ENERGY SYSTEM TRANSITION THROUGH STAKEHOLDER ACTIVATION, EDUCATION AND SKILLS DEVELOPMENT

ENTRUST

Practices and technology deployment for efficiency

Deliverable D6.2

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List of Acronyms:

BAU = Business as usual

CBA = Cost Benefit Analysis

CCS = Carbon Capture and Storage

CFL = Compact Fluorescent Lamp

CO_2-eq = Carbon Dioxide Equivalent

EE = Energy Efficiency

EJ = Exajoules

EPDB = Energy Performance of Buildings Directive

FiT= Feed-in-Tariffs

GFC = Global Financial Crisis

Gtc = Gigatonnes Of Carbon

GW = Gigawatts

Ha = Hectare

KTOE = Kilo-Tonnes of Oil Equivalent

LCOE = The Levelized Cost of Electricity

LED = Light-Emitting Diode

Mha = Million Hectare

Mpg = Miles Per Gallon

MW = Megawatts

Mtoe = Million Tonnes of Oil Equivalent

PEST = Political, Economic, Social and Technological

PPM = Pre-payment meter(s)

PV = Photovoltaic

Tech. = technology

About the ENTRUST Project

ENTRUST is mapping Europe's energy system (key actors and their intersections, technologies, markets, policies, innovations) and aims to achieve an in-depth understanding of how human behaviour around energy is shaped by both technological systems and socio-demographic factors (especially gender, age and socio-economic status). New understandings of energy-related practices and an intersectional approach to the socio-demographic factors in energy use will be deployed to enhance stakeholder engagement in Europe's energy transition.

The role of gender will be illuminated by intersectional analyses of energy-related behaviour and attitudes towards energy technologies, which will assess how multiple identities and social positions combine to shape practices. These analyses will be integrated within a transitions management framework, which takes account of the complex meshing of human values and identities with technological systems. The third key paradigm informing the research is the concept of energy citizenship, with a key goal of ENTRUST being to enable individuals overcome barriers of gender, age and socio-economic status to become active participants in their own energy transitions.

Central to the project will be an in-depth engagement with five very different communities across Europe that will be invited to be co-designers of their own energy transition. The consortium brings a diverse array of expertise to bear in assisting and reflexively monitoring these communities as they work to transform their energy behaviours, generating innovative transition pathways and business models capable of being replicated elsewhere in Europe.

For more information see **http://www.entrust-h2020.eu**

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Executive Summary

This report presents outcomes of Task 6.2 of the ENTRUST project. It sits within the wider ENTRUST project goals to map Europe's energy system, identifying key actors, and the intersections between technologies, markets, policies, innovations. Its aim is to achieve an in-depth understanding of human behaviour around energy from which new understandings of energy-related practices can be identified that encourage stakeholder engagement in Europe's energy transition.

There are growing concerns that despite the availability of government subsidies and enabling policies, many cost effective and profitable technological and behavioural solutions are not being rapidly adopted across a range of key sectors to meet climate change goals. This contradicts rational economic theoretical expectations of what should be occurring and further demonstrates the energy efficiency paradox. The historically poor adoption rates of viable solutions suggest that a gap continues to exist between the availability of technically feasible, cost effective, and energy efficient products and what is actually implemented and required behavioural approaches. It is clear that no single intervention alone will suffice; rather a portfolio of actions and choices, and behavioural changes will be necessary across all sectors of society to reduce carbon dioxide emissions effectively.

This deliverable addresses questions of why some interventions are overlooked whilst others are not; and evaluates the potentials and scope for greater deployment of some well-established solutions, their saving potentials, and net benefits (economic and environmental), and considers how policy could better support those initiatives. The deliverable specifically examines the extent to which individual behaviour change influences need to be catalysed and the role they can play alongside technology adoption and their overall contributions to a low carbon energy transition. Importantly, this deliverable provides a sociotechnical perspective on energy transitions, by moving analysis beyond technology alone to integrate considerations of user behavioural dimensions and considerations of the interplay between behaviour, practices and technology and how these interactions may then influence low-carbon goals. This Deliverable examines the extent to which alignment between technological and behavioural elements may occur in practice in the deployment of specific carbon reduction solutions. It examines whether there are gaps in this process and how these could be addressed in an attempt to meet the sociotechnical challenges underpinning climate mitigation approaches. **The key aims of D6.2 are to develop:**

1. A gap analysis is conducted of areas where technological and behavioural interactions require specific and targeted action.
2. An understanding of how new technologies can support energy system actors, targeting those areas where behaviour is most pliable and where new technologies will have most carbon reduction potential per € of invested capital.
3. How more efficient uses of existing technologies can be applied, most notably in terms of quantifying the savings potentials from activating energy stakeholders in their use of existing technology configurations, and the means through which this can be best achieved through behavioural interventions, including community focused approaches.

A multi-layered gap analysis approach is adopted in response to the aims of this deliverable. Data are collated from existing literature and secondary sources, and drawing on deliverables D4.4 and D2.2 where appropriate. The first element of the gap analysis, examines good practice case study examples of existing solutions in the development and application of an evaluative framework. This helps in the identification of current gaps in technology and behaviour focused interventions. The analysis sign posts

where specific and targeted actions, new technologies and better application of existing technologies, and practice based approaches are most likely to be required to achieve significant carbon reduction goals. This paper synthesises a literature review and evaluative analysis process, and is divided into the following stages:

1. Literature review – scholarly journal articles, ENTRUST deliverable reports, and grey literature where appropriate (Section 2)
2. Examination of multiple case study interventions using a qualitative evaluative framework combining a SWOT and PEST analysis – using existing scholarly literature (Section 4 , 5, and 7)
3. A cost/benefit style gap analysis of the costs/carbon saving potentials of key case study interventions – using existing datasets/figures in the public domain and within existing scholarly literature and government reports (Section 6 and 7)
4. Gap analysis synthesis of implications for policy – findings analysis based on the review processes in stages 2 and 3; and includes a PEST analysis (Section 7)

The deliverable draws on examples and references from across the EU where practical and feasible. In particular, in relation to costs and carbon implications it profiles five member states – UK, Ireland, France, Spain and Italy, corresponding to host countries for the ENTRUST communities of practice. For the purpose of this deliverable, technological interventions refer to non-human technical instruments, products or artefacts, for example energy saving lightbulbs. In contrast, behavioural interventions refer to practice and policy based instruments that seek to curtail energy consumption behaviour through information, advice, incentives, regulation and other mechanisms. Both represent a broad umbrella categorisation for a diverse range of interventions that capture the sociotechnical dimensions and are used for ease of reference in this report. The selected interventions of focus in this report were chosen for their functional heterogeneity and for contrast.

In line with the primary areas of investigation in ENTRUST – which is on human behaviour and energy related practices – D6.2 concentrates on household and micro level interventions. Additionally, the existing literature suggested that substantial areas of opportunity lie in tackling demand-side end-use consumption within the residential or domestic sector, through a range of behavioural and or technological interventions that deliver energy efficiency, energy management and energy conservation. Thus, D6.2 undertakes an in-depth case study examination of existing interventions, which are either well-established or sometimes under-utilised solutions, and on the whole chosen to illustrate the functional heterogeneity and diversity of both technological and non-technological interventions.

For example, technological intervention case studies include building insulation; LED lightbulbs; solar photovoltaics (PV); smart meters; and pre-payment meters (PPMs). Moreover, behavioural or practice based interventions case studies include: information and awareness raising interventions; legal measures and sanctions; community-based sustainability projects and personal carbon allowances (PCAs). Each of the profiled technological and behavioural interventions were evaluated using the following headings:

- Description – what it does
- Adoption – implementation and uptake levels
- Level of behaviour change required (including lifestyle and everyday practices)
- Level of personal/household/ engagement with technology (including user interaction)
- Costs and carbon implications.

Furthermore, analysis of profiled interventions is accompanied by both a SWOT (Strengths, Weaknesses, Opportunities, and Threats) and PEST (Political, Economic, Social, and Technological) analysis. The case study intervention evaluative framework is developed from a review of existing literature and designed to take into consideration the relationship between interventions, the level of user engagement, the level of behaviour change required and their consequent influence on energy use outcomes. This means some interventions will either require high or low levels of behavioural changes or user engagement (including lifestyle changes). Furthermore, the nature of their influence in reducing overall energy consumption outcomes is pre-determined to fall within three broad categories arising from the energy hierarchy: energy management, energy efficiency (fit-and-forget), and microgeneration. These interventions were chosen to reflect the functional heterogeneity in currently available interventions, some of which are viable and have gained social acceptance and others under-utilised and with little social acceptance.

Thus, the aim of the case study analysis of interventions sought to evaluate their strengths and weaknesses and identify which interventions are likely to be more effective at delivering lasting behaviour changes or energy savings than others. Section 4 examines technological interventions – these are mainly technological products or artefacts that seek to influence energy outcomes at the individual or household level. Section 5 examines behavioural interventions typically delivered via third parties or through particular programmes; behavioural interventions represent solutions that rely on individuals curtailing their behaviour as a result of information and advice tools or incentives to deliver energy savings. Each intervention holds the potential to contribute to carbon reduction in different ways, *e.g.,* enable energy management, fit-and-forget fabric efficiency and renewable microgeneration.

Section 2 through a literature review presents the contextual and conceptual basis for this paper, which aided the development of the evaluative dimensions of the differing case study interventions and gap analysis. Hence, the literature review presents the rationales for why particular behavioural practices and technological interventions are increasingly being promoted, integrated and/or deployed in the goal for achieving sustainable transitions.

It offers cross-disciplinary insights (from a range of psychological, economic and sociological approaches) to help unravel the complexity of energy related behaviours and the multitude of factors that shape them. For example, it has been identified that there are many tensions between theories, which by the same token arguably suggest that the different models and perspectives offer complimentary viewpoints on the same theme of energy behaviours. Furthermore, policies on behaviour change appear to take a pragmatic line by combining a mixture of theories in public policymaking across different EU countries to change individual and consumer behaviour, specifically relating to energy consumption and in dealing with the low-carbon and sustainability agenda.

Furthermore, findings from the literature explain why an interest in finding low cost and effective solutions in direct end-user energy consumption reduction have led to a focus on the household domestic energy sector (often representing a significant share of energy consumption in comparison to other economic sectors) in carbon emissions strategies of member states across Europe. Additionally, debates over the effectiveness and challenges of behavioural and technological solutions remain prominent in finding solutions in climate mitigation approaches. Deliverable 6.2 goes beyond the narrow 'barriers and drivers' framing of the adoption of specific technological interventions and examines what behaviour change related influences will need to be applied alongside technology adoption; and to assess, ultimately, their overall contributions to carbon reduction goals.

Section 4 provides in-depth case study examinations of technological intervention that typically target the individual and material context of energy consumption behaviour. In-depth analysis of the chosen technological interventions reveals the following characteristics:

Pre-payment Meters (PPMs): A technological devise that is often presented as a useful budgeting tool, which could encourage energy conservation and help users, avoid debt.

Building Insulation: One of the most commonly adopted energy efficiency measures and considered one of the most cost-effective means of achieving energy efficiency; often aided by government grants and incentives.

LED lightbulbs: A key energy efficient technological appliance. Lighting is one of the highest energy consuming appliance groups in households, and considered to be one of the easiest and most cost-effective one-off purchase interventions.

Smart Meters: Increasingly promoted as an energy saving device. Smart meters record energy usage and provide enhanced information to both consumer and energy suppliers. The emphasis of this technology is on helping consumers/individuals manage their energy use.

Solar PV: It is the most popularly adopted and socially accepted of all the microgeneration technologies which holds great potential for triggering lifestyle adjustments.

Specific contextual and/or use dimensions underline each intervention. For example, pre-payment meters (PPMs) are framed and presented as a useful budgeting tool which could encourage energy conservation, however there are concerns that PPMs disproportionately disadvantage those already vulnerable in society (i.e. low-income, long-term ill and the elderly). Building insulation is a commonly adopted measure, however, there are varying levels of complexity and deployment levels within the differing varieties of wall insulation solution, *e.g.,* cavity wall insulation is the cheapest and easiest whilst internal and external wall insulation are costlier and more complex. The adoption of LED lightbulbs and solar PV is well established, where relative costs have fallen, and both require a number of accompanying user interactions for their full benefits to materialise, i.e. turning LED lights off when leaving a room or using energy consuming appliances when the sun is shining for free solar energy. Furthermore, Solar PV (like many other technologies) holds the risk of perpetuating existing energy intensive practices and/or with no fundamental changes in energy consumption or even resulting in greater rebound effects. Smart meters record energy usage and seek to improve information availability to energy stakeholders, but their full impact is yet to materialise given they are in the early phase of deployment.

Whilst many of these technological interventions are increasingly being deployed, their rates are considered too slow and low to be effective. In particular, current policy instruments are considered to be too weak for improving energy efficiency and to deliver the required long-term energy savings across EU countries. The evaluative review of the five profiled technological interventions shows differing levels of deployment, contrasting functional heterogeneity, differing success levels and key contextual issues underpinning uptake and success of individual measures. This also means that the profiled interventions are not necessarily comparable to one-another. There remains debate on the effectiveness of each intervention in which the cost of installation, savings and payback outcomes are often difficult to specify accurately (discussed further in Section 6).

Five particular behavioural interventions are profiled in Section 5. These are personal carbon allowances, legal measures and sanctions, feedback, community-based sustainability projects, information provision - chosen to broadly represent practice and policy based instruments that arise either from top-down government mechanisms or through community bottom-up initiatives. They are also currently under-deployed yet still hold potentials for greater deployment with the right delivery mechanisms.

First, personal carbon allowances (PCAs) are a radical policy idea for delivering emissions reductions over the mid-to-long term. PCAs are a general term used to describe a variety of downstream cap-and-trade policies, which locate rights/responsibilities for the carbon dioxide emissions from household energy use and/or personal travel at the individual level. PCAs encourage individuals to make the most of existing schemes such as product and building standards, energy labels, and taxation and financial incentives. Whilst this is an instrument that proposes to empower individuals there appears to be no political appetite to implement this instrument in practice. In particular, PCAs would need to be top-down and mandatory, with no opt-outs and a level of enforcement to succeed.

Second, legal measures and sanctions can be implemented through regulation or through conventional economic instruments such as pricing, taxation and incentives as a tool for forcing behaviour change. In order to be effective, legal measures require the relevant laws and regulations are enforced, and that violations are met with some type of punishment or that desirable behaviour is rewarded. Despite debates over their effectiveness, their success in specific policy areas has shown their potential to lead individuals to choose sustainable alternatives, as exemplified by the Irish plastic bag charge, the London Congestion Charge and the Stockholm road tax initiatives.

Third, community-based sustainability projects offer a participatory approach to addressing climate change within a localised context. Community-based projects do not follow one singular approach and usually comprise multiple interventions. They employ various informational and structural strategies and may include but are not limited to information provision, feedback, citizen’s panels, activism, events, incentives, local currencies, local food production, and decentralised energy systems. Community-based sustainability projects seek to offer multiple environmental, economic and social advantages. Typically community based interventions are deployed over a short fixed period of time and their longer term impact are therefore potentially difficult to qualify and identify success factors due to the number of individual and contextual factors at play. Additionally, community projects are usually run by a number of civil society and or voluntary organisations or initiatives, which can suffer from lack of funding, and a lack of overall strategic direction, which can substantially impact the efficacy of such projects to deliver their overall aims. To date there appears to be limited progress in community-based sustainability projects across Europe, where implementation has been nationally disparate and uncoordinated yet relying on local residents and stakeholders for delivery.

Fourth and Fifth, information provision and feedback are often assumed will directly lead to behavioural changes. Providing individuals with information on a range of energy related issues including energy production, consumption and pricing is assumed to increase awareness of aspects of energy that may directly affect upon local residents’ attitudes and behaviours, in turn leading to the desired reduction in consumption practices *etc.* Information can be conveyed in several ways, through workshops, mass media campaigns and tailoring (such as through home audits). Mass media campaigns tend to result in an increase in knowledge, but there is no clear evidence that this results in reductions of energy use. Overall, there is considerable doubt whether this approach alone leads to sustained behavioural changes, thus Information provision has been proved to be more effective when used in conjunction with other interventions.

Section 6 provides an overview of the cost and carbon implications of profiled interventions and completes the evaluative framework analysis for key interventions discussed in Sections 4 and 5. It provides analysis in the following areas: Cost Scenario Calculations; Costs Calculations for Modelled Parameters and the results of Costs Scenario Analysis. This section presents data from the publication *Drawdown: The Most Comprehensive Plan Ever Proposed to Reverse Global Warming* (Hawken, 2017). These tables present solutions, which reduce emissions by avoidance in the first place, or by sequestering CO_2-eq already in the atmosphere. In relation to the Cost Scenario Calculations – results from a multi-variate model of direct costs of carbon reduction at the household level are presented. This model was designed to develop a ranking of technological priority, based on identification of most carbon reduction potential per € of invested capital, as described in the ENTRUST project proposal. Data were sourced for 5 EU countries, corresponding to the 6 study communities in Ireland, Italy, UK, France and Spain, and data has been collated from a range of sources, but with a particular focus on those residential level parameters discussed in Section 4. Cost and carbon reduction potentials for specific interventions are presented, including – Building retrofits, smart meters, LED lighting, solar PV and behavioural curtailment – across 5 profiled member states: UK, Ireland, France, Spain and Italy. The modelled cost/savings are variable across the 5 profiled countries and are contingent upon national energy production/consumption dimensions *e.g.,* carbon intensity of the grid, cultural practices around lighting. Across the five, profiled member states the following generalisations can be made in terms of modelled cost € / KgCO_2 savings, and the expected user engagement required to realise the modelled savings, which highlight areas for greater targeted action, *e.g.*,

- **Building retrofits (*e.g.,* via insulation measures) emerge as one of the most cost-effective means of reducing carbon emissions per € of investment, and their 'fit-and-forget' quality mean they require no post installation behaviour change. Retrofitting measures need continued and enhanced policy support to realise the full potential of carbon savings in the built environment.**
- **Smart Meters appear to be the most costly intervention modelled (mean carbon reduction of €1.93/ Kg CO_2) cost and represent the least value for money (in terms of investment for carbon reduction), and one which also requires considerable user engagement, knowledge and training to be effective.**
- **LED Lighting represents a low costs of carbon reduction in terms of €/Kg CO_2 (mean value of €0.23/ Kg CO_2) prevented and little requirement for user behaviour change, beyond initial installation.**
- **Solar PV - the relatively low costs of carbon reduction for Solar PV (mean carbon reduction cost of €0.90/ Kg CO_2) and the likelihood that these costs will continue to decrease mean that Solar PV will increasingly become a prioritised option in years to come. In terms of requirement for new technology solutions, options to increase the user-friendliness of installing and managing Solar PV are urgently required. Fit-and-forget solutions for Solar PV would likely increase the usability and attractiveness of this carbon reduction solution.**
- **Behavioural Curtailment (1% @0.98€ / Household) - of all of the reduction strategies modelled, this option remains most uncertain in terms of actual realisable savings. While the cost of information campaigns may be relatively low, in comparison to hard technology investments, the outcomes are highly dependent on a wide range of factors. Therefore, achieving a 1% national savings target from electricity users may be extremely challenging in practice. However, its potential for energy management in terms of behaviour curtailment remains attractive (mean carbon reduction cost of €0.18/ Kg CO_2).**

Section 7, builds on Sections 4 to 6 and addresses the question of which interventions can best support energy transitions by discussing and synthesising their findings and implications further. It identifies areas for targeted interventions and considers the implications of the presented costs scenarios; it forwards a PEST analysis of technological and behavioural interventions; and the identification of new areas within the intersections between behavioural and technological interventions. The cost and carbon reduction analysis for specific interventions across 5 profiled member states highlighted areas where interventions could be targeted and this is developed further through the PEST analysis.

In terms of identifying gaps between interventions currently available, the following observations are made. The analysis found that whilst there is greater policy support for technological interventions, those relying on behavioural and lifestyle changes were weaker across the EU member states (also drawing on findings first presented in ENTRUST D4.4). Closer examination of policy categories including guidelines, planning, legislation, regulation and fiscal measures are not well established within behavioural change initiatives. Rather, there is an over-reliance on communication and marketing strategies as well as on service provision. There are a number of reasons for why these patterns have emerged. Primarily, top-down measures enforced through regulation and legislation are undesirable to governments to address behaviour change. The key weakness with behavioural practice based instruments is they are reliant upon voluntary participation with no legal compulsion to change behaviour and which are often community led interventions. The range of profiled behavioural interventions highlighted in this Deliverable would collectively compliment the technological interventions currently in use, if put into greater use. Such an integrated approach holds the potential to provide a pathway to further transition to a low-carbon society and economy; and to a significantly greater extent than is currently being realised.

In relation to addressing some of the gaps and limitations of interventions, a series of suggestions are put forward highlighting how these limitations can be overcome and contribute more effectively to low-carbon transitions. In terms of the future needs from technological and non-technological interventions, a number of short term and longer-term perspectives are proposed. Initially, technological interventions have the potential to become cheaper, longer lasting and more efficient products than their unsustainable counterparts. This could support greater buy-in from individuals at a local level as well as on an industrial scale. The potential of new technologies demonstrates the accessibility that local residents now have to purchase sustainable products providing individuals with an informed choice that, when combined with behavioural interventions such as information provision, allows for greater uptake when comparing like-for-like. Furthermore, the development of smart technologies being incorporated within technological interventions allows people to effectively manage their energy consumption in ways that were once conceived to be challenging. Through the application of new technologies, these interventions can contribute to low-carbon transitions in a number of ways. Improving the insulation of existing housing stock supports improving the energy efficiency of residential buildings as well as being an initial intervention for supporting a low-carbon transition.

In terms of the future needs for behavioural interventions, these will need new practice areas (some more specifically energy related such as legal measures and sanctions) as well as emerging technologies to reflect the diversity of energy-related technologies (such as smart technology, phones and applications). Incorporating new technologies also holds the potential to create new integrated smart energy systems, particularly through a domestic smart energy system and 'Smart PCAs' for individuals or households. Should these two systems be integrated, this could potentially ground sustainable lifestyles within the control of individuals. However, regulatory and legislative support is required to push forward this development. The integration of technological and behavioural interventions would frame a meaningful low-carbon transition that is reflective of political, social and cultural change.

The final discussion considers how the drivers for reducing greenhouse gas and CO_2-eq emissions, and energy security appear fundamentally about reducing societal energy dependency. The deployment of technological interventions seeks to diversify energy production (*e.g.,* through renewable energy sources such as solar); and greater energy management and energy consumption reduction strategies (*e.g.,*smart meters, appliances such as lighting, and behaviour change interventions, *etc*.). These interventions are deployed via top-down as well as bottom up interventions that sometimes target the material and individual context of energy dependencies, and sometimes this is addressed at a social context via community level interventions. It reinforces the view that no single intervention alone will suffice; rather a portfolio of actions and choices, and behavioural changes will be necessary across all sectors of society to reduce carbon dioxide emissions effectively.

Through a sociotechnical perspective, this deliverable provides an in-depth evaluative inspection of the some commonly and less commonly deployed interventions. While some behavioural and technological interventions appear conceptually distinct in practice, there are many overlaps in the way they have to work to effectively deliver energy efficiency, sustainability and carbon reduction goals. Behavioural interventions may offer advice and information on how to address domestic energy efficiency through technological interventions such as insulation or replacing a boiler while at the same time offering advice on accompanying curtailment actions such as not leaving appliances on standby. Thus, there is often interconnectivity in the application of intervention strategies. The analysis outlined the potential strengths and weaknesses of each intervention and considered the extent to which alignment between technological and behavioural elements may occur in practice in the deployment of specific carbon reduction solutions.

In particular, the analysis highlights opportunities for alignment and strengthening existing approaches through the integration of technological and behavioural interventions. Specifically, the alignment of potentially new technological interventions with behavioural interventions not only improves their efficacy but also their sustainability and adaptability to changing preferences and motivations of individuals and communities. Furthermore, applied continuously and consistently allows these interventions to enhance environmental, economic, social and technological outcomes for low-carbon transitions. Unlocking the full potential of interventions requires a hybrid combination of top-down and bottom-up approaches. As a result, it moves away from technical fixes alone and locates the human factor in the energy system and identifies that the power to influence this system and foster change at the individuals and local level. The analysis reinforces existing practical knowledge and theoretical underpinnings of particular interventions; the potentials of differing interventions in terms of their limitations, potentials and contributions and it offers suggestions for how these limitations can be overcome and contribute more effectively to low-carbon transitions.

Key lessons:

- **Effective policy interventions need to help deliver more integrated technological and behavioural approaches delivered consistently with a clear publicly recognised mandatory push (similar to the one currently being rolled out for smart meters);**
- **The design and implementation of interventions needs to give greater recognition to the level of user engagement and behaviour change requirement in the long-term;**
- **No single intervention alone can deliver policy goals and recognition of how each intervention contributes to the wider whole is important, including detailed cost-benefit and acceptability analysis;**
- **Policy measures should avoid over reliance on technical fixes at the expense of behaviour change actions, thus interventions always need to seek to integrate both technological and behavioural elements of energy consumption practices.**

1 Introduction

1.1 Background

Reducing Carbon Dioxide (CO_2) emissions is critical to tackling climate change and developing mitigation strategies for reducing emissions has become a key global priority. Typically, mitigation measures aim to support a greater role for energy efficiency in reducing carbon demand in the short term, and in the long-term aim for the development of low-carbon energy generation systems. Furthermore, new technological solutions are sought to break the dependence on fossil fuel sources that contribute to GHG (Adenle, Azadi, & Arbiol, 2015; Gosens, Lu, & Coenen, 2015).

To date policy-makers have for the most part favoured technological solutions as being more viable and cost-effective. Thus incentives and technological solutions have been favoured for support in energy policy (Foxon, 2013; Lorenzoni, Nicholson-Cole, & Whitmarsh, 2007). This is in part to do with the measurability of performance outcomes associated with physical, technological interventions, which stand in contrast to the perceived unpredictability of changing human behaviours and measuring their outcomes. The literature suggests that multiple solutions will be needed as no single solution can address the climate change problem. In this regard, behavioural change is also crucial if the benefits of new technology are to be fully realised (Dietz, Gardner, Gilligan, Stern, & Vandenbergh, 2009). There is growing recognition that technological innovations are unlikely to be the sole answer to the climate change problem and that behavioural change will also be required (Pacala & Socolow, 2004; Stern, 2006).

Nonetheless, both technological and behavioural interventions hold particular environmental potentials, yet both face particular challenges that limit that potential from materialising. The potentials of existing and new technological solutions and practice and behavioural interventions require further examination. Importantly, this paper provides a sociotechnical perspective on energy transitions, by moving analysis beyond technology alone to integrate considerations of user dimensions and considerations of the interplay between behavior, practices and technology how these interactions may then influence low-carbon goals.

1.2 Aims and Objectives

This report presents outcomes of Task 6.2 of the ENTRUST project. This task has applied a gap analysis approach and has produced a comprehensive desktop study of technological and behavioural interactions. This deliverable includes an identification of current gaps in technology and behaviour focused interventions as well as sign-posting of where specific and targeted action, new technologies and better application of existing technologies and practice based approaches is required to achieve carbon reduction goals. The aims of D6.2 are as follows:

- A gap analysis is conducted of areas where technological and behavioural interactions require specific and targeted action.
- The need for new technologies to support energy system actors is established, targeting those areas where behaviour is most pliable and where new technologies will have most carbon reduction potential per € of invested capital.
- The more efficient use of existing technologies will also be addressed, quantifying the savings potentials from activating energy stakeholders in their use of existing technology configurations, and the means through which this can be best achieved through behavioural interventions, including community focused approaches.

1.3 Scope

This Deliverable examines the extent to which alignment between technological and behavioural elements may occur in practice in the deployment of specific carbon reduction solutions and examines whether or not there are gaps in this process and how these could be addressed in an attempt to address the sociotechnical challenges underpinning climate mitigation approaches.

Deliverable 6.2 examines good practice examples of existing solutions through a review of existing literature and the development and application of an evaluation framework. Technologies that result in energy efficiency (using less) and technologies that promote behaviour change (smart meters) are assessed. In particular this report addresses questions of why some technologies are overlooked while others are not; and evaluates the potentials and scope for greater deployment of some well-established technologies, their saving potentials, and net benefits (social, economic and environmental) and considers how policy can support those savings. It will also specifically examine the extent to which individual behaviour change influences need to be catalysed and the role they can play alongside technology adoption and their overall contributions to a more sustainable transition.

In the context of the rapidly changing energy system, the focus of this deliverable is on residential energy use, and in particular on the capacity of residential end-users to change their energy use patterns, whether through technological or behavioural interventions. In particular, the overlap between technological solutions for energy use reduction and behavioural interventions forms a key theme of analysis (Figure 1).

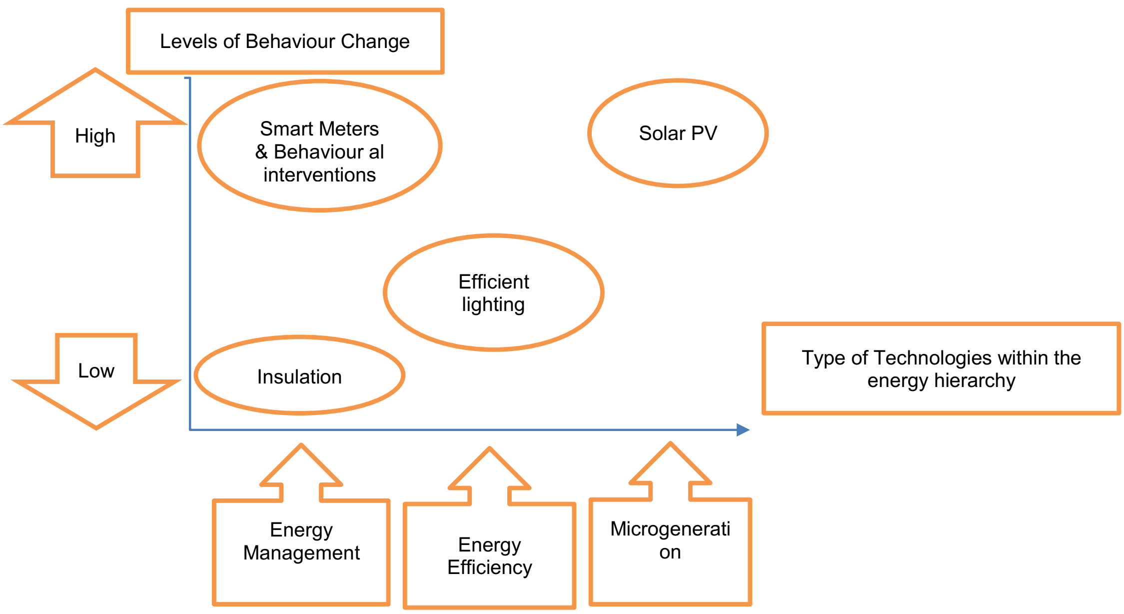

Figure 1: Behavioural Interventions and Associated Technologies

In line with the primary areas of investigation in ENTRUST, D6.2 concentrates on household and micro level interventions. Additionally, the existing literature suggested that substantial areas of opportunity lie in tackling demand-side end-use consumption within the residential or domestic sector, through a range of behavioural and or technological interventions that deliver energy efficiency, energy management and energy conservation. Thus, D6.2 undertakes an in-depth case study examination of existing interventions, which are either well-established or sometimes under-utilised solutions, and on the whole chosen to illustrate the functional heterogeneity and diversity of both technological and non-technological interventions.

The deliverable draws on examples and references from across EU countries where practical and feasible. In particular, in relation to costs and carbon implications it profiles five member states – UK, Ireland, France, Spain and Italy, corresponding to host countries for the ENTRUST communities of practice. For the purpose of this deliverable, technological interventions refer to non-human technical instruments, products or artefacts, such as lightbulbs. In contrast behavioural interventions refer to practice and policy based instruments that seek to curtail energy consumption behaviour through information, advice, incentives, regulation and other mechanisms. Both represent a broad umbrella categorisation for a diverse range of interventions that capture the sociotechnical dimensions of the energy system.

2 Literature Review

2.1 Profiling the Energy System

Systems in transition (such as the energy system) are commonly represented as sociotechnical regimes in the transitions literature; defined as relatively stable configurations of institutions, techniques and artefacts, as well as rules, practices and networks that determine the 'normal' development and use of technologies (Rip & Kemp, 1998; Smith, Stirling, & Berkhout, 2005). A focus on regimes recognises that organisations and technologies are embedded within wider social and economic systems (Rip & Kemp, 1998). Sociotechnical systems are thus conceptualised as clusters of aligned elements, such as technical artefacts, knowledge, markets, regulation, cultural meaning, rules, infrastructure (Kern, 2012). For the ENTRUST project, a comprehensive profile of the energy system sociotechnical regime is being developed and cumulatively enhanced with successive Deliverables. The starting point for the understanding of the energy system for the purposes of this deliverable (D6.2) is the extensive profile of the energy system and its constituent components forwarded in the *Energy Technological Review* presented in ENTRUST D2.2 (Landini, Zerbi, Morrissey, & Axon, 2016). **ENTRUST Deliverable - Summary Box 1** presents a brief overview of key components of the energy system.

ENTRUST Deliverable - Summary Box 1: Findings from D2.2

Overview of Critical Energy Supply Chain Elements – Summary From ENTRUST D2.2 (Landini *et al.*, 2016)

Energy production: Electricity is produced by renewable (*e.g.*, solar, bioenergy, wind) and non-renewable (*e.g.*, coal, oil, natural gas) sources of energy. Accounting for these elements of the energy supply chain, there are a multitude of different technologies that are used including wind turbines; photovoltaic panels; steam engines; fuel cells; diesel engines; solar panels; ground source heat pumps; and elements that make up power plants including alternators, turbines and electrical generators.

District heating: Traditionally, homes have been heated with wood, the most easily obtainable source of heat, and more recently with natural gas and oil. Today in Europe, the predominant way in which to heat homes is through gas boilers rather than electric storage heater and oil burners, as this is a cheaper source of heating for domestic buildings. This section concentrates on different technologies used in centralised solutions for district heating. When it is possible to implement, district heating provides some advantages over single building solutions, since it helps save energy and thus reducing pollutant emissions in the air. The presence of a single bigger central unit provides a simpler and more efficient control, avoiding wastes in fuel consumption. As a particular way to generate heat through recovery of electrical power plants exhaust gases, cogeneration is considered in this chapter as well. Cogeneration, or combined heat and power, is the use of a heat engine or power station to generate electricity and useful heat at the same time. It is a thermodynamically efficient use of fuel, as in the separate production of electricity some energy is discarded as waste heat. Common combined heat and power plant types are gas turbines, biofuel engines, biomass, steam turbine and nuclear power plants.

