Active consumers at the centre of the energy system:
Towards modelling consumer behaviour in OSeMOSYS

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Abstract [English]

This thesis focuses on assessing current technologies, policies, KPIs and modelling tools for enhancing the characterization of current energy demand coming from the residential sector in long term energy models. Today, thanks to the increasing spreading of smart grid and metering systems through the energy sector, new features are made available, allowing for more customized and optimal use of energy technologies, according to consumers' behaviours and attitudes that affect energy demand. Through the assessment undertaken in this study, a more detailed representation of the residential demand has been made possible. In addition, it has been allowed also to identify potential benefits coming from a more flexible use of technologies and the consumer's engagement in optimally monitoring and managing energy consumption. Finally, the OSeMOSYS modelling tool has been enhanced with a better characterisation of the demand side in its Reference Energy System. A solution for defining rates of flexibility for the demand side technologies analysed has been proposed. In addition, a theoretical framework for integrating consumers' behaviours and attitudes in the system has been developed. This has been based on the modelling of virtual technologies representing costs and variations in energy demand associated with specific behavioural patterns, following the example provided by the Socio-MARKAL model.

Abstract [Svenska]

Denna Thesis fokuserar på att bedöma nuvarande teknik, politik, nyckeltal och modelleringsverktyg i syftet att förbättra hur den aktuella energiefterfrågan av bostadssektorn karakteriseras i långsiktiga energimodeller. Idag har spridningen av smarta nät och mätsystem inom energisektorn ökats. Dessa tillbringar nya funktioner som möjliggör en mer anpassad och optimal användning av energiteknik: de kan nu följa beteenden och attityder som påverkar konsumenternas efterfrågan på energi. Bedömningen som genomförts i denna studie möjliggör en mer detaljerad representation av bostäders efterfrågan. Dessutom kan vi nu upptäcka de potentiella fördelarna av att, å ena sidan, ha flexibla användningar av teknologier, och, å det andra, att ha engagerade konsumenter som övervakar det optimala styrning av deras energikonsumtion. Slutligen har det OSeMOSYS modelleringsverktyget stärkts genom en bättre beskrivning av Reference Energy Systems efterfrågesida. En lösning som definierar flexibilitetsnivåer på efterfrågesidan teknologier som analyserats har föreslagits. Dessutom har ett teoretiskt ramverk som integrerar konsumenternas beteenden och attityder in i systemet utvecklats. Med referens till den Socio MARKAL-modellen har detta baserats på modellering av virtuella teknologier som föreställer både kostnader av och variationer i efterfrågan på energi i samband med specifika beteendemönster.

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1 Introduction

As reported in the Green Paper "A European Strategy for Sustainable Competitive and Secure Energy" (COM(2006) 105) by the European Commission, the European Union (EU) is currently working to provide strategies and measures in six different areas of the energy system:

1. The completion of the EU internal market for electricity and gas;
2. To ensure the security of supply, creating solidarity between Member states;
3. To diversify the current energy mix, while increasing efficiency and improving sustainability;
4. To be leader in working against climate change;
5. To support research and innovation towards new energy technologies, to reach and further improve current targets set by EU policies;
6. To create a common EU external energy policy, thus being able to address international dialogue with a common strategy.

Effective and quick actions in these six areas are fundamental to address the three core objectives of the EU energy policies: economic competitiveness, security of supply, environmental sustainability (IEA, 2014a). This in order to fulfil the EU energy and climate objectives set for 2020.

Due to the recent economic and financial crisis of the European economies that required policy makers to focus on supporting the recovery though, today energy security and industrial competitiveness are considered as key drivers for the development of new policies (IEA, 2014a)

Two are the major reforms that the EU is currently undertaking: the energy and the climate ones.

Regarding the energy market, the reform is related to the implementation of the "Third Package" for the liberalisation of the internal electricity and gas markets in all the Member States. More specifically, it aims to create a fully integrated European energy network and market, particularly working on cross-border capacity at interconnections and congestion problems for gas and electricity, considering also the need to connect Eastern and Southern European markets that are currently still isolated. In addition, it intends to increase the share of variable renewable energies and therefore adapt the system to manage this energy production (IEA, 2014a)

For the climate policy sector, there are climate and energy targets that need to be achieved by 2020 as defined within the "2020 Climate and Energy Package". They are about:

1) Reducing greenhouse gasses (GHG) emissions by 20%, in comparison to 1990 levels;
2) Increasing the share of renewable energy installed to 20% in the gross final energy consumption, and to 10% in the transport sector;
3) Reducing the European total primary energy consumption by 20%, in comparison to the projections on energy consumption made in 2007. (IEA, 2014a)

This means that the EU needs to implement and develop new policy initiatives that can stimulate the market to invest in new technologies. In particular, new policies and stimulus should be developed to foster investment on renewables as solar photovoltaic (PV) and onshore wind, and to fully implement measures and directives for energy efficiency and saving (IEA, 2014b).

It is particularly in this context of energy efficiency, emissions reductions and increasing share of renewables that demand side management and 'smart' solutions will become fundamental, to better monitor and adjust the balance between demand and supply sides. Active consumers will increasingly play an important role in managing their consumptions to optimally take advantage of energy supply when available on the grid.

1.1 The Strategic Energy Technology Plan

In order to achieve the goals mentioned above, major EU Research&Innovation(R&I) challenges have been investigated, together with the stakeholders needs (European Commission, 2014). In relation to these challenges, the strategic Energy Technology plan has been defined, where an overview of the major energy system challenges is provided, with guidelines about the aims and the actions the European Union intends to engage in for developing and transforming the current energy system (European Commission, 2014).

Particularly, the "Integrated challenge 1: Active consumers at the centre of the energy system" focuses on the need to engage energy consumers in the system to bring more flexibility to the market, thus allowing better integration of renewable energy and increasing overall efficiency of the system. It includes the following two themes:

- Theme 1: Engaging consumers through better understanding, information and market transformation
  It focuses on trying to understand better consumers' behaviours, and to investigate the relation with consumption data and information to achieve better efficiencies in the system. It intends to stimulate the research and understanding how to better engage and address consumers in the system.
- Theme 2: Activating consumers through innovative technologies, products and services.
  It focuses on specific innovative technologies, products and services that help consumers in better managing their demands in relation to the available supply. It includes new business models and control systems that focus on the consumers to stimulate their engagement on managing energy demands and increase the flexibility of the energy system (European Commission, 2014).

1.2 Smart technologies and definition/relevance

Currently there are several names and definitions available for technologies and solutions that can provide customers with better monitoring and control of their energy consumption. Technologies are generally grouped under a common adjective of "Smart". For the purpose of this thesis, in order to clarify what is meant when referring to smart technologies or systems, the following definitions has been considered.

- Smart Grid: "Upgraded energy network to which two-way digital communication between the supplier and consumer, smart metering and monitoring and control systems have been added" (European Commission, 2012)
- Smart metering system: "Electronic system that can measure energy consumption, adding more information than a conventional meter, and can transmit and receive data using a form of electronic communication" (European Commission, 2012)
- Smart home: "A dwelling incorporating a communications network that connects the key electrical appliances and services, and allows them to be remotely controlled, monitored or accessed." (King, 2003).
- Smart appliance: modern appliances can be integrated into Smart Grids, through remote connection and enhanced functions.

Concerning methods and techniques to engage consumers in managing their consumption patterns and adapting to inputs coming from the grid, Demand Side Managements (DSM) techniques and Demand Response (DR) methods were proven to be effective. For the purpose of this study, the following definitions from Gelazanskas and Gamage (2014) can be considered for a better understanding of the related solutions considered:

- Demand Side Management: "The planning, implementing, and monitoring utility activities that are meant to influence consumers' use of electricity and to encourage them to consume less power during peak times and shift energy use to off-peak times" (Gelazanskas and Gamage, 2014);
- Demand Response (DR): "Specific tariff or program to motivate end-users response to changes in price or availability of electricity over time by changing their normal patterns of electricity use." (Gelazanskas and Gamage, 2014).

More specifically, an overview of DSM and DR methods currently available is presented in the following graph, following the information provided by Gelazanskas and Gamage (2014):

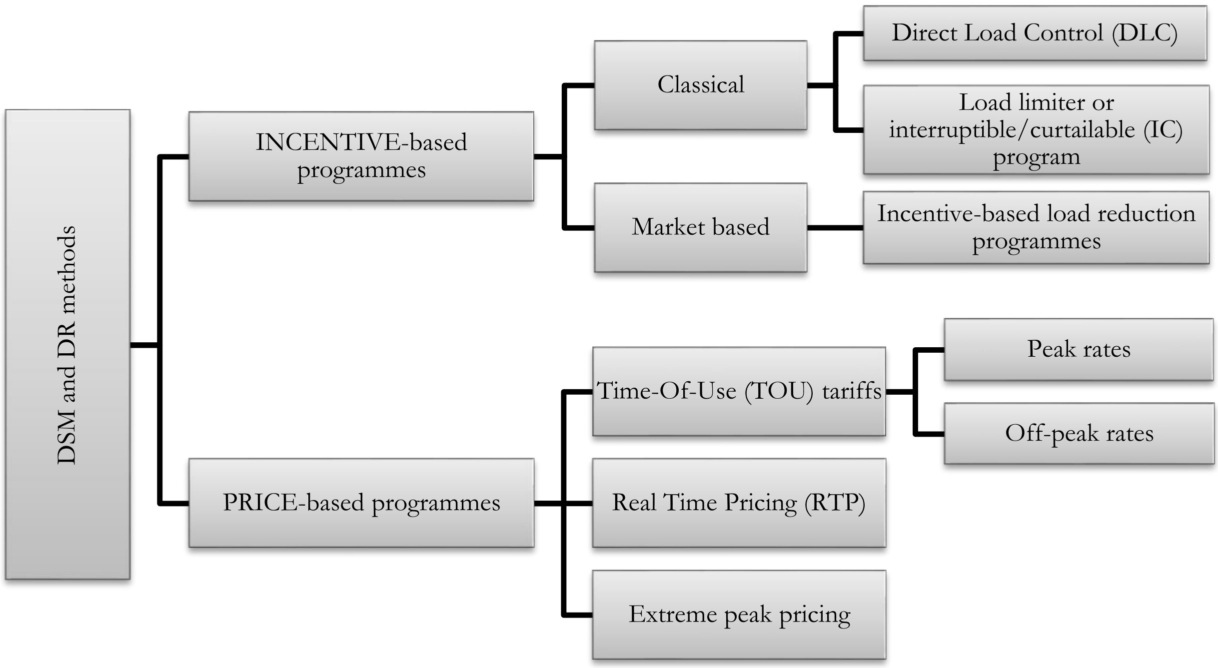

Figure 1: Overview of current DSM and DR methods available, as presented by Gelazanskas and Gamage (2014) and Boßmann and Eser (2016).

Incentives-based programmes include all those measures that "give customers time-varying rates that reflect the value and cost of electricity in different time periods". As can be seen in Figure 1, examples of these types of programmes are:

- Time-Of-Use (TOU) tariffs, where electricity prices vary during the day, according to pre-defined time slots;
- Real Time Pricing (RTP), where electricity prices vary almost on real time, more usually each hour during the day or even more frequently, following standard economic rules applied to the energy market;
- Extreme peak pricing as well as critical peak pricing, where electricity prices vary in a similar way as for TOU tariffs, but with higher prices for limited number of days or hours; these time periods are considered critical due to the critically higher demand registered (Boßmann and Eser, 2016; Gelazanskas and Gamage, 2014).

Price-based programmes instead, are those that "pay participating customers to reduce their loads at times requested by the program sponsor, triggered either by a grid reliability problem or high electricity prices".

They can be distinguished between classical (Direct Load Control, Load interruptible/curtailable control), and market based programmes (incentive based). The main measures involved are the following:

- Direct Load Control (DLC), which engage consumers by asking to give up the control over some domestic appliances;
- Load limiter or interruptible/curtailable (IC) program, where consumers are limited in the amount of electricity they can use;
- Incentive-based load reduction programmes, where load curtailments and mandatory, but can be either controlled, as in the case of Emergency Demand Response Programmes (EDRP) and Peak time rebates (PTR), or negotiated, as in Ancillary service markets (ASM), Demand bidding (DB) and Capacity market programmes (CMP). In this last case, negotiations would be based on energy market rules (Boßmann and Eser, 2016; Gelazanskas and Gamage, 2014).

2 Aim and Objectives

The aim of the thesis is to provide an insight in current energy technologies and policies that are relevant for future development of the EU energy system, in order to activate and engage consumers in managing their energy consumption.

In addition, this thesis intends to develop a modelling framework for the integration of elements of Demand Side Management (DSM) and consumer behaviour in long-term energy system modelling (e.g. OSeMOSYS) of the residential sector.

In order to achieve the aims of this thesis, the following objectives have been defined:

- Assess current technologies, relevant to engage end-users in the active management of their energy consumption
- Assess the EU climate and energy policies, in support of energy efficiency and smart grid measures
- Assess consumer behaviour information and patterns, and the effects on residential energy demand
- Investigate energy modelling approaches and tools for integrating elements of consumer engagement in defining the demand side
- Develop a modelling framework for the residential demand side in the long-term modelling tool called OSeMOSYS.

3 Methodology

The methodology used for this report is a comprehensive literary review of the following:

- Smart technologies that can effectively activate consumers' engagement
- European policies and measures to support the interaction with the demand side
- Demand Side Management and Demand Response methods
- Consumers' behavioural information and patterns, in interacting and participating to the management of energy demand and consumption
- Present modelling tools for energy consuming behaviours and demand side interactions with energy system, and related programming language

In addition, metrics and KPIs relevant to assess performance, effectiveness, and efficiency of smart technologies in relation to consumers' behaviour have been briefly analysed.

3.1 Background of studies

For the assessment of current relevant energy demand technologies for the residential sector, the Technology Briefs released by the Energy Technology Systems Analysis Program (ETSAP) under the International Energy Agency (IEA) have been used as main source of information. Each of them provides the following information about current appliances available on the market: cost, service life, functions, market penetration, energy demand. These information are normally provided targeting the European and the US market respectively, as well as other international market where particular technologies are more widespread. They are also divided between industrial and residential application, thus providing complete overview of technologies available today.

Regarding the European Policy assessment, the Energy portal of the European Commission website as well as the EUR-Lex portal of the European Union have been used to search for specific legislations currently in place, concerning the topic of this thesis and supporting related programmes and initiatives or providing funds. Particularly useful it was looking at the *Summaries of EU legislations* within the Energy section. In this regard, the following topics were considered:

- European energy policy
- Internal energy market
- Energy efficiency
- Renewable energy
- Security of supply, external dimension and enlargement.

Additionally, in order to come up with a complete list of legislations, other sources of references were used to check and fill in possible gaps.

The *Energy Policies of IEA Countries - European Union 2014 Review* by the International Energy Agency (IEA) was consulted, in order to find relevant information about the current legislative framework that regulate the European Energy system and define its future development.

Also, the Energy section of the European Commission website was consulted. Here, a list of documents including mainly Communications, Directives and Recommendations by the European Commission (EC) was identified. These documents are related to the several energy topics, as defined by the European Commission (e.g. energy strategy, energy efficiency, technology and innovation, market and consumers, renewable energy).

