Interference with privacy; Mistrust in the electricity utility; Unawareness on the motive requiring that action; Risk of damaging equipment; Risk of inference with the household activities; Lack of contractual legitimacy; Unawareness on the control actions; Reduced electricity bill savings; No override function.</p> <p>Do you own an air conditioning system? Yes/no.</p> <p>(If yes) How to you use it? I keep it switched on at a constant temperature set-point; I switch it on temporarily to cool or heating a room; I never switch it on.</p> <p><u>In hypothetical future scenario of dynamic pricing of electricity, how willing are you to accept the following control actions over these appliances: shifting to a cheaper period</u> (washing machine; drying machine; dishwasher; water electric heater); turning off for small instants during the most expensive periods (water electric heater, fridge or freezer; air conditioning); changing the temperature set-point during the most expensive periods (water electric heater, fridge or freezer; air conditioning).</p>