Energy transportation and distribution: Energy transportation and distribution usually occurs through a series of technologies. After electricity is generated at a power station, it is transported through overhead and underground cables to step up transformers, which carry electricity across large distances, before entering residential buildings through step-down transformers, transmission sub-stations, and local distribution substations. These networks use components such as power lines, cables, transmission lines, substations, circuit breakers, capacitor banks, transformers and switches.

Energy storage: One of the distinctive characteristics of the power sector is that the amount of electricity that can be generated is relatively fixed over short time periods, although demand fluctuates throughout the day. Electricity storage devices can manage the amount of power required to supply customers at times when need is greatest during peak load. Such devices can also help renewable energy, whose power cannot be controlled by grid operators. Energy storage devices can provide frequency regulation to maintain the balance between the network's load and power generated; achieving a more reliable power supply for high tech industrial facilities. Energy storage systems provide an array of technological approaches for managing power supply to create a more resilient energy infrastructure, bringing cost savings to end-users.

End user technologies: 'Private citizen technologies' that are shaped by the energy-specific behaviours and practices of these same individuals. Lighting, transport, heating, ventilation, air conditioning and control systems were all considered, and are discussed below.

Lighting: Lighting technologies are heavily influenced by social practices and behaviours. Key Performance Indicators (KPIs) on lighting technologies and control systems are explored in D2.2, particularly those related to efficiency and energy consumption, including halogen and LED lightbulbs. Other aspects of lighting controls may include occupancy sensors, time-locks, and photocells hard-wired to control fixed groups of lights independently. Lighting control systems, however, refers to an intelligent networked system of devices related to lighting control, including dimmers, timers, photocells, occupancy sensors. Increasing demand for energy efficiency from end-users reflects desires to reduce energy consumption and costs.

HVAC Heating, Ventilation, Air Conditioning (HVAC): HVAC and their control systems relate to the technologies of indoor and vehicular environmental comfort, notably to ensure thermal comfort and acceptable indoor air quality. HVAC systems are important in the design of buildings, particularly large domestic buildings, skyscrapers and offices, ensuring safe building conditions with respect to temperature and humidity. HVAC systems use multiple technologies, including solid fuel, liquid and gas heaters, heat pumps, dehumidifiers, fans, standalone air conditioning units, solar panels and many others.

Transport: Over a third of energy consumed by individuals is used for transportation in many EU countries. This is often characterised by private transport use such as cars rather than public transport such as buses, rail and plane. Private transport, and some public transport (*e.g.,* buses), can operate with diesel, gasoline, hybrid or electric sources of energy, yet significant cost barriers exist with the adoption of hybrid and electric vehicles. While gasoline and diesel cars are predominant, the number of hybrid and electric private vehicles has increased four-fold across the European Union. Latest developments in private and public transport use include advanced range capabilities for hybrid and electric vehicles without the need for a plug-in capability

The energy supply sector is the largest contributor to global greenhouse gas (GHG) emissions. In 2010, approximately 35% of total anthropogenic GHG emissions were attributed to this sector. Annual GHG-emissions growth from the global energy supply sector accelerated from 1.7% per year in 1990–2000 to 3.1% in 2000–2010 (Bruckner *et al.*, 2014). Based on 2°C target studies, a CO_2-eq concentration of 500ppm is the maximum permissible atmospheric concentration in 2100, with emissions peaking in 2030-2035 at the latest (Dessens, Anandarajah, & Gambhir, 2016). During the 1980s France was reducing emissions at a rate of 3% per year as a result of the large-scale deployment of new nuclear power plant facilities; the UK sustained a reduction reaching 2% per year in the 1970s decade by a strong switch from coal to gas in electricity production. These examples highlight the practical rates achievable through technical changes (Dessens *et al.*, 2016). A full portfolio of low-carbon technologies is needed in order to keep global mitigation costs down. Transformations of the energy system rely on a combination of three high-level strategies (Clarke *et al.*, 2014):

1. Decarbonisation of energy supply
2. An associated switch to low-carbon energy carriers such as decarbonized electricity, hydrogen, or biofuels in the end-use sectors
3. Reductions in energy demand.

Therefore the availability, cost and future performance of key technologies, and the appropriate application of these, has an important role in achieving stringent CO_2-eq emissions reductions targets (Dessens *et al.*, 2016).

Energy efficiency is one of the fastest and most cost-effective contributions to a sustainable, secure and affordable energy system. The macroeconomic benefits play an important role, including so-called "non-energy benefits", "co-benefits" or "multiple benefits" of energy efficiency (Hartwig, Kockat, Schade, & Braungardt, 2017). Global power generation from solar rose from 0.035 Exajoules (EJ) in 2000 to 0.22 EJ in 2011, accounting for 0.04% of global primary energy. In the same period, global wind power generation increased from 0.11 EJ (accounting for merely 0.027% of the total global primary energy) to 1.56 EJ (accounting for 0.28%) over the same period (Dai *et al.*, 2015; International Energy Agency (IEA), 2013). Table 1 shows the realised final renewable energy consumption for 2005 to 2013 in Europe and the growth rates (sourced from European Environment Agency (2016, p.27)). Importantly, Table 1 shows that solar PV shows the most dramatic growth (at 65%) in comparison to other renewable energy sources for electricity generation in the EU.

Table 1: Final Realised Final Renewable Energy Consumption for 2005 To 2013

Technology	Final Energy (ktoe)		Growth Rate
	2005	2013	2005-13
Hydropower excl. pumping (normalised)	29 582	29 987	0 %
Onshore wind (normalised)	5 784	18 189	15 %
Solid biomass	4 773	8 610	8 %
Solar photovoltaic	126	6 953	65 %
Biogas	1 101	4 550	19 %
Offshore wind (normalised)	174	1 201	27 %
Geothermal	464	510	1 %
Concentrated solar power	0	378	n.a.
Bio-liquids (compliant)	0	346	n.a.
Tidal, wave and ocean energy	41	36	– 2 %
Total renewable electricity (normalised, compliant biofuels)	42 044	70 761	7 %
Total renewable electricity (normalised, including non-compliant biofuels)	42 196	70 784	7 %

2.2 The Need for Technological and Behavioural Interventions

There are growing concerns that despite the availability of government subsidies and enabling policies many cost effective, profitable and viable technologies are not being adopted at sufficient pace across a range of key sectors in the EU. Present technology adoption rates points towards the energy efficiency gap – that is, the gap between the availability of technically feasible, cost effective, and energy efficient products and the implementation of these technologies in reality (Department of Energy & Climate Change (DECC), 2012; Global Agenda Council on Decarbonizing Energy, 2015). The presence of an energy efficiency gap contradicts rational economic theoretical expectations of what should be occurring and reiterates the energy efficiency paradox (Jaffe & Stavins, 1994). Identifying and applying means to address this gap has been a key focus of energy policy research. One the one hand economists argue that the main barriers to energy efficiency concern market failures *e.g.,* imperfect information. On other hand, non-economic perspectives suggest that this is a more complex problem including social, cultural, economic and political components. Some authors advocate a more systemic perspective requiring an understanding of a whole range of interconnected factors including the role of stakeholders, barriers, policies and so on (Lorenzoni *et al.,* 2007; Nye, Whitmarsh, & Foxon, 2009; Shove, 1998).

Existing research suggests that people do not rationally adopt technologies and then automatically use them correctly, and that user dimensions in relation to product attributes are important (Caird, Roy, & Herring, 2008; Shove & Walker, 2010). Furthermore, Caird *et al.* (2008) have suggested that socio-economic context (*e.g.,* fuel prices, regulation); communication sources (*e.g.,* professional, interpersonal); consumer variables (*e.g.,* income, attitudes, lifestyle); and the properties of the product or system itself (its functional utility, interconnectedness with other systems, symbolic value, and price) – are likely to influence consumers' adoption decisions and end-use behaviours. An analysis without consideration of this important human contextual dimension would produce a limited technologically biased review. The **'Human Factor'** is therefore important to consider in this evaluation. In this respect, finding the right balance between adopting technologies and changing behaviours is a key challenge for policymakers. Policy innovations and initiatives are important to foster sustainable energy transitions, for example through:

- Sending price signals;
- Stimulating government investment;
- Raising performance standards;
- Facilitating behavioural change, public awareness and technological adoption;
- Lowering barriers to trade.

Such initiatives play an important role in speeding up and or slowing the development and deployments technologies and innovations (Global Agenda Council on Decarbonizing Energy, 2015). One critical political dilemma has been whether to direct adoption of energy efficiency through a top-down, regulatory approach or conversely through adoption of an enabling approach, which seeks to foster grassroots engagement. The selected approach is typically context specific, and relates to how governments see their roles, *e.g.,* whether the role of government should be to facilitate public acceptance of regulations and policies or to stimulate grassroots responses (DECC, 2012; Nye *et al.*, 2009; Ockwell, Whitmarsh, & O'Neill, 2009).

2.3 The Role of Technological Interventions for a Sustainable Future

No 'silver bullets' exist and a range of technological solutions is needed to address energy and CO_2-eq emissions reduction goals. The value and costs of these technologies are important; some are at a more mature stage of deployment while others are in their early stages of development. In addition, the level of technological development, technological availability and technological affordability differs considerably according to national context. As argued by the IPCC, technological transfer is critical in the global perspective. The importance of speeding up the deployment of technologies and innovations which have significant potentials to decarbonize energy is clear. There is also a need to recognise that some technologies have higher CO_2-eq reduction potential than others (Global Agenda Council on Decarbonizing Energy, 2015), including range of carbon reduction potential cost-benefit equations.

The World Economic Forum (2015) argues that a low-carbon transition is likely to present economic opportunity, as deployment of renewable and low carbon energy, and solutions to increase energy efficiency and conservation are deployed across major energy use sectors such as industry, building and transportation and agriculture. More specifically, energy efficiency (EE) is regarded as one of most important options in sustainable energy transition. EE is key to meeting environmental goals and offers multiple economy-wide benefits. EE is seen as one of the most cost-effective for saving energy and contributing to environmental goals. Scaling up EE can make significant contributions in terms of reducing CO_2-eq emissions across multiple sectors (Blewitt, 2008; UNEP, 2016).

However, other viewpoints challenge this, suggesting technology readiness is inadequate and that a more radical shift in mitigation technology is needed. Foxon (2013) argues that a more radical shift is required to achieve a low carbon transition, and advocates systemic change by moving away from market driven approaches for change when devising mitigation options. In particular, Foxon (2013) prioritises the removal of the lock-in of existing behaviours and technologies and infrastructure systems. Existing behaviours and technologies are often closely linked to the dominant social and economic paradigm; hence new technologies and innovations often need to compete with existing entrenched and embedded systems, resulting in muted potentials for new solutions in some cases or a reinforcement of the status quo, rather than more extensive transformational change.

Leonard-Barton (1988) argued that a radical transition might only happen through a co-construction process or co-evolution process between technological and social systems. In particular this means that technological systems need to be adjusted to fit the existing social or user environments. Likewise the human dimension incorporating factors such as user behaviours, practices, routines, infrastructures, policies, and so on also need to be adjusted to accommodate new technological innovations (Leonard-Barton, 1988). This alignment process is underlined by the fact that technological interventions (whether they are objects, artefacts, infrastructures) are often designed to fulfil particular societal functions (*e.g.,* lightbulbs, roads, appliances, renewable technologies) and their production is linked to *e.g.,* regulations, organisations, scientific knowledge, repairs and maintenance, consumer practices and cultural conventions (Shove & Walker, 2010; Smith, Voss, & Grin, 2010).

2.3.1 Technological Approaches –The Stabilisation Wedges Concept

Technological solutions have been identified as playing a pivotal role in the transition towards a low-carbon future (Pacala & Socolow, 2004; Winskel, Markusson, & Moran, 2009). Pacala & Socolow (2004) outline that the fundamental scientific and technical know-how to bring about significant emissions reductions to address climate change already exists. Further, Pacala & Socolow (2004) argue that it is important not to be distracted by revolutionary technology that will inevitably take time to develop and instead argue for a focus on existing technologies to combat climate change. Pacala & Socolow (2004) provided an idealised model for tackling the global warming problem for the next 50 years by simply scaling up only presently available technologies. They asserted that carbon emissions could be significantly reduced to pre-industrial levels by dividing emission reduction targets into seven segments, referred to as 'stabilisation wedges'. These 'wedges' are grouped into 4 broad categories: (1) Efficiency And Conservation; (2) Fossil Fuel Based Strategies; (3) Nuclear Energy; and (4) Renewable Energy & Bio-storage

Table 2 provides and overview of the stabilisation wedge concept, and the suggested technological solutions forwarded to tackle CO_2-eq emissions reductions in the time frame to 2054.

Table 2: The Stabilisation Wedge Approach[1]

'Wedge' Category	Proposed Stabilisation Wedge	Effort by 2054 for one wedge, relative to 14 gigatonnes of carbon per year (GtC/year) BAU
Energy Efficiency and Conservation	Economy-wide carbon-intensity reduction (emissions/$GDP)	Reduce by additional 0.15% per year
	1. Efficient vehicles	Increase fuel economy for 2 billion cars from 30 to 60 mpg
	2. Reduced use of vehicles	Decrease car travel for 2 billion 30-mpg cars from 10,000 to 5,000 miles per year
	3. Efficient buildings	Cut carbon emissions by one-fourth in buildings and appliances projected for 2054
	4. Efficient baseload coal plants	Produce twice today's coal power output at 60% instead of 40% efficiency (compared with 32% today)
Fuel Shift	5. Gas baseload power for coal baseload power	Replace 1,400 GW 50%-efficient coal plants with gas plants (4 times the current production of gas-based power)
CO_2 Capture and Storage (CCS)	6. Capture CO_2 at baseload power plant	Introduce CCS at 800 GW coal or 1,600 GW natural gas (compared with 1,060 GW coal in 1999)
	7. Capture CO_2 at H_2 plant	Introduce CCS at plants producing 250 MtH2/year from coal or 500 MtH2/year from natural gas (compared with 40 MtH2/year today from all sources)
	8. Capture CO_2 at coal-to-synfuels plant	Introduce CCS at synfuels plants producing 30 million barrels per day from coal (200 times Sasol), if half of feedstock carbon is available for capture
	Geological storage	Create 3,500 storage projects
Nuclear Fission	9. Nuclear power for coal power	The required investment rate in nuclear energy is $160/€143 billion p.a. until 2050. When fuel production, decommissioning and waste disposal costs are added this sum might enable construction of 30 new reactors each year, and sustain approximately 1500 reactors in use corresponding to about 1200 GW assuming operation at 0.8 capacity (IPCC, 2014; Trainer, 2017).
Renewable Electricity and Fuels	10. Wind power for coal power	Add 2 million 1-MW-peak windmillls (50 times the current capacity) "occupying" 30x10-to-the-sixth ha, on land or off shore
	11. PV power for coal power	Add 2,000 GW-peak PV (700 times the current capacity) on 2x10-to-the-sixth ha
	12. Wind H2 in fuel-cell car for gasoline in hybrid	Add 4 million 1-MW-peak windmills (100 times the current capacity)
	13. Biomass fuel for fossil fuel	Add 100 times the current Brazil or U.S. ethanol production, with the use of 250x10-to-the-sixth ha (1/6 of world cropland)
Forests and Agricultural Soils	14. Reduced deforestation, plus reforestation, afforestation and new plantations	Halt tropical deforestation instead of 0.5 GtC/year, and establish 300 Mha of new tree plantations (twice the current rate)
	15. Conservation tillage	Apply to all cropland (10 times the current usage)

[1] After Pacala & Socolow (2004)

The stabilisation wedge concept posits that multiple interventions and technologies applied in tandem can fulfil societal energy needs while reaching ambitious carbon reduction goals. The stabilisation wedges concept proposes a relatively broad and idealised plan for tackling the complexity of the global emissions challenge for the next 50 years using only currently available technologies. It is this flexibility that has made it a popular communication tool and starting point for discussions on climate change mitigation. However, the stabilisation wedges approach is not without its criticisms. In particular there have many detailed disagreements over the actual numbers, costs and carbon reduction potentials of each wedge leading to the criticism that the wedges are too simplistic in relation to their treatment of the economic aspects of climate change mitigation (*e.g.,* Hoffert, 2010)[2]. Secondly, the assumption that humanity already has the tools and technologies to halt climate change does not give sufficient recognition to the fact that some technologies are more mature and operational than others. The third key criticism of the stabilisation wedges is that it focuses too much on technological fixes rather than fundamentally challenging the unfettered economic and demographic growth which are seen as key drivers in global climate change (as suggested by numerous IPCC reports). Nonetheless the stabilisation wedges concept has retained a legacy in existing research discourses which seek ways to implement the wedges and in designing effective carbon emission reduction interventions (*e.g.*, Dietz, Gardner, Gilligan, Stern, & Vandenbergh, (2009); Vandenbergh, Stern, Gardner, Dietz, & Gilligan (2010)).

2.4 The Role of Behavioural Interventions

While technological solutions have generally been favoured by the public, as well as by politicians to date in addressing energy use issues (Devine-Wright, 2011; Verplanken, 2011), it is increasingly recognised that technology alone is insufficient to address major global environmental issues such as climate change (Dietz *et al.*, 2009; Moloney, Horne, & Fien, 2010). Improvements in technical efficiency are subject to the rebound effect and have regularly been overtaken by increased consumption (Galvin, 2013; Maréchal, 2010; Steg & Vlek, 2009). Behaviour, practices, and culture constitute a powerful human factor in the energy system; in particular the interactions between technologies, practices and norms that lock individuals in to certain patterns of (often inefficient) energy use. The result has been an increasing focus on behaviour change in research, particularly on the social contexts in which people live, the routines these social contexts shape, and the extent to which people feel empowered to change them.

With over one-third of many developed nations' CO_2-eq emissions attributed to domestic energy use and private travel, both individuals and communities have a key role to play in the transition to a low-carbon future (Whitmarsh, O'Neill, & Lorenzoni, 2013). The need to prioritise behavioural change alongside technological innovation is illustrated in the case of buildings which account for 40% of Europe's total primary energy consumption (Economidou *et al.,* 2011). Household behaviour affects residential energy use to the same extent as equipment and appliances (Lindén, Carlsson-Kanyama, & Eriksson, 2006). Additionally energy-efficiency behaviours accounted for 51%, 37% and 11% of the variance in heat, electricity and water consumption respectively between similar dwellings (Gill, Tierney, Pegg, & Allan, 2010). However improvements in technical efficiency are subject to the rebound effect and efficiency gains have regularly been overtaken by increased consumption (Galvin, 2013; Maréchal, 2010). Even where buildings have been retrofitted to high thermal standards or incorporate energy efficient technologies, ingrained patterns of behaviour mean that many households continue to consume more energy than expected (Galvin, 2013; Gram-Hanssen, 2011). Despite a proliferation of technological interventions improving energy efficiency in advanced economies between 1995 and

[2] The potential costs and carbon savings implications from specific interventions is a theme of focus in this deliverable, discussed in Section 6

2005, these gains were more than offset by increased household demand for energy (Duarte, Mainar, & Sánchez-Chóliz, 2013). Consequently, this trend underlines the importance of changing the everyday behaviours and practices of consumers to effectively reduce energy consumption, particularly given that technological solutions have not resulted in the expected energy efficiency gains (Gram-Hanssen, 2011; Moloney *et al.*, 2010).

A failure to recognise a human behavioural component can ultimately result in significantly higher energy consumption patterns, even in the presence of large-scale conservation efforts (Timm & Deal, 2016). Increasingly, as technological improvements reduce the potential energy footprint of a building for example, behavioural components become more significant in determining energy use patterns and capacity for energy savings (Timm & Deal, 2016). In response, a substantial body of literature has emerged focusing on behavioural change.

Traditionally, research on behaviour change has focussed on a rational choice model of human behaviour where individuals are seen as logically weighing up the costs and benefits of different courses of action before choosing the one which offers the most benefits (Hargreaves, 2011; Shove, 2010). This area of research contends that if you change people's attitudes by providing them with more or better information, or by making pro-environmental behaviour more financially attractive, you will change their behaviour. This model assumes that individual engagements with environmental issues can lead to behaviour change and places the primary responsibility for addressing climate change and sustainability issues on individuals and their choices (Barr & Prillwitz, 2014; Hargreaves, 2011). However, information and incentives alone will not bring about behaviour change (Barr & Prillwitz, 2014). Consequently, rational choice approaches and information deficit models have proven to be insufficient to account for the drivers of energy-related behaviour. Consequently, there has been an increasing emphasis on interventions in the social contexts in which people live, the routines they shape, and empowering people to change them. This requires an understanding of the extent to which people's attitudes, values and perceptions are not fixed and static, and could be changed in response to the expectations of other people and cues in their environment (Blake, 1999; Jackson, 2005). Rather, people's values and attitudes are negotiated, transitory and sometimes (if not, often) contradictory (Blake, 1999). Therefore, there appears to be no simple one-way relationship between attitudes and behaviour.

One strand of research has focused on habit as a factor in energy-related behaviour (Steg & Vlek, 2009). Habit is a predisposition to repeat a well-practiced action in response to cues given by a particular social or environmental context (Maréchal, 2010). Once formed, habits become a strong influence on behaviour, irrespective of our conscious intentions (*e.g.,*the difficulty of changing health related behaviours such as eating habits, weight loss activities or health improvements). It is widely accepted that most energy consumption related behaviours are based on habits and routines (*e.g.,*lighting and heating rooms) and less about one-off behaviours (purchase of particular goods) (Heimlich & Ardoin, 2008; Martiskaïnen, 2007; The Parliamentary Office of Science and Technology (UK), 2012). Habits are repeated behaviours that have become automatic responses in recurrent and stable contexts (Heimlich & Ardoin, 2008), and have three key components:

Repetition: Habits form by successfully repeating behaviour. 'Successfully' should be interpreted in a wide sense, and not confined to what objective observers define as desirable. Habits may be successful from a personal perspective because they provide comfort or status, but such habits could also be unhealthy, asocial or environmentally unfriendly from an outsider's perspective (Verplanken, 2011).

Automaticity: 'Automaticity' can be broken down into features such as an absence of conscious intent; lack of awareness; the difficulty of control; and the fact that habitual behaviour does not tax cognitive resources (Bargh, 1996; Verplanken, Aarts, & VanKnippenberg, 1997).

Execution: Habits are executed in stable contexts, and are more or less done at the same time and at the same location. Verplanken (2011) states that an important caveat here is that habitual behaviours are under the control of the environment where the acts take place, to a large extent. For example, one may execute a habit because it is 8am or because one passes by a particular shop, and not because of conscious intention or willpower. Verplanken (2011) emphasizes the importance of such cues in regulating behaviour, rather than an over-concentration on attitudes or intentions.

Research carried out by Huebner *et al.* (2013) found that habitual behaviour is directly related to domestic energy consumption and that habits can be considered to be a barrier to behaviour change. Social theorists have shifted focus from issues of individual habit to a broader concern about social practice, and the social context of individual habits (Shove, 2010; Barr and Prillwitz, 2014). As such, social practices are more broadly conceived than habits in that they place current individual routinised behaviour into both a social and historical contexts (Barr and Prillwitz, 2014). Practices are performed by individuals and also shaped and sustained by collective conventions and contexts (Gram-Hanssen, 2011; Hargreaves, 2011). Thus, behaviour which is perceived as environmentally damaging or sustainable is seen, not as the result of an individual's attitudes or values or constrained by contextual barriers alone, but as embedded within social practices. Therefore, highlighting the role of social contexts that frame everyday actions (Hargreaves, 2011; Moloney *et al.*, 2010).

2.4.1 Addressing Sustainability: Towards a Behavioural Wedge

While most climate policy attention addresses long-term options and focuses on low-carbon technologies, emerging research suggests a large near-term potential for emissions reduction from behavioural changes involving the adoption and altered use of available in-home and personal transportation technologies, without waiting for new technologies, regulations or changing household lifestyle (Gardner Stern, 2008). It is within this context that Dietz *et al.* (2009) indicate how practical behavioural changes can enable individuals, communities and wider society to have a larger role in addressing climate change. Such changes in practice fully accord with the concept of sustainable living (Barr, Gilg, & Shaw, 2011) and can be incorporated to varying degrees within people's lifestyles to minimise their impact on the environment and climate (Whitmarsh, 2009).

Dietz *et al.* (2009) outline the potential of 17 types of household actions and practical behavioural changes using readily available technology to reduce emissions. Divided into 5 categories (referred to as **W, E, M, A and D**) on the basis of behaviourally relevant attribute, are: (1) home ***Weatherisation*** and upgrades to heating and cooling equipment i.e. insulation and draught proofing; (2) more efficient vehicles and non-heating and cooling home ***Equipment*** *e.g.,* fuel-efficient vehicles and low-flow showerheads; (3) equipment ***Maintenance*** such as routine car maintenance; (4) equipment ***Adjustments*** *e.g.,* resetting household temperatures; and (5) ***Daily use behaviours*** i.e. driving behaviour and carpooling. If practical behavioural changes in households outlined by Dietz *et al.* (2009) were implemented using the United States as an example this would result in 123 MtC reduction in CO_2-eq emissions after 10 years, the equivalent of 7.4% of US national emissions (Carrico *et al.*, 2011; Dietz *et al.*, 2009; Gilligan, Dietz, Gardner, Stern, & Vandenbergh, 2010) This reduction would equate to roughly 3 'stabilisation wedges' outlined by Pacala & Socolow (2004), demonstrating the potential of behavioural changes to impact on climate stabilisation efforts. Consequently, behavioural changes can significantly contribute to addressing climate change and sustainability targets. Given the potential contribution that individual behaviours and practices can play in addressing climate change, it is therefore essential to identify interventions that can support behavioural change and practice change.

Given the potential of the behavioural wedges concept for transition, Carrico *et al.* (2011) argue that the residential sector presents a major opportunity outlining that in major economically developed states that this sector represents up to 40% of carbon emissions and a comparable percentage of energy consumption. Using the United States as an example, Carrico *et al.* (2011) report that energy saving measures targeting behaviours could reduce total emissions by over 7% by 2020. Yet despite this potential, recent regulatory and policy efforts are only beginning to direct substantial attention to these behaviours as a key dimension of energy management. To develop the most effective policy design, Carrico *et al.* (2011) offer 10 important principles to adhere to as key lessons for implementing the behavioural wedge, they are as follows:

Price plays an important but limited role: Price clearly affects behaviour. However, its impact can be overstated. In some cases, price accounts for less variance in behaviour than other factors such as personal commitment or social norms. Yet policymakers often gravitate towards price-based mechanisms such as rebates or other incentives when attempting to influence product purchase decisions.

Both technology adaptation and use are important: Product purchase decisions *e.g.,* efficiency) and product use (*e.g.,* curtailment) to maximise the potential for emissions reductions within the residential sector should be targeted. Efficiency improvements generally offer greater longer-term potential for reducing energy use and emissions. By enacting policies that address both the purchase of efficient products and their use, policymakers can increase the potential of both near- and long-term emissions reductions while reducing the magnitude of take-back effects.

Economic incentives can be counterproductive: Relying solely on economic incentives or disincentives to change behaviour can lead to so-called ‘motivational crowding’, which occurs when external rewards undermine intrinsic motivation, resulting in a reduction in the desired behaviour. Introducing external rewards or punishments in situations otherwise governed by moral norms has been shown to lead to an increase in self-interested behaviour in some contexts. Thus moral norms should also be reinforced using other avenues such as public education programmes.

Decision making is limited by incorrect or incomplete information: Policymakers should not assume that individuals make decisions on the basis of full and accurate information. Individuals often act in ways they perceive to be in their own self-interest or to benefit the common good when in fact their actions are counterproductive to these ends. Although simply providing information is insufficient to change behaviour, accurate and actionable information is often a necessary component to achieving this end.

Decision making is limited by our ability to process information: Individuals often make purchase decisions that are economically sub-optimal in terms of the later operation costs. Most relevant to energy and climate change is the tendency for individuals to act as if they are applying steep discount rates when making product purchase decisions, possibly due to uncertainties about potential savings or future energy costs.

Cognitive costs matter: Traditional rational actor models tend to underestimate the cognitive costs associated with seeking out, evaluating, and acting on new information. Individuals often fall prey to a “status quo bias” in which they revert to the default option due to its convenience even when that option may be less preferable. Major reductions in emissions could be achieved by ‘nudging’ consumers towards environmentally or social optimal options.

Choices depend on the way the options are framed: Individual choices are not always grounded in a stable set of preferences as economics commonly assumes. This literature suggests that individuals reliably prefer certain choices to others based on how these choices are framed. Frames can interact with an individual's previous experiences or ideological worldview to trigger certain responses. Therefore, messages should be framed carefully to avoid polarising effects.

People do not always act the way they feel: Decision makers often gravitate towards an attitude-persuasion model for changing behaviour. Although this approach may raise awareness there are a host of other barriers that prevent people from acting on the way that they feel. Individuals may hold strong values to protect the environment but these values are often overcome by countervailing influences at the time when decisions are made, such as the desire for convenience or status.

People often follow the crowd: People do not like to be in the minority. By bringing attention to a common behaviour within a population (a descriptive norm), may induce many individuals to conform to that behaviour.

People strive for consistency: Dissonance refers to the discomfort that is felt when a person holds contradictory ideas, cognitions or behaviours. To reduce dissonance, individuals will modify their attitudes, beliefs or behaviours to bring them in line with one another. Those interested in changing behaviour have learned that calling attention to behavioural inconsistencies can motivate individuals to act more in line with the way that they feel (Carrico *et al.*, 2011).

Consequently, by following these key lessons in the implementation of behavioural interventions, a number of barriers in the ways in which people act towards energy and sustainability issues can be addressed. The behavioural interventions reviewed in Section 5 indicate how some of the lessons proposed by Carrico *et al.* (2011) can be integrated to implement the behavioural wedge.

2.5 Integrated Technological and Behavioural Interventions

The importance of deploying both technologies and lifestyle solutions in an integrated manner is increasingly recognised by the literature (Blewitt, 2008; DECC, 2012; Dietz *et al.*, 2009; Janda, 2011). While somewhat neglected in the policy mix to date, governments now increasingly promote the need for changing domestic energy consumption habits that will have a significant impact on future energy demands (Stern, 2006; UNEP, 2016). The rationale for both technological and behavioural solutions is underpinned by a need to address supply and demand side emission issues in relation to climate change (UNEP, 2016). To date, behavioural solutions have typically focused on end-users usually consumers, particularly within the domestic sector (DECC, 2012; Dietz, Gardner, Gilligan, Stern, & Vandenbergh, 2009; Gilligan, Dietz, Gardner, Stern, & Vandenbergh, 2010; POST, 2012). However, behavioural solutions need to be combined with the uptake of energy saving technologies, large-scale deployment of electric vehicles and renewable technologies, as well as the need to change consumer and/or end-user behaviour. Energy efficiency technology deployment has to be combined with appropriate changes in practice and behaviour (DECC, 2012; Dietz *et al.*, 2009). Importantly, there is a role for new technologies to play in breaking dependency on specific energy consumption practices (*e.g.,*through smart meters). Technology has the potential to be used as an aid to change behaviour where existing policies, legislation and campaigns have failed.

The dominant psychological behavioural concepts (commonly advocated by government policies) could be used to help identify and target technological interventions where behaviour change has been difficult, *e.g.,*by targeting particular user groups, market segments or communities (Department of Energy & Climate Change (DECC), 2012; Gerpott & Paukert, 2013; Martiskainen & Ellis, 2009).

Behaviour change for reduced energy consumption outcomes will require both curtailment and efficiency behaviours through purchasing decisions (such as buying energy-efficient appliances) and repetitive actions (*e.g.,* not leaving electrical goods on standby) (Barr, Gilg, & Shaw, 2006; Gardner & Stern, 2008; Martiskainen, 2007). There appears to be considerable debate within the existing literature over which behaviours are the most effective and/or which interventions will be effective in energy saving behaviour changes (Abrahamse, Steg, Vlek, & Rotherngatter, 2005; DECC, 2012; Gardner & Stern, 2008). Abrahamse *et al.* (2005) propose that energy saving measures could be categorised into three groupings: ***Antecedent*** measures, which typically rely on information and awareness raising; ***Consequence*** measures, which typically rely upon feedback, rewards and incentive measures and ***Social influence*** measures which often use groups settings and commitment techniques to foster change. It is emphasised in their article that antecedent measures alone are not effective and they more effective when combined with consequence measures (Abrahamse *et al.*, 2005).

From a policy intervention viewpoint, curtailment behaviour is considered to be more sustainable, durable and long term, yet it is also perceived as the hardest to achieve as it requires time and resources and involves a less clear-cut process to deliver. In particular the importance of changing individual consumer behaviours in terms of their choices to deliver sustainable consumption patterns is well established (Barr & Gilg, 2006; Barr, Gilg, & Ford, 2005; Dietz *et al.*, 2009; Verplanken & Roy, 2016). Household energy consumption behaviour has to date been the primary focus of much of these initiatives, whereby policy initiatives have sought to encourage a shift towards more sustainable (water, energy and resource consumption) household practices. To date, numerous studies have focused on how a change in behaviour could curtail overall household energy consumption by identifying the most effective actions households can take to reduce energy consumption, *e.g.,* Barr *et al.* (2006); Gardner & Stern, (2008); Gill, Tierney, Pegg, & Allan, (2010); Martiskainen & Ellis (2009); Martiskainen (2007).

2.5.1 The '4Es' Model of Behaviour Change

DEFRA has produced the '4E's' guidance as a tool to help policymakers to deliver sustainable development through behaviour focused outcomes. The '4E's' guide provides a visual conceptual model based on four simple principles: **Enable, Engage, Encourage and Exemplify**. The model asserts that all four principles need to be met in order to achieve effective behavioural change (DEFRA, 2011).