Several scientific articles accessed mainly through the Science Direct online portal have been used instead to get an overview of current techniques and methods for energy consumers' engagement, and to collect consumer behavioural information and patterns. This source has been used also to collect information concerning the current modelling alternatives for the demand side, together with websites of academic institutions and research centres working on the enhancement of present modelling tools. Among these, it is worth mentioning the University College London (UCL), which is developing independently several energy modelling tools, each of them focusing on specific sector of the energy system. The UCL is also leading partner of the wholeSEM Whole System Energy Modelling Consortium, together with the Imperial College London, the University of Surrey and the University of Cambridge. The consortium is funded by the UK Engineering and Physical Sciences Research Council (EPSRC), and it aims to link and apply interdisciplinary modelling tools to address current key energy policy issues (wholeSEM, 2015).

4 Results

4.1 Current state of the art – Technology development

Within the area of Smart Grids, there are many technologies involved in the activation of consumer in the management of their energy consumption and the interaction with the supply side of the energy system.

Referring to the IEA *Technology Roadmap – Smart Grid* (2011), the following categories of technologies have been identified, which directly relate to the residential sector:

- Information and Communication Technologies (ICT) integration: it includes all the communication infrastructures that support the transmission of data, to guarantee the correct operation of the grid on real-time and provide optimal services and communication system to all the stakeholders involved in the grid.
- Renewable and Distributed generation integration: it includes technologies for automated control of operations on the electricity system, for the integration of small scale renewable and distributed energy resources on residential buildings, as well as electrical or thermal based energy storage systems. Thanks to smart grids, these technologies can be optimally managed to balance supply and demand.
- Distribution grid management: it includes sensor and meters that provide real-time data that are processed to ensure the correct performance and effective utilisation of assets in the grid.
- Advanced Metering Infrastructure (AMI): in involves different technologies for providing consumers with information that can stimulate a change in consumption patterns. For instance, it enables the provision of data on the amount, the time and the price of the electricity consumed. It also enables to detect losses, outages, remote connections or disconnections, etc.
- Electric Vehicle (EV) charging infrastructure: it involves all features to enhance smart charging of EV from the grid, when there is a low energy demand, thus interacting with AMI and the consumers.
- Customer-side systems (CS): for the residential sector, it includes Energy Management Systems (EMS) for houses, smart appliances, energy storage devices, as well as in-home displays, thermostats, price-responsive systems. They can contribute to the monitoring and management of electricity consumptions, the increment of energy efficiency, as demand response solutions (IEA, 2011).

In addition, the following categories of technologies are still needed to build up the smart grid and provide all infrastructures to deliver data and information to provide an optimal service to the demand side:

- Wide-area monitoring and control: it relates to the generation and transmission areas of the supply side of the grid. This category of technologies provides real-time information on the components and performances of power systems, allowing system operators to optimise their use and improve reliability.
- Transmission enhancement applications: it includes all different technologies and application for the transmission system, to enhance the controllability and maximize the capability to transfer power along the network (IEA, 2011).

Concerning the purpose of enhancing present long-term energy modelling tools, this section will focus more specifically on technologies and appliances for the residential sector. Particularly, on those ones that have been identified as potentially relevant in affecting consumers' energy demand and consumption patterns and to provide demand flexibility.

First, a list of relevant domestic appliances is provided as presented by Silva et al. (2011). Here, they distinguished between shiftable and interruptible appliances, according to the degree of flexibilities different appliances allow:

- Shiftable appliances:
    - Dishwasher
    - Washing machine
    - Wash-dryer/tumble dryer
- Interruptible appliances:
    - Refrigerator
    - Freezer

The first group includes appliances classified as either shiftable or flexible, which are those ones that can increase demand flexibility allowing several smart, more efficient operations throughout the day. For instance, they can allow to be scheduled at different times of the day, or to be interrupted during their operation cycle, or to lower the energy demand by choosing to work at lower temperatures. The second group mainly consists of cold domestic appliances, which can enhance demand flexibility by being temporarily switched off when needed for lowering energy demand, as long as temperatures are kept low enough to perform as needed (Silva et al., 2011).

Second, referring to the European Smart-A project conducted in several European countries (i.e. Germany, Italy, United Kingdom, Sweden), the following technologies and appliances have also been considered for enhancing management and flexibility of demand side, together with the previous ones listed by Silva et al. (2011):

- Electric storage heating;
- Heating circulation pump;
- Air conditioner;
- Electric water heater;
- Oven and stove (Intelligent Energy Europe (IEE), 2009).

According to the project results, these technologies can also contribute to load shaping through demand side management techniques or demand response programs (IEE, 2009).

For all the above-mentioned technologies and appliances, it was possible to collect several information and data mainly from the Technology Briefs of residential energy demand technologies provided by the Energy Technology System Analysis Program (ETSAP) (IEA Energy Technology Systems Analysis Programme (ETSAP), 2012), as listed below.

- Building shell, Thermal insulation
- Space heating and cooling
- Water heating
- Lighting
- Cold appliances
- Cooking
- Dish-washing machines
- Dryers
- Other electric appliances
- Electronic devices

This information is fundamental to be able to better characterize them in future energy models and to fully understand the potential for flexibility they can provide on the demand side. For this reason, they have been organized in the following Table 1, so that can be easily accessed and used for future modelling purposes.

Here, information about market penetration, cost, energy source, service life, energy efficiency and consumption are provided.

Regarding washing machines though, all information have been collected through other online sources of reference, since the related Technology Brief from the IEA ETSAP website is currently under revision.

Technologies for Domestic sector		Non-shiftable appliances	Shiftable appliances	Interruptible appliances	EU Market penetration/Market shares	Average cost (capital costs, no taxes included)	Energy source	Equipment	Service life (EU data)	Energy efficiency and consumption
Building shell, Thermal insulation	Not relevant for the purpose of this study									
Space Heating and Cooling	Boilers (dwelling scale)		▯		-	Gas: 115-125 €/kW, Oil: 125-135 €/kW, Biomass: 596 €/kW, Coal: 115 €/kW	Gas (majority), Oil	-	15 yr	Annual Fuel Utilization Efficiency (AFUE): 86-90%
	Furnaces (dwelling scale)		▯		-	Gas: 120-130 €/kW, Oil: 145-165 €/kW	Gas, Oil	-	17-18 yrs	Annual Fuel Utilization Efficiency (AFUE): 78% (up to 85-90% for high-efficiency models)
	Boilers (building-scale, typically 40 dwellings)		▯		-	Gas: 70-80 €/kW, Oil: 75-90 €/kW, Biomass: 375 €/kW, Coal: 100 €/kW	Gas (majority), Oil, Biomass	-	25 yrs	Annual Fuel Utilization Efficiency (AFUE): 75% (up to 85-95% for high-efficiency models)
	Heat pumps (domestic scale)		▯		-	Existing: 1500 €/kW, Ground-to-water: 1625 €/kW, Air-to-water: 1275 €/kW, Air-to-air: 600 €/kW, Gas absorption: 700 €/kW	Electricity (majority), Gas	-	15 yrs	Primary Energy Ration (PER) [for gas fired heat pumps]: 1.5
	Large scale CHP [for District heating networks]		▯		-	800-4500 €/kW	Gas, Biomass	-	15-25 yrs	

	Micro-CHP		□		-	5300-6300 €/kW	Gas	-	15 yrs	
	Mini-CHP		□		-	2382 €/kW	Gas	-	15 yrs	
	Hybrid technologies (boiler + solar/heat pump)		□		-	Boiler-Solar: 275 €/kW, Heat Pump-Boiler: 1402 €/kW	Electricity, Gas	-	15-20 yrs	
	Air conditioners		□		-	440 €/kW	Electricity	-	14 yrs	Energy Efficiency Ratio (EER): 3.2-3.5
Water Heating (dedicated systems)	Storage heaters (with internal storage tank, of at least 15L)		□		EU market shares for Small systems: - gas: 1%, - electricity: 34.8%; Large systems: - gas: 1.1%, - electricity: 20.6%	Small systems: - gas: €400 (medium storage), - electricity: €99-295; Large systems: - gas: €600-1250, - electricity: €394-973	Electricity, Gas (or oil or biomass)		Average: 15 yrs; Large systems: - gas: 13 yrs, - electricity: 13 yrs	Small systems efficiencies: - gas: 27% , - electric: 38%; Large systems efficiencies: - gas: 29-41%, - electric: 27-30%
	Instantaneous heaters (tankless)		□		EU market shares for Small systems: - gas: 15.8%, - electricity (hydraulic): 19%, - electricity (electronic): 3.8%; Large systems: - gas: 1.5%,	Small systems: - gas: €250-350, - electricity (hydraulic): €81-252, - electricity (electronic): €245-448; Large systems: - gas: €312-508/600	Electricity, Gas (or oil or biomass)		Average: 15 yrs; Large systems: - gas: 20 yrs,	Small systems efficiencies: - gas: 21-27% , - electric (hydraulic or electronic): 34-38%; Large systems efficiencies: - gas: 44%,
	Solar Thermal systems		□		EU market shares for Large systems: 2.3%	Large systems: €2940-5880	Solar energy		Large systems: 20 yrs	-
	Heat pumps		□		-	-	Electricity, Gas		Large systems: 15-20 yrs	-

Lighting	General Lighting Service (GLS), [using Incandescent tungsten filament lamps]	▯			EU market share (2010): 52%	€1.93-11.5 per unit (2011)	Electricity		1000 hours	5-17 lumens per watt (lm/W)
	Halogen Lamps (HL), [Infrared coated (IRC) or non-IRC lamps]	▯			EU market share (2010): 20%	€2.00-8.00 per unit (2011)	Electricity		2000-8000 hours	10-30 lm/W
	Compact Fluorescent Lamps (CFLs)	▯			EU market share (2010): 28%	€1.5-11.5 per unit (2011)	Electricity		6000-15000 hours	35-75 lm/W
	Light Emitting Diodes (LEDs) and Organic LEDs (OLEDs)	▯			-	€11.00-57.00 per unit (2011)	Electricity		12000-50000 hours	>15- 1000 lm/W
Cold Appliances	Fridge-Freezer (EU typical size of 213-78l)			▯	47% (UK value, 2009)	€333 (average cost in EU, 2011); Range from €528 to €283 (for A++ class and B class energy label efficiency respectively) [UK Market Transformation Programme data]	Electricity	Various possibilities to increase energy efficiency and sustainability of cold appliances, and lowering lifecycle energy costs: - advances thermal insulation systems, - improved gaskets and refrigeration systems, - use of low global warming process fluids, - more efficient components	15 yrs (2009)	0.84 kWh/l/year (2009); 350-400 kWh per year (normalized average value for new products)
	Refrigerator			▯	28% (UK value, 2009)	€223 (average cost in EU, 2011); Range from €404 to €132 (for A++ class and B class energy label efficiency respectively) [UK Market Transformation Programme data]	Electricity		12.5 yrs (2009)	163.7 kWh per year

	Freezer (temperatures down to -18°C, EU typical size of 169ll)			▯	25% (UK value, 2009)	€186-302 (average cost in EU, 2011); Chest freezers: range from €344 to €141 (for A++ class and C class energy label efficiency respectively); Upright freezers: range from €508 to €188 (for A++ class and B class energy label efficiency respectively) [UK Market Transformation Programme data]	Electricity		15-16 yrs (2009)	1.47 kWh/l/year (2009); 270-370 kWh per year
Cooking	Oven (can be: electric ovens, or gas ovens)	▯			EU residential market shares: - 77% electric ovens, - 28% gas ovens	€200-600 for gas ovens; €350-1500 for electric ovens	Electricity; Gas (natural gas or LPG)	Current focus on improving energy efficiency: - multifunctional options - new cooking methods	Gas/Electric ovens: 15-20 yrs	EU domestic electric ovens are rated A-G, according to the related energy labelling scheme; Average energy consumption: - 184 kWh per year for gas ovens, - 164 kWh per year for electric ovens Convection ovens are generally 20% more efficient that conventional ones 77% of EU domestic oven sales in 2008 had A-class labels Potential future energy efficiency gains: 6-7% for electric and gas ovens

	Microwaves	▯			EU market shares: - 55% conventional microwave ovens; - 10% combi-ovens; - 35% microwave with grills; Predicted growth of microwaves sales: 9.9% in EU-27, for years 2010-2020	-	Electricity		8-10 yrs	Average energy consumption: - 75-91 kWh per year Potential future energy efficiency gains: 4%
	Cooker (with combinations of several heating mechanisms: - conduction - convection - radiation - inductive heating)	▯			In EU market (2007 sales data): - 70.8% radiant hobs, - 19.8% induction hobs, - 9.4% hot plates	€130-1000 for gas hobs; Wide range of variable prices for electric hobs, according to specific types and energy efficiencies: €137 for solid plate hobs, €380 for radiant hobs, €810 for induction hobs (2007 data)	Electricity; Gas (natural gas or LPG); Biomass (in developing countries)	Optional: - digital control systems (for electric appliances) - gas burners (to regulate temperatures on gas systems) - LPG cylinders (for LPG cookers, limited diffusion)	Gas hobs: 19 yrs; Electric hobs: 15-19 yrs	60% of EU domestic cookers sales in 2008 had A-class labels Domestic average consumption data: - 333-996 kWh per year for gas hobs; - 190-250 kWh per year for electric hobs Potential future energy consumption savings of 10-15%, switching from solid plate to induction or radiant hobs
	Grill	▯			In EU market (2008 data): - 15% gas grills - 40% electric radiant grills - 45% electric radiant covered grills	€100-1500 for gas grills; €80-1500 for electric grills	Electricity; Gas (natural gas or LPG)		Gas/Electric grills: 19 yrs	Typical consumption data: - 47 kWh per year for gas grills, - 24-703 kWh per year for electric grills

Dish Washing Machines			□		48% of EU households have it	€ 300	Electricity, hot/cold water (only in the models designed for the US)	Programs and sensor combinations to determine length and type of cycle	9-15 yrs	90% of EU domestic dishwashers are performing at least at the A class energy label efficiency (= less than 1,05 kWh per cycle); Domestic average consumption: 250 kWh per year
Washing Machines			□		market saturated, new sales for replacement of old appliances	-	Electricity	Load Auto-Sensor Automatic Temperature control Automatic dispenser Spin speed Zero control Fuzzy control Neuro Fuzzy control All water washing machine Energy saving function Automatic dosage detergent Availability of 20°C program Hot water supply	15 yrs	Consumption: 0.17-0.19 kWh per kg of dry load

Dryers	Vented		▯		27% annual sales (2009)	Western EU countries: €204-732 (from E to A energy efficiency class respectively); Eastern EU countries: €310-617 (from G to A energy efficiency class respectively)	Electricity, Gas (natural gas or propane)	Time controls (delay timers); On/off stand-by mode switchers; Moisture control runtime option (temperature sensors, moisture sensors, resistance sensing rods)	13 yrs; Usage: 160 cycles per yr	Efficiency: 0.74 (+/- 25%) kWh per kg of dry load (kWh/kg load) (2008); Consumption: 2.36 kWh/cycle (2008)
	Condenser		▯		73% annual sales (2009)		Electricity, Gas (natural gas or propane)			
	Heat-pump condenser		▯		-		Electricity, Gas (natural gas or propane)			
Other electric appliances	Coffee machines (automatic drip filters, single servers, espresso)	▯	□		-	Drip filter machines: €35 per unit, Pad filter machines: €81 per unit, Hard cap espresso: €156 per unit, Semi-automatic espresso: €103 per unit, Fully automatic espresso: €595 per unit	Electricity	Parameters for increasing energy efficiency: - auto-power-down, - improved insulation of hot components, - "energy saving" functioning mode, - reduced/zero standby consumption, - reduced heated water, - reduced thermal capacity of heating unit	Drip filter machines: 6 yrs, Pad filter machines: 7 yrs, Hard cap espresso: 7 yrs, Semi-automatic espresso: 7 yrs, Fully automatic espresso: 10 yrs	Drip filter machines: 1030 kWh, Pad filter machines: 1134 kWh, Hard cap espresso: 843 kWh, Semi-automatic espresso: 1367 kWh, Fully automatic espresso: 1133 kWh [lifetime electricity consumptions]

	Vacuum cleaners (upright, canister, stick, wet-dry, wide area, steam/deep cleaner)	▯			-	Upright: €49-772 per unit, Canister: €39-1000 per unit, Stick: €23-230 per unit, Wet/Dry: €39-540 per unit, Steam: €77-310 per unit			8 yrs (5 yrs, for battery/cordless products)	1.5 kWh/hour of use (0.024 kWh/hour of use, for battery/cordless products)
Electronic devices	Television (Cathode Ray Tube (CRT), Liquid Crystal Display (LCD) or Plasma Display Panel (PDP))	▯			EU market share (2009): - 3% CRT, - 86% LCD, - 11% PDP	€281 for CRT, €985 for LCD, €2411 for PDP [data for Western EU, 2005]	Electricity	Power management features for TVs own energy consumption and that of associated equipment,		On-mode power consumption: - CRT: 55W, - LCD: 67-72W, - PDP: 120W; TV usage pattern (2007): average 240 viewing min/person-day
	Personal Computer (PC) (desktop or laptop)	▯			57% (households ownership, 2008)	€620 (for desktop computers, 2005); €238 (for laptop computers in the UK, 2012)	Electricity		6 yrs (desktop computers), 4 yrs (laptop computers)	Idle mode power consumption (2005): - Desktop PC: 78.2W, - Laptop PC: 32W; Sleep mode power consumption (2005): - Desktop PC: 2.2W, - Laptop PC: 3W; Off mode power consumption (2005): - Desktop PC: 2.7W, - Laptop PC: 1.5W
Solar heating and cooling	No information available yet									

Table 1: Relevant technologies and appliances characterizing residential energy demand.

Space Heating and Cooling

Generally, heating accounts for the largest residential energy demand in temperate regions. However, residential energy consumption associated with heating and cooling demand depends on several factors, like climatic conditions, seasons, and consumers' behaviour.

In Europe, particularly combination boilers and district heating systems, associated with combined heat and power systems, are very popular heating solutions. Boilers especially are convenient since they can provide at the same time space heating and hot domestic water.

The environmental impact associated with this class of technologies is related to their energy consumption. Today though, there is a fuel transition underway, towards switching from oil and coal based technologies to electricity, gas, biomass or renewables based ones, which have lower environmental impacts. Particularly, common renewable alternatives are biomass boilers, solar thermal systems and heat pumps, and they can contribute to increase the share of renewable in use to address the residential energy demand.

Higher efficiencies for space heating and cooling systems are obtained through condensing operations of either boilers of furnaces (IEA ETSAP, 2012a).

Water Heating

Water heating represents the third largest domestic final energy use. Currently, if old technologies would be replaced with the best available ones, there would be the potential for up to 60% energy savings in the domestic sector.

Today, standard requirements for water heating systems in the EU set the need to provide 22-33 litres of hot water at 60°C per person per day, and they are trying to push towards the implementation of solar and heat pump technologies (IEA ETSAP, 2012b).

Lighting

Lighting systems account for 19% of the total electricity produced worldwide, and they represent the second largest end-use for the residential sector.

Today, in the EU the phase out of general lighting services (GLS) using incandescent tungsten filament lamps is ongoing, thus pushing towards the use of alternative more efficient lighting technologies (IEA ETSAP, 2012c).

Cold Appliances

Refrigerators and freezers accounts for 15% of EU domestic energy consumption.

Their efficiencies mainly depend on: the thermal insulation technologies and materials adopted, and the performance of major internal components (i.e. compressor, expansion valve and refrigerant circuit). Since currently the EU market for cold appliances is almost saturated, with penetration rates reaching almost 100%, major barriers for increasing energy savings coming from these appliances seem just to be related to consumers' unawareness of potential benefits of switching to new technologies (IEA ETSAP, 2012d).

Cooking

In 2007, electricity demand for domestic cooking appliances in the EU accounted for 7.5% of the total demand from the residential sector, but consumers' behaviour in this context can have a huge impact thus making demands differing up to 30%.

It has been estimated that potential energy savings in the future, thanks to either the replacement of old technologies with new more efficient ones or the adoption of more conscious behaviours, can reach 7% for ovens and 4% for microwaves. However, extra 20% of annual electricity consumption accounts just for the stand-by mode, thus suggesting extra possible margins for substantial reductions of demand (IEA ETSAP, 2012e).

Dish Washing Machines

As reported in the table above, currently 90% of EU washing machines are performing at the A class of energy labeling or even better, thus meaning consuming on average less than 1,05 kWh per cycle.

The rate of penetration of these appliances on the EU market is reaching 50%, with an average cost of 300€ per machine (IEA ETSAP, 2012f).

Washing Machines

In 2007, washing machines accounted for 6% of total electricity consumption of the EU residential sector.

Today, there is a trend in increasing the standard size of the machines, from 5 kg to 6 kg with potential benefits for improving the energy efficiencies of this class of appliances, although the market is already saturated and the replacement for old technologies is not frequent (Lindström and European Council for an Energy Efficient Economy, 2011).

Dryers

For this class of appliances, the European energy labelling systems seems to have worked well in promoting the selling of efficient technologies so far. Market demand though is currently focusing more on low capacity machines, which are also less efficient, thus preventing manufacturers to sell and produce most efficient ones.

Industry experts say in the future heat pump dryers will be the new technologies increasing their share in the market (IEA ETSAP, 2012g).

Other Electric Appliances

There are currently no European legislations targeting the energy performances and efficiencies of this group of appliances.

In order to reduce the energy demand associated with these technologies, and to stimulate consumers to switch to more efficient products, the following parameters need to be taken into account: cost, style and design of the products, inertia, consumer convenience, lack of consumers' awareness and knowledge on the functions and performances of different products (IEA ETSAP, 2012h).

Electronic Devices

This group of technologies includes personal electronic devices, like for instance personal computers or televisions.

Particularly, concerning televisions, they accounts for approximately 7% of residential electricity consumptions, and the present trend towards buying new TVs with larger and higher resolution screens will further increase the associated energy consumptions (IEA ETSAP, 2012i).

4.1.1 Smart features

In addition to the basic common features domestic appliances can perform, there are smart features available for most of the appliances listed in Table 1. If implemented on large scale across households in the EU, in combination with smart metering systems allowing the transmission and management of real time consumption data and patterns, they could enable optimal monitoring and control of appliances.

Some examples are the ability to connect appliances to WiFi networks and remotely access and operate them through smartphones or other electronic devices. This functionality allows for instance to control operating temperatures and programs on washing machines or ovens, or to track energy usage and allow consumers to visualize their consumption patterns, or to schedule the operation of different appliances at different times of the day. In some cases, trough remote connections, appliances can also allow users to check the status of the machine, and to automatically receive real-time pricing information and schedule more energy intensive operations when prices go down (General Electric (GE) Company, 2015; MIT Technology Review, 2009; Pilkington, 2013)

Many of the largest manufacturing companies that are developing smart home appliances created their own WiFi network platform to allow the interaction of several appliances with the same personal device through specific app, and to stimulate the consumer to buy all home appliances from the same brand.

4.2 Policies, measures and technologies to activate consumers

In the EU there are many policies and legislations currently in place to support and foster Researches, Developments and Demonstrations (RD&D) focusing on solutions and technologies aiming at increasing energy efficiency of the system. Once implemented, these solutions can contribute in reducing Greenhouse Gas (GHG) emissions coming from the energy sector and providing low-carbon alternatives for the future economic development of the Union, thus helping in reaching current targets in place.

There are also specific policies aiming at renovating current energy infrastructures and networks. They intend to provide a better integration of smart technologies and local sources for energy production, as well as to create a common internal energy market and network to effectively allocate the electricity available in the grid. In this context, enabling consumers to better monitor and manage their consumption patterns and taking advantage of Demand Side Management (DSM) and Demand Response (DR) techniques and methods can also have an impact. For instance, according to Gelazanskas and Gamage (2014), demand response methods applied to HVACs, water heaters and electronic devices (e.g. lighting systems) in households allow to shift approximately 20% of the energy load coming from HVACs and 9% of the one related to water heating systems, while maintaining high comfort levels. The DR method used in this case was a passive controller reacting to real-time energy price information, which needs smart meters and grids to be able to perform an effective two-way communication between the grid and the user appliances.

A list of main relevant policies and legislations is provided in Table 2 below, together with brief descriptions of main goals and objectives.

Policy	Document	Topic	Main goal	Objectives	Time horizon	Legally binding	Non-legally binding
2020 Energy Strategy	COM(2010) 0639	EU energy strategy	To set out European Commission's energy strategy until 2020	Five priorities to implement the strategy: - limit the energy use in EU - build a pan-European Integrated energy market - empower consumers and achieve highest level of safety and security - extend EU leadership in the development of energy technology and innovation - strength the external dimension of the EU energy market Building and transport sectors providing relevant energy-saving potential	2010-2020		▯
2030 Energy Strategy	COM(2014) 015	EU energy strategy	To highlight the need for a EU transition to low-carbon economy, following the progress achieved with the EU 2020 targets	Full implementation of the EU 2020 targets and the following additional ones, to be achieved by 2030: - 40% EU GHG emissions reduction, below 1990 levels - at least 27% increase in share of energy from renewable sources consumed in the EU - reform of the Emissions Trading System (ETS), and creation of new market stability reserve and tightening of annual cap on emissions post 2020 - review of 2012 energy efficiency directive, to further improve energy efficiency and establish a new energy saving policy - creation of a new EU governance system for delivery of energy and climate objectives - definition of key indicators for the monitoring of progress in all aspects related to competitiveness, security, sustainable energy	2014-2030		▯

2050 Energy Strategy	COM(2011) 0885	EU energy strategy	To provide new indications for the Energy roadmap 2050, in order to address the commitment to reduce GHG emissions by 80-95% below 1990 levels by 2050	To provide alternative scenarios to achieve competitiveness in future EU low carbon economy by 2050, ensuring security of energy supply. The following factors are identified as relevant: - full implementation of 2020 energy strategy - need to focus on energy efficiency, particularly in building, transport, products and appliances - potential to supply 30% of EU energy consumptions with renewable sources by 2030 - need for investments in R&D and technological innovation to increase affordability of low-carbon energy alternatives - substitution of oil and coal with gas to reduce emissions from energy technologies currently in place - better matching of energy prices and actual costs - development of new energy infrastructures - ensuring safety and security of energy sources - broader and more coordinated EU actions towards international energy relations and climate change - set milestones to achieve goals and give guidance to investors, in relation to the 2030 policy framework	2011-2050		

Energy Security Strategy	COM(2014) 0330	EU energy strategy	To define a strategy for ensuring EU energy security and reduce vulnerability as consequence of current geopolitical context	Key actions that need to be taken - avoid disruption of energy supplies for winter season 2014/2015 - strengthening emergency and solidarity mechanisms among EU's countries, and protecting strategic and critical infrastructures - moderating energy demand, through the enforcement of energy efficiency and energy performance of buildings directives and review of other directives, and attracting private sector investments in low-carbon economic activities - building an integrated, well operating and efficient internal energy market - increasing internal local energy production in the EU - foster the development of energy technologies - diversifying external supply and related infrastructures to reduce dependence form other countries - improving coordination of national energy policies and finding common solutions for communicating on external issues (ensuring coordination on key political decisions related to energy)	2014-			▯
Energy Efficiency Directive	2012/27/EU	EU energy efficiency	To establish a common framework of measures for promoting energy efficiency in the EU	To ensure all Member States will establish national energy efficiency targets to reach the EU energy efficiency target of 20% by 2020, in comparison to 1990, and will establish an energy efficiency obligation scheme to ensure providers will achieve 1.5% cumulative end-use energy savings by the end of 2020	2012-2020	▯		
Energy Performance of Buildings Directive	2010/31/EU	EU energy efficiency	To promote the improvement of energy performance of buildings in the EU, in relation to different climatic and local conditions	The directive aims to define the following: - common general methodological framework for calculating integrated energy performance of buildings and building units - set of minimum requirements regarding the energy performances of various classes of buildings and building units (e.g. new or existing buildings, building elements, technical building systems) - list of existing and potential financial incentives for each country, to promote improvements in buildings energy efficiency	2010-	▯		

Energy Labelling Directive	2010/30/EU	EU energy efficiency	To provide end-users with information concerning energy consumption of energy-related products, thus allowing them to choose the more efficient ones within the EU market	To establish a common EU framework for the provision of: - common labelling and standard product information regarding energy consumption and the associated use of other essential resources - supplementary information for energy-related products in the EU (concerned products are the following: second-hand products, means of transport for persons or goods, product rating plates)	2011-	▯	
Ecodesign Directive	2009/125/EC	EU energy efficiency	To ensure free movement of energy-related products with ecodesign features within the EU internal market	To establish a common EU framework to define ecodesign requirements for energy-related products (except means of transport for persons or goods), thus ensuring their contribution towards a sustainable development; Key points will be: - surveillance of products available on the EU market - free movements of products - promotion of energy efficiency through national targets - ensure conformity assessment of ecodesign requirements - ensure the value of the European Community eco-label - creation of harmonized standards across the EU - stimulate manufacturers to support consumers in using products in sustainable ways	2009-	▯	

Energy Technologies and Innovation	COM(2013) 253	EU technology and innovation	To set out the EU energy technology and innovation strategy, in order to ensure a world-class technology and innovation sector to reach the targets set for year 2020 and beyond	To ensure: - EU support in innovation through regulation and financing that focus on large-scale efforts beyond single countries achievements - energy technologies developments that contribute to deliver cost-effective energy services to final customers - sharing of resources: state and private investments, EU funding - to put in place a framework for delivering economic and viable energy technologies and solutions	2013-		□
Investing in the development of low carbon technologies (SET-Plan)	COM(2009) 0519	EU technology and innovation	To provide Technology Roadmaps 2010-2020 for the implementation of the SET Plan, in order to move towards a new low-carbon economy	To identify key investments and financial instruments for the development of low-carbon technologies within the SET Plan, and to provide the SET Plan initiatives with the support needed at the EU level	2009-	□	□
Electricity Directive - Common Rules for the Internal Market in Electricity	2009/72/EC	EU Markets and Consumers - Market legislation	To establish common rules for the internal EU electricity market	To introduce common rules for generation, transmission, distribution and supply of electricity in the EU, to ensure proper organisation and functioning of the sector	2009(partial implementation in 2011)-		□
An Energy Policy for Consumers	SEC(2010) 1407	EU Markets and Consumers - Consumers rights and protection	To provide an overview of existing European, consumers-related energy policy measures	To highlight good and bad practices that are aimed to have an impact on consumers welfare in the energy sector, and to identify areas that need to be considered for further actions in the future	2010-	□	