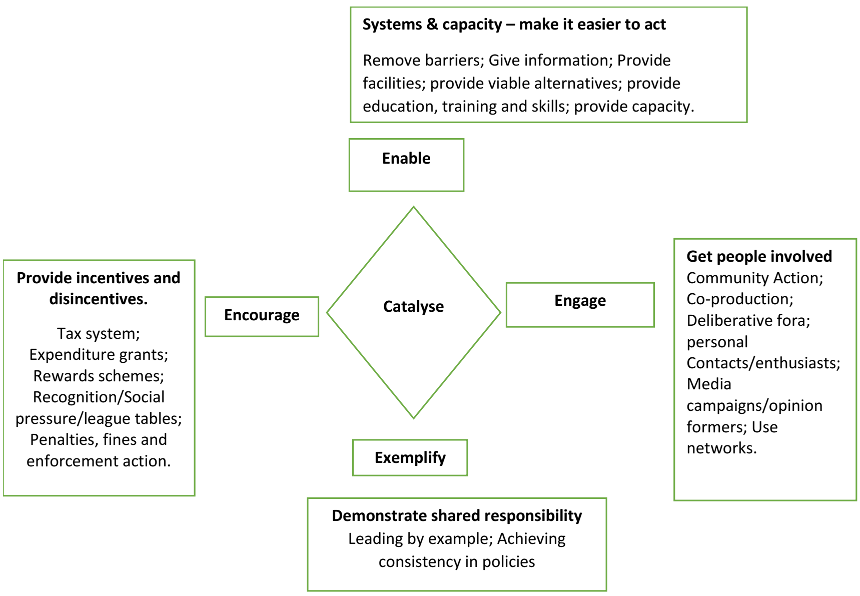

Figure 2: The 4Es Model

For example, **Enable** places emphasis on the removal of information based barriers, and requires that people be given adequate information through educational campaigns and other resources (*e.g.,* education, training). **Engage** requires that people are directly engaged and involved by giving them responsibilities (*e.g.,* community action, deliberative fora). **Encourage** places emphasis on regulation, incentives and rewards to get behaviour change (*e.g.,* boiler cash-back schemes). **Exemplify** is concerned with leading by example and being consistent with policies. Following from this model, it is clear that there is a need to design policies to catalyse people to change behaviour, which work on multiple levels. Thus, putting the 4E's model into effect requires using a whole spectrum of interventions for behaviour change.

Monkhouse & Dibb (2011, p.27) forward a combination of regulation, incentives, standard setting, interventions by businesses, public facing campaigns *etc.* for instance. Interventions need to also be fit-for-purpose and need to be designed according to the audience, intended outcomes and based on evidence of what works. For example, information and awareness raising work best at supporting structural change but not by themselves. In contrast the most success at successful behaviour change evident to date has come from setting mandatory standards, targets and fiscal incentives *e.g.,* Mandatory A-G rating, Carbon Emissions Reduction Targets, Feed-in-Tariffs, *etc*. (Monkhouse & Dibb, 2011, p.28).

3 Identifying and Classifying Technological and Behavioural Interventions

3.1 Approach

In response to the aims of this deliverable, a multi-layered gap analysis approach is adopted, primarily relying on existing literature and secondary sources, and drawing on previous deliverable reports D4.4 and D2.2 where appropriate. The first element of the gap analysis examines good practice case study examples of existing solutions in the development and application of an evaluative framework. This helps in the identification of current gaps in technology and behaviour focused interventions. The analysis sign-posts where specific and targeted action, new technologies and better application of existing technologies and practice based approaches is likely to be required to achieve significant carbon reduction goals. This paper synthesises a literature review process and evaluative analysis divided into the following stages:

- Literature review – scholarly journal articles, ENTRUST deliverable reports, and grey literature where appropriate (Section 2);
- Examination of multiple case study interventions using a qualitative evaluative framework combining a SWOT and PEST analysis – using existing scholarly literature (Sections 4 , 5, and 7);
- A cost/benefit style gap analysis of the costs/carbon saving potentials of key case study interventions – using existing datasets/figures in the public domain and within existing scholarly literature and government reports (Sections 6 and 7)
- Gap analysis synthesis of implications for policy – findings analysis based on the review process in stage 2 and 3; and includes a PEST analysis (Section 7)

Existing literature is applied to understand key issues relating to technology adoption and behaviour change interventions. Deliverable 6.2 will go beyond the narrow 'barriers and drivers' framing of the adoption of specific technological interventions and will examine what behaviour change related influences will need to be applied alongside technology adoption; and to assess, ultimately, their overall contributions to carbon reduction goals. An analytical framework is developed and applied to evaluate specific existing technologies, as well as technologies that require behavioural interventions. The framework is applied to evaluate technologies that can be deployed now and have the potential to make significant contributions to tackling climate change by reducing GHG emissions from one of the largest sectors that contribute in CO_2-eq, such as the residential/household domestic sector. The evaluative analysis in this paper does not take an exhaustive list of interventions but takes a selection of well-established technologies and/or those that are increasingly promoted by governments, or sometimes under-utilised which can make a significant contributions to energy efficiency and emissions reductions goals (as suggested by Pacala & Socolow, 2004 and Dietz *et al.,* 2009). They are on the whole chosen to illustrate the functional heterogeneity and diversity of both technological and non-technological interventions.

Each of the chosen profiled interventions will be evaluated in-depth using the following headings:

- Description – what it does;
- Adoption – implementation and uptake levels;
- Level of behaviour change required (including lifestyle and everyday practices);
- Level of personal/household engagement with technology (including user interaction)

- Costs and carbon implications (Section 6).

Profiled intervention analysis is accompanied by both a SWOT (Strengths, Weaknesses, Opportunities, Threats) and PEST (Political, Economic, Social, Technological) analysis.

3.2 Identifying Technological and Behavioural Interventions

The effectiveness of a given technological intervention may depend on the behaviours that it targets and engages with. In addition, the nature, and extent, of user involvement with a given technology may influence energy conservation and efficiency outcomes. The literature suggests that energy efficiency measures (of the 'fix and forget' nature such as installing insulation) are considered to be more effective than curtailment behaviours (Abrahamse *et al.*, 2005) at the voluntary individual level. For example, smart meters, enable energy management through a nudge approach to help individuals manage habitual energy use (POST (Parliamentary Office of Science and Technology), 2012). Some studies (Caird & Roy, 2010; Keirstead, 2007) suggest that the adoption of microgeneration technologies could produce spill-over benefits. This would result in households not only generating their energy use but also undertaking other energy efficiency measures such as insulating their home as a pre-requisite good-practice prior to the adoption of micro-generation. Such interventions could also raise awareness of energy saving. Technological interventions fall into 3 broad categories:

1. Energy management (conservation behaviours);
2. Energy efficiency (adoption of technologies);
3. Microgeneration (adoption of renewables).

These categories are adapted from the 'energy hierarchy' concept. Accordingly, best practice used in building sustainability policy and industry follows this 'energy hierarchy' pyramid model (Figure 3).

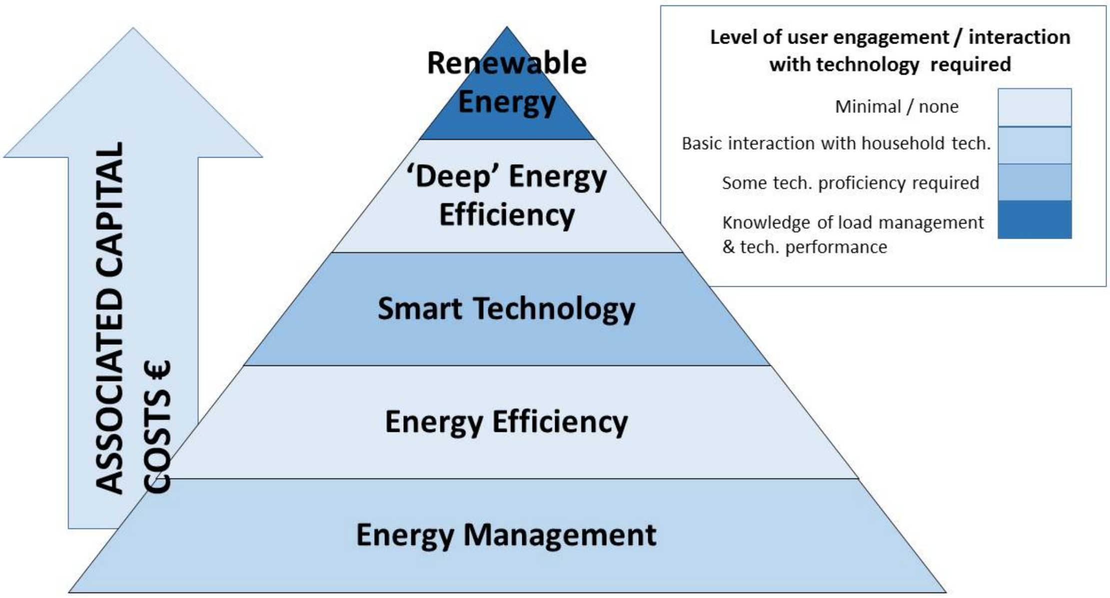

Figure 3: The Energy Hierarchy Consumption Reduction Pyramid Model

Figure 3 suggests that there is an order which interventions potentially could follow. The model suggests that within the residential sector, firstly, households or individuals should adopt more energy management behaviours such as turning off lights *etc.* In the second tier, interventions could consider energy efficiency actions, such as insulation and buying energy efficient technologies. Thirdly, individuals would only consider the installation of micro-generation technology once the former tiers have been satisfied. This research proposes the proliferation of smart technologies and 'deep' energy efficiency measure adoptions could expand the energy efficiency tier to comprise two additional tiers on their own in the future.

The Energy Hierarchy takes into consideration that energy systems change will require investment in time, money, resources and user commitments amongst other things. It advocates that the most efficient sustainable strategy would first incorporate the easiest and cheapest solutions, followed by the most complex and costly ones, higher up in the hierarchy. Although there are a number of variations in the way the energy hierarchy is used, nearly all capture the basic principles. These include, energy management, energy efficiency and microgeneration renewable technology adoption in a clear adoption hierarchy.

3.3 Characterisation of Technological Interventions

Appendix 3 highlights some of the most common adopted technological interventions available to households. Nearly all of the interventions reviewed focus on reducing direct energy use (*e.g.,* LED light bulbs) and the energy efficiency of the building fabric (*e.g.,* insulation) although many of these will still require behavioural energy management responses (*e.g.,* curtailment behaviours, such as switching lights off when not in use, even where efficient lighting has been installed). However, energy efficiency at the individual household and building level, and where technological interventions are undertaken, can be summarised into three broad categories: energy efficiency (fit-and-forget), energy management and microgeneration (Figure 3).

In contrast to behavioural interventions, strategies that incorporate technological interventions seek to address the material context of energy consumption practices. Technological interventions encompass technologies, their infrastructures, their systems, which may then influence the nature of behavioural responses and consequently on the forms of consumption that arise from them (Southerton, McKeen, & Evans, 2011).

These technologies and their associated infrastructures may serve to reinforce and/or result in the lock-in of existing practices. Nevertheless, technological solutions represent an intervention in the existing material contexts, holding the potential to shift existing practices and habits towards more sustainable behaviours. The extent of the behavioural shift through technological interventions is debatable, yet is still seen by policymakers as an important feature of a transition to a sustainable society (Southerton, McKeen, & Evans, 2011). Interventions to change the material context are prominently found in the building energy efficiency and residential sector where infrastructures of energy, water and so on, affect patterns of energy behaviour (DECC, 2012).

The diverse nature of technological interventions is demonstrated in Appendix 3. Building upon Appendix 3, Figure 4 illustrates this relationship between technologies, the level of behaviour change required and their consequent influence on energy use outcomes. The selected profiled technologies (insulation, LED lightbulbs, smart meters and solar PV) were chosen because they are the most commonly adopted technological interventions, and for their heterogeneity in comparison with each other. The nature of their influence in reducing overall energy consumption outcomes can be summarised into three broad categories arising from the energy hierarchy: energy management, energy efficiency (fit-and-forget), and microgeneration.

Importantly, nearly all the technological interventions reviewed (Appendix 3) address the reduction of direct energy use (*e.g.,* LED light bulbs, micro-generation renewable technologies); and energy efficient performance of the building fabric (*e.g.,* insulation). Although many will still require behavioural energy management responses (*e.g.,* curtailment behaviours, such as switching lights off when not in use even where efficient lighting was installed). Therefore, this means some interventions will either require high or low levels of behavioural changes (including lifestyle changes) in order for the full environmental credentials of the intervention to materialise. For example, insulation would require low levels of behavioural change due to their fit-and-forget qualities while solar renewable technologies would require high levels of behavioural responses. This interaction will be further explored through the in-depth profiles of selected interventions. A further dimension for the evaluation of the chosen case studies is the responsiveness of interventions in terms of the level of individual/household involvement required in order to produce their desired or potential outcomes (Figure 4). According to Figure 4, depending on the nature of technological intervention (*e.g.,* fit-and-forget technologies such as insulation) the level of personal and household engagement required will be limited, some moderate and some requiring substantial personal engagement.

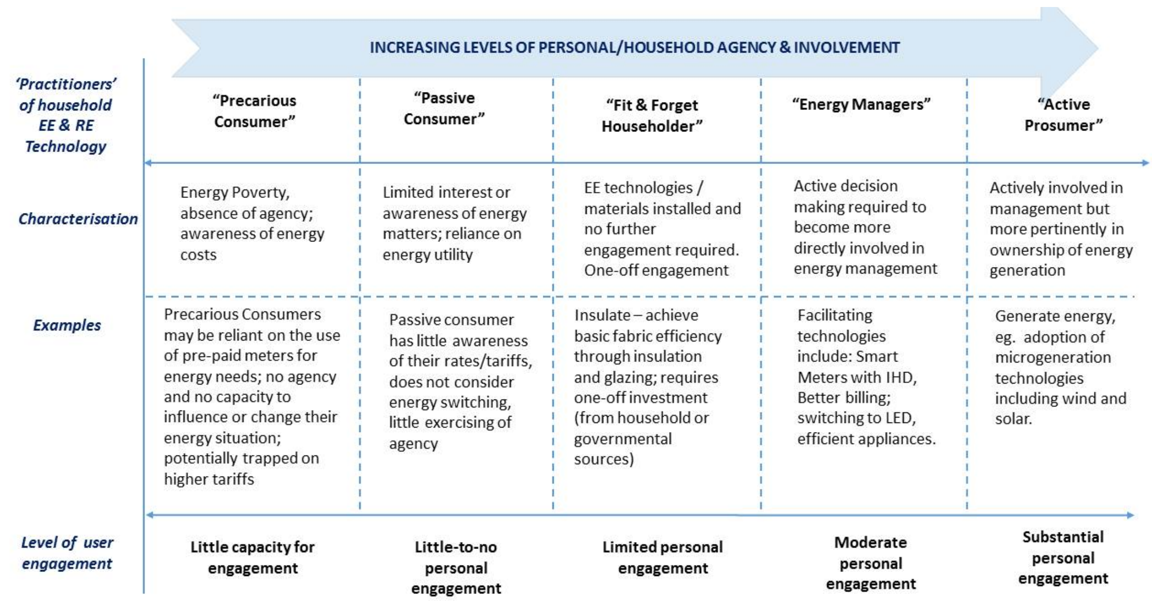

Figure 4: Technology-Practice Spectrum

3.3.1 Selection of Technological Intervention Case Studies

Based on the broad categorisations of technologies within the energy hierarchy discussed, 5 profiled technological interventions were chosen for qualitative in-depth analysis. These include (in order of increasing practitioner agency and involvement, according to Figure 4):

Pre-payment Meters (PPMs): A technological devise that is often presented as a useful budgeting tool which could encourage energy conservation and help users avoid debts (Boardman & Fawcett, 2002; Faruqui, Sergici, & Sharif, 2010). The main user interaction with this type of technology involves the action of purchasing energy credits using money or a key or token, which is then slotted into a meter (Owen & Ward, 2010).

Building Insulation: One of the most commonly adopted energy efficiency measures and considered one of the most cost-effective means of achieving energy efficiency; often aided by government grants and incentives (Energy Saving Trust (EST), 2011; Roberts, 2008). Building fabric or envelope insulation include wall insulation (for cavity or solid walls – insulated internally or externally), roof, loft or upper storey ceiling insulation, basement ceiling, window/door draught proofing, and others (Energy Saving Trust (EST), 2011; Roberts, 2008).

LED lightbulbs: Lighting is one of the highest energy consuming appliance groups in households, after refrigeration. LEDs are increasingly seen as the most efficient and affordable efficiency solution for lighting. Reducing energy consumption via replacement and installation of energy efficient lighting, particularly LED lightbulbs, is considered to be one of the easiest and most cost-effective one-off purchase interventions (Energy Saving Trust (EST), 2017a).

Smart Meters: Increasingly promoted as an energy saving device. Smart meters record energy usage and provide enhanced information to both consumer and energy suppliers. They enable energy savings through the user display-monitoring device, provide accurate billing and reduce the cost of operating the electricity and gas networks for suppliers (Barnes & McKnight, 2014; Darby, 2012).The emphasis of this technology is on helping consumers/individuals manage their energy use (Barnes & McKnight).

Solar PV: Solar PV is the most popularly adopted and socially accepted of all the microgeneration technologies. Microgeneration technologies also include: micro-wind, micro-hydro, micro-CHP, fuel cells, solar thermal and heat pumps (air, water and ground source) and biomass. It is tentatively suggested that the adoption of microgeneration could produce spill-over benefits resulting in end-users not only undertaking other energy efficiency measures such as insulating their home but also raised awareness of energy consumption triggering lifestyle adjustments (Caird & Roy, 2010; Keirstead, 2007).

The chosen technologies were selected for their heterogeneity in comparison with each other. By their nature, these technologies demonstrate that domestic technological interventions are multifunctional even though they may all seek to reduce the overall energy consumption of the domestic sphere. They do this in very specific ways in relation to how they influence domestic energy consumption practices and the level of user interactions and specific behaviour change that needs to be accompanied. Each of the chosen technologies will be evaluated using particular criteria: providing a description of the interventions and what they do, their rates of adoption, their costs, and accompanying levels of user interactions and behaviour change required. The evaluation of case studies will be supplemented by both a SWOT of each intervention and PEST analysis of two broad intervention groupings classified as behavioural and technological interventions.

3.4 Characterisation of Behavioural Interventions

From the behavioural interventions reviewed in **Appendix 2**, it is clear that these interventions can be placed along a continuum. This illustrates a number of characteristics reflective of the level of behavioural change (minimal to meaningful); the associated technologies utilised to facilitate the behavioural intervention; and the level of personal engagement required (ranging from limited to substantial engagement) with each intervention. These characteristics can be clearly shown in **Figure 5.**

Outcome of intervention	**Limited behavioural change**	**Moderate behaviour change**		**Meaningful behavioural change**	
Intervention	*Information and awareness raising*	*Feedback systems*	*Legal measures e.g. plastic bag charge and congestion charge*	*Community-based sustainability projects*	*Personal Carbon Allowances*
Invested technologies	Social media, information apps and media	Smart meters and billing	Information technologies, media and communication platforms	Social media, information apps, information technologies and communication platforms	Monitoring and recording smart technologies, smart watches and applications
Level of engagement required	**Limited personal engagement**	**Moderate personal engagement**		**Substantial personal engagement**	

Figure 5: Behavioural Interventions, Associated Technologies and Personal Involvement

The characteristics identified in Figure 5 illustrates that substantial changes in behaviour can only be achieved through substantive engagement with the behavioural intervention and the associated technologies used to facilitate behavioural changes. This co-evolution of technologies and practices influencing one another is well-established within the sustainability transitions and behavioural change literature (Foxon, 2011). Notably, the interventions requiring substantial personal engagement are community-based sustainability projects that apply a tailored collective approach to lifestyle change and personal carbon allowances (PCAs) that deliver guaranteed levels of carbon savings in successive years in an equitable way (Capstick & Lewis, 2010; Fawcett & Parag, 2010). The examples of behavioural interventions identified in Figure 5 are drawn from a number of informational and structural strategies (Steg & Vlek, 2009). These strategies are applied to engage people more effectively and meaningfully with sustainable lifestyles, applying antecedent (changing the factors that precede behaviour) and consequence (changing the consequences that follow behaviour) methods (Steg, Perlaviciute, & van der Werff, 2015; Steg & Vlek, 2009; Verplanken & Roy, 2016). Informational strategies attempt to change perceptions, knowledge, norms and motivations and include information provision; social marketing; and behavioural commitments. In contrast structural strategies change the circumstances or contextual factors of behaviour such as the availability or the costs and benefits of sustainable alternatives and can be used to reward 'good' behaviour and punish 'bad' behaviour (Abrahamse, Steg, Vlek, & Rothengatter, 2005; Steg & Vlek, 2009).

In Figure 5, a number of informational strategies including information and awareness raising and feedback systems are identified while examples of legal measures such as plastic bag charges and congestion charges are indicative of structural strategies. Community-based sustainability projects and PCAs reflect a hybrid combination of informational and structural strategy approach that is dependent upon the level of engagement with the intervention. For example, this involvement can be reflective of surface-level engagement or meaningful, sustained engagement. The level of engagement can significantly affect the outcome of particular interventions, as well as particular 'entry points' and influencing periods during life course changes such as moving home (Evans & Abrahamse, 2009; Verplanken, 2011; Verplanken & Roy, 2016).

3.4.1 Selection of Behaviour Change Case Studies

For the purposes of this deliverable, a number of case studies of behavioural interventions are chosen to provide insights into how particular technologies can be used to support energy system actors and target areas where behaviour is most pliable. Additionally, the selection of the following case studies of behavioural interventions outline how diverse, and multiple, interventions can have different intended outcomes dependent upon the attitudes and behaviours targeted for change:

Information and awareness raising: often the most commonly used informational strategy. This can be applied generally or specifically about possible solutions to change unsustainable actions. Providing information serves to increase understanding where rationality may influence behaviours. Tailored information, however, is highly personalised and specific. If advice is followed, this approach can have substantial behavioural change impacts up to 2 years after (Abrahamse *et al.*, 2005; Abrahamse, Steg, Vlek, & Rothengatter, 2007);

Feedback systems: often applied to give information about energy consumption or savings, a widely used structural strategy. If these interventions are provided immediately after actions are undertaken, feedback has the most impact. Various types of feedback are identified including generic, continuous and comparative feedback (Abrahamse i, 2005, 2007);

Legal measures and sanctions e.g. congestion charge and plastic bag charges: structural strategies that influence the context or circumstances of behaviour such as not being able to drive through city centres and the development of congestion charges *e.g.,* London Congestion Charge or the charging for single-use plastic bags (Thomas, Poortinga, & Sautkina, 2016; Verplanken, 2011). These measures often apply a self-perception model of behaviour change whereby behaviours are changed directly and individuals infer differences in their attitudes predicated on new behaviours, therefore leading to more sustainable-oriented perspectives (Verplanken, 2011);

Community-based sustainability projects: taking a hybrid informational and structural strategy approach, community-based sustainability projects can take various forms with local residents governing the direction of initiatives and the activities undertaken (Heiskanen, Jalas, Rinkinen, & Tainio, 2015; Heiskanen, Johnson, Robinson, Vadovics, & Saastamoinen, 2010). Often incorporating various behavioural and technical interventions such as peer-to-peer exchanges, information and feedback, as well as activism and events, community-based projects draw upon collective action to address the barriers of individual actions and facilitate low-carbon sustainable lifestyles at the community level (Axon, 2017);

Personal Carbon Allowances (PCAs): a forward-looking yet un-utilised policy idea and structural strategy which could provide national and international frameworks for delivering emissions reductions over the mid-to-long term (Fawcett & Parag, 2010). The impact that PCAs could have are significant with a PCA policy including household energy use and personal travel (yet excluding international aviation) would cover an average of 45% of national CO_2-eq emissions in major developed countries (Fawcett & Parag, 2010). Thus, the role that PCAs could play in targeting energy-related behaviours is substantial. Each intervention is discussed in more depth in Section 5, outlining how the intervention is applied, its main objectives, and an evaluation of its successes and failures to date in activating energy stakeholders.

4 Profile of Selected Technological Interventions

4.1 *Pre-payment meters (PPMs)*

4.1.1 Overview of Intervention - Pre-payment Meters

Pre-payment meters (PPMs) are sometimes framed and presented as a useful budgeting tool that could encourage energy conservation (Boardman & Fawcett, 2002; Faruqui *et al.*, 2010). PPMs are a type of energy meter installed in domestic properties, where energy is paid for upfront. Typically, pre-payment meters have a 'pay as you go' tariff in which consumers pay for their energy before they use it – usually by adding money to a 'key' or by purchasing special tokens. These need to be then inserted into a slot in the meter, which credits the energy onto the meter for gas or electricity. The meter will then use the credit purchased until it runs out (Owen & Ward, 2010; UK Power, 2017). This also means if there is no credit in the meter, there is no energy supply to the home. PPMs operate as a distinct form of metering, with significant contrasts evident from the model where energy is paid for in arrears through a billing system. Pre-payment meters mean that consumers can pay for gas and electricity on a pay-as-you-go basis, paying for energy in advance rather than paying monthly or quarterly in arrears. Pre-pay meters can be topped-up at post offices and other shops, or online. This is assumed to enable consumers to manage their energy use and finances more closely than waiting for quarterly or monthly bills (Owen & Ward, 2010; UK Power, 2017; uSwitch, 2017a).

The main user interaction with this type of technology involves the action of purchasing energy credits using money or a key or token, which is then slotted into a meter. The meter boxes themselves are often located in peripheral locations within the house, *e.g.,* often found in corridors, utility rooms or external cupboards or porch areas. This physicality of the technology and its location does not suggest a user-friendly technical device. Furthermore, many consumers do not understand how much they are paying for each unit or for what appliances and so on as many do not have any user displays (Denton, 2015; Money Super Market, 2017; Vyas, 2014). Furthermore, PPM keys are exclusive to a particular meter and will not work with any other, and newer meters use smart cards rather than keys. The key benefit of these is that information about a consumer's tariff and energy consumption is saved onto the card, meaning that it will be easier to change tariff without a home visit by an engineer. To purchase credit for PPMs the consumers' need to take the key or smart card to an official outlet and once the key or card is topped up; it is inserted in it in the meter, which will top up with the amount of credit paid for. The meter displays how much credit is left; when this runs out it needs to topped up again with the key or card (Centre for Sustainable Energy (CSE), 2017b).

4.1.2 The Intervention Model - Pre-payment Meters

PPMs are particularly well established in countries such as Tasmania, South Africa and the UK, while their use remains rare in the USA and across many EU countries. The UK shows the greatest deployment of PPMs, with long established use going back to the 1980's. In contrast across Europe there is very low deployment. This is partly because of consumer protections in many European countries, includingan incompatibility with disconnection bans (also found in the USA); additionally, billing and debt management approaches differ across Europe and are not easily compatible with a pre-payment model. PPMs of varying forms are widely used across the globe with recorded use in over 50 countries. However, the subtle differences in their design have particular implications for the ways in which users engage with them. For example, while in England most pre-payment meters operate with the use of keys, tokens or smart card, in Northern Ireland PPMs are operated through a keypad meter without requiring anything being inserted into the machine. Thus, it does not create the problems associated with tokens and cards. The key difference is that most of Northern Ireland's pre-payment keypad meters come with customer display monitors that enable consumers greater ability to monitor and manage their energy consumption and available credit. In contrast, meters in England typically do not offer this utility (Owen & Ward, 2010). Elements of best practice can be gleaned from Northern Ireland where PPMs have had relatively positive social acceptance. By mid-2009, 30% (230,000) of all electricity customers were using a keypad pre-payment meter in Northern Ireland, with new connections being made at a rate of 2000 per month. The largest group of PPM customers – approximately 58% - were people on low incomes yet a significant yet smaller group of PPM customers – 32% - were from middle and higher incomes. The popularity of the system is largely attributed to the favourable tariffs, discounts, credit rates and range of top-up options and limiting the scope for self-disconnections. The Norther Ireland example of PPM uptake illustrates a positive social acceptance of the technology and a normalisation of PPM for utility payment (Owen & Ward, 2010, p15-16).

The concept of PPMs are considered to be able to make energy (otherwise invisible) more visible in energy consumption practices (Burgess & Nye, 2008) in contrast to standard meters. They offer the potential for more upfront control over the amount being spent on energy without debts being accrued (Doble & Bullard, 2008). However, O'Sullivan, Howden-Chapman, & Fougere (2011) and Vyas (2014), argue that the use of pre-payment metering to pay for electricity actively disadvantages those on low-incomes and the elderly, and that because of these limitations PPMs are not a suitable policy instrument to address fuel poverty. On the one hand, a pre-payment meter could help a customer to budget their energy use. However, on the other hand, the metering model can also be one of the most expensive ways to pay for gas and electricity due to the higher associated tariff rates.

There are variable figures in relation to how many PPMs are in use. It is reported that there may be approximately six million PPMs in households across the UK (Money Super Market, 2017). Citizens Advice Bureau reports around 16 per cent of energy customers use PPMs – equivalent to households with a combined population of ~ 10.8 million people. The number of PPM users is also on the rise. There was an increase of PPMs installed for reasons other than debt recovery in 2012. This potentially reflects customers seeking greater control over their bills as household budgets tighten, although the installation of the majority of new PPMs remains largely driven by debt recovery arrangements' (Vyas, 2014, p6). Pre-payment customers often pay more for each unit of energy than standard customers do. Additionally, they do not normally have access to the best deals (Boardman & Fawcett, 2002; Money Super Market, 2017). According to Citizens Advice, people on PPMs typically pay around £80 per annum more than direct debit customers for their energy (Vyas, 2014).There is usually a fee attached to installing or removing a PPM. Energy suppliers typically charge to install or remove pre-payment meters, as they do not want to pay for an engineer's visit, and sometimes remove them free of charge at their discretion. Thus, there can often be huge charging disparities (Boardman & Fawcett, 2002; O'Sullivan *et al.*, 2011; UK Power, 2017). According to Ofgem's social monitoring statistics from 2012, the majority of new PPMs were installed to manage debt and the overall increase in PPM installations was largely driven by the increase in customers entering debt repayment arrangements (Miller, 2015). Ofgem reports that not all pre-payment customers are financially vulnerable. However, pre-payment customers are disproportionately on low incomes with more than 60% of pre-payment meters installed due to debt (Miller, 2015). Pre-payment customers also have very low switching rates from pre-payment to credit tariff models (Miller, 2015).

4.1.3 Evaluation of Intervention - Pre-payment Meters

This technological intervention targets the individual context of energy consumption behaviour. PPMs are designed to help consumers manage their energy usage overtime, ostensibly with the advantage of helping users to remain debt free. However, there remains debate on the effectiveness of this tool

(Barnes & McKnight, 2014; Darby, 2012) and the considerably higher rates which PPM users pay for gas and electricity raise important social justice issues. In particular, there are real concerns that PPMs disproportionately disadvantage those already vulnerable in society (i.e. low-income, long-term ill and elderly) (Boardman & Fawcett, 2002; O'Sullivan *et al.*, 2011; Vyas, 2014). There is a call to remove some of the disadvantages of PPMs to those already vulnerable in communities by removing specific barriers. This may mean PPM consumers need to be able to benefit from the substantial savings available for switching to the cheapest direct debit tariffs and not incur charges for installing and removing PPMs once debts are repaid and the use of security deposits removed (NEA, 2015; O'Sullivan, Howden-Chapman, & Fougere, 2011; Vyas, 2014).

Table 3: SWOT Analysis for Pre-Pay Meters

Strengths	Weaknesses	Opportunities	Threats
Ostensibly enables control of the amount spent on energy – helps people on low incomes to budget (on a very short-term basis).	Price of energy tends to be more expensive compared to credit meters; Coercive aspects of disadvantaging low-income households with higher utility tariffs.	Potential to be combined with smart meter technology *e.g.*, Free low credit alerts – a text or alarm on the smart energy display to warn when credit is low	Smart meter PPM technology provides considerable control to the energy suppliers
Customers spared shock of unexpected bills	With pay-as-you-go basis more likely to pay more over the winter months	Offer more competitive, affordable and flexible pay as you go tariffs.	Self-disconnection is the most visible indication of a market that is failing some consumers
It is possible to switch either to a different pre-payment tariff or to a credit meter	There is a fee attached to a switch from PPM to credit meter	It may be feasible to top-up via a phone app	PPM customers will also contribute to the cost of smart deployment through increased energy bills over the whole rollout period
	Need to be constantly vigilant about available credit, and ensuring there is always an emergency reserve.		
	Inconvenience of making trips to the shop for top-up. Potential for being left without electricity in the middle of the night if the closest payment outlet is closed.		
	Impractical for those with medical issues, or mobility problems that limit their ability to access the pre-Payment meter or travel out of the home to obtain top-up		
	Users are less likely to achieve the same energy savings as those customers using other payment methods		

PPMs can make energy (otherwise invisible) more visible in energy consumption practices than standard meters. They offer the potential for more upfront control over the amount being spent on energy without debts being accrued (Burgess & Nye, 2008; Doble & Bullard, 2008). While a pre-payment meter could help a customer budget their energy use, however, it can also be one of the most expensive ways to pay for gas and electricity due to the higher associated tariff rates. In Ireland, Electric Ireland offer €175 of free credit for switching to their 'Smarter Pay As You Go' tariff, as well as free meter and installation. However, it is unclear how the ongoing rates for pre-payment meters compare to their credit tariffs (Electric Ireland, 2017). Similar to Smart Meters, pre-payment holds the potential to stimulate awareness of energy usage and should make everyday energy consumption more visible and trigger people to manage its use. PPMs will require little physical interaction – apart from the action of keeping an eye on the monitor – yet much rests on reactive individual behaviour change to deliver energy savings (Darby, 2012; POST, 2014). The main behaviour change requirement is that users have to vigilantly self-monitor their energy consumption so that they do not run out of credit. There is some evidence that suggests that use of PPMs can result in energy use reduction it is unclear which factors contribute to this (Doble & Bullard, 2008). The design of the technology does not allow users to see which activities use the most energy nor how different households use energy. Existing research on home energy monitors serve to highlight that while energy consumption can be reduced through such systems it is difficult to sustain energy savings in the long term (*e.g.,* Darby, 2006; van Dam *et al.*, 2010).

Furthermore, unlike smart meters and home energy monitors, PPMs do not typically come with some form of portable monitoring device. Consequently, the technology does not really offer the same scope for monitoring and feedback, particularly in terms of knowledge of when energy is being used most and on what activities. Feedback potential is therefore very limited, apart from the ability to monitor monetarily how much is left on the meter. As a result, this technology offers little scope for behaviour changes within existing energy practices.

4.2 Insulation of Homes

4.2.1 Overview of Intervention- Insulation

To reach EU 2020 efficiency targets, retrofits will need to double from about one percent of existing stock today to between two and three percent (Torregrossa, 2015). Further to this, The Global Alliance for Buildings and Construction reports that current renovation rates generally amount to 1% or less of the existing building stock each year. To achieve the 100% net zero carbon by 2050 goal, renovation rates must increase to 3% per year if we start in 2017, or higher if we start later (Laski & Victoria Burrows, 2017). The World Green Building Council forward that Carbon is the ultimate metric to track for projects in the built environment, particularly in view of the goals of the Paris agreement (Laski & Victoria Burrows, 2017). The following measures are forwarded (Global Alliance for Buildings and Constuction, 2016):

- Renovation rates in industrialised countries to reach 2% on average of the existing stock by 2025 and 3% by 2040 - typically with energy efficiency improvements in the order of 10% to 15%.
- The introduction of energy control can achieve up to 30% energy savings of the controlled energy (mainly lighting, heating and cooling) and is a quick win solution
- Developing energy management practices with a target of energy reduction [2% to 3%] per year [or 20% to 30% by 2025], with the aim to cover 80% of large real estate by 2025.

It is estimated that there are 25 billion m^2 of useful floor space in the EU27, Switzerland and Norway. Half of the total estimated floor space is located in the North & West region of Europe while the remaining 36% and 14% are contained in the South and Central & East regions, respectively (Economidou *et al.*, 2011). Annual growth rates in the residential sector are around 1% while most countries encountered a decrease in the rate of new build in the recent years, reflecting the impact of the current financial crisis on the construction sector (Economidou *et al.,* 2011).

Table 4: National Values of Kg Co_2 per Floor Space[3]

Member States included in analysis	% Residential - Single Family homes	~ Space m^2	% Residential - Apartments	Space m^2	% pre-1960	% 1961-90	% 1991 - 2010	CO_2 per useful floor space: *Kg CO_2 / m^2*
Ireland	89%	41	11%	36	35%	25%	40%	125
Italy	72%	50	18%	31	40%	52%	8%	42
UK	88%	41	12%	36	55%	22%	13%	65
France	68%	41	32%	36	45%	35%	20%	25
Spain	34%	50	66%	31	32%	40%	28%	30

The average specific CO_2-eq emissions level in Europe is 54 $kgCO_2$ /m^2 where the national values of $kgCO_2$ per floor space vary in the range from 5-120 $kgCO_2$ /m^2. The building performance is a key component in this. In addition, CO_2-eq emissions are linked to the particular energy mix used in buildings in a given country (Economidou *et al.,* 2011). The extent to which renewable energy is employed in the buildings, the use of district heating and co-generation, the sources of electricity production in each country affect the CO_2-eq emissions related to buildings. Variations in the energy supply mix highly influence the CO_2-eq performance of buildings where, for instance, Norway and France are among the lowest in Europe due to their dependence on hydroelectricity and nuclear energy, respectively (Economidou et al., 2011).

Insulating a building through its walls, floors, windows, ceilings and roof is a commonly adopted measure and considered one of the most cost-effective means of achieving energy efficiency (EST, 2011; Roberts, 2008). Insulation is an important energy efficiency measure as it prevents heat loss from a building's fabric or envelope, and most heat is typically lost through the walls and roof of uninsulated homes. Building fabric or envelope measures include wall insulation (for cavity or solid walls – insulated internally or externally), roof, loft or upper storey ceiling insulation, basement ceiling, window/door draught proofing, and others (Energy Saving Trust (EST), 2011; Roberts, 2008).

4.2.2 The Intervention Model – Insulation

While the Energy Performance of Buildings Directive (EPDB) has been a key catalyst for improving building energy efficiency across EU Member States, there remains concern that progress is in this area remains relatively slow (Lechtenbohmer & Schuring, 2011). Large scale building renovation has been hard to trigger; and present standards are mainly focused on new buildings and there are numerous technical, functional and economic constraints on the existing building stock (Ferreira & Almeida, 2015). For example, in Germany, current refurbishment rates are rather low: the annual refurbishment rate for building façade insulation was roughly 0.8% between 2005 and 2008, and the annual rate of roof insulation 1.3% (Diefenbach *et al.* 2010 in Weiss *et al.*, 2012, p.405). The situation across the EU is not significantly better when compared to Germany, with average renovation rates of about 1.2% (Weiss *et al.*, 2012). The situation in the UK and the Netherlands reflects a similar picture (Meijer, Itard, & Sunikka-Blank, 2009; Weiss *et al.*, 2012). In most countries in Western Europe in 2017, the existing building stock is the main focus for building insulation interventions. Existing buildings are the largest component of the building stock and new build replacements tend to be nominal (Lechtenbohmer & Schuring, 2011; Meijer *et al.*, 2009); this is particularly the case post-2008, when the impact of the

[3] After (Economidou *et al.*, 2011)

financial crisis on the construction sector is considered, particularly in countries such as Spain and Ireland. In the UK turnover of the housing stock is very low at about 1% a year (Ravetz, 2008).

Progress in terms of implementation of insulation across Europe reflects trends in refurbishment rates in general and can be described as variable and reflective of the local specificities of each country's existing building stock. The UK and France have a large historic building stock with brickwork facades for which the selection of external insulation will not only be expensive, but such interventions will also be objectionable on the grounds of amenity (Meijer *et al.*, 2009; Ravetz, 2008; Weiss *et al.*, 2012). Furthermore, France is reported to have a high percentage of solid wall construction buildings (up to 90%). In contrast, in the UK the percentage of solid wall construction totals around 30% of buildings; and only 4% of the Dutch dwelling stock has solid walls (Meijer *et al.*, 2009). Meijer *et al.* (2009) report that cavity walls are insulated more frequently than solid walls in their survey of the European building stock in 8 countries (Austria, Finland, France, Germany, The Netherlands, Sweden, Switzerland, the UK).

The cost of installation, savings and payback outcomes are difficult to specify. Costs typically vary significantly depending on the type of building and on the level of work required. Further, variations will exist between terraced houses and semi-detached house and so on, which may have varying levels of insulation needs (Ravetz, 2008; Roberts, 2008). According to a UK study by the Energy Saving Trust, finding the investment capital for insulation represents a challenge for many householders. The costs of insulation can vary between differing insulation measures and housing types and sizes. In consideration of the various insulation measures, cavity and/or loft insulation measures are perceived to be a low-cost and the least complicated insulation measure which may cost under approximately €570[4] for each type (Energy Saving Trust (EST), 2011). In contrast, the unsubsidised cost of solid wall insulation (internal or external wall insulation) would cost approximately from €11,000 to €29,500or more and costs may vary significantly depending on level of work required and on the nature of the house, i.e. whether it is semi-detached, detached, flat, *etc.* (Energy Saving Trust (EST), 2017b). Table 5 illustrates indicative costs associated with different types of building fabric insulation measures (excluding windows), provide in £ sterling (original data) and converted to € equivalents. The estimated figures are based on insulating a gas-heated home and are based on fuel prices as of April 2017.

Table 5: Estimated Costs of 6 Common Insulating Measures For Homes[5]

Intervention	Typical installation Costs (approximates)	Annual Fuel bill savings (£/year) & € equivalent /year approx.
Draught proofing windows/doors	£50 €57	N/A
Roof and Loft insulation	£285 – £395 €227 - €449	£195 – 240 €222 - €272
Cavity insulation	£33 – £720 €38 - €818	£70 – £250 €80 - €284
External wall insulation	£9,000 – £26,000 €10,227 - €29,545	£150 – £460 €170 - €523
Internal wall insulation	£4,000 – £16,000 €4,546 - €18,185	£150 – £460 €170 - €523
Floor insulation	£950 – £2,200 €1080 - €2,500	£40 €45

[4] Based on an assumed exchange rate of €1.14 per stg£1
[5] After EST (2017b)

A study of typical family houses in Germany estimated that three measures in particular could make a significant impact in reducing primary energy demand and GHG emissions. These were the insulation of façade walls, insulation of the roof, and deployment of renewable heating systems. Results suggest that even without changes to existing heating systems, insulation of the building envelope alone could significantly reducing the primary energy requirement (20% reduction) (Weiss *et al.*, 2012).

4.2.3 Evaluation of Intervention – Insulation

Installing insulation is a key intervention that could significantly reduce CO_2-eq emissions in the residential sector and represents one way to use technology to reduce energy demand. While increasing and embedding building insulation across the EU has been successful to a degree, progress has been too slow, particularly in light of the savings potentials present in the built environment and in the context of the dramatic emissions reductions which are required in the coming 20-30 years. Current policy instruments are characterised by a predominantly 'soft law, voluntarist and incentivising approach'; confounded by the unique barriers that relate to the construction of existing older building stock (Boardman, 2007; Murphy, Meijer, & Visscher, 2012). Consequently, policy instruments for improving energy efficiency across many European countries (*e.g.,* Germany, Netherlands, UK) are too weak to deliver the required long terms energy saving to buildings (Boardman, 2007; Murphy, Meijer, & Visscher, 2012; Weiss *et al.*, 2012).

Table 6: SWOT Analysis for Building Fabric Insulation Measures

Strengths	Weaknesses	Opportunities	Threats
A range of low cost and high cost insulation options are widely available on the market	Some measures are more popular that others	Many government incentives available *e.g.,* through ECO funding target those on low incomes and hard to treat homes	Adoption of insulation is not happening at the rate and scale needed to meet government environmental goals
	Increased risks of condensation needs to be addressed alongside higher insulation of building		Households may refurbish their homes building aspects but fail to improve or up-date the existing insulation or thermal efficiency of their home.
	Poor levels of wall insulation installation *e.g.,* solid insulation is technically a complex task		Households often forget ventilation is not implemented
			Insulation materials have a lifecycle, after which they need to be replaced or improved. *E.g.,* Loft insulation is effective for at least 40 years

The inert nature of these technological measures means that insulation does not require any form of user operation requirement. Insulation can be classified as a passive measure involving the building fabric in contrast to active measures such as heating systems, which require some form of active engagement with controls in operation and to gain its full benefits (Doble & Bullard, 2008). One of the key benefits for the user of insulation is that they are able to attain greater and improved thermal comfort from a once-off 'fit-and-forget' intervention. This type of intervention does not necessarily require the user to change everyday energy practices or lifestyle. There is also no active operational energy input required from using this measure (POST (Parliamentary Office of Science and Technology), 2012, p4).

While greater insulation of the home should mean using less energy, optimisation of energy gains nevertheless still require some form of energy management of energy practices, i.e. not leaving windows open while heating may be on or turning off when no longer required, turning off radiators in unoccupied rooms *etc.* This means that consumers will still need to actively manage their everyday energy practices in order to avoid the rebound effect (Energy Saving Trust (EST), 2011; Which?, 2013). This represents one of the key challenges for the occupants, post-installation of insulation. For example, it is estimated by OFGEM that "15% of the energy saved by insulation is "taken back" by improved comfort in the form of higher temperatures" (POST (Parliamentary Office of Science and Technology), 2012, p4). A number of studies have reported that insulating as part of a bundle of measures (energy advice, information and feedback interventions) for behavioural changes such as turning lights off, *etc.*, could help to further increase the energy saving potential of insulation (Carroll & Berger, 2008; Department of Energy & Climate Change (DECC), 2012; Relish, 2010).

4.3 LED (Light Emitting Diodes) Lightbulbs

4.3.1 Overview of Intervention – LEDs

Currently, more than 33 billion lamps operate worldwide, consuming more than 2650 TWh of energy annually, which is 19% of the global electricity consumption. This accounts for emissions of almost 1900 million tonnes Mt of CO_2 (De Almeida, Santos, Paolo, & Quicheron, 2014 p31). Lighting use is a slightly smaller fraction in the European Union where it represents 14% of electricity consumption (EIA, 2006 cited in De Almeida, Santos, Paolo, & Quicheron, 2014, p.30). Energy consumption from lighting is reported to be decreasing as a result of prohibitive EU policies, and in particular the prohibition of conventional lightbulbs and the move towards greater use of energy efficient lightbulbs such as LEDs (De Almeida *et al.*, 2014; Jagerbrand, 2015).

According to the Energy Saving Trust, lighting is one of the highest energy consuming appliance groups in households, after refrigeration (Energy Saving Trust (EST), 2017a). Research for the EST has shown that in a typical UK home, fixed lighting alone accounts for approximately 15% of all electricity use (this amount rises significantly if plug in lighting is also included) (P. Owen, 2012). Reducing energy consumption via replacement and installation of energy efficient lighting, particularly LED lightbulbs, is considered to be one of the easiest and most cost-effective one-off purchase interventions. Gardner and Stern (2008) highlight that using energy saving lightbulbs could yield potential savings of approximately 4% – out of a total of 16.7% achievable potential savings through behavioural changes (Gardner and Stern, 2008).

LED lightbulbs are now more efficient than CFLs (Compact Fluorescent Lights) and traditional incandescent lightbulbs (considered the least energy efficient). LED lightbulb technology works by using "an electrical current which passes across semiconductor material (usually silicon), and as electrons migrate between charged atoms in the semiconductor, photons of light are released" (Energy Saving Trust (EST), 2016, p12). In comparison to traditional incandescent light bulbs (which provide approx. 12 lumens per watt and a life of ~1,000 hours) LED lightbulbs offer an output exceeding 100 lumens per watt and potentially 35,000 hours of use or more (Energy Saving Trust (EST), 2016). Prior to the proliferation of LED's, Compact Fluorescent Lamps (CFLs) and Halogen Incandescent lamps initially offered the main alternatives to traditional tungsten incandescent bulbs (Energy Saving Trust (EST), 2016).

4.3.2 The Intervention Model – LEDs

The need for energy efficient lighting is a long and well established EU policy driver. Thus, many lighting products are subject to EU energy labelling and Ecodesign requirements. In particular the proliferation of energy efficient lighting has been assisted by the establishment of an energy efficiency rating scale for lightbulbs (from A to G) in 1998, similar to the ones already in place for other electrical appliances i.e. washing machines and refrigerators. The rating system ranges from A++ (the most efficient) to E (the least efficient) (European Commission (EC), 2017b). Additionally, the establishment of LEDs has been aided by decisions to phase out the least efficient lightbulbs, i.e. to phase out tungsten incandescent lamps and most halogen lamps including proposals to phase out the majority of D rated halogen lamps by 2018 (Energy Saving Trust (EST), 2016; European Commission (EC), 2017b).

Thus, the increasing proliferation of LEDs comes as a result of a number of policy drivers since 1998 that have contributed to stimulating their growth and adoption across new and existing homes (Energy Saving Trust (EST), 2016, p3). Table 7 shows how LEDs typically perform to an A star rated standard while the lowest ratings are associated with tungsten incandescent bulbs which are E rated or below.

Table 7: Lightbulb Energy efficiency Ratings[6]

Status	Energy Rating	Comparative Energy Use	Ranges for Lamp Types
New European ratings from 2013 for highly efficient lamps	A++	< 11%	LEDs
	A+	11–17%	LEDs; CFLs
	A	17–24%	LEDs; CFLs
	B	24–60%	CFLs; Halogens (incandescent)
	C	60–80%	Halogens (incandescent)
To be phased out from 2018	D	80–95%	Halogens (incandescent)
Products now being phased out	E	100%	Halogens (incandescent) ; Tungsten (incandescent)
These older European ratings now deleted. E & F rated lamps now phased out for everyday domestic use.	F	100–130%	Tungsten (incandescent)
	G	> 130%	Tungsten (incandescent)

According to the European Commission, the adoption of energy efficient lighting by households could mean that their electricity bills could fall by €25 per year. Additionally, the replacement of a halogen lamp with an LED lightbulb could save households up to €100 over the product's lifetime of around 20 years. Energy efficient lighting could collectively save enough energy to power 11 million households for one year and avoid the emission of 12 million tonnes of CO_2 in Europe (European Commission (EC), 2017b). The upfront cost of purchasing LED lamps has until relatively recently been a major barrier to wide-scale uptake and use. For homeowners, however, price reductions, coupled with greater

[6] Data sourced from (Energy Saving Trust (EST), 2016).

awareness of the other advantages of LED lighting has positively impacted on adoption levels. LED lighting is increasingly positively accepted by public as a viable and effective technology (De Almeida *et al.*, 2014; Jagerbrand, 2015). For LEDs, the initial upfront cost is relatively higher than for other lighting options; nevertheless overtime LEDs generate financial savings for homeowners because of their very low use of energy and long life (De Almeida *et al.*, 2014; (Energy Saving Trust (EST), 2016; Jagerbrand, 2015). The critical change since 2014 has been on affordability and good quality lamps are now available for under £6/€7 (in the UK) (Energy Saving Trust (EST), 2016).

4.3.3 Evaluation of Intervention - LEDs

Overall, LED technology is rapidly expanding and has been evolving over the last 10–15 years. LED lightbulbs do have a 'fit-and-forget' quality similar to insulation in so far as they require typically a one-off purchase as they rarely need to be replaced, and once installed do not require much behavioural operation apart from switching them on and off for use. Adopting LED lightbulbs by replacing older compact fluorescent lightbulbs (CFLs) and incandescent lightbulbs is considered an easy (technically) and affordable energy saving intervention. This can be undertaken as a one-off purchase and DIY action at any time. The predominant benefit from this action is that it can save money for the consumer by reducing their energy costs (EST, 2016, 2017a; Gardner & Stern, 2008).

Table 8: SWOT analysis for LED lightbulbs[7]

Strengths	Weaknesses	Opportunities	Threats
Considered the most efficient type of bulb, have great claimed longevity, give instant light, work in low temperatures	Quality varies, colour rendering isn't quite as good as old-fashioned bulbs, may need to update any dimmer switches to compatible models	LED prices have come down over the last few years and are increasingly becoming more affordable.	LED market is currently a self-regulated market, so a CE mark on the bulb does not necessarily mean that it has been through all of the required quality checks. The quality of LED bulbs can therefore vary.
Energy efficiency class A+: rated as 'energy efficient' under Part L1A of the Building Regulations	Higher purchase price (but prices falling rapidly)	LED lightbulbs together with motion sensor or smart monitoring could help reduce power wastage when not in use	
LEDs claim to be ultra-long lasting - lasting for 25-30 years, depending on which one you buy and how you use it.	Risk of glare as a result of small lamp size		
Long lamp life: 30,000 hours or more predicted for many products	Need for thermal management to avoid degradation in lifetime		
Minimal heat output and wide range of colour temperature 2,700-6,000K Good colour rendition available			

[7] Source: (De Almeida, Santos, Paolo, & Quicheron, 2014; EST, 2016, 2017a; Knight, 2017)

While purchasing action is required, a degree of efficient operating behaviour is required to maximise the benefit of this technology, i.e. turning off lights when not in use or more often. A degree of behavioural and lifestyle choices will be required as increased amenity could give rise to rebound effect rather than energy and carbon savings (Gardner & Stern, 2008; Roberts, 2008; WHICH?, 2013). The behavioural aspect is important to note. The effectiveness of LED lightbulbs could be further maximised through a number of accompanying habitual actions. For example: turning lights off when leaving a room regardless of how long for, being conscious of how many lights are on, whether they all need to be in use, arrange light switches so that its convenient to turn them off, i.e. by placing switches at the top and or bottom of stairs, each end of a hallway and by each door to a room, and finally the additional use of a sensor and timer on external lights so they are only in use when they need to be (EST, 2017; Knight, 2017).

4.4 Smart Meters

4.4.1 Overview of Intervention – Smart Meters

Smart meters record energy usage and seek to improve information availability to energy stakeholders through a two-way process to both consumer and energy suppliers. Smart Meters have the potential to enable energy savings, provide accurate billing, and reduce the cost of operating the electricity and gas networks (Barnes & McKnight, 2014; Darby, 2012). The smart meter is typically comprised of two components, usually a technical device that is attached in-situ, connected to the existing gas and electricity meter boxes, and secondly a (portable) smart energy monitor provided to the consumer to monitor their energy use. Smart meters enable accurate billing and real-time measurement of energy use by communicating this information through a wireless smart home energy monitor or in-home display unit (Barnes & McKnight, 2014; uSwitch, 2017b). The emphasis of this technology is on helping individual consumers manage their energy use. Although the meters themselves cannot directly reduce electricity consumption, smart meters can assist consumers to reduce their overall energy consumption (Barnes & McKnight, 2014; POST, 2014; uSwitch, 2017b).

Conventionally, gas and electricity meters are located in peripheral locations in the home or outside of it with no user accessibility or legibility of the energy usage figures that could be observed in the meters, and where consumers have had to physically record the numbers before relaying meter readings to the supplier by phone or digitally online. With new smart meters, once consumers have the smart meter installed into the existing systems, they will no longer need to take meter readings manually. This may mean paying greater attention to the home energy monitor and actively monitoring energy use via the monitors. It will provide the user with more real time information (feedback) on how they use their energy and even when they use it (Which?, 2017). This awareness of energy usage should make everyday energy consumption more visible and trigger people to better manage energy use. Smart Meters should require little physical interaction – apart from the action of keeping an eye on the monitor – yet much rests on reactive individual behaviour change to deliver energy savings (POST (Parliamentary Office of Science and Technology), 2014).

4.4.2 The Intervention Model – Smart Meters

In aggregate, 263858367 metering points are expected to be installed in the EU member states by 2020, with Expected Diffusion rate of ~72% for EU-27 rate by 2020. The total Number of Smart Metering Points to be installed up to 2020 is 195322543, for member states which data are available for (European Commission, 2014a). This represents the installation of about 195 million of smart meters by 2020 for electricity (ca. 72% of European consumers considering the EU-27) and an accumulated investment of €35 billion (European Commission, 2014a). The key driver for smart metering arises from

EU legislation. The EU seeks through its 'Third Energy Package' to replace 'at least 80% of electricity meters with smart meters by 2020 wherever it is cost-effective to do so (European Commission, 2017c). This smart metering and smart grids rollout could help reduce emissions in the EU by up to 9% and annual household energy consumption by similar amounts. By 2020, it is expected that almost 72% of European consumers will have a smart meter for electricity (European Commission, 2017c). The cost of installing a smart meter in the EU is on average between €200 and €250. Additionally, on average, smart meters provide savings of €160 for gas and €309 for electricity per metering point over the lifetime of the meter, as well as an average energy saving of 3% (European Commission, 2017c).

Nearly 45 million smart meters have already been installed in three member states, i.e. Finland, Italy and Sweden, representing 23% of envisaged installation in the EU by 2020. Uniquely, Italy was one of the first countries to comprehensively roll out smart metering technology on a national level. Furthermore, Ireland, Italy, Luxembourg, the Netherlands and the UK have decided to roll-out smart meters by 2020 or before. There have been moves in countries outside of the EU such as Norway where steps towards large-scale deployment of smart meters have been taken (European Commission, 2014b). Nevertheless, questions remains on whether each country's roll-out will incorporate the most future-proofed and high performing functionalities in smart meters, with the risk that the deployment of low cost equipment will limit the performance of the solutions installed (European Commission, 2014b).

It is clear that the business case for rolling out smart metering is not yet overwhelming throughout Europe, and poses a potential challenge in the case of gas particularly (European Commission (EC), 2014, p.3-4). Table 9 provides an overview of smart meter deployment for 5 EU case study countries.

Table 9: Smart Meter Overview, 5 EU Study Countries[8]

	UK	Ireland	Spain	France	Italy
Roll-out of smart-metering by 2020 status	Wide-scale (80% or more) roll-out of SM by 2020	Wide-scale (80% or more) roll-out of SM by 2020	Wide-scale (80% or more) roll-out of SM by 2020	Wide-scale (80% or more) roll-out of SM by 2020	Wide-scale (80% or more) roll-out of SM by 2020
Expected diffusion by 2020 status (%)	100	100	100	95	99
Metering points in the Country by 2020	31992000	2200000	27768258	35000000	36700000
Total Number of Smart Metering Points to be installed up to 2020	31832040 (99.5% diffusion)	2200000 (100% diffusion)	27768258 (100% diffusion)	33250000 (95% diffusion)	36333000 (99% diffusion)
Roll-out period start date	2012	2014	2011	2014	2001
Roll-out period end date	2020	2019	2018	2020	2011
Metering Market	Competitive	Regulated	Regulated	Regulated	Regulated
Deployment Strategy	Mandatory	Mandatory	Mandatory	Mandatory	Mandatory
Financing of roll-out	Suppliers	Network Tariffs	Network Tariffs + SM rental	NA	Network Tariffs + DSO resources

[8] Data sourced from (Joint Research Centre, 2017); (European Commission, 2014a).

	UK	Ireland	Spain	France	Italy
Responsible Party – implementation and ownership	Supplier	Distribution System Operators	Distribution System Operators	Distribution System Operators	Distribution System Operators
Responsible Party – access to metering data	Central Hub	Distribution System Operators	Distribution System Operators	Distribution System Operators	Distribution System Operators

Individual adoption of smart meters as a technological intervention is being supported via regulatory intervention, which currently suggests only a voluntary requirement. There are a number of costs and benefits associated with smart meter roll-out. There are no direct installation or purchase costs for smart meter individual household adopters, in the UK. It is a voluntary measure taken up by requesting it through an energy supplier free of charge. However, there are societal and macro-level costs of the roll out which are already covered in consumer energy bills in the same way that installation and maintenance of traditional meters are (uSwitch, 2017b).

Most trials and studies demonstrate relatively modest savings that can be made and none so far exceeds more than 20% savings mark (Barnes & McKnight, 2014). For example, studies on smart meters undertaken in the US and Norway, suggest the feedback from such systems can help save on average, about 10-15% (Darby, 2006). These results indicate the types of savings that could materialise but also are contingent upon a whole range of household factors that determine household/individual level energy consumption. Furthermore, direct feedback could be made more effective as long as it is used alongside a user friendly display, and given more frequently over a long period of time with some appliance specific breakdown, through clear and legible interactive tools (Darby, 2006; Fischer, 2008). It is this aspect that smart meters and their corresponding home energy monitors appear to tap into.

4.4.3 Evaluation of Intervention – Smart Meters

Smart meters provide feedback and information on energy consumption and help consumers to manage their energy usage overtime. Smart meter delivery processes appears to work on two broad conceptual levels. First, on a rational, economic level, smart meter interventions require high levels of consumer engagement. There is an assumption that smart meters displays, through providing better information to consumers, will make these consumers better informed resulting in behavioural changes and reduced energy use. Secondly, at a macro-level, the nationwide roll-out of smart meters seeks to produce a technological, systemic, cultural and infrastructural change in order to deliver on macro-level energy policy and industry goals (*e.g.,* achieving energy security). What is therefore evident is that smart meters are part of the effort to create a smart grid, which is part of a wider agenda for providing low-carbon, efficient and reliable energy to households. In particular, smart meters are increasingly linked to the development of smart homes combining smart technologies which hold the potential for increased energy saving solutions for homes (Chan, Estève, Escriba, & Campo, 2008; Risteska Stojkoska & Trivodaliev, 2017; Rokach, 2012).

Table 10: SWOT Analysis for Domestic Smart Meters[9]

Strengths	Weaknesses	Opportunities	Threats
Real-time data could mean energy savings and accurate billing	Requires active and daily vigilance with where and when energy used	The future is smart, and smart meters are part of the effort to create a smart grid, which is part of providing low-carbon, efficient and reliable energy	Smart meters may currently lose smart functionality When switching suppliers, meters may have to turn to "dumb" mode. Early

[9] Information sourced from: POST, 2014; uSwitch, 2017; WHICH?, 2017; Darby, 2012.

Strengths	Weaknesses	Opportunities	Threats
		to Britain's households.	adopters of smart meters may have a first generation meter (SMETS1) that is not compatible with all suppliers. In this case, you would have to revert to giving meter readings. This issue is set to be resolved by 2018.
Installation free of charge	The cost of the roll out is covered already in your energy bill All consumers are really paying for nation-wide roll out through the energy bills even those not adopting them	Reduces the cost of operating the electricity and gas networks	The distribution of roll-out benefits for different sectors and social groups, and that costs could rise
Faster and easier energy switching Because your usage data are so easily accessible, the aim is to make energy switching as quick as just a half hour.	Disputes about inaccurate data	Innovative energy tariffs Using the data collected on when and how households are using energy, suppliers can create more competitive time-of-use tariffs with cheaper prices for off-peak use	Increased volume of data from smart metering could present privacy and cyber security challenges
	The benefits of smart metering may be less accessible for vulnerable and low-income groups. This could be due to a lack of ability to change their patterns of energy use because of housing, work or health constraints	Smart meter programme represents infrastructural change to the energy system to help create a smart grid.	Public concerns about health effects Some campaign groups have raised concerns that being exposed to the electromagnetic fields (EMFs), which are produced by smart meters, could lead to health effects ranging from nausea to cancer
	Unauthorized access and cyber-attacks Smart meters and their data could be used illegally (POST, 2014)	Smart meters also offer additional possibilities for the future – such as improved 'time-of-day tariffs' offering cheaper rates at off-peak times to smooth out national energy usage through the day.	
	The location of your meter could be inaccessible If your meter is located in a place where signal may be an issue (*e.g.,* in the basement) your supplier's current generation of meter may be unable to achieve an appropriate signal to send information remotely to your supplier — in this case you won't	Potential to connect smart meters to microgeneration systems or for additional ones which connect all the energy systems in the home so generation and usage information can be combined into one home energy monitor unit	Some smart meters are not currently compatible with solar or microgeneration You may find that your supplier cannot offer you smart meters just yet as they are not able to work with solar or microgeneration.

Strengths	Weaknesses	Opportunities	Threats
	presently be offered one.		
	May not be suitable the UK adult population struggle with basic numeracy and literacy, engaging with concepts such as energy may be problematic and not result in the savings anticipated		

While there is a regulatory and nudge like approach to the adoption of smart meters similar to energy switching, it is not mandatory to do so therefore many people may simply choose not to adopt them (POST (Parliamentary Office of Science and Technology), 2012). For those who do voluntarily adopt smart meters, in-home monitors with displays offer feedback and an opportunity to manage habitual energy use. Thus, they act to provide real-time personalised feedback and serve to make the hidden nature of energy use more visible (Burgess & Nye, 2008). These technologies rely on the principle that individual users will act rationally to save energy if they know how much they are using and how much it costs at any given time, and ideally, it will encourage people to adopt energy conservation behaviours.

Existing research on home energy monitors highlight that while energy consumption can be reduced through such systems, it is difficult to sustain consistent levels of energy saving in the long term (*e.g.,* Darby, 2006; van Dam *et al.*, 2010). For example, one study of home energy displays in the Netherlands reports initial savings in electricity consumption of 7.8% after 4 months but these figures could not be sustained in the long-term, after the initial 4 month period. This problem was exacerbated by the fact that specific groups of people were more likely to respond to energy savings interventions than others (van Dam *et al.*, 2010). Furthermore, a Swedish case study suggests that the potential energy savings could not be fully reached, as there was not enough information provided by the smart meter that consumers could understand and take action from in relation to appliance energy consumption. In particular the study by Vassileva & Campillo (2016) highlights the need for users to be better informed and educated in understanding appliance energy consumption. Another study of home energy monitors suggests that the design and usability of these should be important considerations for their more effective use. Additionally, important factors for the effectiveness of displays include the type of information itself that is displayed, how it is displayed, the way the devices look and ease of use, and where the devices are situated or whether they are portable (van Dam *et al.*, 2010).

4.5 Solar PV

4.5.1 Overview of Intervention – Solar PV

There are currently two specific types of solar panel technology: solar photovoltaic (SPV) technology utilises the sun's energy for electricity generation using photovoltaic cells while solar thermal hot water technology uses the sun's energy for heating hot water only. Solar PV generates energy from sunlight via photovoltaic cells (Centre for Sustainable Energy (CSE), 2017a; Energy Saving Trust (EST), 2017c). Solar PV panels convert the energy in sunlight into electricity. Any, surplus electricity is automatically exported into the national grid. There are times when the sun is not shining adequately, or when more electricity is being used than is being produced by the panels, in which case the extra energy demand will be imported from the national grid. This will be charged via an energy supplier at the normal rate (Centre for Sustainable Energy, 2017a; Keirstead, 2007).

4.5.2 The Intervention Model - Solar PV

Solar energy has higher rates of adoption when compared to other micro-renewable technologies (Balcombe, Rigby, & Azapagic, 2013; Keirstead, 2007). The Renewable Energy Directive is one of the key policy drivers supporting the deployment of solar technologies as a form of renewable technology across the EU. It requires the EU to fulfil at least 20% of its total energy needs with renewables by 2020 which is to be met by Member states through individual national targets (European Environment Agency, 2016). The EU's increased generation of renewable energy, compared to the level of generation in 2005, has contributed to reducing demand for fossil fuels by 110 Mtoe in 2013 (equivalent to almost one tenth of all fossil fuels used across the EU (European Environment Agency, 2016, p11). In 2014, the EU-28 had the largest installed and connected solar PV capacity in the world (three times more than China) and the largest wind power capacity globally. The pace of development of these technologies has also picked up since 2010 in other parts of the world (European Environment Agency, 2016, p.13).

Across the EU, in 2013, the highest share of solar PV generated electricity was produced in Germany (38%); followed by Italy and Spain at a 27% and 10% share respectively. Member States with very large absolute capacity additions were Germany (1.9 GW) and France (1.0 GW). The largest relative capacity increase was in Poland (by a factor of 5.8), and Croatia, Cyprus, Malta, Sweden and the UK all saw increases of more than 80%. The considerable growth in solar PV electricity has been driven by rapid technological progress, cost reductions, and relatively short project development times (Ecofys, 2014 citied in European Environment Agency, 2016, p.31).

Table 11: European Solar PV Total Capacity Until 2016 For Selected Countries[10]

Member States included in analysis	2016 Total Capacity (MW)	Total Capacity Medium Scenario by 2021 (MW)	Compound Annual Growth Rate (%)	Total PV Capacity - % of total comprised of residential	Share Of Electricity Demand Covered By Solar 2016[11]
Ireland	17	3,233	187%	55%	0%
Italy	18,983	22,525	3%	20%	9%
UK	11,547	15,822	7%	15%	3%
France	7,134	15,229	16%	15%	2%
Spain	5,491	6,771	4%	5%	3.5%

According to Balcombe, Rigby & Azpagic (2013), while government support for microgeneration has helped to increase uptake especially of solar PV (through significant financial support including for example, through feed-in-tariffs to stimulate adoption of microgeneration energy technologies) consumer uptake remains low (Balcombe, Rigby, & Azapagic, 2013). The amount of solar PV being installed in the UK has fallen in the year 2016-2017 (Schmel *et al.,* 2017). This drop is attributed to government reduction of the tariff rates for householders and the ending of subsidies to commercial solar farms. In contrast, globally there has been a substantial growth in this sector worldwide, and particularly in the USA and China. Nevertheless, the widespread political recognition of the potentials of solar energy technology as a crucial tool for the world to meet its climate change commitments (*e.g.,*

[10] Data sourced from (Solar Power Europe, 2017)
[11] Share Of Electricity Demand Covered By Solar 2016, total for Europe = 4% (Solar Power Europe, 2017)

meet the Paris climate agreement targets) suggests that the solar industry that will continue to develop and expand (Schmel *et al.,* 2017).