Regulation on guidelines for trans-European energy infrastructure	No. 347/2013	EU Markets and Consumers - Smart grids and meters	To provide guidelines for the timely development of priority corridors and areas for energy infrastructures at the trans-European level	To help in: - identifying projects of common interest, - facilitating timely implementations of projects - providing indications for allocation of costs and risk-related incentives at cross-borders locations - setting conditions for eligibility of projects for obtaining financial assistance	2013-	□	
Smart Grids: from innovation to deployment	COM(2011) 202		To propose actions for the development of Smart Grids, in support to the Europe 2020 Strategy targets	Five main objectives are defined: - to develop common European standards for Smart Grid - to guarantee the security and protection of consumers' data - to support smart grid deployment with incentives for investments - to develop smart grids looking at consumers' interests in a competitive and transparent retail market - support innovation investing in research and development	2011-	□	
Protection of Personal Data Directive	1995/46/EC	EU Data protection	To protect people's right and freedoms when personal data are processed and free to move	To ensure that processing of data are lawful and that principles of data quality are respected	1995-	□	

Commission Recommendation of 9 March 2012 on preparations for the roll-out of smart metering systems	2012/148/EU	EU Markets and Consumers - Smart grids and meters	To provide guidelines to Member States for designing and operating smart grids and smart metering	These guidelines are meant for: - ensuring the protection of personal data - defining measures that need to be taken when deploying smart metering applications, to ensure that national legislations on the processing of personal data are respected in accordance to the EU Directive 95/46/EC they also provide: - methodology for long-term CBA of smart metering systems - set of minimum requirements for smart metering systems for electricity	2012-	□	
Commission Recommendation of 10 October 2014 on the Data Protection Impact Assessment Template for Smart Grid and Smart Metering	2014/724/EU	EU Markets and Consumers - Smart grids and meters	To provide guidelines to Member States, regarding Data Protection Impact Assessment (DPIA) Template for Smart Grid and Smart Metering Systems	To help to ensure that the protection of personal data and privacy in the deployment of Smart Grid and Smart Metering Systems is guaranteed	2014-	□	
Directive on the deployment of alternative fuels infrastructure	2014/94/EU	EU Markets and Consumers - Smart grids and meters	To establish a framework for the deployment of alternative fuel infrastructures in the EU	To help minimizing dependence on fossil fuels (especially oil) and therefore mitigate the environmental impact associated to the transport sector, setting out minimum requirements for new fuel infrastructures	2014-	□	

Renewable Energy Directive	2009/28/EC	EU Renewable Energy	To establish a common framework for the promotion and production of renewable energy sources	Key points are to: - set national targets for the overall share of final gross energy consumption that must be provided by renewable energy sources in the transport sector; - establish criteria for ensuring the sustainability of biofuels and bioliquids; - provide rules for dealing with further issues (e.g. joint projects, administrative procedures, guarantees of origins, access to electricity grid) between Member States, related to energy form renewable sources.	2009	▯	
A Roadmap for moving to a competitive low carbon economy in 2050	COM(2011) 112	EU strategy for low-carbon economy	To delineate roadmaps to achieve GHG emissions' reduction targets up to 2050	To suggest the most cost-effective solution to reduce domestic emissions by 30% for 2030 and 40% for 2040 (compared to 1990 levels) ,in order to achieve the 80-95% GHG emissions' reduction targets by 2050; various contributions are considered, coming from the following sectors: power sector, transport, buildings, industry, agriculture	2011-		▯
Establishing Horizon 2020 - the Framework Programme for Research and Innovation (2014-2020)	No. 1291/2013	EU Horizon 2020	To establish "Horizon 2020 - the Framework Programme for Research and Innovation (2014-2002)" and determine the framework governing support for the EU to related activities, to deliver the Europe 2020 Strategy	To support research and innovation, achieving the target of 3% of GDP for R&D in the EU by 2020, through the following priorities: - excellent science - industrial leadership - societal changes	2012-2020	▯	

Horizon 2020 - the Framework Programme for Research and Innovation (2014-2020)	No. 1290/2013	EU Horizon 2020	To set rules for delivering and monitoring funds for RD&D projects under Horizon 2020 framework programme	Focus on participation of indirect research projects (i.e. direct research done by the EC's Joint Research Centre) and specific forms of funding: - grants - prizes - procurement - financial instruments	2013-2020	□	
Benchmarking smart metering deployment in the EU-27 with a focus on electricity	COM(2014) 356	Smart metering deployment in the EU-27 - focus on electricity	To monitor the progress of smart meter roll-out in the EU	To benchmark current smart metering deployment and future time plans of Member States, as set by the Electricity and Gas EU Directives	2014	□	
Energy Efficiency and its contribution to energy security and the 2030 Framework for climate and energy policy	COM(2014) 520	EU energy efficiency	To propose the energy saving target of 30% by 2030, to improve EU energy efficiency and to move towards a more competitive, secure, sustainable energy system	To assess current EU's energy efficiency targets for 2020, and to propose a new one of 30% by 2030	2014-2030		
EUROPE 2020 A strategy for smart, sustainable and inclusive growth	COM(2010) 2020	EU strategy for growth and employment	To promote smart, sustainable, inclusive growth	2020 targets: - at least 75% increase of employment rate - 3% GDP invested in R&D - 20/20/20 targets from the 2020 Energy strategy - reduce school drop out rate by at least 10% and increase tertiary degrees by 40% - reducing the number of poor or socially excluded people by 20million	2010-2020		

Eco-design Regulation	No. 801/2013	EU energy efficiency	Eco-design requirements for standby and off-modes of electrical and electronic household and office equipment	Setting the specific requirements for related appliances	2013-		

Table 2: Current EU policies and legislations concerning energy efficiency, GHG emissions reduction and implementation of smart infrastructures, indirectly supporting consumers' engagement in energy management.

Particularly in relation to the topic of this thesis, more details are provided for the following legislative documents, as they were identified as the most relevant in supporting and developing technologies, products and services contributing in enhancing the role of energy consumers in the system.

Energy Efficiency Directive (EED, 2012/27/EU)

This directive aims to achieve the energy efficiency target of 20% by 2020, in comparison with 1990 data.

In order to do so, it provides a framework of binding measures for the EU Member States that acts on promoting from general requirements for all Member States to more targeted measures, for specific economic sectors. (IEA, 2014a)

More specifically, first it determines the following measures for all EU countries:

- Provision of indicative energy savings targets for different Member States, to be achieved by 2020 in order to reach the EU 20% target on time;
- Identification of cost-effective potentials for the implementation of innovative, efficient heating and cooling systems in all Member States by end of 2015;
- Assessment of gas and electricity infrastructures for the identification of measures and investments for the deployment of a cost-effective energy efficient renovation of existing network infrastructures by end of June 2015;
- Obligations for energy providers to reduce end-use energy consumptions by 1,5% per year, during the period 2014-2020;
- To secure the provision of metering and billing services on actual energy consumption of all energy sources in place for different sectors, allowing end users to take informed decisions;
- Rules for assuring that public procurements from central governments opt for high-efficient products only;
- Facilitated development of national financing solutions for energy efficient measures (IEA, 2014a).

Secondly, it determines more specific measures for the following different technology sectors:

- Industry;
- Buildings;
- Appliances and equipment;
- Heating and cooling;
- Transport;
- Energy providers;
- Energy efficiency funding (IEA, 2014a).

For the purpose of this thesis, looking at the end-users in the residential sector, the following measures were identified as particularly relevant:

- Within the Building sector, the legal framework provided by the revised EU Energy Performance of Buildings Directive (EPBD, 2010/31/EC) included in the EED, which requires the establishment and application of Minimum Energy Performance Requirements (MERS) for new buildings and old renovated ones.

  The MERS should set the common basis for a set of building energy code requirements that looks at the integrated energy performances of buildings, considering all their uses.

The EPBD also asks to all Member States to define mandatory energy performances certificates (EPCs) for informing tenants and buyers about energy performances of buildings, allowing comparisons and assessments, and recommending cost-effective options for improvements.

- Regarding Appliances and Equipment, the EU legislation currently in place refers to the Energy Labeling Directive (2010/30/EC) and the Eco-design Directive (2009/125/EC).
  The first one sets a rating system for some residential appliances, and defines a set of MERS for 16 different groups of products. The second aims at reducing the environmental impacts and energy consumption of products through a life-cycle perspective.
- For Energy Providers, the EED requires them to increase cumulative end-use energy savings of 1,5%, referring to the annual energy sales over the period 2014-2020 (as mentioned above), and requires Member States for the full implementation of smart metering infrastructures.
- Regarding Energy Efficiency Funding, through Horizon 2020 Programme, several International Financial Institutions like the European Investment Bank (EIB) will support research and innovation projects providing increasing funds. These are included in the European Local ENergy Assistance (ELENA) Facility for the period 2014-2020 (IEA, 2014a).

In addition, the EED provides the present EU definition for "Smart metering system" (Article 2, point 28, directive 2012/27/EU): "electronic system that can measure energy consumption, providing more information than a conventional meter, and can transmit and receive data using a form of electronic communication".

All in all, through all these measures, the EED supports the development of services for end-users based on data about their energy behaviours as provided by smart meters, demand response solutions and dynamic prices (COM(2014) 356).

Third Energy Package

Consisting of three regulations and two directives that came into force on September 2009, the Third Energy Package aims at creating an effective EU single energy market for electricity and gas. The purpose of this common energy market will be to ensure low energy prices and increase standards of service and security of supply (European Union, 2015).

The two directives included in the package are the Electricity Directive (2009/72/EC), defining common rules for the internal electricity market, and the Natural Gas Directive (2009/93/EC), setting common rules for the internal gas market. The three regulations included in the package instead, which were adopted in July 2009, define the following conditions:

- to access the natural gas transmission networks ((EC) No 715/2009),
- to access the network for cross-borders exchange of electricity ((EC) No 714/2009),
- to establish the Agency for the Cooperation of Energy Regulators (ACER) ((EC) No 713/2009).

The two directives aim at creating common European internal markets for electricity and gas, thus enhancing competitiveness, liberalisation, market efficiency, and supporting the creation of large European utilities. Large utilities can benefit of a broader market area and should provide consumers with better tools and services addressing the demand-side (IEA, 2014a).

The three regulations focuses on defining common rules for the establishment and operation of Transmission System Operators (TSO) unbundled from energy utilities: the first ones dealing with transmission networks, whereas the latter focusing on energy production and supply. These regulations also established the ACER, to foster cooperation between national regulatory authorities and taking care of cross-border related issues, and the European Network for Transmission System Operators (ENTSO) to develop the EU network and to support collaboration between electricity and gas grid operators towards more integrated common security standards, technical and commercial codes and investments in infrastructures (IEA, 2014a).

Among the requirements set by the Third Energy Package, it intends to ensure long-term benefits for consumers through tightening up consumer protection rules and pushing on the implementation of smart metering systems. Particularly for electricity, it asks to all EU country members for the roll-out of 80% of smart meters by 2020 (COM(2014) 356).

As reported by the *Benchmarking smart metering deployment in the EU-27 with a focus on electricity* (COM(2014) 356), each Member State conducted a Cost-Benefit Analysis (CBA) to analyse the long-term economic costs and benefits of a large scale smart meter roll-out. Currently, 16 Member states have already decided to proceed to the large-scale roll-out plan by 2020, as required by the EU. Regarding the remaining EU countries, they decided to either collect and manage data through different solutions, or to implement alternative solutions.

The so-called Third Package intends to create opportunities for consumers to be able to benefit from a more liberalised and therefore competitive energy market. Increasing competitiveness among energy producers and suppliers and allowing more of less regulated retail prices can benefit those consumers that decide for engaging in a more active and responsible management of energy. Smart meters should provide them with the information needed to monitor and change consumption patterns as desired, for instance to meet lower retail prices or to choose for the consumption of electricity coming from renewable energy sources (IEA, 2014a).

Horizon 2020

Known as the most relevant financial instrument for Research and Innovation in the EU, Horizon 2020 allocated funding for approximately €80 billion over the period 2014-2020. These funds need to be spent on research projects for fostering global competitiveness of Europe, thus hoping they will contribute also in creating occupation and driving economic growth (European Union, 2016a).

Among the different societal challenges highlighted as more relevant to achieve the above mentioned aims under this framework programme, "Secure, Clean and Efficient Energy" has been identified as fundamental to create a competitive energy future for the Union, and approximately 7.5% of the funding has been allocated to this. Particularly, the following three focus areas has been presented as priorities that Horizon 2020 intends to support: Energy Efficiency, Low Carbon Technologies and Smart Cities and Communities. All energy challenges has been formulated after the revision of the SET Plan (European Union, 2016b).

2020 Climate and Energy Package

As already mentioned before in the introduction, the 2020 Climate and Energy Package sets the main broad objectives that lay behind current all European efforts towards enhancing sustainability in our society. It consists of a legal framework including several legislations, particularly the Directive No 2009/28/EC, also known as Renewable Energy Directive, to foster the use of renewable energy sources in the Union, and the Energy Efficiency Directive (2012/27/EU) already detailed above (IEA, 2014a).

With regards to the Renewable Energy Directive (2009/28/EC), it is worth mentioning that it asks to each country member to develop the so-called "National Renewable Energy Action Plan", in order to ensure their contribution towards having 20% of the EU gross final energy consumption produced by Renewable Energy sources. In this context, updated energy transmission and distribution systems as well as new tariffs programmes and consumers' participation could be fundamental to effectively use the energy sources deployed by the countries.

4.3 Metrics and KPIs to quantify the effectiveness of different parameters on energy demand

Identifying key parameters for evaluating energy performances of the technologies mentioned above is important, in order to quantify the potential of new technological features and the contribution of human interaction in the management of the energy system.

Traditionally, energy intensity and energy productivity have been used to approximate the demand and to relate it to the underlying economic structure of a country.

The energy intensity of an economy is measured in terms of Total Primary Energy Supply (TPES) per unit of GDP. It provides a general estimation of energy demand, without giving detailed information of all economic variables and other factors that lie behind the general well-being that is correlated to this measure. The energy productivity instead express how much of the GDP is produced per a single unit of energy in a country. This data can be more relevant for policy makers, since it gives some information about the correlation between energy efficiency and the economy of a country. It can help in designing policies and guidelines to support economic grow in a more efficient and sustainable way (IEA, 2014b).

Nonetheless, today more accurate data and detailed information need to be considered for better taking into account changes in energy use related to different economic and social purposes. It has been identified the need for disaggregating and decomposing energy data into several indicators, to better track the effects of key policies and measures, particularly towards increasing energy efficiency (Chung et al., 2011; IEA, 2014b).

The decomposition analysis has been used by IEA to trace how various driving forces or factors impact energy consumption, and to quantify this impact. Focusing on investigating key elements affecting energy efficiency, the overall energy consumption data has been decomposed into six sectors, among which the residential one. For this sector, the following energy uses have been identified as the major components that need to be tracked to understand the effect of residential consumers on energy efficiency trends:

- Space heating;
- Space cooling;
- Water heating;
- Lighting;
- Cooking;
- Appliances.

Concerning these energy uses, the following additional information has been identified as key elements in driving and influencing energy consumption patterns:

- The technology chosen;
- Consumers' preferences;
- Households income;
- Type, age and efficiency of the building, the appliance used, the single dwelling (OECD/IEA, 2014).

The rule of thumb in this context is that the more details we add to the measuring data, the more relevant is the information that can be obtained for the purpose of policy and regulation development. The key factors mentioned above provide useful information to contextualise the numerical data and to identify key factors that influence changes in energy consumption over the years. Not always it is possible to collect all these information though. Depending of the amount of statistical data available for each end-use, it can be discussed the level of details that should be reached in order to provide meaningful outcomes from the analysis.