The high upfront capital cost and long payback time is considered to be the main deterrent to adoption of solar PV (Balcombe *et al.*, 2013; Caird *et al.*, 2008). The cost of solar panels has reduced over time as the technology is improved. The average cost of solar panels and installation is between £6,000/€6,825 and £9,000/€10,240 (uSwitch, 2017c). Additionally, the Energy Saving Trust reported that the average domestic solar PV system is 4kWp and costs £5,000/€5,688 - £8,000/€9,100 (Energy Saving Trust (EST), 2017c). An online survey found that the most frequently cited barriers to installing microgeneration systems were all related to costs: capital costs (86%), long payback time (68%) and lack of grants (60%) (Caird & Roy, 2010). In principle, solar technology units are designed to be interconnected and compliment other existing systems within a building such as electricity or heating systems. Furthermore, lack of space for the physical location of the technology on the roof may deter some. In some cases lack of the correct orientation of roof or no adequate space on a roof means, some buildings are not suitable for this option. Often the inverter box is installed in out-of-the-way peripheral locations, (i.e. storage rooms, lofts, *etc.*), that can make them less accessible and therefore hinder users' ability to monitor their energy consumption (Aiesha, 2016). This is a barrier that can be overcome by installing an additional monitor in a more accessible and convenient location, and may also be linked to a personal computer, allowing users greater monitoring and feedback overtime (Centre for Sustainable Energy (CSE), 2017a).

4.5.3 Evaluation of Intervention - Solar PV

Solar technology encourages a high level of user-interaction with technology to generate energy and reduce demand. Solar PV can be viewed as a successful technological intervention due to its higher rates of adoption when compared to other microgeneration technologies. In terms of understanding the sociotechnical relationships of this technology, what is evident is that Solar PV needs to be accompanied by active user behavioural change – including energy saving practices - to deliver its full environmentally beneficial potential. However, like other energy efficiency technologies Solar PV also runs the risk of perpetuating existing energy intensive practices and/or no fundamental changes in energy consumption or even rebound effects.

Table 12: SWOT Analysis for Domestic Solar Technologies

Strengths	Weaknesses	Opportunities	Threats
Free and renewable source of energy	Requires appropriate roof orientation and can suffer from inconsistent electricity generation	Battery storage could extend potential for storing unused energy	Consumer level product batteries are still relatively expensive
Nominal user interactions required with technology – just feedback and monitoring	Remains unaffordable for some	Battery storage creates potential for decentralised energy system therefore no need to feed into the National Grid	Reduced Government tariff may act to de-incentivise
Takes little time to install when compared to for example internal wall insulation	In relation, solar thermal technology concerns are raised over the durability and reliability in terms of supply of hot water in relation to user demands.	Greatest potential as a decentralised and sustainable source of energy across the world, especially in communities that are off a centralised grid system.	Need for financial incentives and R&D for the development of the solar energy sector as a whole and should enable complimentary energy storage technologies.

	In some areas – *e.g.*, listed buildings or buildings in conservation areas - planning consent maybe required for installation and could serve to deter some from adopting.	Improved designs in the technology could allow it to be integrated into the roof or other part of a building, installed from inside a building or even ground mounted.	

Information on how to make the most of solar PV suggests a need to adapt everyday energy consumption practices and routines in order to gain the fullest of the associated benefits. For example, this could mean using a washing machine or dishwasher during the day rather than in the evening, where users may need to have a shower in the middle of the day rather than at night to utilise solar heated hot water (Centre for Sustainable Energy, 2017a; Keirstead, 2007).

Furthermore, in order to benefit fully from free energy generation, users need to become more aware of how much energy each individual appliance uses (Keirstead, 2007). In response, users may need to stagger the use of high-wattage appliances to make the most of the solar PV generated electricity available. This might mean waiting for a washing machine to finish before running the dishwasher for example (Centre for Sustainable Energy (CSE), 2017a). An inverter helps to convert the electricity generated by solar PV into a form that typical household appliance can use and its display can demonstrate to users how much electricity is being generated. Appropriate use of inverter and display technology can help with household solar PV electricity management (Centre for Sustainable Energy (CSE), 2017a; Energy Saving Trust (EST), 2017c). In terms of ease of use, Solar PV has a short installation time (can be done within a day) and once installed, solar panels can supply hot water or electricity straightaway and does not require much user interactions or operational actions with the technology itself. However, optimisation of the energy savings potential of the technology requires advanced management from the end users. This can be considered to be risk to proliferation and technology optimisation. Inverter displays may be considered user un-friendly, often due to design and accessibility (due to location) issues.

5 Profile of Selected Behavioural Interventions

5.1 Information Provision

5.1.1 Overview of Intervention - Information Provision

Providing individuals with information on a range of energy related issues including energy production, consumption and pricing provides increased awareness of aspects of energy that may directly impact upon local residents (Abrahamse *et al.*, 2005; Steg & Vlek, 2009). Information provision is defined as an antecedent method of behavioural change, that is, a method which changes the factors that precede behaviour (Steg & Vlek, 2009). More specifically, information provision is an example of a strategy that seeks to change perceptions, knowledge, norms and motivations (Steg & Vlek, 2009). Steg, Perlaviciute, & van der Werff (2015) identify a range of behavioural interventions aimed to encourage sustainable energy consumption and indicate that these will be more successful should they target important antecedents of behaviour, and remove significant barriers to change. Specifically, Steg *et al.* (2015) suggest that knowledge is essential for a sustainable energy transition insofar as people need to be aware of the need for, and possible ways to contribute to, a sustainable energy transition. However, the limitations of such approaches are increasingly recognised. It is often assumed that providing individuals with information will directly lead to behavioural changes (Jackson, 2005), however such approaches have been largely discredited as they rarely lead to sustained behavioural changes (Abrahamse, Steg, Vlek, & Rotherngatter, 2005; Abrahamse, Steg, Vlek, & Rothengatter, 2007).

5.1.2 The Intervention Model- Information Provision

In general, people are well aware of the problems related to household energy use, and are concerned about these problems (Abrahamse *et al.*, 2007). Yet knowledge of the causes and consequences of climate change, as well as the impact of human behaviour on climate change is not always accurate (Steg *et al.*, 2015). Indeed, there is still confusion about the processes that cause climate change, and only half of the public know that if today's greenhouse content in the atmosphere would be stabilised the climate would still warm for at least another 100 years (Steg *et al.*, 2015; Whitmarsh, Seyfang, & O'Neill, 2011). The general public have a limited understanding of the extent to which their behaviour contributes to climate change, for example, and only a limited number of people know that heating and cooling homes contribute to climate change (Bord, Connor, & Fisher, 2000). In addition, people have misperceptions regarding the relative contribution of different activities and generally identify the causes of climate change with distant activities such as industry rather than their own actions (Whitmarsh *et al.*, 2011). Information provision seeks to actively improve knowledge of these issues, particularly when it comes to basic science principles and addressing misperceptions of energy consumption and how it contributes to climate change (Steg & Vlek, 2009).

Information is a commonly used strategy to promote energy conservation behaviours. Providing information serves to increase households' awareness of energy problems and their knowledge about possibilities to reduce these problems (Abrahamse *et al.*, 2005). Information can be conveyed in several ways, through workshops, mass media campaigns and tailoring (such as through home audits). Workshops providing information about energy saving measures including providing information about energy conservation are shown to lead to higher levels of concern and knowledge about energy conservation, as well as stronger intentions to adopt energy-saving measures (Abrahamse *et al.*, 2005). Yet while information influences underlying determinants of energy use, it does not result in direct behavioural changes (Abrahamse *et al.*, 2005).

Abrahamse *et al.* (2005) review previous studies regarding the efficacy of mass media campaigns. They reported no observable difference in energy related behaviour between those participants, who had viewed a media campaign and those who had not. A campaign by the Dutch government aimed at communicating the nature and causes of climate change and the possible ways of dealing with it has revealed a slight increase in knowledge on some aspects but overall levels of awareness of the problem remained unchanged (Abrahamse *et al.*, 2005). Tailored information is highly personalised and specific information (Abrahamse *et al.*, 2005; Abrahamse *et al.*, 2007). An advantage of this approach is that participants receive relevant information only, rather than getting an overload of generic information which may not always apply to their household situation (Abrahamse *et al.*, 2005; Abrahamse *et al.*, 2007). Examples of tailoring in the realm of energy conservation are energy audits, consisting of a home visit by an auditor who gives households a range of energy-saving options (efficiency and curtailment belabours) based on their specific circumstances (Abrahamse *et al.*, 2005). Several studies have investigated the effect of home energy audits. In one study those who had received an energy audit used 21% less electricity compared to a control group whereas in a separate community, households had reduced their gas use by 4% following an initial audit 2 years prior (Abrahamse *et al.*, 2005).

5.1.3 Evaluation of Model- Information Provision

Information provision has proved to be a more effective when used in conjunction with other interventions (Abrahamse *et al.*, 2005). The effects of information seem to depend largely on its specificity (Abrahamse *et al.*, 2005). Mass media campaigns tend to result in an increase in attitudes or knowledge, but there is no clear evidence that this results in reductions of energy use (Abrahamse *et al.*, 2005). More personalised approaches such as tailoring would appear to be more effective. Home energy audits for example, using tailored energy advice has been proven to have positive effects on household energy use and on the extent to which efficiency actions were taken (Abrahamse *et al.*, 2005). Table 17 presents a SWOT analysis for information and awareness raising interventions.

Table 13: SWOT Analysis for Information Provision Interventions

Strengths	Weaknesses	Opportunities	Threats
Can be used to increase awareness and attitudes towards energy conservation	Generic information is often not relevant and does not lead to behavioural change	Used in conjunction with other methods, information can be a successful intervention	Used alone to increase knowledge will not lead to behavioural changes for energy use
Can be tailored to provide specific information, that could lead to behavioural change	If not applied in conjunction with other methods, this can lead to minimal changes in attitude or knowledge	Can raise awareness of energy policies and actions at a national level on energy consumption and climate change	Often assumed to lead to behavioural changes by policymakers and is widely used inappropriately
Can be used flexibly depending upon attitudes and knowledge	Often disregarded by individuals who already have confirmation bias	Can be used to build support for further sustainability projects	Poor understandings of application from policy backgrounds

5.2 Feedback

5.2.1 Overview of Intervention - Feedback

Generally people do not understand the impacts of their actions, particularly related to energy consumption and the impacts this has on climate change (Bord, Connor, & Fisher, 2000; Steg, Perlaviciute, & van der Werff, 2015). To address this uncertainty, feedback systems allow for people to better understand the impacts of their actions, whether for environmental or economic purposes (Abrahamse, Steg, Vlek, & Rotherngatter, 2005; Abrahamse, Steg, Vlek, & Rothengatter, 2007). Feedback systems may be defined as a consequence strategy aimed at changing the consequences following behaviour, in a similar ways to rewards and penalties (Steg & Vlek, 2009). While feedback systems can be used to gain an insight into an individual's behaviour, they are more broadly examples of a structural strategy to behavioural change whereby the circumstances are changed following behaviour so as to increase individual opportunities to act pro-environmentally and to make pro-environmental behaviour choices more attractive (Steg & Vlek, 2009). In this way, structural strategies may indirectly affect perceptions and motivational factors as well (Steg & Vlek, 2009).

5.2.2 The Intervention Model - Feedback

Feedback is often applied to promote energy conservation behaviours and consists of giving households information about their energy consumption, or energy savings (Abrahamse *et al.*, 2005; Abrahamse *et al.*, 2007). Feedback can influence behaviour because households can associate certain outcomes such as energy savings with their behaviour (Abrahamse *et al.*, 2005; Abrahamse *et al.*, 2007). Ideally, feedback should be provided immediately after the behaviour occurs, however this is not always possible. There are many forms of feedback: continuous; daily; weekly and monthly; and comparative feedback. Abrahamse *et al.* (2005) and Abrahamse *et al.* (2007) discuss these different types of consequence interventions in more detail illustrating their efficacy in changing behaviour.

Continuous feedback is provided to individuals over a prolonged period of time, and not on a singular or shorter term basis. Abrahamse *et al.* (2005) identify a number of studies that have been undertaken on continuous feedback and highlight that providing households with the monetary costs of electricity use of the course of 11 months allowed those households to use 12% less electricity than a control group. When combined with information, feedback is an effective approach. Other studies underpinned by action research have shown the differential effect of continuous versus monthly feedback on gas consumption by means of a feedback monitoring displaying daily gas use as well as daily target consumption (based on annual gas use), the latter serving as a conservation goal (Abrahamse *et al.*, 2005). In this study, those households who had received continuouse feedback saved more gas (12.3%) than those who had received monthly feedback (7.75%). However, lower users of gas actually increased their gas use during the intervention, and one year following the intervention gas use had increased for all groups, compared to baseline levels (Abrahamse *et al.*, 2005).

Feedback about individual performance relative to the performance of others may be helpful in reducing household energy use as well (Abrahamse *et al.*, 2005; Abrahamse *et al.*, 2007). By giving comparative feedback, a feeling of competition, social comparison, or social pressure may be evoked, which may be especially effective when important or relevant others are used as a reference group (Abrahamse *et al.*, 2005). Abrahamse *et al.* (2005) found that comparative feedback typically consisted of a comparison with consumption levels of households in similar settings, with individual feedback, monetary rewards and information also used as interventions. Yet only marginally significant differences emerged between the groups. For electricity use, households who had either received comparative feedback, individual feedback or rewards tended to save more than the control group, while for gas use households who had received either individual feedback or rewards tended to save most (Abrahamse *et al.*, 2005). Overall, comparative feedback was not more effective than individual feedback, and providing households with information alone was not effective at all (Abrahamse *et al.*, 2005).

5.2.3 Evaluation of Intervention - Feedback

Abrahamse *et al.* (2005) acknowledge that feedback appears to be an effective strategy for reducing household energy use, although some exceptions do exist. Results of the studies reviewed by Abrahamse *et al.* (2005) seem to suggest that the more frequent the feedback is given, the more effective it is. Positive effects have for instance been found for continuous feedback. However, high frequency is not necessarily the key to success: by giving feedback, evoking cognitive dissonance one single time, households significantly reduced energy use. It is not clear, however, whether it makes a difference to give feedback in terms of monetary rather than environmental costs since studies investigating this difference did not find any (Abrahamse *et al.*, 2005). Studies using comparative feedback did not find it to be more effective than individual feedback, yet combining comparative feedback with rewards in a contest setting proved to be successful.

Differences between socio-demographic groups have been found in studies of the efficacy of feedback, with income and current energy consumption levels correlating with energy use following the intervention, particularly where comparative feedback is employed. While high and medium energy consumers did reduce their consumption, low energy consumers actually increased their energy use as a result of feedback (Abrahamse *et al.*, 2005). The question remains whether it is right to expect those who consume little energy as a result of low incomes or energy poverty to reduce their energy consumption. This question should be one of the major components of the human factor of the energy system given that addressing energy poverty is becoming a rapidly significant issue (Simcock, Walker, & Day, 2016). This is an important finding from a policy and practice perspective, in the sense that policies aiming to reduce energy use may especially want to target high users of energy, because of a higher energy saving potential. Table 14 outlines the strengths, weaknesses, opportunities and threats that feedback systems have as a behavioural interventions.

Table 14: SWOT Analysis for Feedback Interventions

Strengths	Weaknesses	Opportunities	Threats
Various types of feedback can be employed in different contexts depending on outcome desired	Not suitable for low consumers of energy who actually increase their energy use following intervention	Substantive energy savings are possible if intervention targets high users of energy rather than low consumers	Often viewed as a time consuming intervention to employ and requires specialist technical knowledge to apply
A successful intervention that can have significant effects long after the intervention has been discontinued	Baseline energy consumptions levels are needed before intervention can commence	Has the potential to influence other behaviours i.e. spillover to other practices	If done incorrectly, the intervention could lead to an increase in energy consumption
Computerised feedback is more effective than feedback provided via paper-based methods	Some energy use may increase once intervention is stops depending on context	Numerous studies support its application as a successful intervention that changes behaviour	Its impacts are limited if used alone and not in conjunction with other interventions
Continuously providing feedback leads to greater results	General feedback is not sufficient as an intervention method	Can be used in conjunction with other interventions	

5.3 Legal Measures and Sanctions

5.3.1 Overview of Intervention - Legal Measures and Sanctions

It is often assumed that to change behaviours, underlying attitudes need to be addressed firstly, a view rooted in socio-psychological research (Ajzen, 1991; Jackson, 2005). Behavioural change can sometimes be effected without an explicit change in attitudes, through regulation or through economic instruments such as pricing, taxation and incentives (Heiskanen *et al.*, 2010; Owens & Driffill, 2008; Thomas *et al.,* 2016). Legal regulations can be implemented (*e.g.,* prohibiting the use of harmful propellants in spray cans) reflecting a structural strategy whereby contextual factors and consequences following behaviour are changed which may indirectly affect perceptions and motivational factors (Steg & Vlek, 2009). Legal measures and sanctions may be defined as being both an antecedent and consequences approach to change behaviour whereby such a method changes the factors that precede behaviour and can change the consequences following behaviour (Steg & Vlek, 2009; Verplanken, 2011). However, legal measures require that the relevant laws and regulations are enforced, and that violations are met with some type of punishment (Steg & Vlek, 2009). Carrico *et al.* (2011) state that regulatory and policy efforts are only beginning to direct substantial attention to the individual and household sector for behavioural change. In most cases, regulations and legal measures often aim to reward "good" behaviour or punish "bad" behaviour (Steg & Vlek, 2009).

5.3.2 The Intervention Model- Legal Measures and Sanctions

Heiskanen *et al.* (2010) suggest that regulations and incentives together with education and awareness raising are used almost exclusively in European societies with little success. Yet there are examples where regulations including legal measures and sanctions have worked to encourage sustainable energy behaviours and individual choices of sustainable alternatives for transport. In 2002, Ireland became the first country in the world to introduce a plastic bag levy, which led to a 90% drop in use of plastic bags, with one billion fewer bags used, and the generation of approximately €8.5 million for a green fund supporting environmental projects (Irish Environment, 2015). Wales became the first region of the UK to introduce a minimum charge for single-use carrier bags in October 2011 requiring all businesses to charge shoppers £0.05 (approx. €0.07) for each bag used (Thomas *et al.*, 2016). An alternative for shoppers is to purchase stronger carrier bags, which are designed to be re-used by shoppers when they go shopping. These re-usable bags are often marketed as "bags for life" which can be replaced for free once they worn out, and has so far proved to be a very effective intervention to reducing plastic bag consumption (Poortinga, Whitmarsh, & Suffolk, 2013; Thomas *et al.*, 2016). The number of single-use carrier bags distributed since 2010 has fallen by 81% with an associated decrease in plastic bags used per capita per month from 9.7 plastic bags in 2010 to 1.8 bags in 2012 (Thomas *et al.*, 2016). Yet while the primary aim of the regulation has led to a reduction in plastic bag usage there have been notable spill over effects, namely with an increase in recycling, using less resources and greater purchasing of sustainable items (Thomas *et al.*, 2016).

Other examples of legal measures and sanctions for environmental resource issues include congestion charges, the most notable being the London Congestion Charge and Stockholm congestion charge (Armelius & Hultkrantz, 2006; Eliasson, Hultkrantz, Nerhagen, & Rosqvist, 2009; Shove & Walker, 2010). For example, the London Congestion Charge introduced a charge of £5/€5.70 to be paid by people driving into a central charging zone on week days between 7am and 6.30pm. The scheme included a parallel programme of investment in public transport representing a highly visible and deliberate effort to reduce car use in the UK capital (Shove & Walker, 2010). The scheme was policed by a system of cameras and the charge has incrementally increased. The results show that within the first year of its introduction there was a 30% reduction of car use and an increase in cycling of 43% alongside a reduction of traffic pollutants (Shove & Walker, 2010). Research shows that 67% of inner Londoners made some change to their travel practices and patterns as did 36% of those who lived within the congestion charging zone (Shove & Walker, 2010).

The Stockholm congestion charging trial in 2006 demonstrated the effects of a full scale time-differentiated urban road toll scheme (Eliasson *et al.*, 2009). This was supplemented by an extension of public transport services and demonstrated how a congestion charge scheme works before a vote to establish a permanent scheme in a referendum was held (53% voted for keeping the toll) (Eliasson *et al.*, 2009). The aim of the toll was to reach a target reduction of car traffic of 10-15%. However, the scheme had the unexpected result of changing public opinion on road tolls in Stockholm by provoking a sea-change in favour of tolls (Armelius & Hultkrantz, 2006; Eliasson *et al.*, 2009). Charges were time-differentiated over the day and week, and the fee for passing a control point was SEK 10/€1, SEK 15/€1.50 or SEK 20 /€2, dependent on the time of day while London initially charged £5/€6 (later increasing to £8/€9.10) (Eliasson *et al.*, 2009). In addition, public transport services were extended by 7% and park-and-ride scheme capacity were increased by 29% in Stockholm. The trial of the congestion charge resulted in a 20-25% reduction in traffic within Stockholm, travel times fell by 32% and emissions from inner city traffic fell by 14% (Eliasson *et al.*, 2009).

These congestion charges are examples of governments forcing people to be 'green', if voluntary action is not working to address sustainability-related issues (Ockwell *et al.*, 2009). The introduction of these congestion charges has resulted in a dramatic reduction in vehicles in the city centre and an uptake of sustainable alternatives for mobility including the tube or bus (Ockwell *et al.*, 2009; Shove & Walker, 2010).

5.3.3 Evaluation of Intervention - Legal Measures and Sanctions

Individuals may have surprising responses towards legal measures and sanctions as interventions, that can support further sustainable energy behaviours (Steg, Perlaviciute, & van der Werff, 2015; Verplanken, 2011). One concept on attitude formation is self-perception theory (Bem, 1972) which proposes that people acquire knowledge about the type of person that they are, and thus insight into their attitudes by observing their own behaviour (Hogg & Vaughan, 2013). According to Bem (1972), attitudes are constructed from observing our own overt behaviours (i.e. the opinions we openly express with regard to particular attitude objects) and then attributing them to either internal or external causes, with internal attributions more likely to positively influence task performance when the behaviour was freely chosen (Hogg & Vaughan, 2013). Interpretation of an individual's attitude from behaviour is more feasible when a person has little or no existing knowledge regarding a particular issue or does not hold a strong attitude towards it (Hogg & Vaughan, 2013).

Bem (1972) argues that individuals analyse their own overt behaviours in a similar manner as they construct attributions to explain others' behaviour. In essence, the individual is functionally an 'outside observer' who relies on external (behaviour) cues to infer the individual's internal (attitudes) cues. Self-perception processes can also be constructed by simply imagining ourselves behaving in a particular way (Hogg & Vaughan, 2013). Imagery affects self-conception which in turn produces performance consistent with that particular self-conception. Self-attributions have substantial implications for motivations (Hogg & Vaughan, 2013). Self-perception theory predicts that an individual is induced to perform a task by either substantial rewards or severe penalties (Hogg & Vaughan, 2013). However, if minimal or no external factors such as financial incentives can be attributed to performance, it can be inferred that the task performed is intrinsically attributed and thus motivation increases (Bem, 1972; Hogg & Vaughan, 2013; Verplanken, 2011).

At one level, policymakers may think that the congestion charging scheme has made a difference and tangible consequences observable (Shove & Walker, 2010). It is also evident that intervention-in-effect is an unstable, dynamic and emergent outcome of the way in which constituent element of London life (cars, bikes, information systems, data, regulations, time, destination and attendant practices) fit together (Shove & Walker, 2010). Although many governments acknowledge the important role that consumers and citizens play in addressing climate change, governments are reluctant to regulate consumption due to a fear of political backlash and du to bureaucratic costs associated with new regulation (Ockwell, Whitmarsh, & O'Neil, 2009; Whitmarsh, Seyfang, & O'Neill, 2011). Where examples of regulation do exist such as the Irish plastic bag charge, the London congestion charge, environmental taxes across the EU, and the Stockholm road toll (Armelius & Hultkrantz, 2006; Ekins, 1999; Jägemann, Fürsch, Hagspiel, & Nagl, 2013; Shove & Walker, 2010; Thomas *et al.*, 2016; Verplanken, 2011), there is limited appetite to implement additional regulations on sustainability related behaviours.

People often engage with sustainable energy behaviours when the behaviour is extrinsically rewarding. Indeed, positive effects of financial incentives to promote sustainable behaviours disappeared as soon as the incentives were removed (Steg, Perlaviciute, & van der Werff, 2015). Thus incentives tend to have short-term effects only, as long as the reward is in place (Steg & Vlek, 2009). Yet these often are more acceptable to the public rather than using sanctions or punishing "bad" behaviour (Steg *et al.*, 2015; Steg & Vlek, 2009). External incentives could make unsustainable energy use more costly or less pleasurable, for example, by introducing taxes or laws and regulations; a key issue here is that such strategies often lack public support (Steg, Perlaviciute, & van der Werff, 2015). However, incentives that are aimed at changing contextual factors that define the costs and benefits of sustainable energy choices are sometimes necessary to facilitate sustainable energy choices (Steg *et al.*, 2015; Steg & Vlek, 2009). Additionally, if people engage in sustainable energy behaviour due to rules or regulations, rather than autonomous choice, the behaviour may have a weaker signalling value for prestige or identity effects and therefore be less likely to strengthen environmental self-identity and promote positive spill over (Evans *et al.*, 2013; Spence, Leygue, Bedwell, & O'Malley, 2014; Steg *et al.*, 2015; Thøgersen, 1999). Table 15 presents a SWOT analysis of legal measures and sanctions as an intervention for behavioural change.

Table 15: SWOT Analysis for Legal Measures and Sanctions Interventions

Strengths	Weaknesses	Opportunities	Threats
Top-down measure can lead to direct changes in behaviour	Some individuals may feel uncomfortable about the 'forcing factor'	Can be used in conjunction with other interventions	Political appetite to introduce regulations is lacking
When used in conjunction with other approaches, spillovers can result into other behaviours	Initial responses to regulations may be particularly negative before individuals view impacts of regulation	Other interventions can be used to direct funding into public services to support sustainable alternatives	Fear of political backlash and bureaucratic costs to regulate consumption of energy are major considerations for governments
Individuals can transition to greener perspectives and become motivated to take further actions	If incentives to act are removed, pro-environmental actions stop	Substantial benefits to multiple environmental targets and economic benefits to other sectors can result	Political party differences may scupper plans to regulate consumption *e.g.*, right vs left wing parties

Legal measures and sanctions can, and do, work to change behaviour and motivate sustainable energy behaviours. It has been shown that while public acceptance may be particularly sceptical towards regulations that in some ways "forces" individuals to change behaviour to consume less, however attitudes can be changed in time - where individuals infer a greener perspective towards their lifestyle with the potential for behavioural spill-overs (Steg *et al.*, 2015; Verplanken, 2011).

5.4 Community-Based Sustainability Projects

5.4.1 Overview of Intervention - Community-Based Sustainability Projects

There is a growing recognition of community action as a vital strategy in addressing climate change (Burch, 2010; Seyfang, 2010). Wiesenfeld and Sanchez (2002, p631) state that community participation to address environmental issues are most viable as the community "…is a level of …organisation that stands midway between the individual and society as a whole, wherein there is frequent interaction among the members and certain values, feelings, needs and resources are shared in a given space and time". Community-based sustainability projects offer a participatory approach to addressing climate change within a localised context, and can usually comprise of multiple interventions such as information provision, citizen panels, feedback and activism (Alexander, Hope, & Degg, 2007; Heiskanen *et al.*, 2010; Peters, Fudge, Hoffman, & High-Pippert, 2012).

5.4.2 The Intervention Model- Community-Based Sustainability Projects

Community-based sustainability projects do not follow one singular approach. They are dynamic and flexible given the requirements of the local community and the stated aims of the project in question. In this context, community-based projects are tailored to the needs of the community and reflect the values and actions that local residents wish to address. Consequently, community-based projects employ various informational and structural strategies to influence individual behaviours (Abrahamse *et al.*, 2005; Steg & Vlek, 2009). Community projects can be governed in many different ways, yet the most acceptable to local residents are those that are run by residents themselves, using their own skills to manage, fund, advertise and promote the activities of the project (Alexander *et al.*, 2007; Seyfang, 2010). This provides these residents with a degree of citizen control over their local transition that Arnstein (1969) identifies as citizen power, as opposed to a more superficial and common tokenistic participation.

The development of community participation varies according to context and time (Wiesenfeld and Sanchez, 2002); involvement is not static and can fluctuate. Therefore, community participation in sustainability projects is built on the nature of the initiative instigated, the stated goals to be achieved, access to resources such as funding and the political conditions that form a context conducive to participation (Alexander *et al.*, 2007). Future participation is affected by the quality of previous experiences and attitudes being favourable towards the project.

In order to facilitate and sustain participation in community-based projects a number of interventions can be applied. These may include but are not limited to: information provision, feedback, citizens panels, activism, events, incentives, local currencies, local food production, and decentralised energy systems (Abrahamse *et al.*, 2005; Alexander *et al.*, 2007; Heiskanen *et al.*, 2010). Indeed, these interventions can be applied creatively within different time periods of the project being established to facilitate meaningful engagement. Events and activities that are interactive and social in nature support involvement where individuals can observe other members of the community participating towards shared local priorities (Jackson, 2005). These events may be more formal in nature to meet particular aims of the project, for example citizen panels may be carried out to highlight democratic principles of the scheme (Alexander *et al.*, 2007). More informal activities such as carbon clinics, quiz nights and social gatherings reflect informational exchange and social aspects of community project (Heiskanen *et al.*, 2010). Combined, these interventions and activities can engage individuals cognitively, affectively and behaviourally with addressing climate change at the community level (Axon, 2017).

Local approaches should use a tailored "what works" model to effectively engage individuals in the local community. This ensures that the interventions applied and activities and events that are run reflect the interests and values of residents, while motivating them to take action. Axon (2017) indicates that interventions should be employed continuously, and suggests that these should address the enablers and barriers to sustainable lifestyles. For example, ideally, residents should be provided with information about a new project to increase knowledge while feedback should be provided to reinforce positive pro-environmental actions. These interventions generally conform to those that support sustainable living (Abrahamse, Steg, Vlek, & Rothengatter, 2007; Verplanken & Roy, 2016). It is important that interventions are applied in a "stepping up" manner, where interventions that require deeper engagement such as decentralised energy systems are not introduced without gradually building support for interventions that require substantial changes to behaviours and practices (Axon, 2017).

5.4.3 Evaluation of Intervention - Community-Based Sustainability Projects

Alexander *et al.* (2007), Charnock (2007) and Heiskanen *et al.* (2010) illustrate that = multiple environmental, economic and social advantages can be offered by community-based sustainability projects. The Ashton Hayes Going Carbon Neutral Project in Cheshire, England represents a case study of best practice in becoming the UK's first carbon neutral village (Alexander *et al.*, 2007). Its model has been applied in Norway and Australia. Since being established the project has reduced its emissions by 23% from a 2005 baseline, have supported local suppliers of low-carbon energy technologies supported local businesses, and the community has become more cohesive with equality of participation and benefits directly resulting from the project (Alexander *et al.*, 2007). Similar results can be found from similar community-based projects. ENTRUST Deliverable 4.4 indicates examples of other community initiatives that have implemented local projects to reduce whole community energy consumption (Morrissey *et al.* 2016). The Transition Towns Network is another example of a 'branded' form of sustainable community that replicates the values of permaculture to address issues of resilience within local communities (Seyfang & Haxeltine, 2012;Seyfang & Longhurst, 2013). This model has been replicated extensively across Europe.

Many behavioural change programmes can suffer from a conceptual problem: methodological individualism (Heiskanen *et al.*, 2010). Drawing on purely economic and psychological representations of behaviour fail to recognise the socially grounded nature of behaviour and such approaches appear insufficient to produce the significant shifts in behaviour required for addressing climate change (Heiskanen *et al.*, 2010; Jackson, 2005; Moloney *et al.*, 2010). Community-based projects present, at least, a partial solution to these problems of individual and collective behaviour change.

However, behavioural considerations need to be fully integrated with considerations of low-carbon technology, including the provision of critical infrastructure to enable transition. The capacity to which individuals and communities manage sustainability transitions and their efficacy differs considerably across time and space. Systematic changes across national and international scales may be required to support such transitions, particularly with reference to economic and political dimensions of sustainability (Burch, 2010; Jackson, 2005). Additionally, community projects are usually run by volunteers who can often face 'burn out', suffer from lack of funding and a lack of overall strategic direction that can substantially impact of the efficacy of community-based projects to deliver their overall aims and activities (Feola & Nunes, 2014).

While community-based sustainability projects can offer numerous environmental, economic and social benefits to local communities, there are difficulties in turning initial excitement to sustained participation (Alexander *et al.*, 2007). This has led to an emerging focus on how to meaningfully and effectively engage residents with community approaches (Whitmarsh *et al.*, 2013). A SWOT Analysis of community-based sustainability projects is shown in Table 16.

Table 16: SWOT Analysis of Community-Based Sustainability Projects

Strengths	Weaknesses	Opportunities	Threats
Can be comprised of multiple interventions to change behaviour at the local level	Infrastructural barriers can inhibit sustainability actions in areas where alternatives are not possible	Can overcome barriers to behavioural change such as methodological individualism	Lack of external funding for local projects can impact upon their efficacy and longevity
Are supported by local residents, receiving significant support and acceptability as an intervention for sustainability	Difficulty in turning initial excitement into sustained participation reflects wider scale threats and lack of continued support	Implementing a "what works" approach can allow for a diversified local economy and societal transition that meets climate targets	Changes at national and international scales to support local initiatives are not developed far enough to support local transitions
Community approaches can be tailored to the needs and values of residents	Local volunteers and residents can face 'burn out' and impact on strategic direction	Can engender wider support for sustainability and climate related actions	Political and economic priorities continue to be prioritised rather than sustainability
Can be environmentally, socially and economically beneficial for local communities	Lack of support (financial and involvement) can impact on success	Can promote wider societal and cultural change for sustainable lifestyles if scaled-up	Inconsistent implementation may result in scepticism of approach

The introduction of community-based sustainability projects across Europe has been disparate and uncoordinated given that the onus of establishing local initiatives lies with the creative energies of residents and local stakeholders. However, research suggests that should community-level initiatives be scaled-up worldwide, these would play a significant role in climate stabilisation efforts (Mulugetta, Jackson, & van der Horst, 2010). If concerted efforts to address climate change are to be made at the local level, community-based sustainability projects could become a viable solution that contributes a behavioural wedge as proposed by Dietz *et al.* (2009) for addressing climate change.

5.5 *Personal Carbon Allowances*

5.5.1 *Overview of Intervention - Personal Carbon Allowances*

Personal Carbon Allowances (PCAs) are examples of Personal Carbon Trading (PCT). PCAs are a radical policy idea which could provide a national and international framework for delivering emissions reductions over the mid-to-long term (Fawcett & Parag, 2010). PCAs are a general term used to describe a variety of downstream cap-and-trade policies, which locate rights and responsibilities for CO_2-eq emissions from household energy use and/or personal travel at the individual level. Such a policy could cover an average of 45% of national emissions of CO_2-eq emissions (Fawcett & Parag, 2010). PCAs are markedly different from other policies covering energy use and CO_2-eq emissions. To date policies addressing household energy have typically operated at a distance from individuals (*e.g.,* obligations on energy suppliers), do not require direct engagement (*e.g.,* minimum efficiency standards for products), and fail to communicate the significance of different decisions on personal emissions (Capstick & Lewis, 2010; Fawcett & Parag, 2010; Howell, 2012). Should PCAs be implemented as a means of reducing emissions at an individual level, they would constitute a highly personalised structural behavioural intervention (Lorenzoni *et al.,* 2007; Ockwell *et al.*, 2009).

5.5.2 *The Intervention Model - Personal Carbon Allowances*

PCAs are not envisaged as replacing most current policy on changing individual behaviour, but rather as an enabling policy which (strongly) encourages individuals to make the most of existing schemes such as product and building standards, energy labels, and taxation and financial incentives (Fawcett & Parag, 2010). Fawcett & Parag (2010) outline the model for PCAs as follows: a national cap is set for emissions from household energy use and personal travel, including air travel. Allowances are allocated periodically on an equal per capita basis to individuals for free to cover these emissions. For every purchase of electricity, gas, transport fuels and services, allowances are surrendered. Transactions are carried out electronically and allowances are tradable in the personal carbon market. Similarly, household carbon trading is a similar proposal that sets a yearly cap of CO_2-eq emissions for residential energy use based on emission reduction targets. Allowances would not include carbon embedded in products and services purchased by the individual, as this would be expected to be covered, very broadly, by other policies such as the EU Emissions Trading Scheme (EUETS) or other carbon cap and trade schemes (Parag & Strickland, 2010).

Howell (2012) presents findings from communities that have piloted PCA schemes. In the first year, it was reported that members of groups who lived with PCAs reduced their average per capita carbon footprint by 32%, from 4.95 tonnes to 3.36 tonnes of CO_2-eq (Howell, 2012). This average of 3.36 tonnes footprint is 35% below the UK average of 5.2 tonnes (2012 figures) for direct CO_2-eq emissions, excluding emissions from public transport, but including a multiplier of 3 for emissions from air travel. The average baseline was 5% below the UK average and studied communities were not significantly different from other members of the general public (Howell, 2012). In this study, Howell (2012) provides qualitative findings from interviewees outlining changes to their lifestyles. Results demonstrate that individuals describes specific changes such as not using supermarkets and instead using local food shops as well as other behavioural changes including turning down heating; turning lights off, cutting down or given up flying; installed double glazed windows and wood burning stoves. Howell (2012) suggests that motivated individuals can achieve carbon footprints that are significantly lower than national average baseline figures. Although barriers do exist (Parag & Eyre, 2010), Howell (2012) identifies that participants in the study suggested that there was a need for government grants and action to make some changes easier. This suggests that wider structural strategies (Steg & Vlek, 2009) are required to support the success of PCAs.

As a policy instrument, PCA schemes need to be mandatory to work, with no opt-outs. Additionally, allowances are tradable, enabling a market in allowances to deal with the different surrender requirements of above-average and below-average carbon consumers; allowances are reduced over time in line with national carbon reduction commitments (Fawcett & Parag, 2010; Parag & Strickland, 2010).

Technically, the measurement and deductions to allowances could be done by swiping a carbon credit card or entering a PIN (personal identification number) at the time of payment (Parag & Strickland, 2010). With the advancement of smart technologies, additional methods such as smart watches and smart phones may be employed to also act as PCA methods. Such technologies hold the possibility to be more interactive with users that go beyond the invisible mental accounting that behavioural economists associate with overspending finances on products and services not needed (Thaler & Sunstein, 2008). Consequently, PCAs provide a radical step-change to current methods of carbon reduction strategies for individuals through a more enforced approach (Ockwell *et al.*, 2009; Parag & Strickland, 2010). In this sense, PCAs are innovative and radical and in many senses challenges the way policymakers think about the role individuals should play in the climate mitigation effort (Parag & Strickland, 2010). If people emit more carbon than their allowance, they would need to buy additional carbon credits. On the other hand, those who emitted less carbon could sell the excess into the personal carbon market. The price of carbon would be set by the market and would reflect the shortage or excess of allowances (Parag & Strickland, 2010).

5.5.3 Evaluation of Intervention - Personal Carbon Allowances

Fawcett & Parag (2010) forward that a major weakness of the policies enacted by many European governments to encourage emissions reductions from individuals is the lack of an overarching approach for personal emissions reduction. An overarching approach would create a coherent perceptual and cognitive framework enabling individuals to integrate understanding across emissions from different activities, and in the contexts of energy use as it occurs. For example, such an approach would put into proportion savings gained by installing energy-efficient light bulbs and emissions that are saved by flying less. Significant emissions reduction of the carbon content of energy requires fundamental, expensive, and time-consuming infrastructural changes to the current energy system (Parag & Strickland, 2010). Until low-carbon energy is widely available, emissions reductions will need to also be achieved through reducing energy demand, which entails behavioural change. Fawcett & Parag (2010) argue that PCAs have the potential to deliver these, as arguably, the instrument empowers individuals and increases agency over their own personal CO_2-eq emissions. Furthermore, PCAs could act as an enabling policy, that is, as a policy that boosts the uptake of new low-carbon technologies and increases the implementation of other relevant, and already existing, policies. PCA schemes provide various motivations to behavioural change that operate through three basic interacting mechanisms, which broadly conform to three different methodological approaches to behaviour change: economic, psychological and social (Parag & Strickland, 2010).

There are a number of lessons that are important for PCAs. No scheme can be effective unless it can be enforced. It should be noted that this is a previously neglected area of research and that policy and practice should identify effective enforcement approaches predicated on the socio-demographic characteristics of communities and residents and what works best for individuals. This may reflect upstream, mainstream and downstream enforcement (Fawcett & Parag, 2010). However, other studies have posed the question whether now is the right time to implement PCAs as an instrument to effectively engage individuals with reducing their CO_2-eq emissions (Fawcett, 2012). PCAs had a moment in the UK political and policy limelight in 2007/2008, yet policy and media interest declined, while a slight growth in academic interest persisted (Fawcett, 2012). This presents clear implications for establishing an effective PCA policy, highlighting the need for strong political will and the risks for policy failure if political momentum behind the policy dissipates quickly. Table 13 on the following page presents a SWOT analysis of PCAs.

Table 17: SWOT Analysis for Personal Carbon Allowances

Strengths	Weaknesses	Opportunities	Threats
Allows individuals to reduce substantial amount of carbon footprint	PCAs are a largely unexplored field of research and practice-based understandings are limited.	Can provide a substantial reduction in carbon emissions in the domestic energy and personal transport sectors.	Policy measure has been influenced by short-term government perspective. Policy is not viewed as a priority area.
Holistic system of carbon accounting in form of electronic 'credit cards'	Number of practicality issues remain to be addressed.	PCAs do not need to replace existing policy to reduce emissions, but complement these.	Questions over whether now is the right time to implement PCAs given policy and media interest has declined.
Ability to substantially engage the public with reducing carbon footprints and increase carbon capability.	Public acceptability of PCAs are questioned with public identifying practicality as a concern.	PCAs can be used as a technique to drive further innovations towards a low-carbon economy and society in other industries.	Widespread implementation of PCAs would take number of years to become fully effective.
Provide various motivations for behaviour change.		Policy measure could achieve cross-party political support to meet aims of national carbon emissions targets.	

Questions remain on the public appetite for such an approach, the logistical feasibility and on issues of distributive and social justice. Bresnihan (2016) discusses the challenges faced by Ireland in establishing a new semi-state water utility, with organisational and financial issues to the fore for instance. The case of Irish water also saw widespread social mobilisation in opposition to the scheme. As public opposition to water charges grew the "Right2Water" campaign was formed in September 2014 as "a public campaign by activists, citizens, community groups, political parties/individuals and trade unionists who are calling for the Government to recognise and legislate for access to water as a human right" and to "abolish the planned introduction of water charges" (Hearne, 2015 p6). Protests constituted the largest local level, cross-country, protest in recent Irish history. This clearly shows the risks in implementing payment and measurement regimes for what hitherto were regarded as public goods.

A prefeasibility study conducted by the Labour administration in the UK in 2006-2008 identified a number of elements of PCAs such as equity and distributional impacts, social acceptability, economic and technical feasibility, and effectiveness (Parag & Strickland, 2010). The analysis identified PCAs to be a progressive policy in which poor people are mostly winners as their emissions are generally lower, yet social acceptability was vastly divided with attitudes identifying "very negative" and "quite positive" ratings predominant when referring to PCAs (Parag & Strickland, 2010; Wallace, Irvine, Wright, & Fleming, 2010). Concerns were raised on issues of fairness, administration and practicalities, yet technology was not found to be an obstacle (Parag & Eyre, 2010; Parag & Strickland, 2010). DEFRA (Department for Environment, Food and Rural Affairs) estimated the costs of PCAs would considerably outweigh the benefits and concluded that while personal carbon trading has the potential to engage individuals in taking action to address climate change, it is essentially 'ahead of its time' and expected costs for implementation are high (Parag & Strickland, 2010). Yet PCAs remain a largely unexplored field of research and a policy application that could lead to promising results.

6 Cost and Carbon Implications

6.1 *Overview of Cost and Carbon Implications*

According to the IPCC the low carbon power sector needs to be capable of delivering 6150 GW, and the nuclear plus CCS sectors need to be sufficient to deliver around 1332 plus 1,060=2,392 GW (IPCC, 2014). This would leave 3760 GW to come from renewable sources. The question thus set is whether the investment sum for the renewable sector stated as of $465 /€416 billion p.a. by 2050, is likely to be sufficient for this (Trainer, 2017). Hatfield-Dodds *et al.* (2017) report that resource efficiency[12] could provide pro-growth pro-environment policies with global benefits of USD $2.4/€2.14 trillion in 2050. To decarbonise the entire energy system by 2050 will require about USD $44/€39 trillion of additional spending. This investment is more than offset by over USD $115/€102 trillion in fuel savings, resulting in net savings of USD $71/€63 trillion.

The publication *Drawdown: The Most Comprehensive Plan Ever Proposed To Reverse Global Warming* (Hawken, 2017) presents solutions to rapidly and cost-effectively reduce CO_2-eq emissions by avoidance in the first place, or by sequestering CO_2 already in the atmosphere. The data (Summarised in Tables 18 and 19) can be interpreted as follows (Hawken, 2017, pxiv):

- Toal Atmospheric CO_2-eq Reduction (GT) = The amount of CO_2-eq reduction in gigatonnes for the time-horizon 2020-2050
- Net Cost COST (Billions US$) = Assumed costs for each solution take the higher end of currently available cost spectrums and maintain these as relatively constant for the time-horizon 2020-2050 (cost calculations are therefore conservative and likely to be lower in reality)
- Savings (Billions US $) = Net savings are based on the operating costs of solutions after implementation from 2020-2050

Table 18: Summary of Technical Solutions for Carbon 'Drawdown' for Buildings and Cities Sector[13]

Sectoral Rank	Solution	TOTAL ATMOSPHERIC CO2-EQ REDUCTION (GT)	NET COST (BILLIONS US$)	NET COST (BILLIONS € EQUIVALENT)[14]	€ / KgCO2
1	District Heating	9.38	$457.10	411.39	0.04
2	Insulation	8.27	$3,655.92	3290.33	0.40
3	LED Lighting (Household)	7.81	$323.52	291.17	0.04
4	Heat Pumps	5.2	$118.71	106.84	0.02
5	LED Lighting (Commercial)	5.04	$-205.05	184.55	0.04
6	Building Automation	4.62	$68.12	61.31	0.01
7	Walkable Cities	2.92	-	-	-
8	Smart Thermostats	2.62	$74.16	66.74	0.03

[12] Resource efficiency, in this cited paper refers to the economic efficiency of the use of materials e biomass, fossil fuels, metal ores and non-metallic minerals and can be expressed either as material productivity (GDP per unit of material use) or material intensity (material use per unit of GDP) (Hatfield-Dodds *et al.*, 2017, p404).

[13] Tables 18, 19 sourced from (Hawken, 2017)

[14] Assumption that 1 USD$ = €0.9

Sectoral Rank	Solution	TOTAL ATMOSPHERIC CO2-EQ REDUCTION (GT)	NET COST (BILLIONS US$)	NET COST (BILLIONS € EQUIVALENT)[14]	€ / KgCO2
9	Landfill Methane	2.5	$-1.82	1.64	0.00
10	Bike Infrastructure	2.31	$-2,026.97	1824.27	0.79
11	Smart Glass	2.19	$932.30	839.07	0.38
12	Water Distribution	0.87	$137.37	123.63	0.14
13	Green Roofs	0.77	$1,393.29	1253.96	1.63
	Building and Cities TOTAL	54.5	$4,778.30	4300.47	0.08

Table 19: Summary of Technical Solutions for Carbon 'Drawdown' for Energy Sector

Sectoral Rank	Solution	TOTAL ATMOSPHERIC CO_2-EQ REDUCTION (GT)	NET COST (BILLIONS US$)	NET COST (BILLIONS € EQUIVALENT)[15]	€ / KgCO2
1	Wind Turbines (Onshore)	84.6	$1,225.37	1102.83	0.01
2	Solar Farms	36.9	$-80.60	72.54	0.00
3	Rooftop Solar	24.6	$453.14	407.83	0.02
4	Geothermal	16.6	$-155.48	139.93	0.01
5	Nuclear	16.09	$0.88	0.79	0.00
6	Wind Turbines (Offshore)	14.1	$572.40	515.16	0.04
7	Concentrated Solar	10.9	$1,319.70	1187.73	0.11
8	Wave and Tidal	9.2	$411.84	370.66	0.04
9	Methane Digesters (Large)	8.4	$201.41	181.27	0.02
10	Biomass	7.5	$402.31	362.08	0.05
11	Solar Water	6.08	$2.99	2.69	0.00
12	In-Stream Hydro	4	$202.53	182.28	0.05
13	Cogeneration	3.97	$279.25	251.33	0.06
14	Methane Digesters (Small)	1.9	$15.50	13.95	0.01
15	Waste-to-Energy	1.1	$36.00	32.40	0.03
16	Micro Wind	0.2	$36.12	32.51	0.16
	Energy TOTAL	246.14	$4,923.36	4431.02	0.02

To investigate this carbon costs reduction picture further, and to develop specific data related to the residential level in Europe, a number of costs scenarios were developed for the 5 EU member states with current ENTRUST communities of practice; Ireland, Italy, UK, France and Spain. Details of residential level costs analysis are presented in Section 6.2.

[15] Assumption that 1 USD$ = €0.9

6.2 D6.2 Cost Scenario Calculations

A multi-variate model of direct costs of carbon reduction at the household level was developed. This was conducted to enable a ranking of technological priority, based on identification of most carbon reduction potential per € of invested capital, as described in the ENTRUST project proposal. Data were sourced for 5 EU countries, corresponding to the 6 study communities in Ireland, Italy, UK, France and Spain. Data were collated from a range of sources, but with a particular focus on those residential level parameters discussed in Section 4. These include:

- Building Envelope Efficiency
- Smart Meters
- Solar PV
- Lighting
- Behaviour change, with concentration on curtailment of electricity use.

Table 20 presents an overview of the data collated, including description of meta-data for each parameter, the year data were sourced for and the source of the data. The full-data set is provided in Appendix 1.

Table 20: Meta-Data for Scenario Calculations[16]

Parameter	Year	Meta-data	Data Source
Electricity consumption by households	2015	1000 tonnes of oil equivalent	(Eurostat, 2017a)
Smart Meters	2020	No. Metering points	(European Commission, 2014a)
Smart Meters - cost	2017	€	(European Commission, 2014a)
Electricity Prices for Residential Sector	2016	€ per kWH	(Eurostat, 2017b)
Number of residential buildings	2014	Absolute no.	(European Commission, 2017a)
Electricity consumption of lighting for residential	2014	1000 tonnes of oil equivalent	(European Commission, 2017a)
CO_2 intensity of Grid	2017	gCO_2-eq/kWh	(Electicitymap.org, 2017)
Smart Meters - Potential for Energy Saving (%)	2017	% energy saving potential	(European Commission, 2014)
Total Capacity PV Electricity	2016	MW	(Solar Power Europe, 2017)
Share of Electricity Demand covered by Solar	2016	% of total electricity	(Solar Power Europe, 2017)
LCOE for generation of residential PV	2015	€/kWh	(Vartiainen, Masson, & Breyer, 2015).
Installed lighting capacity	2011	(W) per household	(De Almeida, Fonseca, Schlomann, & Feilberg, 2011)
% CFL Lamps of total	2012	% of total	(Lapillonne, Pollier, & Samci, 2015)
Heating consumption per m2	2012	ktoe /m^2	(Lapillonne *et al.*, 2015)

[16] Full Data Model Appears in Appendix 1 and associated Excel File

Parameter	Year	Meta-data	Data Source
Floor Size	2017	Million M^2	(European Commission, 2017a)
Average Floor Size	2011	m2	(Economidou et al., 2011)
Heating Load	2017	million ktoe	(Lapillonne *et al.*, 2015); (European Commission, 2017a)
Number of buildings pre-1991	2011	number	(Economidou et al., 2011)
% buildings pre-1991	2011	%	(Economidou et al., 2011)
% non-ee lighting	2012	% of total	(Lapillonne *et al.*, 2015)
Installed non-ee lighting capacity	2011-2015	(W) per household	De Almeida, Fonseca, Schlomann, & Feilberg, 2011); (Lapillonne *et al.*, 2015)
Number of 35W equivalent bulbs	2016	Absolute No.	(Energy Saving Trust (EST), 2016, p15)
CO_2 per useful floor space	2011	Kg CO_2 / m^2	(Economidou *et al.*, 2011)

6.2.1 Costs Calculations for Modelled Parameters

Buildings: Data on cost-benefit of retrofit were sourced from Economidou *et al.* (2011).

Calculation of €/KgCO_2 - Buildings: Data were sourced directly from Table 3C7 – "Overall results to 2050" in Economidou *et al.* (2011).

Solar PV: The cost of power from large scale photovoltaic installations in Germany fell from over 0.40 €/kWh in 2005 to 0.09€/kWh in 2014. Power costs of 0.04-0.06 €/kWh are expected by 2025, reaching 0.02-0.04 €/kWh by 2050 (Mayer, Philipps, Hussein, Schlegl, & Senkpiel, 2015). Residential PV LCOE varies currently from about 75 €/MWh in Spain to about 135 €/MWh in the UK and Sweden with a 2% real Weighted Average Cost of Capital (WACC) (Vartiainen *et al.*, 2015). These figures are applied in analysis. In addition, VAT rates were accounted for as follows: Ireland 13% (energy rate), UK and France 20%, Spain 21% and Italy 10% (Vartiainen *et al.*, 2015).

Calculation of €/KgCO_2 – Solar PV:

- 15% of total residential energy load (kWh per country) was calculated.
- LCOE cost of generation of these energy loads were calculated for each country, using the data and figures specified by Vartiainen *et al.* (2015).
- kWh saving per country quantified; these energy savings were converted to CO_2-eq using carbon intensity of the electricity grid for each studied EU country
- LCOE cost of generation expressed as fraction of annualized carbon savings from Solar PV generation in €/KgCO_2

Behaviour Change, Energy Curtailment: Some household behavioural change (*e.g.,* curtailing habits) is very low-cost in terms of financial outlays, while other behavioural change (*e.g.,* adoption of efficiency-improving solar panels) is very high-cost (Nauges & Ann, 2017). 'Curtailment' includes actions such as turning off lights when leaving a room. 'Efficiency-improving behaviours' account for adoption of energy-saving equipment and technology (for example, insulation) (Nauges & Ann, 2017, p88). Table 21 presents an overview of the Energy Saving Potential from a range of household curtailment actions, reported in Gardner & Stern (2008).

Table 21: Estimated Household Energy Reductions- Curtailment Actions[17]

Focus	Action	Energy Saving Potential
Lighting	Do not leave one 60-watt bulb on all night	0.5%
	Replace two 100-watt kitchen bulbs with 75-watt bulbs	0.3%
Refrigeration/freezing	Turn up the refrigerator thermostat from 0.5°C to 3°C and the freezer thermostat from –20.5°C to -18°C	0.5%
Clothes washing and drying	Change washer temperature settings from hot wash, warm rinse to warm wash, cold rinse	1.2%
	Line-dry clothing (do not use dryer) 5 months of the year	1.1%
Colour TV	Watch 25 percent fewer hours of TV each day	0.6%
Total Electricity Savings	Simple Curtailment	4.2%

The theoretical figure of 4.2% for total electricity savings presented in Table 21 roughly accords with the range of 1% to 3% actually recorded for savings per household, in a survey of behaviour change projects reported by (RAND Europe, 2012). Schultz (2002) estimates a costs of 3 cents per household to create and disseminate the materials for an information based campaign – taken here to equate to approximately €0.03. However, this is deemed to be too low a figure to be realistic. White & Johnston (2016) report that the total cost of producing, distributing and publicising the an information leaflet on a UK referendum across the state was is £9.3 million – a cost of around £0.34 per household or approximately €0.38. Harrison (2015) reports a cost of €300,000 for an information campaign targeting 303,574 households, equating to a cost of €0.98 per household. Here a value of €0.68 is taken as a mid-way value for cost per household for a basic marketing campaign. From Table 21, modelled savings were 1% electricity and 2% electricity savings scenario, based on the 50% of potential savings actually realised, reported by (RAND Europe, 2012). A cost of €0.68 per household for a basic information campaign to realise these savings was modelled, with sensitivity analysis conducted using €0.38 and €0.98 cost per household.

Calculation of €/KgCO_2 – Behavioural Curtailment:

- Total residential energy load (kWh per household) adjusted by both 1% and 2% for behavioural curtailment scenarios.
- kWh saving per country quantified; these energy savings were converted to CO_2-eq using carbon intensity of the electricity grid for each studied EU country
- Costs per household for information campaigns sourced from White & Johnston (2016) and Harrison (2015).
- Costs of behavioural curtailment information campaigns expressed as fraction of annualized carbon savings accruing in €/KgCO_2

__Smart Meters:__ 16 Member States (Austria, Denmark, Estonia, Finland, France, Greece, Ireland, Italy, Luxemburg, Malta, the Netherlands, Poland, Romania, Spain, Sweden and the UK) have decided in favour of large-scale roll-out of smart electricity metering by 2020 or earlier (European Commission, 2014a). Table 22 presents an overview of Smart Meter CBA Scenarios for EU Member States (European Commission, 2014a).

[17] Data from a USA Study, after (Gardner & Stern, 2008)

Table 22: CBA Scenarios For EU Member States[18]

Member States rolling out smart metering	Cost per metering point/ €	Normalised benefit values per metering point in the Member States €	Potential for Energy Saving (%)
Ireland	€473	551	2.9%
Italy	€94	176	*(Range 0-5%)*
UK	€161	377	2.2%
France	€135	*(Range 18-654)*	*(Range 0-5%)*
Spain	*(Range 90-600)*	*(Range 18-654)*	*(Range 0-5%)*
EU Average	€223		2.5%

Most EU Member States have given a consistent evaluation of the potential for energy savings from smart meters, in the range of 1% to 5%. However, the case for the associated benefits from smart meters is complicated. The estimation of benefits per metering point seems to also return a scattered picture of smart metering roll-out in Member States (European Commission, 2014a).

Calculation of €/KgCO_2 – Smart Meters:

- Assumed smart meter life-span of 7 years; sourced from (Weaver, 2015).
- kWh per household adjusted to account for smart meter savings, using country specific savings potentials
- kWh saving per household per country quantified; these energy savings were converted to CO_2-eq using carbon intensity of the electricity grid for each studied EU country
- Total upfront meter cost expressed as fraction of 7 year annualized carbon savings from smart meters in €/KgCO_2

Lighting: From the data in Table 23, which provides an overview of LED lighting compared with CFLs and other lamps, it is clear that LEDs offer the dual benefit of very low energy consumption and a long lamp life of up to 30 years. These data were applied to inform cost calculations on lighting.

Table 23: A Comparison of LEDs with CFLs and Halogens[19]

Parameter	LED	CFL	HALOGEN
Watts (equivalent lamps)	6W	11W	35W
Purchase price per lamp (Euro equivalent prices from original £ data)	€6.78	€3.96	€2.26
Typical annual lamp use (hours)	1,000h	1,000h	1,000h
Typical annual lamp lifetime (years)	30 years	10 years	2 years
Annual energy consumption per lamp	6kW	11kW	35kW

[18] Data sourced from Figures 7-9 (European Commission, 2014, p40). Shaded Cells Indicate No National Level Data Available for This Country
[19] (Energy Saving Trust (EST), 2016, p15) (Prices converted to € from original £ sterling)

Calculation of €/KgCO_2 - Lighting:

- Assumed energy savings of 68.57% for CFL bulbs and 82.86% for LED, compared to halogen bulbs (Energy Saving Trust (EST), 2016)
- Costs taken from data in Table 23.
- Household lighting data were processed to provide indicative savings data at both household and country level. Data on the % of lighting currently provided by non-EE lighting were sourced from Lapillonne *et al.*, 2015. Assumption made that 35W bulbs were used to provide non-EE lighting component and that this component of lighting was to be replaced by EE options, in accordance to the data in Table 23.
- kWh per household used for lighting adjusted to account for EE lighting options, using country specific data
- kWh saving per household per country quantified; these energy savings were converted to CO_2-eq using carbon intensity of the electricity grid for each studied EU country
- Total upfront lighting cost (for all household in country) expressed as fraction of year annualized carbon savings from EE lighting in €/KgCO_2

6.3 *Results of Costs Scenario Analysis*

Table 24: Scenario 1: Impact of Smart Meters

Scenario 1: Impact of Smart Meters	Year of Data	Meta-data	Ireland	Italy	UK	France	Spain	Mean Value
Energy use after uptake, incl. savings	2015/2017	KWh per household	4386.51	2018.93	3726.62	4385.15	2571.01	3417.64
Energy Savings	2015/2017	KWh per household	131.01	51.77	83.83	112.44	65.92	88.99
Emissions Savings	2015/2017	$KgCO_2$ per household	42.58	19.88	19.70	5.17	19.84	21.43
Cost emissions savings (7 yr annualized)		€ / $KgCO_2$	1.59	0.68	1.17	3.73	2.48	1.93

Table 25: Scenario 2a: Lighting (100% LED Efficient Lighting)

Scenario 2a: Lighting (100% LED Efficient Lighting)	Year of Data	Meta-data	Ireland	Italy	UK	France	Spain	Mean Value
Energy use after uptake, incl. savings	2014	KWh per household	137.13	51.76	68.12	46.46	52.52	71.20
Energy Savings	2014	KWh per household	662.91	250.23	329.32	224.61	253.91	344.20
Emissions Savings	2014	$KgCO_2$ per household	215.44	96.09	77.39	10.33	76.43	95.14
Cost emissions savings (30 yr annualized)		€ / $KgCO_2$	0.04	0.09	0.12	0.80	0.12	0.23

Table 26: Scenario 2b: Lighting (100% CFL Efficient Lighting)

Scenario 2b: Lighting (100% CFL Efficient Lighting)	Year of Data	Meta-data	Ireland	Italy	UK	France	Spain	Mean Value
Energy use after uptake, incl. savings	2014	KWh per household	251.45	94.92	124.92	85.20	96.31	130.56
Energy Savings	2014	KWh per household	548.58	207.08	272.53	185.87	210.12	284.84
Emissions Savings	2014	$KgCO_2$ per household	178.29	79.52	64.04	8.55	63.25	78.73
Cost emissions savings (10 yr annualized)		€ / $KgCO_2$	0.09	0.20	0.25	1.69	0.26	0.50

Table 27: Scenario 3: PV to Provide 15% Residential Energy

Scenario 3: PV to provide 15% residential energy	Year of Data	Meta-data	Ireland	Italy	UK	France	Spain	Mean Value
15% of residential energy	2015	KWh	1182073200.00	9928123950.00	16223501100.00	22866208200.00	10508344650.00	12141650220.00
LCOE cost of generation	2015	€	185112663.12	833962411.80	2672010631.17	2929161270.42	969394793.96	1517928354.09
Emissions Savings (based on 2017 grid)	2017	$KgCO_2$	384173790.00	3812399596.80	3812522758.50	1051845577.20	3163011739.65	2444790692.43
Cost emissions savings (annual)		€ / $KgCO_2$	0.48	0.22	0.70	2.78	0.31	0.90

Table 28: Retrofit Summary of Intervention Scenarios[20]

Scenario	**Baseline**	**Slow & Shallow**	**Fast & Shallow**	**Medium**	**Deep**
Investment costs (present value) (€)	164,000,000,000	343,000,000,000	451,000,000,000	551,000,000,000	937,000,000,000
2050 saving as % of today	9%	34%	32%	48%	68%
Savings (present value) (€ million)	187,000	530,000	611,000	851,000	1,318,000
Annual CO_2 saving in 2050 tCO_2	742,000,000	821,000,000	814,000,000	868,000,000	932,000,000
2010-2050 accumulated Carbon Savings tCO_2	2,9680,000,000	32,840,000,000	32,560,000,000	34,720,000,000	3,7280,000,000
Total Costs of 40 year Carbon Savings (present value) (€ /tonne CO_2)	0.18097561	0.09574344	0.072195122	0.063012704	0.039786553
Total Costs of 40 year Carbon Savings (present value) (€ /Kg CO_2)	**0.00018**	**0.00010**	**0.00007**	**0.00006**	**0.00004**

[20] Sourced from "Table 3C7 – Overall results to 2050" (Economidou *et al.*, 2011)

Table 29: Scenario 4a: Behavioural Curtailment (2%) electricity

Scenario 4a: Behavioural Curtailment (2%)	Year of Data	Meta-data	Ireland	Italy	UK	France	Spain	Mean Value
98% of residential energy	2015	KWh	7722878240.00	64863743140.00	105993540520.00	149392560240.00	68654518380.00	79325448104.00
Electricity Savings	2015	KWh	157609760.00	1323749860.00	2163133480.00	3048827760.00	1401112620.00	1618886696.00
Electricity Emissions Savings (based on 2017 grid)	2017	$KgCO_2$	51223172.00	508319946.24	508336367.80	140246076.96	421734898.62	325972092.32
Total Costs of Information @0.38€ /household			662883.40	12146263.00	10785999.80	12879720.00	10095486.60	9314070.56
Total Costs of Information @0.68€ /household			1186212.40	21735418.00	19301262.80	23047920.00	18065607.60	16667284.16
Total Costs of Information @0.98€ /household			1709541.40	31324573.00	27816525.80	33216120.00	26035728.60	24020497.76
Cost emissions savings (annual) @0.38€ /household		€ / $KgCO_2$	0.01	0.02	0.02	0.09	0.02	0.03
Cost emissions savings (annual) @0.68€ /household		€ / $KgCO_2$	0.02	0.04	0.04	0.16	0.04	0.06
Cost emissions savings (annual) @0.98€ /household		€ / $KgCO_2$	0.03	0.06	0.05	0.24	0.06	0.09

Table 30: Scenario 4b: Behavioural Curtailment (1%) electricity

Scenario 4a: Behavioural Curtailment (1%)	Year of Data	Meta-data	Ireland	Italy	UK	France	Spain	Mean Value
99% of residential energy	2015	KWh	7801683120.00	65525618070.00	107075107260.00	150916974120.00	69355074690.00	80134891452.00
Electricity Savings	2015	KWh	78804880.00	661874930.00	1081566740.00	1524413880.00	700556310.00	809443348.00
Elctricity Emissions Savings (based on 2017 grid)	2017	$KgCO_2$	25611586.00	254159973.12	254168183.90	70123038.48	210867449.31	162986046.16
Total Costs of Information @0.38€ /household			662883.40	12146263.00	10785999.80	12879720.00	10095486.60	9314070.56
Total Costs of Information @0.68€ /household			1186212.40	21735418.00	19301262.80	23047920.00	18065607.60	16667284.16
Total Costs of Information @0.98€ /household			1709541.40	31324573.00	27816525.80	33216120.00	26035728.60	24020497.76
Cost emissions savings (annual) @0.38€ /household		€ / $KgCO_2$	0.03	0.05	0.04	0.18	0.05	0.07
Cost emissions savings (annual) @0.68€ /household		€ / $KgCO_2$	0.05	0.09	0.08	0.33	0.09	0.12
Cost emissions savings (annual) @0.98€ /household		€ / $KgCO_2$	0.07	0.12	0.11	0.47	0.12	0.18

7 Which Interventions Can Best Support Energy Transitions?

7.1 Targeted Technological and Behavioural Interventions

Building Retrofits:

For all countries surveyed, retrofit remains the number one most cost-effective means of reducing carbon emissions per € of investment. The report by Economidou *et al.* (2011) presents a savings range of 0.00018 € / KgCO_2 for first stage efficiency measures ("baseline scenario") to 0.00004 € / KgCO_2 for "deep retrofit" scenario, across a 40 year time-horizon for European buildings. These figures ensure that retrofit needs continued and enhanced policy support to realise the full potential of carbon savings in built environment.

Smart Meters:

Smart meters are the most costly intervention modelled and represent the least value for money (in terms of investment for carbon reduction), for all surveyed countries. The modelled cost € / KgCO_2 saved ranges from €0.68 to €3.73 for a 7 year life-span smart meter. The lowest value is attributable to Italy, due to high energy consumption for households, the highest CO_2 intensity of the electricity grid of the 5 profiled EU member states and the relatively low cost of smart meters per installation. The highest value of € / Kg CO_2 was observed for France. This is due to the low carbon intensity of the grid, which means that emissions savings from smart metres in France are much lower than the other 4 profiled member states, 5.17 Kg CO_2per household compared to a mean of 21.54 Kg CO_2. A mean value of € / KgCO_2 1.93 was found for the 5 profiled member states.

- **Lowest observed € / KgCO_2: €0.68 -Italy**
- **Highest observed € / KgCO_2: €3.73 -France**
- **Mean € / KgCO_2: €1.93**

Lighting - LED:

The modelled cost € / KgCO_2 saved ranges from €0.04 to €0.80. These figures are relatively comparable to those published by Hawken (2017), at the lower end of the range (€0.04 / KgCO_2). In the case of France, the high cost of LED in terms of carbon reductions is explained by the relatively low amount of electricity used for lighting in France, combined with the low carbon intensity of the French Electricity grid (observed carbon reduction cost of €0.80/ KgCO_2). Conversely, in the case of Ireland (€0.04 / KgCO_2 saved, the lowest observed figure) the high amount of energy used for lighting combined with the relatively high carbon intensity of the grid make LED lighting a much cheaper carbon reduction strategy. A mean value of € / KgCO_2 0.23 was found for the 5 profiled member states.