The decomposition analysis as explained so far can be visualised as a pyramid of indicators. As long as more details and information are added to overall consumption data available, it becomes possible to get a clearer idea of the mechanisms and the reasons behind energy consumption trends in different geographical areas and social contexts (OECD/IEA, 2014). From the top to the bottom of the pyramid, and increasing level of details is provided by different indicators that vary from the most largely available ones to the less common ones, which are also more difficult to measure or estimate and understand.

An example of the pyramid of indicators for the residential sector is outlined below (Figure 2).

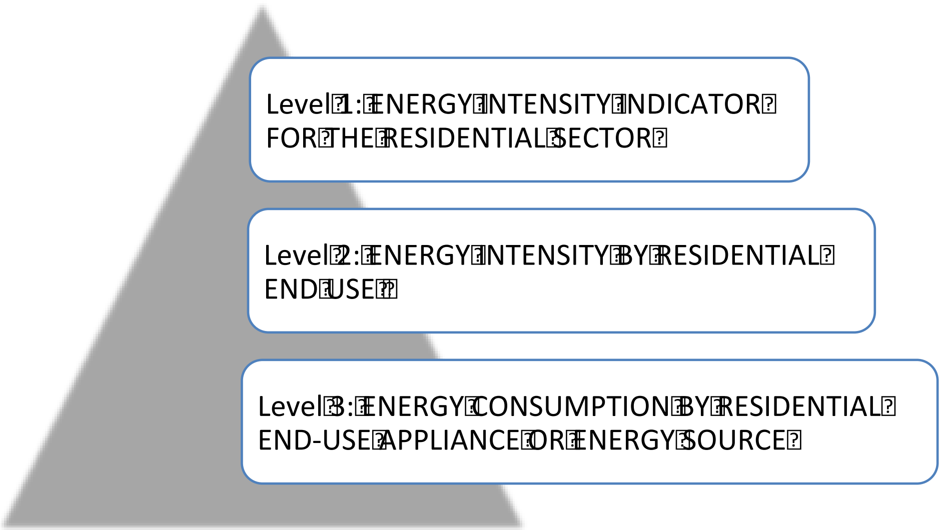

Figure 2: Pyramid of indicators for the residential sector.

Concerning both space heating and cooling demand, the measuring unit used by IEA is the total final consumption (TFC) of energy used per residential floor area, expressed in GJ/m^2. For water heating instead, typical unit of measure is energy used per dwelling, expressed in GJ/occupied dwelling. For lighting and cooking purposes, consumption data are typically measured as energy used per dwelling (GJ/occupied dwelling), although lighting demand can also be expressed as energy consumed per floor area (GJ/m^2). Finally, for common domestic appliances, energy demand can be either expressed as energy consumption per dwelling, or as energy consumption per appliance unit or type of appliance (GJ/dwelling or GJ/unit) (IEA, 2014b).

Table 3 below shows several possible indicators for each of the main energy uses in the residential sector, as indicated in the IEA's *Energy Efficiency Indicators: Essentials for policy making* (OECD/IEA, 2014). Highlighted in light orange are the preferred indicators for the purpose of identifying key energy demand and consumptions that could benefit energy efficiency policy development.

Main uses	Indicators	
	Unit consumption level	*End-use level*
Space heating	energy consumption per capita	for dwelling type: energy consumption per floor area heated
	energy consumption per dwelling with heating	for type of heating system: energy consumption per floor area heated
	energy consumption per floor area heated	for energy source: energy consumption per floor area heated
Space cooling	energy consumption per dwelling with air conditioning	for dwelling type: energy consumption per floor area cooled
	energy consumption per floor area cooled	for type of cooling system: energy consumption per floor area cooled
		for energy source: energy consumption per floor area cooled
Water heating	energy consumption per capita	for type of water heating system: energy consumption per dwelling
	energy consumption per dwelling with water heating	for energy source: energy consumption per dwelling
Lighting	energy consumption per capita	for type of dwelling: energy consumption per dwelling
	energy consumption per dwelling	for type of dwelling: energy consumption per floor area
	energy consumption per floor area	
Cooking	energy consumption per capita	for energy source: energy consumption per dwelling
	energy consumption per dwelling	
Appliances	energy consumption per capita	for appliance type: energy consumption per appliance unit
	energy consumption per dwelling with electricity	

Table 3: Possible Energy Efficiency Indicators for the residential sector (OECD/IEA, 2014).

Particularly interesting for the purpose of this thesis is to note that the IEA identified the energy consumption of each appliance as fundamental indicator. This can be explained as it has been proven that people tend to buy more electrical appliances as soon as they earn higher salaries and gain better quality life. For this reason, consumers' behaviour could turn out to be not so effective in reducing energy demands as tightening up energy efficiency labelling regulations for appliances and pushing towards the development of more efficient technologies (Chung et al., 2011). Therefore, in this context it becomes increasingly relevant to investigate which type of appliance affects more the overall residential energy demand, and how much switching to new technologies could lower consumptions.

4.4 The impact of active consumers on the energy system

Energy load curves, which represent the distribution of consumers demand across time, are determined primarily by dynamic behaviour. This in turn depends on the distribution of human activities across time and the circumstances in which these activities take place (e.g. weather conditions, social and cultural context) (Spataru and Barrett, 2013). For this reason, it is important to understand which are the values, the main attitudes and motivations that lie behind consumers choice and habits in energy use (Mengolini and Vasiljevska, 2013). Based on this, different motivational factors can be used to stimulate the consumer sector to choose different energy consumption strategies and patterns, as well as technological product that allows to better manage energy usage. Most common motivational factors have been identified by Mengolini and Vasiljevska (2013) as the following:

1. Environmental concerns related to the energy system;
2. Reduction of/control over electricity bills;
3. Better comfort; to increase the level of comfort and control over energy consumption;
4. Trust in energy utilities and companies.

Concerning the "Reduction of/Control over electricity bills", it seems that consumers are still sceptical about the benefits that this solution could bring them in real life. Previous disappointing, frustrating experiences in interacting with energy utilities make them being distrustful on this issue. Therefore, it appears clear the importance of building and strengthening relationships with consumers, committing to clearly presents costs, risks and benefits associated with different options provided. Influencing consumers perception of these parameters can affect their technology choices and increase their level of engagement. In addition, it seems also that consumers trust more relationships where third parties are involved. These are usually represented by neutral and well trusted organizations or persons, as for guaranteeing the reliability of the interaction (Mengolini and Vasiljevska, 2013).

Other successful factors in engaging consumers on monitoring their energy usage have been reported by Boork et al. (2014) in their paper that investigated consumers participation in several European smart grid pilot projects. Here, positive factors seems to be the consideration energy utilities have of end users, as human beings that have different habits and social, cultural background and therefore need to be approached as different target groups, according to their needs. Moreover, the sense of place and of peculiar community dynamics going around the individual consumers seems to be important to understand and address better their expectations and to raise consensus and engagement. In addition, gaming strategies, funny and positive messages and communication resulted to be effective motivational factors for consumers engagement (Boork et al., 2014).

Regarding communication strategies, the World Economic Forum (2010) mentioned the need for using marketing and outreach activities in order to stimulate proactive engagement among end users and built consensus and understanding. This is important for enabling the technical capabilities provided by the implementation of new energy management strategies, allowed through the deployment of smart grids.

Gelazanskas and Gamage (2014) also highlighted how consumers can choose to engage in different control strategies depending on the communication developed with energy utilities, thanks to demand response and dynamic pricing programmes. Four main control strategies for energy use and consumption from domestic appliances can be developed today thanks to the use of energy management units, namely passive, active, interactive and transactive (according to their level of technological development)(Gobal Environment Fund and Global Smart Energy, 2008). Mengolini and Vasiljevska (2013) also stressed the importance of testing and measuring the rate of behavioural change different feedback solutions can bring to the system (e.g. smartphones applications against in-home displays, to allow the monitor and control of energy usage).

All in all, it looks clear that there is need to further investigate psychological aspects behind human behaviour towards the acceptance of a more sustainable energy system that is under development, in order to develop a more consumer-centric approach towards energy use. Fundamental is to focus on consumers beliefs, values and social interactions, to develop the ability of classifying them between different target groups and to effectively make them active players in the energy system. Social and cultural backgrounds need to be considered to fully understand energy use patterns, and to become able of enhancing consumers' engagement and participation in the transition towards more efficient and sustainable energy systems (Mengolini and Vasiljevska, 2013).

In order to do so, it is useful to understand that there are 3 main roles that need to be considered, when talking about consumer engagement. People can be divided between:

- The Consumers, who have a passive role in the energy system and aim only to lower their bill and keep their current level of comfort;
- The Customers, who play an active role in the energy system and are eager to establish a position/role in the electricity market;
- The Citizens, who have a "we-centred" mind-set and are happy to feel like being part of the community or group of people that surround them, in order to optimize the "smartness" fi the power system as a whole (Boork et al, 2014).

Boork et al. (2014) then identified key success factors and barriers for end-users engagement in smart grid projects, and they summed up key elements missing in literature for understanding end-users engagement, divided in nine challenges that need to be overcome:

1. Understanding target groups;
2. Products and services contribution in fostering smart energy behaviour and providing added value to end users;
3. Effects or empirical evidences of incentives and monetary or non-monetary price schemes, to foster energy behaviour;
4. What information or channels, when providing end users with feedbacks, can contribute to fostering smart energy behaviour;
5. Project communication, looking at how to recruit of engage users in smart grid projects, and which are the effects of using market techniques to address this issue;
6. Cooperation between stakeholders, investigating what is the influence of non-energy stakeholders in engaging consumers
7. Smart energy communities;
8. New market structures;
9. Stability and replicability: problems in dealing with diverse audiences when trying to scaling up the roll-out of smart grid pilot projects.

They also summed up key success factors in for end-users engagement in smart grid projects, as listed below:

- Addressing end users as human beings, looking at their everyday life routines, needs, demands, expectations
- Establishing closer interactions with end-users to understand target groups thoroughly
- Create a sense of place, through the provision of regional connections to local stakeholders in the project
- Drawing upon community dynamics, establishing the feeling of affinity and belonging to a group, learning from each other in the community
- Testing technologies/services/solutions, before the official roll-out
- Building personal relations and trust, addressing individual needs and expectations
- Motivating the end users with funny activities and good news, through e.g. gaming elements

Testing several strategies through smart grid pilot projects conducted in many countries, both in Europe as in other continents around the world, successfully proved several benefits coming from consumer engagement in residential energy demand management. Adopting some of the above-mentioned key elements and motivational factors, for stimulating and supporting end-user active participation in the energy system, provided various positive results (i.e. improving energy efficiency and lowering consumers electricity bills). Below, brief descriptions of significant pilot projects conducted in different countries, both in Europe and in other continents around the world, are presented together with the main benefits registered in relation to specific setups that allowed reaching those outcomes.

BeAware – Boosting Energy Awareness

BeAware – Boosting Energy Awareness, was a three years collaborative European research project co-funded by the EU under the Seventh Framework Programme, supporting Information and Communication Technology (ICT) development (BeAware, 2009a).

The project results that are interesting for this thesis refers to a four-month trial of a sensor system in real households located between Finland and Italy. 24 people were involved in this trial, recruited between families that were interested in the services offered by the BeAware programme and that have been considered having an interesting profile for the energy providers involved in the project. The participants resulted in having numerous and various technological devices, which was possible to monitor and analyse as relevant for energy saving purposes (BeAware, 2009b).

The research plan undertaken with the BeAware programme consisted in installing a sensing platform accessible through the EnergyLife application in the selected trial households, training the users and setting up the platform for connecting all the interesting devices, monitoring the use of the EnergyLife application and the related impact on energy consumption profiles of the participants. Throughout the entire project, the participants were also asked to fill in satisfaction surveys to monitor their perception on the use of the EnergyLife application and the changes it brought to their habits (BeAware, 2009b).

The most relevant outcome from this project was to register a decrease in energy consumption, thanks to reduced use of those appliances that had been monitored by the sensor system, particularly computers that registered 26% usage reduction in four months. This result proved that awareness tips and consumption feedbacks provided by the EnergyLife application, accessible by the users through smartphones (i.e. Apple iPhone), have been effective on raising users awareness level on energy usage (Tusa et al., 2010).

In addition, the project outcomes highlighted a higher level of participants' concern in relation to the following household appliances: fridge, computer, dishwasher (Tusa et al., 2010). Therefore, this can suggest the need for monitoring these devices with more attention in the future, for investigating their potential for better management of consumer energy demand.

Moreover, the project allowed to register an increasing awareness of the participants in their lack of knowledge and attention in the use of energy associated to some household appliances: microwaves, battery chargers, dishwashers, standby modes of several devices. It also showed that energy consumption reductions varied along the trial period, reaching its peak after the first two months. Also, participants' use of the EnergyLife application decreased along the trial period. This information needs to be considered, as it can be an indicator for investigating the reliability and the perseverance of end users engagement in the energy system, due to the use of smartphones applications (Tusa et al., 2010).

Another useful information is about the acknowledgement from participants on how the project affected their energy consumption habits. In general, it seems participants perceived that the trial period brought them to change their energy usage habits (Tusa et al., 2010). This can be ascribed again to the effectiveness of the communication strategy adopted in the BeAware project.

The problem about this project is the statistical significance of the data collected for some of the single devices monitored, because of the small subset of households involved. A second trial of an improved system is under implementation, as initially planned for the project (BeAware, 2009c; Tusa et al., 2010).

Address

The Address project intended to propose and test solutions for adding flexibility, reliability, accessibility and economy to the European energy network, in order to enable active demand among energy consumers and support the development of smart grids. In particular it focused on integrating and analysing elements of active demand in the power system. The test sites were located in three different European countries that could represent a significant variety of geographical and demographic characteristics: Spain, Italy and France (ADDRESS Project, 2008a, 2008b).

Particularly relevant for the purpose of this thesis is the trial conducted in the Spanish field test site, located in the city of Castellón de la Plana. Here, 263 participants were recruited by the main energy retail and distribution company called Ibedrola. Six test cases were conducted in total, to test several specific aspects of the Active Demand services offered through the Energy Box (EBox) for managing household appliances, targeting the end user segment of the energy network. Participants had been provided with various metering and appliances equipment (smart plugs, smart washing machines, air conditioning management systems, aggregator, EBoxes), in order to allow studying possible tangible benefits deriving from the system developed under the Address project. The study allowed the identification of acceptance or rejection from residential consumers of active demand services from several points of view, thus allowing future targeted researches on more technical, sociological or legal issues involved (Caujolle et al., 2013).

The devices involved in the test were 255 in total, divided between 125 power shiftable loads and 130 power interruptible loads, which it was possible to control thanks to the use of the smart plugs provided.

Concerning the response of consumers to the system provided, Test Case 4, 5, 6 were considered to be the most significant. These tests investigated if consumer active engagement in energy management could have reduced overall energy consumptions over specific periods of time, in response to different incentives provided through various signals.

Test Case 4 investigated consumer response to price and volume signals, related to usual consumption patterns, provided during peak times and off-peak times, for lowering and raising consumption respectively. In both cases, the results showed that the signal worked well and consumers responded modifying their load curves accordingly.

Test Case 5 focused on consumer response to similar price and volume signals that differ in the incentives provided. Here, consumers proved how incentives can motivate them in paying attention to their usual behaviour, as to modify it for choosing to consume more power when higher incentives are provided.