- **Lowest observed € / KgCO_2: €0.04 -Ireland**
- **Highest observed € / KgCO_2: €0.80 -France**
- **Mean € / KgCO_2: €0.23**

Lighting – CFL:

The modelled cost € / KgCO_2 saved ranges from €0.09 to €1.69, with Ireland and France representing the lowest and highest observed value respectively, as with LED lighting. The explanation for the relative costs for these countries is the same as for LED, that is, a function of the proportion of energy used for lighting, the carbon intensity of the grid and the upfront cost of efficient bulbs. More competitive values are obtained for LED, in comparison to CFL, due to the longer life-span of these bulbs, and the greater capacity for energy savings (on a per bulb basis) annually. A mean value of € / KgCO_2 0.50 was found for CFL lighting for the 5 profiled member states.

- **Lowest observed € / KgCO_2: €0.09 -Ireland**
- **Highest observed € / KgCO_2: €1.69 -France**
- **Mean € / KgCO_2: €0.50**

Solar PV:

The modelled cost € / KgCO_2 saved ranges from €0.22 to €2.78, with Italy and France representing the lowest and highest observed values respectively. A mean value of € / KgCO_2 0.90 was found for the 5 profiled member states. Figures are higher than those reported by Hawken (2017) (€0.02) for residential solar, although Hawken's figures are global and the data presented in this report are weighted by northern European country conditions/data. The high figure for France is again noteworthy, and reflects the low carbon intensity of the electricity grid in France. It follows that the same carbon reductions are not achievable for application of the same technologies in France, as is the case in countries with much more carbon intense grids (Electricity from Italy, at 384g CO_2-eq per kWh is over 8 times more carbon intensive than electricity from the grid in France, at 46g CO_2-eq).

- **Lowest observed € / KgCO_2: €0.22 -Italy**
- **Highest observed € / KgCO_2: €2.78 -France**
- **Mean € / KgCO_2: €0.90**

Behavioural Curtailment (1% @0.98€ / Household):

The modelled cost € / KgCO_2 saved from application of behaviour curtailment initiatives realising a 1% reduction in electricity saving ranges from €0.07 (Ireland) to €0.47 (France). A mean value of € / KgCO_2 0.18 was found for the 5 profiled member states. Of all of the reduction strategies modelled, this option remains most uncertain in terms of actual realisable savings. While costs of implementing information campaigns may be relatively low, in comparison to hard technology investments, the outcomes are highly dependent on a wide range of factors, meaning that achieving a 1% savings target across a whole nation of electricity users may be extremely challenging in practice, and over optimistic.

- **Lowest observed € / KgCO_2: €0.07 -Ireland**
- **Highest observed € / KgCO_2: €0.47 -France**
- **Mean € / KgCO_2: €0.18**

7.1.1 Ranking of Country Level Interventions

Table 31: Ranking of Interventions, Ireland

Ranking of Carbon Reduction Scenarios (Cost)	€ /Kg CO_2
1. Retrofit - Deep Retrofit Scenario	0.00004
2. Retrofit - Baseline Scenario	0.00018
3. Lighting (100% LED Efficient Lighting)	0.04
4. Behavioural Curtailment (1%) @0.98€ /household	0.07
5. Lighting (100% CFL Efficient Lighting)	0.09
6. PV to provide 15% residential energy	0.48
7. Impact of Smart Meters	1.59

Table 32: Ranking of Interventions, Italy

Ranking of Carbon Reduction Scenarios (Cost)	€ /Kg CO_2
1. Retrofit - Deep Retrofit Scenario	0.00004
2. Retrofit - Baseline Scenario	0.00018
3. Lighting (100% LED Efficient Lighting)	0.09
4. Behavioural Curtailment (1%) @0.98€ /household	0.12
5. Lighting (100% CFL Efficient Lighting)	0.20
6. PV to provide 15% residential energy	0.22
7. Impact of Smart Meters	0.68

For Ireland and Italy, installation of 100% LED Efficient Lighting represents a priority cost-effective carbon reduction scenario, closely followed by behavioural curtailment.

Table 33: Ranking of Interventions, UK

Ranking of Carbon Reduction Scenarios (Cost)	€ /Kg CO_2
1. Retrofit - Deep Retrofit Scenario	0.00004
2. Retrofit - Baseline Scenario	0.00018
3. Behavioural Curtailment (1%) @0.98€ /household	0.11
4. Lighting (100% LED Efficient Lighting)	0.12
5. Lighting (100% CFL Efficient Lighting)	0.25
6. PV to provide 15% residential energy	0.70
7. Impact of Smart Meters	1.17

Table 34: Ranking of Interventions, France

Ranking of Carbon Reduction Scenarios (Cost)	€ /Kg CO_2
1. Retrofit - Deep Retrofit Scenario	0.00004
2. Retrofit - Baseline Scenario	0.00018
3. Behavioural Curtailment (1%) @0.98€ /household	0.47
4. Lighting (100% LED Efficient Lighting)	0.80
5. Lighting (100% CFL Efficient Lighting)	1.69
6. PV to provide 15% residential energy	2.78
7. Impact of Smart Meters	3.73

Table 35: Ranking of Interventions, Spain

Ranking of Carbon Reduction Scenarios (Cost)	€ /Kg CO_2
1. Retrofit - Deep Retrofit Scenario	0.00004
2. Retrofit - Baseline Scenario	0.00018
3. Behavioural Curtailment (1%) @0.98€ /household	0.12
4. Lighting (100% LED Efficient Lighting)	0.12
5. Lighting (100% CFL Efficient Lighting)	0.26
6. PV to provide 15% residential energy	0.31
7. Impact of Smart Meters	2.48

For UK, France and Spain, behavioural curtailment represents a more cost effective strategy than installation of 100% LED Efficient Lighting. In the case of the UK and Spain, the difference is marginal between these mentioned strategies. However, for France behavioural curtailment is considerably more cost-effective than LED lighting, at 0.47 € / KgCO_2, compared with 0.80 € / KgCO_2 for LED lighting.

7.1.2 Implications from Costs Scenarios

Some clear targets for action emerge from analysis. Figure 6 presents an overview of the scenarios modelled, in terms of associated carbon savings costs and also in terms of the expected user engagement required to realise the modelled savings.

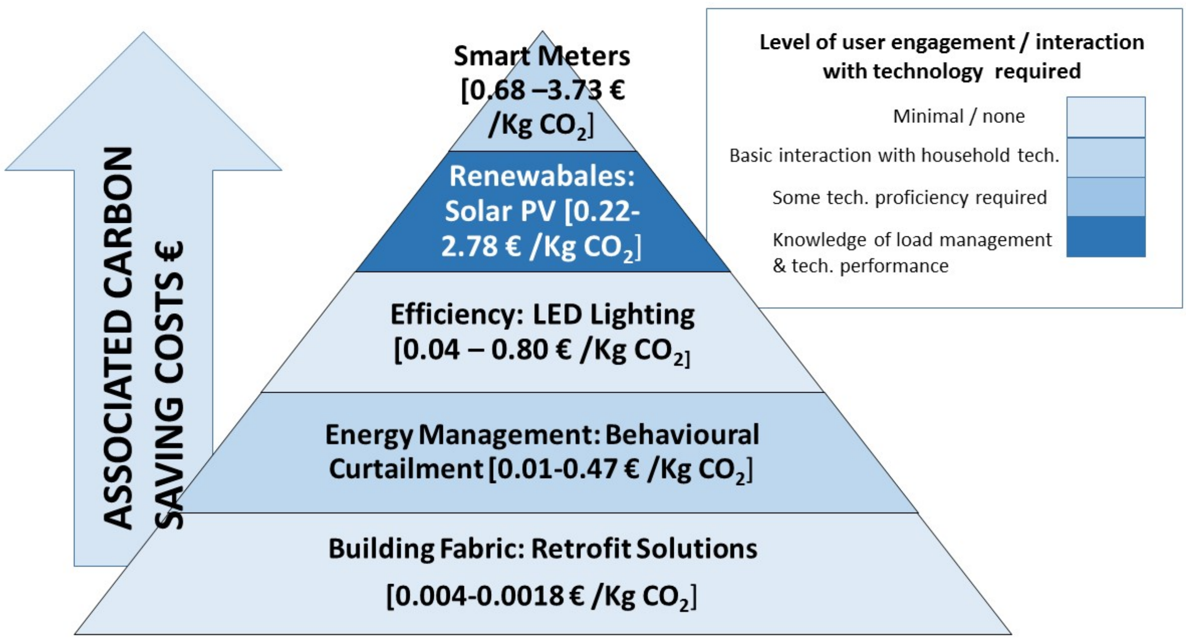

Figure 6: Energy Hierarchy Showing Targeted Interventions

- Building Retrofit remains the most cost-effective and 'behaviour proof' intervention, for all countries surveyed.

- LED Lighting represents a 'sweet spot' of low costs of carbon reduction in terms of €/Kg CO_2 prevented (mean value of €0.23/ Kg CO_2) and with little requirement for user behaviour change, beyond initial installation.
- Smart meters would appear to be the most costly intervention (mean carbon reduction cost of €1.93/ Kg CO_2) which also requires considerable user engagement, knowledge and training to be effective.
- The potential of energy management in terms of behaviour curtailment remains attractive (mean carbon reduction cost of €0.18/ Kg CO_2). However, there remains much uncertainty on the realisation of energy savings, with results contingent on the profile and types of communities engaged, means of engagement *etc.*
- The relatively low costs of carbon reduction for Solar PV (mean carbon reduction cost of €0.90/ Kg CO_2) and the likelihood that these costs will continue to decrease mean that Solar PV will increasingly become a prioritised option in years to come. In terms of requirement for new technology solutions, options to increase the user-friendliness of installing and managing Solar PV are urgently required. Fit-and-forget solutions and battery storage for Solar PV would likely increase the usability and attractiveness of this carbon reduction solution.

7.2 PEST Analysis of Interventions

7.2.1 PEST Overview

PEST is an acronym standing for Political, Economic, Social and Technological features. PEST is a well-established tool for analysis that arises from business, strategic and organisational management disciplines. A breakdown of the PEST framework adapted for the analysis of the technological interventions is presented in Table 36, and provides a summary overview of key issues at the broad macro-level (national and international issues), and includes the following themes:

- **Political dimension** – this includes how the government intervenes in the economy, i.e. through the goods, services and infrastructures it provides and influences; changes to government policy, which can present risks and opportunities for interventions identified; and other aspects, i.e. general public pressures.
- **Economic dimension** – this includes supply and demand side issues; changes to economic climate; changes to taxes and legislation (*e.g.,* taxes, levies. Budget allocations, *etc.*); energy costs; availability of funding; and other mechanisms that influence interventions.
- **Social dimension** – includes cultural and social trends, particular socio-demographic pressures; social acceptance issues in relation to interventions; impact of climate change and specific interventions on society.
- **Technological dimension** – includes research and development activity, technology maturity, the rate of technological change and innovation; advances in technology, cost variations, deployment of new technology, their use and capacities and upgrades to existing infrastructures (*e.g.,* new technology can be designed to assist sustainable energy consumption but may not be used to full capacity).

A series of SWOT analyses were presented in Section 4 for each technology and behaviour case-study to outline the key potentials and limitations of the profiled interventions. The SWOT analyses presented are supplemented here by a PEST analysis to provide an overview of the status at the macro-level for technological and behavioural interventions examined. The use of both SWOT and PEST in energy research is abundant and well established (*e.g.*, Rodrigo, Grijalvo, & Palacios, 2016; Simanaviciene, Volochovic, & Simanavicius, 2015; Yuan, 2013).

The main advantage of PEST is that it can help simplify complexity into an easy to use framework while the disadvantage is that it could oversimplify due to the subjectivity of the evaluator and the omission of key information or perspectives. A PEST overview can also present a static perspective of current trends and therefore analysis needs to be repeated or undertaken on a regular basis to overcome this (McDonald & Hugh, 2011). The analysis presented here represents a snapshot in time of the profiled interventions presented in this deliverable

7.2.2 PEST Analysis of Technological Interventions

A PEST Analysis for behavioural interventions is presented in Table 36 and indicates broader (national and international) political, economic, social and technological dimensions of each profiled technological intervention.

Table 36: PEST Analysis of Case Studies of Technological Intervention.

Technology	Political	Economic	Social	Technology
Smart Meters	High levels of political commitment	Seeks to support consumers and energy suppliers, free at the point of delivery	Low social acceptance; claimed to benefit suppliers and end-users	Early development; many varieties available in the market, quality variable; requires user monitoring
Pre-Payment meters	Energy supplier led approach, tariff caps proposed; regulatory push to move towards smart metering	Seen as a budgeting tool; costs to install or remove; users payer higher tariffs	Low social acceptance; social stigma; targets low-income and vulnerable communities; actively reduces agency of households	Mature technology; requires user monitoring, proposed transition into smart pay-as-you-go meters
Building Insulation	High levels of political commitment; well established	Seen as a cost effective and efficient interventions	High public acceptance; well established	Mature and evolving technology – *e.g.*, new cheaper products emerging
Solar PV	High levels of political commitment; well established	A number of financial incentives help promote adoption (i.e. feed-in-tariff)	High public acceptance; high social status	Mature and evolving technology *e.g.*, new cheaper products emerging
LED lightbulbs	High levels of political commitment; well established	Costs of product is reducing	High public acceptance	Mature and evolving technology *e.g.*, new cheaper products emerging

The PEST analysis shows the diverse makeup of technological measures that offer specific solutions to reducing domestic end-user energy consumption. Each presented technology holds the potential to contribute to carbon reduction in different ways, *e.g.,* enable energy management, fit-and-forget fabric efficiency and renewable microgeneration. For example, smart meters and PPMs are active energy management interventions; both offer a form of feedback and monitoring mechanism directly to occupant users. In contrast, building insulation, LED lighting and solar PV represent more indirect and inactive fit-and-forget fabric efficiency interventions at the building level. In particular, building insulation can enhance the building's energy performance by reducing the amount of energy that is lost through the buildings envelope thereby enabling users to use less energy. This can be further enhanced by the adoption of efficient appliances such LED lightbulbs and solar energy for microgeneration of renewable energy thereby reducing energy demand from the national grid and contributing to overall reduction of the domestic sector carbon footprint.

Furthermore, in terms of the summary PEST of the five profiled technological interventions, the following could be observed. Increasingly, political support on the whole for these technological interventions appears well established - through a range of legislation, regulations, codes and standards. For example, in response to EU level policy interventions there have been significant shifts in social and political commitments across national contexts in EU member states. These push the market for technology development and innovations. The economic dimension is interlinked to the political, and suggests that market supply of most of these products is now well established and supported by a number of government instruments. There appears to be some level of government directed financial support for interventions. The costs of most technologies remain the responsibility of individuals and householders, and their adoption is voluntary. This means that cost, specifically upfront investment costs, remains a major barrier for the adoption of proven cost-effective technological interventions. It seems that while many of these technologies are being increasingly adopted, there are government concerns that energy efficiency uptake is not occurring at a fast enough rate and at requisite scale needed to meet national and international goals (*e.g.* EU climate change policy goals for 2020). Furthermore, while social acceptance for smart meters is developing, the PPMs appear to be losing favour socially. Technological innovations mean that there are proposals for PPMs to transition into smart meter pay as you go technologies which will offer the same potential benefits as smart meters do. New technological innovations should mean in principle that they are more effective in delivering their attributed energy efficiency credentials, easier to install and cost less, so there is greater adoption of these measures across society.

This analysis has examined how and why particular technological interventions are being used as means to address a number of energy and sustainability policy agendas by governments across Europe. In particular, drivers for reducing greenhouse gas and CO_2-eq emissions, and energy security appear fundamentally about reducing societal energy dependency. The deployment of technological interventions seeks to diversify energy production (*e.g.* through renewable energy sources such as solar); and greater energy management and energy consumption reduction strategies (*e.g.* smart meters, appliances such as lighting, and behaviour change interventions, *etc*.). These interventions are deployed via top-down as well as bottom up interventions that sometimes target the material and individual context of energy dependencies, and sometimes this is addressed at a social context via community level interventions.

7.2.3 PEST Analysis of Behavioural Interventions

A PEST Analysis for behavioural interventions is presented in Table 37 and indicates broader (national and international) political, economic, social and technological dimensions of each behavioural intervention.

Table 37: PEST Analysis of Case Studies of Behavioural Interventions

Intervention	Political	Economic	Social	Technological
Information Provision	High levels of political commitment to providing information on energy policy and issues, including behavioural changes and technological interventions.	Cost of intervention is low in comparison to others. Financial savings to residents is limited, dependent upon lifestyle changes made after information provided.	Moderate social acceptance, dependent upon attitudes of individuals towards energy consumption. Often limited impact on direct behavioural change but increase knowledge.	Often applied through paper-based approaches or through (social) media including internet and TV programmes. Potential to expand into smart technologies.
Feedback systems	Moderate levels of political support, often provided by energy suppliers or practitioners on energy consumption. Provided through bills or smart technologies.	Viewed as a cost effective and efficient intervention that can save residents money by outlining peaks in consumption and energy saving measures within home.	Moderate social acceptance, but increasing given introduction of smart meters. Often useful for those wishing to reduce energy consumption and energy bills. Moderate use, but increasing.	Vast array of feedback systems exist including home energy audits, energy bills and smart technologies. Modelling can also be applied. Emerging technologies being developed.
Legal measures and sanctions	Limited political commitment to establishing further regulations on energy consumption given potential for backlash and social unacceptability.	Seen as a cost effective measure to reduce spending on carbon intensive products and services and support transition to low-carbon areas.	Initially low public acceptance, yet increases following positive observed impacts that arise from regulation *e.g.,* reduction in traffic or single-use carrier bags.	Dependent on regulation enforced. Majority applied through financial rewards and sanctions. For congestion charging, through digital technology.
Community-based projects	Moderate to high political commitment for community projects for sustainability, yet policies and funding support is limited.	Costs to run community projects are minimal, given volunteers and local led initiative. Limited funding to support activities affects efficacy and sustainability. Reduces energy costs for residents.	High social acceptance if projects are locally run and address needs of community. Localism supported by national government.	Multiple existing and evolving technologies including renewable energy technologies, smart technologies and energy efficient appliances.
Personal Carbon Allowances	Limited political commitment; often predicated on short-term government priorities; and few feasibility studies supported by research and public acceptability.	Potential high cost of establishing PCAs nationally with uncertain impacts on this scale. Use of credit cards and smart technologies would be initially high, but cost effective later.	Mixed public acceptability with considerations focused on practicality and impacts on lifestyle. Positive findings for spill overs to other behaviours including heating and transport.	Initial systems envisioned as a credit card system. Potential to evolve to smart technologies including smart watches and online accounting methods.

Each presented behavioural intervention (Table 37) has the potential to influence the attitudes and actions of energy stakeholders in different ways. These interventions can be applied through a top-down or bottom-up approach, with each specifically targeting particular behaviour and practice to encourage sustainable lifestyles. From the PEST analysis, it is clear that political support for behavioural interventions is mixed, confirming somewhat that technological interventions are favoured more so than behavioural interventions. This can be attributed to a fear of political backlash and public unacceptability of a 'forcing factor' to change public lifestyles (Ockwell *et al.*, 2009; Verplanken, 2011). Clear interventions that constrain choice are seen as an undesirable option by governments who wish to remain in power. However, particular behavioural interventions are subjected to favourable political support such as community-based sustainability projects that are congruent with recent transitions towards localism (Alexander *et al.*, 2007). Yet support for regulating behaviour beyond interventions such as the carrier bags levy in Ireland and congestion charging in Sweden is limited. Economic factors illustrate that while many behavioural interventions are a cost effective approach to reducing energy consumption, some initial costs are high due to the relative dependence on digital and smart technologies (such as PCAs). For residents, these interventions may lead to savings in energy bills that result from a reduction of energy consumption. However, negative spill over effects may result should this money then be spent on other carbon intensive products or services.

With respect to social factors of the reviewed behavioural interventions, public acceptance is generally high. In some examples, particularly those interventions that are regulatory in nature including PCAs, public acceptability may be low initially with concerns reflecting 'forcing factors' towards behaviour change and issues towards practicality of establishing congestion charges (Ockwell *et al.*, 2009; Verplanken, 2011). Behavioural interventions that are interactive and allow for widespread participatory approaches such as community-based sustainability strategies promote multiple pathways to engagement; cognitively, affectively and behaviourally (Lorenzoni, Nicholson-Cole, & Whitmarsh, 2007; Whitmarsh, O'Neill, & Lorenzoni, 2013). Should these approaches be scaled-up, these may contribute significantly to what Dietz, *et al.* (2009) identify as a behavioural wedge in stabilising carbon emissions. While termed as behavioural interventions, these approaches can be disseminated and applied through technology including digital and smart technologies. Historically, interventions such as information provision and feedback systems may have been applied via paper-based methods or through peer-to-peer exchanges. Interactive forms of engagement require face-to-face involvement with other residents and individuals that provide key social dimensions to interventions (particularly community-based sustainability projects) (see Alexander *et al.*, 2007; Heiskanen, Jalas, Rinkinen, & Tainio, 2015; Heiskanen *et al.*, 2010). However, new forms of disseminating behavioural interventions exist through smart technologies that include continuous feedback such as smart meters (Abrahamse *et al.*, 2007). Interventions such as PCAs rely on technology to monitor and record carbon emissions (Fawcett & Parag, 2010).

This PEST analysis highlights the predominant political, social, economic and technological factors involved with implementing a number of behavioural interventions to address energy and sustainability targets across the EU. While political commitments underpinning the use of behavioural interventions appears to be increasing, effective reduction of energy through this avenue will require more extensive financial investment, and an exploration of approaches that go beyond individualistic, and information only based approaches. Technological developments including smart technologies are emerging as a valuable asset to disseminating and applying behavioural interventions, yet political support is needed to develop these approaches and ensure their sustainability without compromising their efficacy.

7.3 *Gaps in Behavioural Approaches*

ENTRUST Deliverable - Summary Box 2: Findings from D4.4

Identification and Characterisation of Energy Behaviour Change Initiatives: Summary of Key Findings from ENTRUST D4.4 (Morrissey *et al.*, 2016)

- The existing policy landscape review suggests that energy conservation behaviour change have not received the relatively strong policies that exist for new and existing building's energy efficiency (*e.g.,* building regulations on energy efficiency). The case studies reviewed in Deliverable 4.4 illustrate that in relation to individual behaviour change there is a predominant use of incentives (*e.g.,* grants) and voluntarism (*e.g.,* nudges) and combined with social marketing tools, which dominate this policy arena. This softer non-mandatory policy approach can be criticised for not providing the right push at the right time. Nevertheless, the policy landscape for energy conservation or behaviour change suggests that it relies on a mix of tools and with different scopes across the various countries included in this review and thus reflected in the diversity of intervention case studies examined in Deliverable 4.4.
- Deliverable 4.4 reports that energy related behaviour change interventions are heavily clustered to 'communication and marketing' and 'service provision' policy categories, and also concentrate mostly on education, modelling and enablement interventions.
- While it is well-known that information alone does not lead to changes in behaviour (Moloney *et al.*, 2010), the initiatives reviewed indicate that communication approaches are favoured when seeking to influence energy-related behaviours. While there have been significant advances in research on the topic of climate communication (Ballantyne, 2016; Bostrom, A., Bohm, G. and O'Connor, 2013), there is a divergence between what is known to work from best practice and the practical application of a wide range of behaviour change initiatives.
- Narrow approaches towards behaviour change limit the ability of initiatives to have wider sustainability related impact. Deliverable 4.4 indicates 2 broad challenges with current energy behaviour change interventions: (1) a neglect of wider social elements in practices, and (2) a lack of consistency with wider policy approaches. Given that there are a number of policies that significantly influence the energy system and individual lifestyle choices (see Deliverable 4.1 of the ENTRUST project for a review), there appears to be a lack of consistency of using such policies as a platform for energy related behaviour change.
- The reluctance to apply regulation, fiscal measures and legislation approaches to influence energy behaviour reflects a widespread belief that a top-down influenced approach to changing behaviours is unpopular and may backfire (Verplanken, 2011). Yet there are studies that suggest changing behaviour through legislation and/or regulation may, unexpectedly, be received more positively than previously considered and may lead to negative attitudes and behavioural responses towards unsustainable and other undesirable practices (Olson and Stone, 2005). This reflects the concept of self-perception; that individuals infer their own attitudes from their behavior (Bem, 1972). While being perceived negatively, the feeling of coercion that could result from legislation-driven changes will eventually fade and the conditions underpinning self-perception become favourable to consolidate sustainable actions and practices (Verplanken, 2011). Examples of this include the Ireland smoking ban in 2004 and the London Congestion Charge.
- A reliance on the information deficit model of behaviour change fails to take into account the heterogeneity of messages, audiences and prior understanding of issues (Sturgis & Allum, 2004). While information can be an important first step in prompting behaviour change, information alone is unlikely to motivate change (Darnton, 2008; Gilg, Barr, & Ford, 2005)*et al.*. Information is also unlikely to result in sustained behavioural change beyond the life of a given campaign, since enthusiasm for 'new' actions wanes and participation decays in the absence of continual

reinforcement (Abrahamse *et al.*, 2005; Moloney *et al.*, 2010). There is an assumption that if people are presented with facts relating to how their behaviour is affecting the environment, they will respond rationally and change to more sustainable practices. However there is a risk that responses to such information could lead to disinterest, disempowerment, fear and scepticism (Moloney *et al.*, 2010; Whitmarsh, 2011).

- Engaging individuals at a deeper level raises a number of questions about the choice of techniques used in behaviour change programmes including the appropriate focus on the individual rather than the collective; the role of social norms; and the extent to which initiatives explore what is shaping and influencing behaviours, they seek to change (Moloney *et al.*, 2010). The WWF (Crompton, 2008) recommends framing approaches around appealing to intrinsic values such as personal growth and community involvement. This potentially introduces social norms focused on sustainability issues, which recognises that behaviour is socially constructed and therefore needs to be considered at the collective or social level (Moloney *et al.*, 2010).

Figure 7 presents outcomes of a 'behaviour change wheel' analysis conducted for 72 behaviour change initiatives/projects across Europe. The full list of surveyed initiatives is presented in Appendix 2.

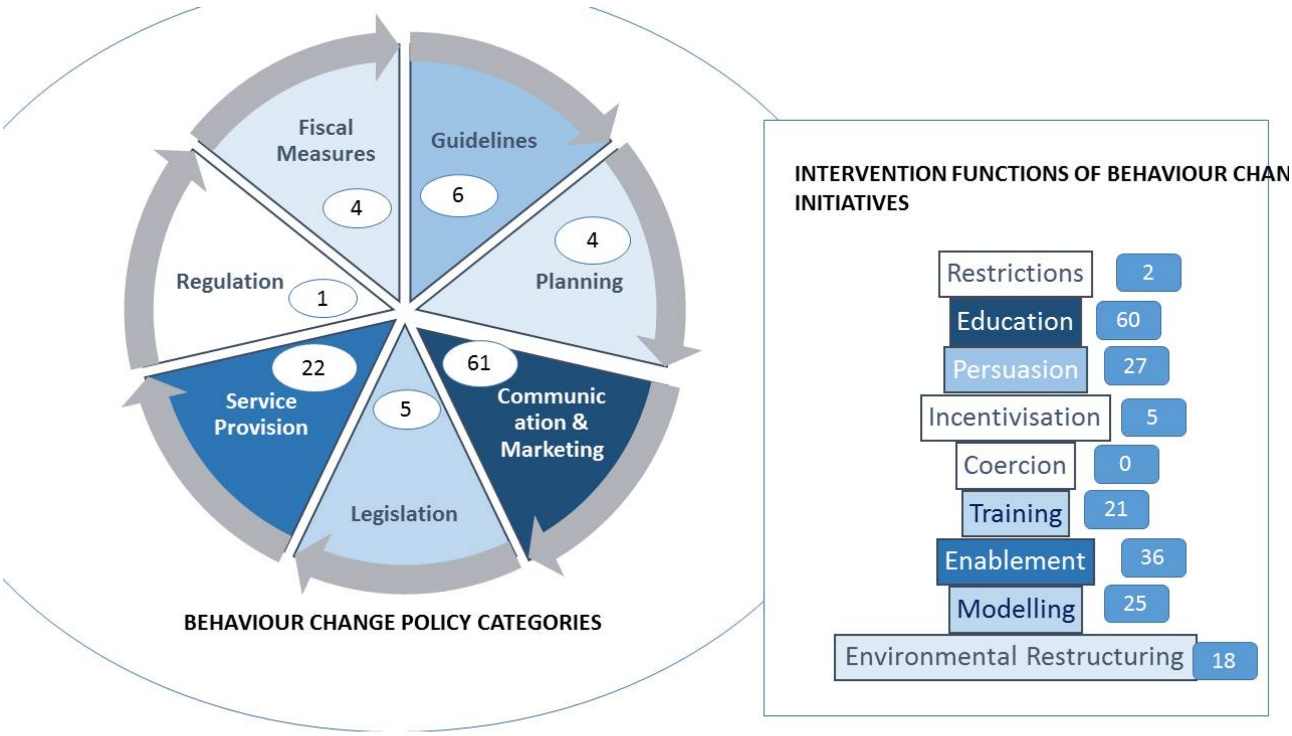

Figure 7: Behaviour Change Wheel – Current Gaps in Behaviour Change Initiatives

Figure 7 was developed further from analysis first presented in ENTRUST D4.4, from a total of **72 surveyed European projects**. From this analysis, it is clear that there are significant gaps in the application of behavioural change programmes across EU member states. There is striking evidence that policy categories including guidelines, planning, legislation, regulation and fiscal measures are not well established approaches for behavioural change initiatives. Rather, there is an over-reliance on communication and marketing strategies as well as service provision. There are a number of reasons for why these patterns have emerged. Primarily, considerations of top-down measures enforced through regulation and legislation are undesirable to governments who wish to remain in power, particularly where short-term fixed parliaments are concerned (Ockwell *et al.*, 2009). While this is not necessarily an issue, it should be acknowledged that top-down behaviour change programmes can, and do, work. The examples of the Ireland smoking ban in 2004, the Irish and Welsh plastic bag charges and the Stockholm congestion charge have proven that regulation and legislation do work to achieve environmental, economic and social outcomes (Eliasson *et al.*, 2009; Thomas *et al.*, 2016; Verplanken, 2011). Should regulation and legislative categories of behaviour change be implemented in similar ways to the examples of the Stockholm congestion charge and the Irish single-use carrier bag charge, it is not unreasonable to assume that such approaches cannot yield similar positive outcomes for energy consumption and lifestyle changes.

Fiscal measures, guidelines and restrictions are other policy categories where gaps exist in implementing behavioural change programmes. While examples do exist, restrictions and guidelines are often viewed as being prescriptive and clearly identifiable as forcing individuals to reduce consumption (Ockwell *et al.*, 2009). Moreover, fiscal measures do exist yet these measures have decreased in recent years in the aftermath of the Global Financial Crisis (GFC). Fiscal measures are often short-term behavioural change initiatives, and while these may lay the groundwork for incorporating sustainable technologies, other financial incentives often have limited impacts on sustaining behaviour change following the withdrawal of such incentivised behaviours (Stewart Barr, Ford, & Gilg, 2003; Jackson, 2005; Verplanken, 2011).

Incentives rarely work to create lasting behavioural change. Rather than financial rewards, a potential reconsideration of incentives could be reoriented towards satisfaction and happiness related outcomes of behaviour change. Such an approach would clearly relate to what Lorenzoni *et al.* (2007) identify; that individuals need to be motivated and care about climate change. Relating effective engagements with actions and involvement in sustainability-related activities presents new pathways for engagement with behaviour change programmes (Axon, 2016). Unlocking this potential requires creative interventions and activities for residents and communities to become involved with. The behavioural change wheel, as such, could (if not, should) be amended to incorporate social components as an intervention function whereby these activities enable individuals to participate in sustainability-related behaviour change programmes as part of a collective. Thus, the behaviour change wheel may, itself, be flawed insofar as many behavioural change programmes (particularly at the local level) involve some social and collective elements that address feelings of powerlessness (Aitken, Chapman, & McClure, 2011).

From the analyses in this deliverable and review of behaviour change programmes presented in deliverable 4.4, it is clear that application of particular top-down intervention functions such as coercion, restrictions and incentivisation are minimal. To date, many behavioural change projects have been established, and run, in local communities with an emphasis on informing individuals about strategies for energy saving. While these projects have been beneficial to minimising energy consumption, there impact on overall consumption levels to date has been limited. Consequently, the full range of intervention functions across the behaviour change wheel would, collectively, provide a pathway to further transition to a low-carbon energy system than is currently being realised. The gaps that are highlighted from the analysis of interventions reviewed in deliverable 4.4 reflects a concentration on some, limited approaches to behaviour change and a failure to apply the full range of policy approaches available and highlighted in the literature.

Table 38: Overview of Behaviour Change Initiatives, Classified by Policy Category and Country

Behaviour Change Initiative	Guidelines	Planning	Communication & Marketing	Legislation	Service Provision	Regulation	Fiscal Measures
TOTAL COUNT OF POLICY CATEGORIES	12	8	**118**	10	44	2	8
UK totals	2	1	**31**	3	11	1	4
Ireland totals	2	1	**8**	0	3	0	0
Italy totals	1	1	**6**	2	2	0	0
Spain totals	0	0	**7**	0	4	0	0
France totals	1	1	**7**	0	2	0	0

Table 39: Overview of Behaviour Change Initiatives, Classified by Intervention Type and Country

Behaviour Change Initiative	Restrictions	Education	Persuasion	Incentivisation	Coercion	Training	Enablement	Modelling	Environmental Restructuring
TOTAL COUNT OF INTERVENTIONS	2	60	27	5	0	21	36	25	18
UK totals	0	32	9	3	0	6	15	6	8
Ireland totals	1	9	4	1	0	3	5	6	2
Italy totals	0	6	5	0	0	4	5	4	2
Spain totals	0	5	4	1	0	4	5	4	5
France totals	1	7	4	0	0	4	5	5	1

7.4 New Technologies to Support Energy System Actors

It is clear that for the technological interventions presented in this deliverable that there are substantial impacts from a lack of public engagement and low adoption of proven cost effective technologies for energy efficiency. In addition, how technical interventions are currently employed as well as susceptibility of technical solutions to behavioural influence points to important areas for focus in addressing residential energy consumption and associated CO_2-eq emissions. Table 40 highlights how these limitations can be overcome and new technologies can be leveraged to contribute more effectively to low-carbon transitions by suggesting avenues for new technology development to support energy system actors to realise the full potential of energy savings in the built environment.