Test Case 6 instead, focused again on consumer response as in Test Case 5, but the duration of the same price and volume signals differed between 30’ and 1h 30’. When the duration of the signal was longer it meant that consumers should have adapted to change their behaviour for a longer period of time. In addition, the way the system was designed to control the interruptible domestic appliances only allowed to disconnect devices for maximum 15’ per time, with an interval of 1h 30’ between each interruption. This can also explain the reason why it was difficult to adapt the longer signal provided, as it was asking for reducing consumption over a long period of time (Caujolle et al., 2013).

All in all, the project demonstrated that different types of incentives and signals sent to consumers could effectively stimulate the active participation of domestic energy consumers in the European power system market.

EcoGrid EU

The EcoGrid EU project aimed at demonstrating that a real time market concept, with energy prices varying every 5 minutes, can be effective in large scale smart electricity distribution networks as the European one, with a high share of renewable energy sources and possible active consumers' engagement.

The idea behind this goal was to develop a system that, through real-time price signals and flexible resources, could be able to optimally balance the power system.

The project trial was conducted within approximately 2000 participants over a period of time including two heating seasons. The market regulating the real-time energy price signal was updated every 5 minutes based on real-time measurements made with the same frequency. The feedback system, developed for the consumers to monitor and react to the flexibility of the market provided, was the online website "My EcoGrid" (EcoGrid, 2015).

The participants to the project were divided between 5 experimental groups. One group was equipped only with smart meters and access to the feedback system, to enable the manual response to the price signal. Three groups were distinguished between the customers provided with the automated control equipment for the heating system, depending on the heating technology in place (electric heating or heat pump) and the type of control system. One last group was monitored as reference group, and therefore the customers involved did not receive any information or equipment (Lund et al., 2016).

All participants were provided with the same smart meters that were able to register both energy consumption and generation from local renewable sources, with 5 minutes resolution. In addition, the three selected experimental groups for automated control were also provided with electric heating systems or heat pumps connected to two different Household Energy Management Systems provided by Siemens and IBM respectively. Although the two different HEMS solutions were equipped with different optional technologies and allowed customers to perform different controls over the automated operation, both systems were connected to DR-controllers communicating with the network. In fact, both systems were able to send signals and control the heating systems through the HEMS solutions installed, but temperatures and the degree of flexibility were controllable only in some cases through the online feedback system mentioned above (Lund et al., 2016).

All in all, it emerged that the real-time price signal adopted was effective in activating flexibility in energy consumption and reducing significantly the peak load. Particularly, automatic response of the heating systems to price signals proved to account for 87% of the total peak load reduction registered, whereas manual control was proven to be not very reactive to price variation. In addition, through monitoring of consumers demand, it seemed to be possible to forecast demand response up to a certain degree, with consequent benefits for the efficiency of the system. Finally, the real-time market developed worked effectively in providing economic benefits to the energy system, for instance increasing the share of renewable energy sources exploited (EcoGrid, 2015; Lund et al., 2016).

Consumers seemed to accept positively the automated control over their heating systems, although they might have preferred to be able to customize settings for room temperatures. Instead, the feedback system did not work as well as expected. The use of the website from manual customers increased slightly towards the end of the project, but in total just around 30% of customers from both manual and automated experimental groups used it on a regular basis. In addition, participants manifested their preference in changing time of use of their appliances, instead of the frequency. In response to price variation, it was easier for tem to turn on the appliance at a different time, while maintaining the same intensity of use, thus contributing more in shifting load than reducing overall energy demand (Lund et al., 2016).

Perth Solar City (Australia)

Perth Solar City is an initiative sponsored by the Australian government that tested several energy efficiency initiatives aiming at helping residential energy consumers to reduce their energy consumption and gain economic benefits, while helping the environment. All in all, thanks to this initiative, residents have been able to save more than $1 million on their electricity bills.

The solutions adopted were generally very simple. They involved:

- Telephone calls, to coach residential consumers in reaching the energy efficiency goals;
- Feedback letters, targeting each participant differently according to how they could have improved energy and water consumptions at the household level;
- Eco-consultation services at home, stimulating consumers in installing photovoltaic PV and solar hot water systems.

Key element of success was the targeted communication undertaken with each of the customers involved.

This initiative proved that energy efficiency at the household level can have great positive outcomes for both residents and the energy system (SmartGridGB, 2013).

Oklahoma Gas&Electricity (USA)

The Oklahoma Gas& Electricity plan aimed at reducing the need for investing in additional energy generation units, at least until 2020, to provide for energy demand especially during summer peaks (SmartGridGB, 2013).

Participants were tested in their response to several dynamic pricing plans (i.e. variable peak pricing and time-of-use tariff with critical peak pricing). They were provided with in-home displays, programmable smart thermostats and personalised web portals, allowing to monitor the change in energy price and react; email and text messages, as well as phone calls, were used to alert participants and to stimulate their active engagement in energy management (U.S. Department of Energy, 2014).

The trial run of the project involved 4000 residences and it was successful in achieving significant energy load reductions, together with lowering energy bills for the customers. Proactive communication strategies were fundamental for keeping participants informed and stimulate their active engagement, in order to achieve the expected outcomes (U.S. Department of Energy, 2014).

4.5 Energy modelling systems for the demand side

To ensure the European energy system transformation, as outlined in the Strategic Energy Technology plan, today technologies and policies mentioned above, together with elements of flexibility, are being introduced into the system. Energy modelling tools should therefore be enhanced for considering these new elements when planning future strategies and optimizing investments for strategically develop the energy sector (Welsch et al., 2015).

In fact, today significant changes are affecting both generation and demand side, which are reshaping internal dynamics of the energy system. Through energy modelling, the aim is to manage resources available in the most socially, economically and environmentally effective and sustainable way. For this reason, it is interesting to analyse how these new elements of the energy system can be better represented, in order for the modelling tools to capture how they can be beneficial for the system. This is fundamental for developing realistic scenarios that can give an overview of possible paths to speed up the transformation of the energy sector. Moreover, this is relevant to better investigate energy usage in the residential sector, which still represent a major energy sink in current energy systems according to (Swan and Ismet Ugursal, 2009).

Energy models can be divided mainly between short-term and medium to long-term models. The first ones are traditionally used in solving issues concerning energy dispatch over a short period of time. They have been used for analysing electricity market models and power systems operation and design, and for dealing with issues concerning unit commitment, start-up costs or forced outages. They work with high temporal resolutions, typically in the range of few minutes or hours and therefore need for lots of detailed data input. An example of this type of tool is the PLEXOS Integrated Energy Software. The second ones instead, can better analyse issues related to system adequacy. They work with lower temporal resolutions, over a longer period of time (typically in the range of years or decades). TIMES, MESSAGE, MARKAL, OSeMOSYS are typical examples for this class of modelling software (Welsch et al., 2015).

Energy modelling tools differ also in the modelling methodology, and therefore the reason why they have been developed. They can either aim at optimizing costs, or determining best technological solution possible, or forecasting energy demand and emissions, or maximising profits. Moreover, they can differ in the spatial resolution they are allowed to reach: from community level, to energy systems of a single country or even wider regions with interconnected grids (as in the case of some European countries). Similarly, they can focus on modelling just some parts of the energy system (e.g. the electricity market, the supply side of the system), as well as the whole system (supply and demand sides, electricity and power sectors).

Furthermore, energy models can differ in the modelling approach they use. Top-down approach is typically used in technological models that required aggregated data on historical energy consumptions to estimate future demands. Bottom-up approach instead requires a larger amount of data and detailed information about the technological options investigated. It is typically used for more complex simulation techniques, and it can explicitly account for different end-use demands based on additional factors (Swan and Ismet Ugursal, 2009).

Below, Table 4 presents a list of energy modelling tools that have been considered particularly relevant for the purpose of this study. Most of them have been selected because of their focus on modelling elements of flexibility, and allowing to better defining the demand side. Others have been listed because of their relevance in long-term energy planning.

They represent a brief assessment of innovative energy modelling tools with enhanced functionalities for modelling the effects of policies, technologies or human behaviours on the demand side. These models have contributed in providing inputs and ideas to develop the modelling framework for integrating elements of demand flexibility and consumer behavioural impact in the long-term energy system model OSeMOSYS, which will be presented in the following chapter.

Energy Modelling tool	Spatial resolution	Temporal resolution	Modelling methodology	Parts of the energy system modelled	Input data	Output data
DynEMo	Single energy systems (UK, France)	From minutes to years (through sample periods in years 2010-2050)	Dynamic energy simulation + optimisation model for demand and supply	Technology and costs	Variable constant in time + variable to define variation across years	Physical data + energy data + cost data
BLUE (Behaviour Lifestyles and Uncertainty Energy model)	Single energy system (the UK)	Annual time steps between 2010-2050 + 24h electricity demand load curve	Multi-arrayed probabilistic dynamic myopic, least cost formulation of the energy system; layered structure that reflects energy system interactions	Whole system (focus on electricity supply and energy demand)	It incorporates the following micro-economic behavioural elements: - market heterogeneity - intangible costs/benefits - hurdle rates - retrofitting/replace rate - demand elasticity model variables: - government policy - demand sector - fuels - technology type - lifestyle driver - time of the day - income levels	Least cost formulation of the energy system
D-EXPANSE (Dynamic version of Exploration of PAtterns in Near-optimal energy ScEnarios)	UK	Annual (period 2010-2050)	Dynamic technology-rich cost optimisation + exploration of near-optimal transition pathways [modelling-to-generate-alternatives approach]; multiple, maximally different near optimisation	Power supply	Detailed info about electricity demand	Optimal power supply mix
EleServe	-	Half-hourly	Simulation + optimisation	Electricity demand and supply - generates load curves		
SmartCED (Smart Consumers and Energy Demand Model)	UK	Days to weeks	Simulation + optimisation (smart grid)	Smart grids + demand-side management systems + appliances and heating		

EnergyPLAN	Single country	Hourly steps over one year	Deterministic model for comprehensive technical and economic analyses, based on analytical programming	Whole energy system	For the energy system: - energy demand - energy production units and resources - regulation (technical and market economic) - costs	Several data, e.g.: - energy balances - resulting annual production - fuel consumption - import/export - total costs
EMCAS (Electricity Market Complex Adaptive System)	Single electricity sector	Hourly steps over user-specific period of time	Agent-based (in a complex adaptive system) modelling + multi-agent-based profit maximisation for power system investments (+ dynamic cost minimization for investment, under development)	Electricity sector in the energy system with specific market regulations	Information about: - agents = independent entities in the power market - interaction on physical/business/regulatory layers	Economic impact on individual companies and consumer groups
CIMS (Canadian Integrated Modelling System) energy model	British Columbia communities	Period from present to 2050	Energy consumption and emissions forecast	Purchase, use, retirement of energy using technologies (based on technologies and human behaviour)	Data available from Community Energy and Emissions Inventories (CEEI)	Reference scenario energy and emissions forecasting + realistic analysis of individual and multiple policies on energy and emissions
E2M2s (European Electricity Market Model)	Defined regions (that allow to capture interactions between diverse countries)	Flexible (recommended hourly steps for typical days every two months periods, to capture differences in load and price patterns)	Stochastic modelling approach for cost-minimization	European electricity market	Description of generation, transmission and demand, combining technical and economical aspects	Estimation of the value of electricity produces by RES (particularly wind turbines)
LEAP (Long range Energy Alternatives Planning System)	National energy system	Annual time steps for 20-50 years	Demand side: range from bottom-up end-use techniques, to top-down macroeconomic ones supply side: accounting and simulation methodologies for modelling electric sector generation and capacity expansion planning; simulation model	All sectors and technologies in the energy system (to track energy consumption, production and resource extraction)		Information to track energy consumption, production and resource extraction
TIMES (The Integrated MARKAL-EFOM System)	Global, multi-regional, national, state/province, community level	Flexible number and length of time slices; three levels possible: seasonal/monthly, weekdays/weekends, hour of the day	Multi-year, bottom-up optimization model	Whole energy system	Data concerning demand, supply, policy, techno-economic	Installed capacities for each supply and demand technologies, energy fluxes, final energy prices, total system costs, GHG emissions

MARKAL	Flexible (national, regional levels)	Long-term perspective: 30-45 years	Bottom-up, technology-based, dynamic, least-cost linear optimization model; scenarios are developed using the 'what-if' framework	Analytical tool for both demand and supply sides of the energy system	All energy flows in the system + constraints concerning basic properties of the model	Discounted sum over the time horizon of: investment, operating and maintenance technologies costs + energy imports costs
Socio-MARKAL	Regional level	Long-term perspective: 30-45 years	Multi-period linear programming formulation of the energy system, integrating behavioural parameters as virtual technologies in the system	Focus on lighting technologies	Technological, economic and behavioural contribution to the environmental impact of the system	Optimal least-cost energy system formulation, minimizing environmental impacts
Social Practices Agent Based Model (ABM)	Currently under development by University of Surrey (UK), based on the Social Practice Theory, focusing on 5 social practices: heating, laundry, television watching, cooking, electronic communication. The aim is to demonstrate the value of considering energy consumption as a by-product of social practices					
OSeMOSYS	Flexible	Flexible (medium- long-term period, 2010-2050)	System optimisation model	Whole energy system (focus on the supply side)	7 functional blocks including specifications of: - objective - costs - storage - capacity adequacy - energy balance - constraints - emissions	Optimal cost-efficient scenario for the energy system

Table 4: Relevant energy modelling tools and main characteristics.

DynEMo

Developed by the University College London (UCL) Energy Institute, the dynamic energy model DynEMo simulates and optimises the entire energy system over time frames that range from few minutes to months or even years. It computes energy flows, economic costs and carbon emissions using finite time difference equations, and it also include an integrated dynamic domestic stock model that can be run for specific consumers and dwellings or climate conditions (Barrett and Spataru, 2015; UCL Energy Institute Models, 2015a).

DynEMo aims at investigating how human society, with its habits and behaviours, generate demand for energy services, and how this energy demand is affected by time and climatic conditions. Furthermore, it looks at how different energy resources can be deployed then, to meet the demand (UCL Energy Institute Models, 2015a). In order to do so, this modelling tool disaggregates the whole energy demand in the following sectors: domestic, services, industry and transport, with relative subsectors. It also allows to model several control systems working with information collected by human and technological sensors (Barrett and Spataru, 2015).

Main limitation of this modelling tool is the limited spatial resolution. So far, only the UK and the French energy systems have been modelled, but it would be interesting to use DynEMo to investigate the potential for international electricity trades.

Behaviour Lifestyle and Uncertainty Energy model (BLUE)

The BLUE model uses a multi-arrayed probabilistic dynamic approach to incorporate behavioural elements of specific sectors or actors in the UK for providing the least cost formulation of the energy system. It also adopts a multi-level perspective framework, based on the interaction between government landscape, current electricity regime and different lifestyle information affecting demand. This is fundamental to allow the model to integrate behavioural uncertainties and simulate changes in technology diffusion, energy demand and CO_2 emissions. Thanks to this, the accuracy of the results is increased; otherwise the model would operate using a myopic approach and assuming that initial conditions are maintained over the entire period of modelling (UCL Energy Institute Models, 2015b).

The model is written using an object-based simulation environment (called Analytica). It presents a layered structure that can effectively represent interactions in the energy system (UCL Energy Institute Models, 2015b).

Dynamic version of Exploration of PAtterns in Near-optimal energy ScEnarios (D-EXPANSE)

D-Expanse is a modelling tool for investigating cost-optimal, as well as multiple and maximally different near-optimal transition pathways for the UK power supply mix of the energy system, from 2010 till 2050.

The model uses a dynamic, modelling-to-generate-alternatives approach, which allows to limit the fragmented spread of alternative pathways that could be generated. Through the near-optimal outcome, the model provides alternative pathways in terms of technology choice and investment timing, based on initial detailed definition of electricity demand (Trutnevyte and Strachan, 2013).

EleServe

EleServe is a model for the simulation of electricity demand and supply over short-term period. It includes four different models:

1. A highly detailed demand model;
2. A model for generation technologies based on a heuristic control algorithm;

3. A system control algorithm to ensure that available reserves and storage systems are exploited;
4. A model for managing loads that optimises operational dynamics in the system (UCL Energy Institute Models, 2015c).

Smart Consumers and Energy Demand Model (SmartCED)

SmartCED is a model designed to optimise the control over demand-side management solutions. It focuses on consumers' management of their energy demand, their behaviours and diversities in energy consumptions, through smart grids. This in order to foresee possible effects of load shifting and heating systems control in future smart energy systems.

SmartCED uses a stochastic optimisation model built using the Matlab software, developed by MathWorks, to elaborate data and provide optimal times for when operating load shifting and other demand-side management solutions (UCL Energy Institute Models, 2015d).

EnergyPLAN

The EnergyPLAN model has been developed and maintained through the years by the Aalborg University, Denmark. It is a deterministic model that optimises the system operations, working with hourly time resolution over one year. It can be used to analyse different technical regulation and market-economic optimisation strategies, in order to assist policy makers in designing strategies for national or regional planning of energy systems. The model base its analysis on data about energy demand, production units and other resources, regulations in place and costs, in order to develop different scenarios that differ for instance in costs, annual productions, fuel consumptions.

The software is developed using the Delphi Pascal programming language, and it uses an analytical approach to fasten the computing of data (Department of Development and Planning, Aalborg University, 2015a)

Electricity Market Complex Adaptive System (EMCAS)

The Aalborg University developed the EMCAS, which is currently updated and maintained by the Argonne National Laboratory in the U.S.

The system uses an agent-based modelling approach to investigate how external events can impact the electricity sector of an energy system, concerning operational and economic aspects. It works with an hourly temporal resolution in analysing interactions between independent entities (i.e. the agents, that take part in the power markets) on several physical, business and regulatory layers. Recently, new features for analysing issues related to new investments and the expansion of the power system have been added, using a multi-agent-based profit maximisation approach (Department of Development and Planning, Aalborg University, 2015b).

Canadian Integrated Modelling System (CIMS) energy model

The CIMS model is based on the data available from the British Columbia Community Energy and Emissions Inventories (CEEI). It was developed to assist communities in the region of British Columbia (Canada) in forecasting energy demand and emissions under several assumptions and scenarios, in order to plan new effective policies and targets.

It can simulate consumers' behaviour and decisions in purchasing, using and retiring technologies in different energy sectors, including buildings. Thanks to this, it estimates how these human factors affect energy consumptions and related polluting emissions until 2050. It also provides some measures of the activity and the efficiency of each sector analysed (Navius Research, 2012a, 2012b).

It is interesting to look at the decomposition of energy use for the residential sector, and the data used to initially define the sector in the model. The CISM uses provincial average energy intensity data and it extends these data to entire communities, for most of the technologies and services modelled. Instead, for space heating energy intensities it uses more detailed data, in order to better represent energy usage in relation to different climatic conditions and building structures (Navius Research, 2012b).

European Electricity Market Model (E2M2s)

The E2E2M is an innovative energy model to minimize costs in the European power network, when increasing share of variable renewable energy sources are integrated in the electricity system. It uses a stochastic bottom-up modelling approach to analyse the EU electricity wholesale market, taking into consideration the uncertainties related to the integration of fluctuating renewable sources in the electricity generation mix.

The model combines technical and economic aspects, aiming at investigating electricity prices in relation to marginal generation costs over a time period of approximately 15 years. It works with hourly time resolutions of several typical days every two months, in order to represent seasonal variations of renewable generation within the years. It can be used also to investigate benefits and constraints related to the availability of grid interconnections between countries for allocating the electricity generated (Swider et al., 2004).

Long range Energy Alternatives Planning System (LEAP)

Developed by the Community for Energy, Environment and Development (COMMEND), the LEAP software is a tool that allow to model different energy systems according to their characteristic structures. It is quite flexible and easy to be used by a wide range of users, and it allows to input detailed data concerning the demand side of the energy system. Two conceptual levels are used in the model: the first dealing with all the calculations related to energy, emissions and cost-benefit analysis; the second allowing users to input characteristic time-varying data or other variables to enable additional econometric analysis and simulation to be incorporated in the analysis.

LEAP typically uses annual time-steps to run calculations over medium to long-term time horizons. LEAP models have been largely used in developing energy and environment policies, thanks to their ability to separately define different policy measures and to combine them into alternative scenarios, to evaluate associated social costs and benefits, environmental impact and energy requirements (Stockholm Environment Institute, 2015).

TIMES (the Integrated MARKAL-EFOM System)

Developed by the IEA-ETSAP (Energy Technology Systems Analysis Program) international community, the TIMES (The Integrated MARKAL-EFOM System) modelling tool has been used to combine technical engineering ad economic analysis of the energy sector, for in-depth study of future long-term possible scenarios. It uses a linear-programming method over multiple time periods to minimise costs in the energy system through a bottom-up approach, under specific constraints (IEA ETSAP, 2011a).

The model can represent the whole energy system, from primary energy sources to the demand-side. The demand side can be split into different sectors, from residential to industrial, agricultural, transport and commercial ones. Each scenario is made of technologies, commodities, scenarios and related flows and interlinks. The model results provide optimal mixes of technologies and fuels to supply the energy demand over the entire modelled period, at the minimum cost. It also provides estimations of related emissions and associated abatement costs, to follow specific regulations and policies constraints (IEA ETSAP, 2011a).

MARKAL

Being the previous version of the TIMES model, the MARKAL modelling tool has been largely used for long-term energy planning by several countries, regions and communities around the world. Today, the MARKAL model is still used as a generic model for analysing possible evolutions of energy systems over a time frame of 40 to 50 years. Differently from the TIMES model, it allows to set fewer constraints over GHG emissions. It mainly focuses on providing the cheapest feasible mix of technologies to meet energy services demand, as inputted by the user (IEA ETSAP, 2011b).

Socio-MARKAL

The Socio-MARKAL model has been developed in 2011 as a new formulation of the MARKAL modelling tool. It focused on the enhancement of the MARKAL model, with the integration of behavioural contributions to improve the sustainability of the system modelled.

The basic concept behind is that consumers' behaviours can be represented in the MARKAL model as so-called "virtual" technologies that participate in the energy system. The parameters used to define these virtual technologies are derived from sociological surveys, aiming at investigating how people perceive and behave in relation to their energy consumptions. Therefore, the virtual technologies are able to bring into the system sociological and intangible parameters that affect consumers' demand for energy (Nguene et al., 2011).

This new model will be adapted based on the social data collected. For each of the sociological factors to be modelled, key barriers and benefits should be identified in order to develop a strategy for motivating consumers in changing their behaviours and producing an impact on the system. Once the strategy has been implemented and tested, virtual technologies can be mathematically modelled using data from both surveys and test field observations. Main relevant measures for modelling these technologies are the associated costs and changes in energy demand that these strategies and campaigns stimulated. The last ones can be defined as functions of the share of people that gain positive motivations and that actively engaged themselves in following the advices provided by the campaigns (Nguene et al., 2011).

Social Practices Agent Based Model (ABM)

Focusing on the interactions between agents and environments, it aims at evaluating social practices as underlying constraint affecting energy consumptions.

It is based on social practice theories; it creates links between practices and household performances as well as product developments at the industry level. Particularly, it investigates social practices related to heating, laundry, television watching, cooking and communication through electronic devices. Qualitative empirical data, collected through interviews, as well as energy consumption data related to the performance of these activities serve as inputs for the model.

The practices investigated are particularly relevant as they represent a large share of total residential energy demand, and they also present interlinks between human practices and natural resources deployment in performing them.

The final aim of the model is to demonstrate to policy makers that there are hidden values and benefits in considering energy consumption as a result of social practices, instead of pure consequence of rational choices (Balke et al., 2014).

OSeMOSYS

OSeMOSYS is an open source long-term energy modeling tool for the planning and optimization of energy systems. It is written in the software GNU Mathprog and it uses a linear programming solver. Its goal is to provide optimal solutions at the minimum costs, for the development of the energy system over a long time period, which typically span over 30-50 years.

It has been developed in order to be easily learnt and used by a large community of people, ranging from students to researchers and governmental energy experts, without the need of upfront investment costs. It is provided with a user interface built in a Microsoft Access-based environment. It can also be run and compiled through the LEAP software mentioned above.

At the moment, several prestigious institutions collaborate to its updating and enhancement. These include the KTH Royal Institute of Technology (e.g. Stanford University, University College London (UCL), the Stockholm Environment Institute (SEI), the United Nations Industrial Development Organization (UNIDO)) (Howells et al., 2011; "OSeMOSYS: an open-source energy modelling system," 2015).

5 Discussions

Looking at the above-mentioned present modelling tools for long term planning of energy systems, the focus now is directed towards the OSeMOSYS software. In order to enhance its functionalities and to better define the demand side, some changes in the Reference Energy System (RES) has been suggested for a better characterisation of the model.

Figure 3 below provides an overview of the suggested enhanced RES, where a more detailed demand side for the residential sector is presented, following the classification of residential energy demand technologies provided by ETSAP.

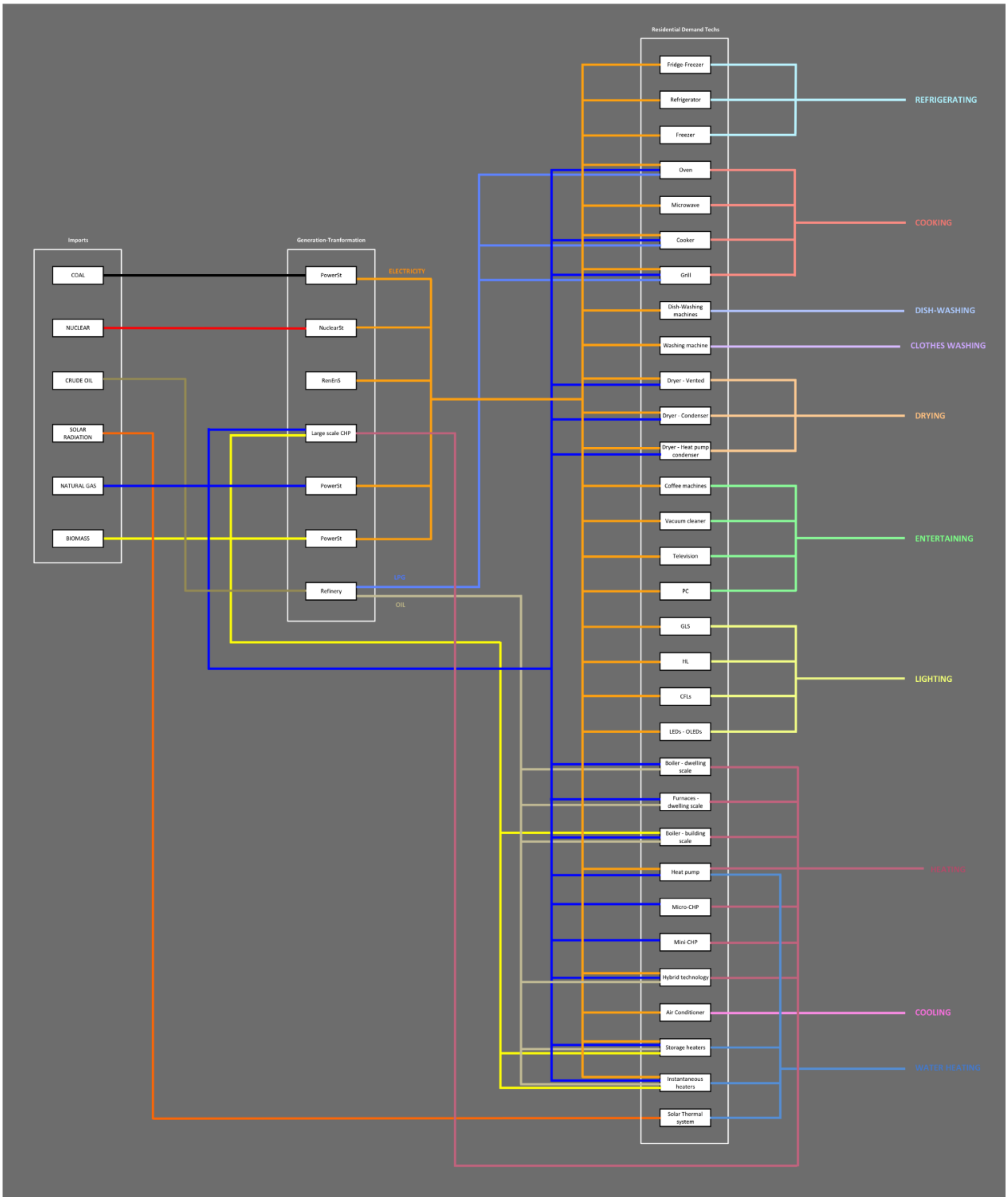

Figure 3: Enhanced Reference Energy System in OSeMOSYS.

As already highlighted in the previous chapter, today it is possible to split energy demand between different technologies that typically characterize consumers' needs. These technologies can be well defined and accounted for the related energy source, thus enhancing the correct representation of the energy system by the model. In fact, following the coloured lines in Figure 3 that link each of the residential energy demand technology to the related generation and transformation technologies considered and the imported energy resources, it is possible to correctly let the model compute detailed energy flows and related environmental impacts and costs.

For instance, considering possible cooking technologies, according to the improved RES it is possible to read clearly how they can typically can affect directly the demand for liquefied petroleum gas (LPG), oil, natural gas, and electricity, thus involving related emissions and costs for import, generation, transmission within the considered energy system. Similarly, when looking at water heating demand, it looks clear now that it can affect directly the demand for various energy resources (i.e. biomass, solar radiation, natural gas, oil), but also indirectly for nuclear or coal resources, as main resources used in producing electricity.

In order to model additional elements of demand flexibility then, looking at the new RES proposed above, few solutions have been suggested based on the enhancements developed by Welsch et al. (2012).

Finally, a modelling framework for the integration of behavioural elements in the model has been developed, based also on the example provided by the Socio-MARKAL tool (Nguene et al., 2011).

5.1 Solution for modelling elements of demand flexibility

Thanks to the information collected through the technology assessment presented above, for some of the demand technologies identified it was found out that it is possible to define a degree of flexibility related to their energy demand. This can be expressed in terms of rate of flexibility as defined by Welsch et al. (2012), depending on consumers' willingness to participate in demand shifting programs and their need for the service each of the technologies is providing them. This allows the model to shift the exact time when energy demands need to be met, in order to better allocate it throughout a day in the modelled period and to optimize costs. It also allows foreseeing the effects of better matching between energy supply and demand over the entire energy system.

Following what suggested by Welsch et al. (2012), this rate of demand flexibility can be modelled in OSeMOSYS as follow:

$$\forall_{fdt,y,ls,ld,lh,f,r}: RateOfDailyFlexibleDemand_{fdt,y,ls,ld,lh,f,r} = SpecifiedDailyFlexibleDemand_{fdt,y,ls,ld,f,r} * {SpecifiedDailyFlexibleDemandProfile_{fdt,y,ls,ld,lh,f,r}} \Big/ {DaySplit_{y,lh}}$$

Here, these variables are defined:

- $DaySplit_{y,lh}$ = it defines the length of one daily time span in one specific day, as a fraction of the year.
- $SpecifiedDailyFlexibleDemand_{y,fdt,ls,ld,f,r}$ = it is the demand for each output fuel throughout one day of a specific day-type, season and year that is flexible in the day.
- $SpecifiedDailyFlexibleDemandProfile_{y,fdt,ls,ld,lh,f,r}$ = it indicates the proportion of flexible energy demand in each daily time bracket. For each day, the sum must be equal to one.

They are linked to the following indexes that are used to define the modelled system:

- y = year modelled
- ls = season
- ld = type of day modelled
- lh = daily time bracket
- f = fuel used by the technology
- r = regional parameter
- fdt = type of flexible demand modelled, that can vary according to the demand profile and the degree of flexibility allowed

This can be applied to the following list of technologies:

- Dish-washing
- Clothes washing
- Clothes drying
- Entertaining appliances, e.g. coffee machine, vacuum cleaner, etc.
- Space heating
- Space cooling
- Domestic hot water

In most of these cases, the rates of flexibility vary according to consumers' preferences and willingness to engage in energy management programs. Concerning space heating and cooling demand though, it seems it is possible to shift up to 21% of total load, without compromising consumers comfort and needs. For domestic hot water also, it has been tested that the rate of flexibility can reach up to 9% of the total associated load (Gelazanskas and Gamage, 2014).

Concerning other residential technologies instead, it is worth mentioning some of the outcomes from the Smart Domestic Appliances in Sustainable Energy Systems (Smart-A) project, as reported by Bilton et al. (2014). It emerged that consumers tend to allow shifting the working cycles of some appliances just up to a certain time period, typically up to 3 hours for washing machines or combined washing and drying machines, and up to 6 hours for dishwashers.

5.2 Solution for integrating consumer behaviours in energy modelling

Concerning the integration of consumers' behavioural attitudes and the possible effects of targeted educational or marketing campaigns in managing residential energy demand and enhancing efficiency, the most relevant example identified by this study is provided by the Socio-MARKAL modelling tool. This enhanced version of the MARKAL model aims at considering how technologies and individual human's attitudes and behaviours can benefit the environment (Nguene et al., 2011).

Based on the Socio-MARKAL example, a similar approach could be used to consider the effects of intangible inputs in generating energy savings or technology switch within the residential energy sector.

Based on what suggested by Nguene et al. (2011), the following framework has been developed, to provide some ideas on how the so-called "virtual" technologies could be integrated in OSeMOSYS as well.

Two different logical sequences to be integrated in the OSeMOSYS modelled system are presented below. The first one in Figure 4 is intended to be used for modelling communication campaigns to raise awareness on efficient energy use and stimulate technology switch towards new more efficient appliances. The second one in Figure 5 instead wants to suggest a possible way of modelling Automated Demand Side Management options.

All boxes presented in both Figure 4 and Figure 5 need to be defined through associated measures of their effects on costs and energy demands within the system, in order to be integrated in the model and affect final outputs. The light blue arrows in between represent the existing cause-effects correlations that should be reproduced in OSeMOSYS to ensure the correct modelling of these elements.

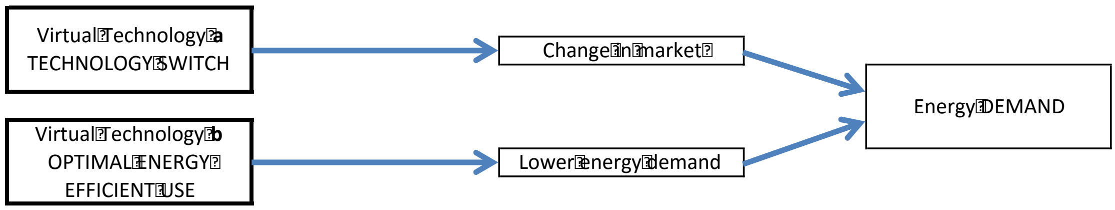

Figure 4: the Socio-MARKAL concept for communication campaigns applied to OSeMOSYS.

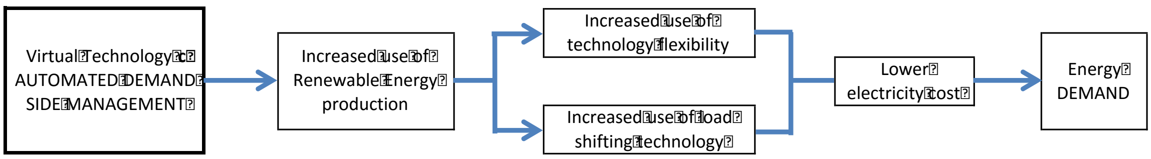

Figure 5: developing the Socio-MARKAL modelling approach for integrating Automated DSM in OSeMOSYS.

Figure 6 below finally shows how the virtual technologies can be integrated in the RES, and thus providing the first basic framework for future real integration of these elements in OSeMOSYS through actual modelling. This study suggests that virtual technologies are input in the model as energy supply technologies. Through communication techniques aiming at affecting people behaviours and interactions with energy appliances and technologies, the virtual technologies can therefore produce an impact on final energy demand and costs of the system.

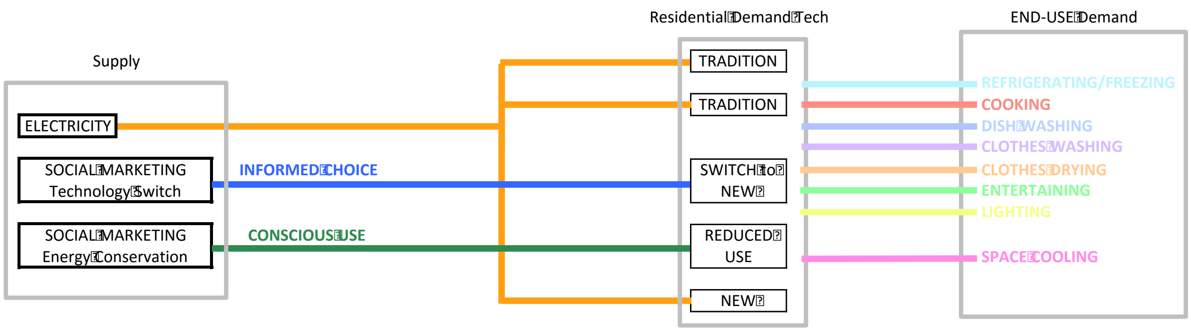

Figure 6: Integration of Virtual Technologies in the OSeMOSYS Reference Energy System (RES).

The ultimate integration of such technologies in the OSeMOSYS code though, should eventually model variations in energy demand in terms of related kWh that need to be exogenously defined.

Also, the integration of Automated DSM options in the RES has not been possible so far, due to the fact that as from the logical description presented in Figure 5 it would require OSeMOSYS to adopt non-linear programming language. This is not the case at the moment, and for this reason this study would leave to further research the duty to develop a solution to model such virtual technology.

6 Suggestions for future studies

The theoretical framework presented above aimed at integrating new features in the OSeMOSYS modelling tool, based on how technologies are defined in the current model and trying to follow the linear structure based on which the tool has been developed so far. However, OSeMOSYS is an open source model based on GNU Mathprog software that allow for changing and adapting the model to the needs of the developer. For this reason, it would be interesting to investigate in the future the possibility of modifying the sets of parameters and data to input when defining residential appliances or technologies. This would allow to better represent modes of use of different technologies, and to define appliances in a way that might facilitate the modelling of customer's willingness to provide flexibility to the system. For instance, characterising energy demand from household appliances in terms of e.g. cycles of washing machine per hour, or lumen per hour, as a measure of the service needed by the consumer. This would facilitate the representation of consumers' willingness to change their habits or their needs to reduce their demand, as well as the collection of information concerning their interest in engaging in such kind of programs. It would also allow for an easier way for communicating to the consumers what kind of action would be needed in order for them to impact their energy demand, as well as to motivate them with clear and easy actions to undertake.

All in all, future studies should focus anyway on how to effectively collect data and information to quantify the rate of flexibility that consumers' participation could provide to the system. Common, detailed methodologies about collection of information on energy consumption patterns and behaviours would ensure a better overview over possible actions that can impact residential energy demand. This would also generate more inputs and ideas for further enhance modelling tools with features to take into consideration the human factor and its possible interactions with the energy system.

7 Conclusions

Thanks to the large scale deployment of smart grids and metering systems, today a new source for potentially increasing energy efficiency and the optimal use of renewable energy sources available in the system it has been identified. This relies on consumers' active participation in managing their energy demand and it has been enabled thanks to new features and technologies made available in the market for the residential sector.

This study was meant to provide overall assessments of current technologies, policies, metrics and KPIs and modelling tools as presented in Table 1, Table 2Table 3 and

Energy Modelling tool	Spatial resolution	Temporal resolution	Modelling methodology	Parts of the energy system modelled	Input data	Output data
DynEMo	Single energy systems (UK, France)	From minutes to years (through sample periods in years 2010-2050)	Dynamic energy simulation + optimisation model for demand and supply	Technology and costs	Variable constant in time + variable to define variation across years	Physical data + energy data + cost data
BLUE (Behaviour Lifestyles and Uncertainty Energy model)	Single energy system (the UK)	Annual time steps between 2010-2050 + 24h electricity demand load curve	Multi-arrayed probabilistic dynamic myopic, least cost formulation of the energy system; layered structure that reflects energy system interactions	Whole system (focus on electricity supply and energy demand)	It incorporates the following micro-economic behavioural elements: - market heterogeneity - intangible costs/benefits - hurdle rates - retrofitting/replace rate - demand elasticity model variables: - government policy - demand sector - fuels - technology type - lifestyle driver - time of the day - income levels	Least cost formulation of the energy system
D-EXPANSE (Dynamic version of Exploration of PAtterns in Near-optimal energy ScEnarios)	UK	Annual (period 2010-2050)	Dynamic technology-rich cost optimisation + exploration of near-optimal transition pathways [modelling-to-generate-alternatives approach]; multiple, maximally different near optimisation	Power supply	Detailed info about electricity demand	Optimal power supply mix

EleServe	-	Half-hourly	Simulation + optimisation	Electricity demand and supply - generates load curves		
SmartCED (Smart Consumers and Energy Demand Model)	UK	Days to weeks	Simulation + optimisation (smart grid)	Smart grids + demand-side management systems + appliances and heating		
EnergyPLAN	Single country	Hourly steps over one year	Deterministic model for comprehensive technical and economic analyses, based on analytical programming	Whole energy system	For the energy system: - energy demand - energy production units and resources - regulation (technical and market economic) - costs	Several data, e.g.: - energy balances - resulting annual production - fuel consumption - import/export - total costs
EMCAS (Electricity Market Complex Adaptive System)	Single electricity sector	Hourly steps over user-specific period of time	Agent-based (in a complex adaptive system) modelling + multi-agent-based profit maximisation for power system investments (+ dynamic cost minimization for investment, under development)	Electricity sector in the energy system with specific market regulations	Information about: - agents = independent entities in the power market - interaction on physical/business/regulatory layers	Economic impact on individual companies and consumer groups
CIMS (Canadian Integrated Modelling System) energy model	British Columbia communities	Period from present to 2050	Energy consumption and emissions forecast	Purchase, use, retirement of energy using technologies (based on technologies and human behaviour)	Data available from Community Energy and Emissions Inventories (CEEI)	Reference scenario energy and emissions forecasting + realistic analysis of individual and multiple policies on energy and emissions
E2M2s (European Electricity Market Model)	Defined regions (that allow to capture interactions between diverse countries)	Flexible (recommended hourly steps for typical days every two months periods, to capture differences in load and price patterns)	Stochastic modelling approach for cost-minimization	European electricity market	Description of generation, transmission and demand, combining technical and economical aspects	Estimation of the value of electricity produces by RES (particularly wind turbines)
LEAP (Long range Energy Alternatives Planning System)	National energy system	Annual time steps for 20-50 years	Demand side: range from bottom-up end-use techniques, to top-down macroeconomic ones supply side: accounting and simulation methodologies for modelling electric sector generation and capacity expansion planning; simulation model	All sectors and technologies in the energy system (to track energy consumption, production and resource extraction)		Information to track energy consumption, production and resource extraction

TIMES (The Integrated MARKAL-EFOM System)	Global, multi-regional, national, state/province, community level	Flexible number and length of time slices; three levels possible: seasonal/monthly, weekdays/weekends, hour of the day	Multi-year, bottom-up optimization model	Whole energy system	Data concerning demand, supply, policy, techno-economic	Installed capacities for each supply and demand technologies, energy fluxes, final energy prices, total system costs, GHG emissions
MARKAL	Flexible (national, regional levels)	Long-term perspective: 30-45 years	Bottom-up, technology-based, dynamic, least-cost linear optimization model; scenarios are developed using the 'what-if' framework	Analytical tool for both demand and supply sides of the energy system	All energy flows in the system + constraints concerning basic properties of the model	Discounted sum over the time horizon of: investment, operating and maintenance technologies costs + energy imports costs
Socio-MARKAL	Regional level	Long-term perspective: 30-45 years	Multi-period linear programming formulation of the energy system, integrating behavioural parameters as virtual technologies in the system	Focus on lighting technologies	Technological, economic and behavioural contribution to the environmental impact of the system	Optimal least-cost energy system formulation, minimizing environmental impacts
Social Practices Agent Based Model (ABM)	Currently under development by University of Surrey (UK), based on the Social Practice Theory, focusing on 5 social practices: heating, laundry, television watching, cooking, electronic communication. The aim is to demonstrate the value of considering energy consumption as a by-product of social practices					
OSeMOSYS	Flexible	Flexible (medium- long-term period, 2010-2050)	System optimisation model	Whole energy system (focus on the supply side)	7 functional blocks including specifications of: - objective - costs - storage - capacity adequacy - energy balance - constraints - emissions	Optimal cost-efficient scenario for the energy system

Table 4 presented in this report, allowing for a better characterization of the consumers side of the energy system and the related potential for energy efficiency and savings within the residential environment.

The results from these assessments constituted the basis for investigating how to enhance the characterization of the demand side in current energy modelling tools. Particularly, this study focused on how to better define the Reference Energy System for the long-term energy model called OSeMOSYS, adding flexibility parameters for the characterisation of residential appliances and technologies. In addition, it also developed a theoretical framework for modelling elements of consumers' behaviours and attitudes in response to communication campaigns, based on the Socio-MARKAL example.

All in all, it emerged that there are potential benefits coming from the integration of such elements in planning future energy systems, particularly for reducing associated residential energy demand in the system. It also emerged though the need for more detailed monitoring and collection of data concerning this source of energy demand, thus providing the basis for better estimating demand reduction potential for each of the technologies considered and allowing a correct representation of the sociological dimension involved.

After this, next step will be the actual implementation of virtual technologies in the OSeMOSYS modelling tool, through their mathematical formulation and coding in programming language. This will allow to finally starting considering consumers' engagement as a solution for optimizing future energy systems in long term energy planning.

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