Table 40: New Technology Support for Technological Interventions

	Building insulation	**Smart meters**	**Prepayment Meters**	**LED lightbulbs**	**Solar PV microgeneration technology**
Limitations of current technology	Difficult to retrofit external and internal insulation	Not socially embedded, difficult to know how much it can affect behaviour change, and connect to micro technologies and other domestic appliances	Does not offer affordable prices to its users and does not help people adopt energy saving behaviours; Active disadvantaging of users	Remain expensive and not enough people see its benefits; Can suffer from user rebound effects.	Remain expensive and not enough people see its benefits and adopt them; they do not offer a user friendly interface (like home energy monitors)
Potential of new technology in intervention	In the short term, DIY and off the shelf super-efficient product, and cheaper. In the long term, nano-technology could mean products are compact enough that they can be painted on. Longer shelf life of 100 years rather than the 40 years or so for current products.	In the short term, can enhance management of energy use and detect patterns to deliver each household with ‘smart living plan’, early phase just help greater management of energy use. In the long term, further additions to ‘smart living plan’ would include rewards or penalties *e.g.,* carbon credits, council tax allowance, or other; smart metering could link to battery storage capacities to microgeneration technologies to address energy supply/demand/costs issues better.	In the short term, smart meters could help manage through phones and computer apps. In the long term, credit is added via phone and monitored via phone app.	In the short term, cheaper and longer lasting, wider design range. In the long term, motion sensor detection technology built into lightbulb; also so long lasting that they probably do not need replacing at all;	In the short term, product innovations mean they are more affordable and can be bought off the shelf; smarter tariffs for different user groups can encourage more adopters; integration with smart meters to display generation information, *etc.* In the long term, their design is lightweight and compact and can be mounted on any wall and not just those with the right orientations, they may even enable energy storage capacity with the product itself, battery storage will become standard requirement with any microgeneration technology.
How could this contribute	Retrofit is considered a transition	Could aid in the development a smarter home	As part of tackling fuel poverty and a	Contribute to an energy efficient	A proliferation solar PV with other micro generator householders

	Building insulation	Smart meters	Prepayment Meters	LED lightbulbs	Solar PV microgeneration technology
to low-carbon transitions?	intervention; any future new build housing stock would be zero carbon ideally and built to almost passive-house standard where there is very little need for domestic room heating required.	energy system where energy consumption is managed and minimised at a societal level to lessen the impact of unsustainable lifestyles; where the system is so smart that no energy is ever wasted; this is needed to achieve sustainable lifestyles.	more inclusive approach where every consumer can fulfil role as an energy citizen and takes personal responsibility for their energy use; this is needed to achieve sustainable lifestyles. Energy credit linked to social supports	domestic sphere where product designs have energy efficiency and longevity built into them; and a world where no product can be sold unless it is A rated or above and its parts must contribute to the circular economy at the end of its lifecycle.	could collectively aid a local decentralised energy network system with less reliance on the national grid, which could bring new meaning to being prosumer to neighbourhood prosumers. Can aid reducing fossil fuel dependency and form part of a national renewable energy mix system.

The potential for new technological interventions illustrates a number of short term and longer term perspectives. Initially, profiled technological interventions have the potential to become cheaper, longer lasting and more efficient than their unsustainable counterparts. This would engender greater buy-in from individuals at a local level as well as on an industrial scale. The potential of new technologies demonstrates the accessibility that local residents now have to purchase sustainable products providing individuals with an informed choice that, when combined with behavioural interventions such as information provision, allows for greater uptake of these solutions. Furthermore, the development of smart technologies and integration with other technological interventions allows for householders to effectively manage their energy consumption in ways that were once conceived to be challenging. This new visualisation of energy consumption allows for residents to more easily understand energy and their relationship with it, as well as how their actions influence their energy consumption. In the long term, it is suggested that nanotechnologies, enhanced smart technologies, mobile technologies and smart living plans could all have a vital role to play in making residential energy use more manageable, more efficient and less polluting.

Through the application of new technologies, these interventions can contribute to low-carbon transitions in a number of ways. Improving the insulation of existing housing stock supports improving the energy efficiency of residential buildings as well as being an initial intervention for supporting zero-carbon living. Similarly, improvements in lighting also support energy efficiency in residential buildings as well as moving towards improved energy management. When combined with smart technologies and decentralised energy systems, these interventions can substantially change the ways in which energy is consumed within homes as well as the type of energy produced. Decentralised energy systems can contribute significantly to reorienting local systems towards renewable energy and provide sustainable energy to communities. In so doing, this allows for a localised and tailored energy model for each community that removes barriers related to distance in the production and consumption of energy.

From the behavioural perspective, this deliverable has argued that behavioural interventions have not to date successfully orientated lifestyles towards a sustainable paradigm. Only in conjunction with the application of new technologies can the potential of behavioural interventions be unlocked to support low-carbon transitions to the level required.

Table 41: New Technology Supports for Behavioural Interventions

	Information Provision	**Feedback Systems**	**Legal measures and sanctions**	**Community-based projects**	**Personal Carbon Allowances**
Limitations of current technology	Information rarely leads to behavioural change, and meaningful changes to individual lifestyles. Sometimes used in conjunction with other interventions.	Feedback systems can be intrusive and time consuming to prepare. May be ignored if disseminated incorrectly. Focus on billing and consumption.	Political commitment is lacking for regulations and legislation to curb consumption. Often relate to transport and waste.	Lack of funding, wider support and legislative backing. Rely on volunteers and motivation of local community. Spend more time surviving than actions.	Lack of political commitment to idea, uncertain public support, and only one means of monitoring and recording of carbon footprint.
Potential of new technology in intervention	In the short term, tailored information is required to provide individuals with more meaningful advice about energy consumption, disseminated through paper-based and online methods. In the long term, personalised information should be disseminated through attitude apps and smart technologies. Home energy systems should provide 'alerts' indicating where heating and cooling practices could be amended and altered with practical changes.	In the short term, all homes should be provided with smart meters and residents should receive information and training about how to use these technologies effectively for energy management. In the long term, the development of integrated energy systems that provide tailored information on energy consumption and current usage should also provide continuous and comparative feedback within the home and community. Integrating this with SmartPCAs would provide integrated systems.	In the short term, feasibility studies for new legal measures should be considered that relate to energy consumption *e.g.,* percentage of energy provided by renewable sources and banning environmentally inefficient products and technologies. In the long term, regulations should consider further transport and energy related regulations *e.g.,* cap and trade schemes on emissions related to air travel. This measure would complement the use of PCAs as an intervention to support a low-carbon transition.	In the short term, community projects should be supported with access to funding and support. A new community transitions network should be established to share best practice with a knowledge and communication platform incorporated. In the long term, a community hub demonstrating new technologies and practices should be established in the community as a "pop up shop" to disseminate ideas and innovations to residents. Smart technologies should be demonstrated here.	In the short term, applying this intervention would support the creation of new means to record carbon footprints and initially reduce them through an electronic credit card method. In the long term, new smart technologies should replace the credit card method in order to create new "smart users" that can easily identify and manage their carbon footprint with easy access to their personal data. The application of smart phones, watches and meters could lead to SmartPCAs being developed.
How could this contribute to low-carbon transitions?	Through the provision of tailored information disseminated through integrated energy systems, this	Providing instant feedback on energy consumption with tailored information through integrated	Placing a 'ban' or cap and trade scheme on energy use and transport related consumption practices could drastically	Should all or most communities in the EU implement a project, this could substantially contribute a	PCAs could provide a new framing for minimising carbon footprints leading to new innovation for monitoring, recording and supporting sustainable lifestyles and technologies. Combined

	Information Provision	Feedback Systems	Legal measures and sanctions	Community-based projects	Personal Carbon Allowances
	could provide instant access to advice when needed when choosing to act on conscious energy decisions. Exchanging comfort practices with practical changes could reduce energy consumption by up to 30%.	energy systems would allow the visualisation of energy use to become more visible, particularly if the economic costs were aligned with these systems. Such changes could spillover into other behaviours.	reduce material gains that are embedded with carbon intensity. Reducing demand for unsustainable products and activities would support the development of a low-carbon economy and society.	"behavioural wedge" and drastically reduce energy consumption and support new social norms reflecting a low-carbon paradigm. Establishing microgeneration of renewables would support a diversified low-carbon energy system.	with the previous interventions, this could provide a framework for sustainable living that changes the contexts in which people act.

The potential to improve behavioural interventions through the incorporation of new technologies illustrates where particular gaps exist in the current application of these interventions. Most notably, a redesign of behavioural interventions to incorporate new practice areas (such as legal measures and sanctions) as well as integration of technological and behavioural initiatives to more effectively reflect the diversity of energy-related technologies (such as smart technology, phones and applications), could support a meaningful low-carbon transition. Through implementing these interventions concurrently taking account of changing lifestyles and consumption practices, a more significant impact on practice could accrue. Importantly, the improvements to behavioural interventions through incorporating new technologies also holds the potential to create new integrated smart energy systems, particularly through a domestic smart energy system and SmartPCAs. Should these two systems be integrated, this could potentially ground sustainable lifestyles within the control of individuals. However, regulatory and legislative support is required to push forward with the development of this transition. Improved behavioural interventions, supported by emerging technology, could feasibly frame a meaningful low-carbon transition that is reflective of political, social and cultural change. Figure 8 highlights where new technologies are required in the context of existing behaviour change approaches.

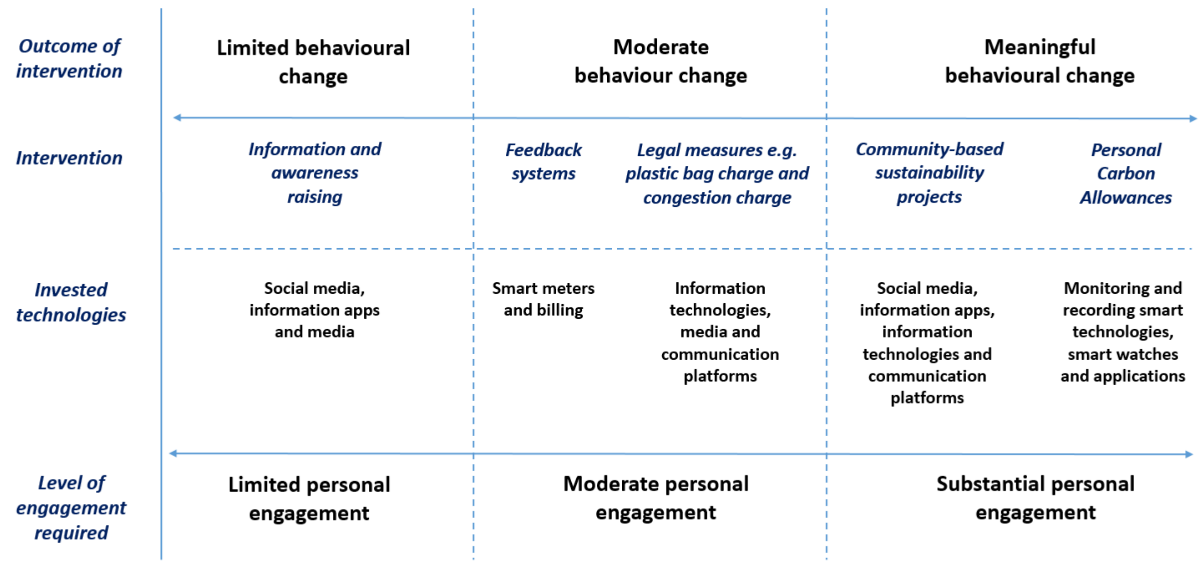

Figure 8: New Technologies Required to Support Behavioural Interventions

Incorporating potential new technologies to behavioural interventions not only improves the ability to influence heterogeneous publics but also improves potential adaptability to changing preferences and motivations of individuals and communities. Behavioural approaches have already demonstrated a number of positive outcomes, but considerable potentials to develop further social change and environmental outcomes remain unrealised. Unlocking this potential could provide enhanced economic outcomes as well as motivation for communities within a wider framework that is personally relevant and meaningful to the individual and to the community. The key element of agency is a critical part of the human factor in the energy system, in terms of enhanced capacity to influence this system and ability to change circumstances at the individual level.

8 Discussion and Conclusions

Governments across the EU have used a range of interventions to deliver CO_2-eq reductions and climate change goals. This has typically been achieved through a mix of interventions, which can be classified into two broad groups, i.e. technology, or behavioural interventions. Through a sociotechnical perspective, this deliverable has provided an in-depth evaluative review of some of the most commonly deployed interventions, including emerging technological and behavioural interventions, as well as less established approaches. Ostensibly there would appear to be a conceptual distinction in current approaches, i.e. that technological interventions and behavioural interventions are typically framed as distinct spheres in policy terms. However, in practice there are many overlaps in the ways in which successful interventions are designed and delivered for effective energy efficiency, sustainability and carbon reduction goals. Behavioural interventions may offer advice and information on how to address domestic energy efficiency through technological interventions such as insulation for instance, while at the same time providing advice on curtailment actions. There is often interconnectivity in the application of intervention strategies and a clear delineation in practice does not exist between behaviour and technology in terms of end-user engagement. For example, smart meters rely much more than other technologies on behavioural changes to be effective; this raises the issue of whether smart meters should be re-classified as a behaviour change intervention rather than as a technological one purely, and interpreted as a tool that affects behaviour. These questions have emerged from analysis in this deliverable and are discussed further in this section.

The analyses of interventions outlined the potential strengths and weaknesses of each intervention. The analyses reinforce existing practical knowledge and theoretical underpinnings of particular interventions and highlights implications of their impact and future development. For example, it observed that typically behavioural interventions focus on changing the individual and to a more limited degree the social context of household energy consumption. In contrast technological interventions (including infrastructures and associated support systems) typically seek to address the material context of energy consumption practices, which may then influence the nature of individual behavioural responses and consequently the forms of consumption that arise (as proposed by Southerton *et al.* (2011).

Table 42: Summary of Key Characteristics of Behavioural and Technological Interventions

Technological interventions	Key features	Level of user effort or engagement with interventions	Behavioural Change interventions	Key features	Level of user effort or engagement with interventions
Building insulation	Technology adoption measure/ Consequence measure	Low user effort	Information and awareness raising	Antecedent measure	Low user effort
LED lightbulbs	Technology adoption / Consequence measure	Low user effort	Feedback systems	Consequence measure	High user effort
Solar PV	Technology adoption / Consequence measure	High user effort	Legal measures and sanctions	Consequence measure	Low user effort
Smart Meters	Consequence measure	High user effort	Community-based sustainability projects	Social influence/ Antecedent measure	High user effort
Pre-payment meters	Consequence measure	High user effort	Personal Carbon Allowances	Consequence measure	High user effort
4Es Element: ENCOURAGE/ENABLE			**4Es Element: ENGAGE**		

Table 42 above summarises some of the most salient characteristics identified for groups of profiled interventions as well as key features, level of user effort required and policy engagement. As described, behavioural interventions typically rely on antecedent measures using information, awareness raising and feedback through *e.g.,* information workshops; energy audits, energy saving campaigns. These are also commonly deployed within community-based sustainability projects, which often combine antecedent, and social influence measures. However, behavioural interventions that rely solely on legal or sanction style measures are much rarer in practice. Behavioural interventions nearly always require voluntary participation and emphasise nudging people to change as well as increasing people's choices rather than limiting or controlling choice. However, controls on choice intrinsically underpin technological interventions through the regulations, legislations, standards and other tools (discussed later below) from which they arise.

Technological interventions were chosen to demonstrate their functional heterogeneity and the diverse scales across which they operate. The technological interventions profiled encompass building specific technological interventions (i.e. insulation), appliance specific (*e.g.,* LED lightbulbs, and solar PV); and infrastructural and energy management and renewable technologies (*e.g.,* Smart meters and PPMs). These interventions in contrast to the *antecedent measures* typical of behavioural interventions tend to be defined as *consequence measures* but often include technology adoption as their key defining feature. The presented analysis in Section 5 suggests that Abrahamse *et al.*'s three tier categories (*e.g.,* Antecedent, Consequence and Social influence measures) of energy saving measures should perhaps include a further dimension to include 'energy efficiency measures' as a fourth dimension where people simply adopt insulation or efficient appliances as a stand-alone measure.

The profiling of interventions enabled further understandings of the level of user effort or engagement required with each intervention. While distinctions such as those between efficiency behaviours (purchasing LED lightbulbs or any energy efficient appliances) and curtailment behaviours (require user actions where the lightbulbs are switched off when not being used) are important for energy saving interventions, in practice an integrated understanding of behavioural and technological understandings is required. Such an integrated perspective could better frame how users engage with differing interventions and the actions involved. A key feature of all the interventions examined was that each intervention required some form of user effort or engagement with it. Importantly, differing levels of user efforts are required depending on whether the technology in question is a building, appliance or lifestyle specific intervention. Thus, while solar PV is a technological intervention that requires high user effort in terms of gaining the full optimal level of benefits, in contrast building insulation or information based interventions will require low levels of user effort. In relation to any given technological adoption, energy efficiency competency is typically 'black boxed' into the technology, which means that the design of the technology is blind to any user indifference and assumes correct use. However, energy efficiency technology adoption is a process not a single event, where the energy savings credential takes time to materialise through correct user appropriations. It cannot be assumed that correct use of technology and energy efficiency will materialise as soon as the end-user adopts it. Ultimately, technological interventions foster change at different scales from individual, buildings, technological and societal contexts, and there is likely to be a gap between potential technology performance and actual end-user interactions with interventions (similar to the energy performance gap).

The evaluation of the profiled interventions holds particular implications in relation to the 4Es policy tool to help policymakers to deliver sustainable development and behaviours (Described in Section 2). One of the key assertions of this framework is that all four principles need to be met in order to effectively achieve behavioural changes. The profiled interventions highlight strong policy support for technological adoption while policy support for behavioural interventions remains relatively weak and not extensively applied.

Technological interventions profiled seem to largely reply upon *Encourage and Enable* policy such as financial incentives including feed-in-tariffs, subsidy incentives such as boiler scrappage schemes, or energy labelling, *etc.*

In contrast, behavioural strategies largely rely upon *Engage* (which represent social influence/antecedent measures). These work on an information deficit model and seek to engage individuals, and target voluntary behaviour changes and often undertaken by NGOs or civil society, usually without the underpinning of a direct formal mandatory policy or regulatory push. The two intervention groups show that in practice they both are driven by one or two components of the 4Es framework rather than all four. Hence, it appears tipped in favour of technology adoption. The profiled evaluations reinforce that a mix of behavioural and technological interventions are required to address energy and emissions goals. Many of the successes in delivering sustainability to date have come from setting mandatory standards, targets and fiscal incentives *e.g.,* Mandatory A-G rating, Carbon Emissions Reduction Targets, Feed-in-Tariffs, *etc.* Thus, their potentials and inter-dependencies should not be under-estimated and they could collectively contribute to the whole – in overall environmental goals. Stakeholder agency and capacity for involvement is an important theme that emerged from analysis. Figure 9 shows the 4E's model for sustainable lifestyles mapped onto the Energy Practitioners Agency Spectrum developed for this deliverable. It is clear that differentiated engagement strategies need to be applied for stakeholder with different levels of agency, control and capacity.

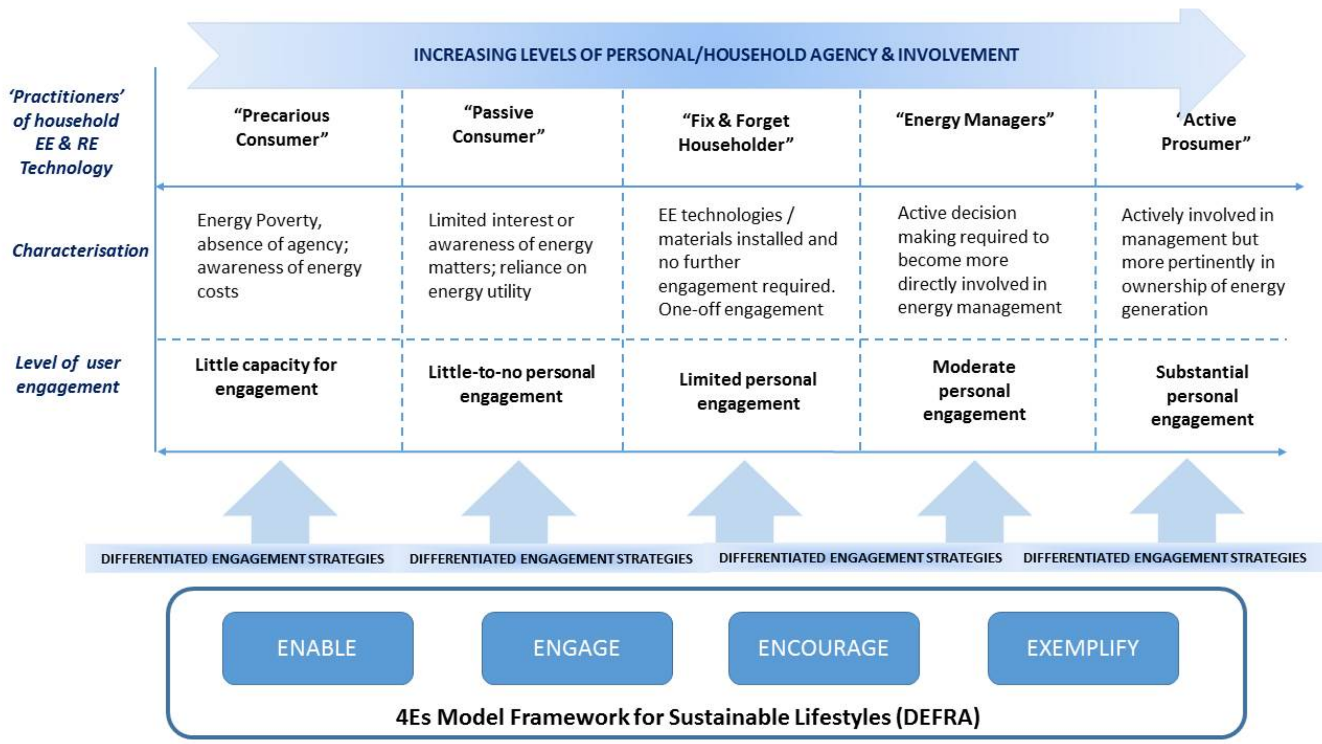

Figure 9: Applying the 4E's Model for Sustainable Lifestyles to the Energy Practitioners Agency Spectrum

To mobilise stakeholders sufficiently for the low-carbon transition, more stakeholders need to be located to the right hand side of the "Energy Practitioners Agency Spectrum". This raises a number of important questions

(Key Questions that emerge from Figure 9):

- **How can we move Energy Practitioners from the 'Precarious Consumer' end of the spectrum to the 'Active Prosumer' end of the spectrum?**
- **Which of the '4Es' strategies should be applied, at which point of the spectrum?**
- **How can we build energy capacity and practitioner agency for all energy users, in a way cognisant of distributive justice and social equity principles?**
- **Should the low-carbon transition be re-framed as a transition of stakeholder agency, capacity, skills and knowledge rather than a technological transition?**

Profiled interventions selected for analysis fall within three key themes of the energy hierarchy (Figure 3); these include, **energy management**, **energy efficiency** and **microgeneration renewable technology** adoption within the hierarchy. The first tier at the bottom of the energy hierarchy pyramid and the largest component broadly advocates energy management (including energy conservation) which should ideally be considered before other measures in the hierarchy. This level emphasizes reducing demand for energy by removing waste in end-user consumption. Energy management is perceived the cheapest and easiest level of the hierarchy in which to achieve change. The energy management level is where a large proportion of behavioural interventions are focused and where the message is often about 'changing individual or household behaviour to save money on bills'. In practice reducing demand usually requires avoiding waste, which means turning off heating, lighting and other energy systems when they are not needed, or not leaving things on standby. Energy curtailment behaviour change is increasingly being addressed in conjunction with smart technology or home energy monitors.

The second level of the hierarchy focuses on energy efficiency improvements, which should only considered after a level of reduced demand has been achieved. This level is likely to be more expensive than simple curtailment based behavioural interventions yet less expensive and easier to deliver than the adoption of renewable energy technologies. Typically, improving energy efficiency require some form of technological intervention, for example at the building this commonly means using insulation to reduce the energy use in space heating and through low-energy efficient lighting systems such as LEDs. Thus, energy use reductions are achieved by improving the efficiency of heating, lighting and other energy-consuming processes. Once energy management and efficiency measures have been effectively applied, the impact of renewables is enhanced by the previous improvements, where renewable microgeneration will now reduce energy demand from fossil fuel generation (at the macro-level centralised energy supply systems).

In practice, the current nationalised roll-out of smart meters and the drive for smarter homes suggests government reliance on technological interventions as a starting point to energy management rather than behaviour change first. The design and function of smart meters by virtue of the fact that this technology largely provides feedback to the user positions itself between both technological and behavioural interventions. As a stand-alone measure, smart meters cannot reduce energy consumption nor provide energy efficiency through a fit-and-forget means like insulation. Smart meters (with associated home energy monitors) represent a material object being used to drive and influence user behaviour and to encourage particular forms of energy consumption. Therefore as technical tool smart meters contain conceptual ambiguities which suggest that this particular technology does not fit neatly into the energy hierarchy, as described in Figure 3. Arguably smart meters represent an opportunity to become a new level within the hierarchy and one that would actually precede the energy management level. Smart meters therefore have the potential to become a tool that could activate behaviour change (Figure 10 shows revised energy hierarchy which reflects this potential capacity to 'script' energy use and subsequent energy management practices in the home).

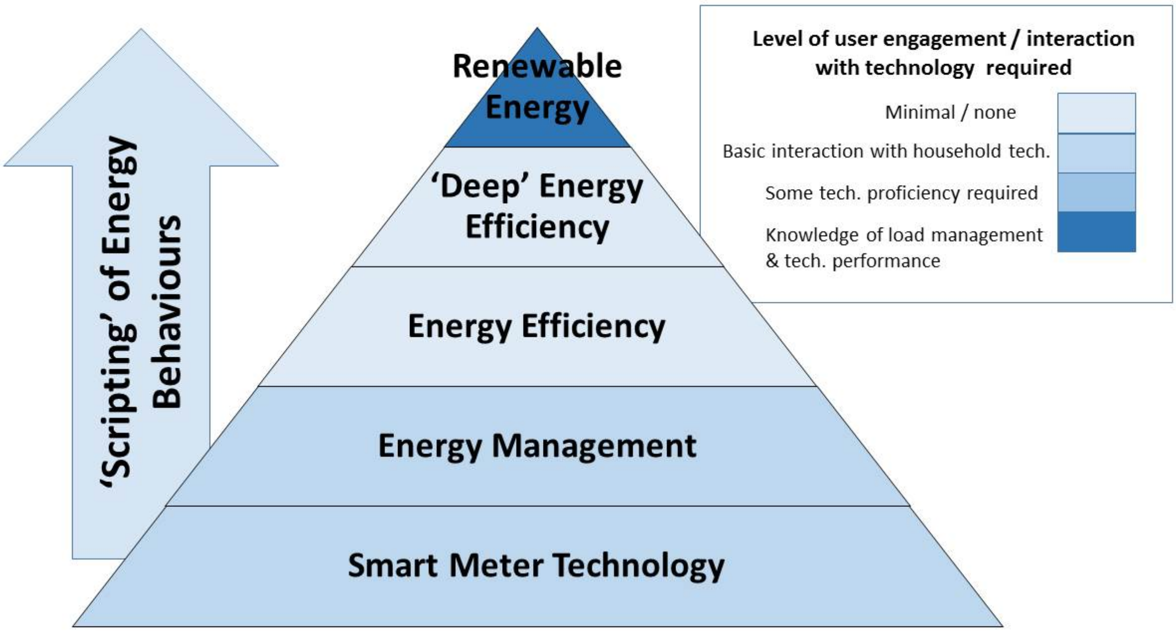

Figure 10: Revised Energy Hierarchy Consumption Reduction Pyramid Model

Thus, the insertion of smart meters and other smart technologies proposes a new dynamic and a reconfiguration of where other interventions sit in relation to this technology. The policy drive for smart meters suggests a radical change in capacity for control and management emerging at the household level. At a micro level, smart meters in order to be effective require high levels of consumer engagement and assumes through an information deficit model whereby better information to consumers will result in reduced energy use. Secondly, at a macro-level, the nationwide roll-out seeks a technological, systemic, cultural and infrastructural change to deliver macro-level energy policy and industry goals (*e.g.,* achieving energy security). Hence, smart meters have become part of a nationalised effort to create smarter homes and a smart grid, which itself part of a wider international low-carbon and climate change agenda.

While existing research shows how differing theoretical viewpoints underpin differing understandings of energy behaviour and where there are many theoretical conflicts and tensions, in practice policies take a whole range of theories into account when designing policies. For example, when deciding to adopt insulation, the economic considerations remain important (i.e. installing costs and whether it is affordable) for the adoptee. There are also social factors, for instance how different actors – homeowners, suppliers, installers *etc.* – relate to each other, what likely level of knowledge and acceptability of the intervention will be *etc.* From a policy intervention viewpoint, curtailment behaviour is considered to be a sustainable, durable and long term option, yet also acknowledged as being exceptionally difficult to successfully deliver as it requires time and resources as well as a less clear-cut delivery process. In designing such policy, interventions need to take account of both internal factors: attitudes, values, habits, personal norms) and external factors: fiscal and regulatory incentives; institutional constraints; and social practices and contexts.

This deliverable has sought to categorize and outline the extent to which profiled interventions have been successful. The analysis of the adoption of interventions reinforces the view that it is easier to change single investment decisions (adoption insulation or buy energy efficiency appliances) rather than changing daily behaviour. Furthermore, greater support for technology adoption suggests that policymakers may perceive the energy savings resulting from such measures as more likely to deliver long term and predictable impacts. Conversely, behavioural measures may have transitory effects and may appear to be more difficult to sustain in the medium-long-term.

Finally, this deliverable provides indications for the direction for policy change to achieving low-carbon transition. A comparative review of profiled interventions with the 4Es model indicates that the Engage and Exemplify components are not effectively activated adequately and are the weakest of the four components of this model in current approaches. In order to bridge this gap household energy solutions should be co-produced, as part of a collective and participatory approach, where citizens are engaged as active energy consumers or prosumers. This requires sociotechnical solutions where stakeholders bring together human, non-human artefacts and other components to address what is a collective public (environmental and social) problem. The interconnectivity of behavioural and technological interventions and the need for their integration – as shown in this analysis - suggest that the goal to achieve a low-carbon transition needs to be pursued with a broad sociotechnical understanding. Formulating a co-produced sociotechnical approach proposes a transition marked by stakeholder agency, capacity, skills, artefacts and knowledge inputs in mobilizing change that may open it up to differing possibilities for social and systemic changes.

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Appendix 1

Full Costs Data Model

Parameter	Year of Data	Meta-data	Ireland	Italy	UK	France	Spain
Number of residential buildings	2014	Absolute no.	1744430	31963850	28384210	33894000	26567070
Electricity consumption by households	2015	1 000 tonnes of oil equivalent	677.60	5691.10	9299.80	13107.60	6023.70
Electricity consumption by households		Total kWh	7880488000	66187493000	1.08157E+11	1.52441E+11	70055631000
Electricity consumption per household (KwH)		KWh per household	4517.514604	2070.698398	3810.452149	4497.59214	2636.934784
CO2 intensity of Grid	2017	gCO2-eq/kWh	325	384	235	46	301
% fossil fuel use for electricity	2017	% value	54%	61%	46%	5%	46%
Electricity Prices for Residential Sector	2016	€ per kWH	0.234	0.234	0.183	0.171	0.228
Smart Meters - numbers	2020	No. Metering points	2200000	36700000	31992000	35000000	27768258
Smart Meters - cost	2017	€ / meter	473	94	161	135	345
Smart Meters - Potential for	2017	% energy saving potential	2.9%	2.5%	2.2%	2.5%	2.5%

Parameter	Year of Data	Meta-data	Ireland	Italy	UK	France	Spain
Energy Saving (%							
Electricity consumption of lighting for residential	2014	1 000 tonnes of oil equivalent	120	830	970	790	700
Electricity consumption of lighting for residential (kWh)	2014	kWh	1395600000	9652900000	11281100000	9187700000	8141000000
Electricity consumption of lighting per household	2014	KWh per household	800.0321022	301.9942842	397.4428036	271.0715761	306.4319852
% CFL Lamps of total	2012	% of total	14%	17.50%	12%	15.50%	8%
Installed lighting capacity	2011	(W) per household	1600	1700	1600	1500	1600
% non-ee lighting	2012	% of total	86%	83%	88%	85%	92%
Installed non-ee lighting capacity		(W) per household	1376	1411	1408	1275	1472
Number of 35W equivalent bulbs		No.	39	40	40	36	42
Total Capacity PV Electricity	2016	MW	17	18983	11547	7134	5491
Share of Electricity Demand covered	2016	% of total electricity	0.00%	9.00%	3.00%	2.00%	3.50%

Parameter	Year of Data	Meta-data	Ireland	Italy	UK	France	Spain
by Solar							
LCOE for generation of residential PV	2015	€/kWh	0.1566	0.084	0.1647	0.1281	0.09225
Heating consumption per m2	2012	ktoe /m2	8.00	8.00	10.5	11	4.00
Total Floor Space	2017	Million M2	210.75	2,986.71	2,726.83	3,115.25	2,433.82
Heating Load	2017	million ktoe	1686	23893.68	28631.715	34267.75	9735.28
Number of buildings pre-1991	2011	number	1046658	29406742	21855841.7	27115200	19128290.4
% buildings pre-1991	2011	%	60%	92%	77%	80%	72%
CO_2 per useful floor space	2011	Kg CO2 / m2	125	42	65	25	30
Average Floor Size	2011	m2	40.45	41.58	40.4	39.4	37.46
CO2 per household: Electricity	2015	Kg CO2	1468.19	795.15	895.46	206.89	793.72
CO2 per household: Lighting	2015	KgCO2	260.01	115.97	93.40	12.47	92.24

Appendix 2

Survey of Behaviour Change Projects – Behaviour Change Wheel Categories

Behaviour Change Initiative/Project	Country	Guidelines	Planning	Communication & Marketing	Legislation	Service Provision	Regulation	Fiscal Measures
Green Doctors - Southway Housing Trust	UK			1		1		
Relish - Worthing Homes	UK			1				
Bexley Warm Homes Scheme	UK					1		
EDRP	UK			1				
Smart Meters & Smart People	UK			1		1		
Stockbridge Village Energy Champions	UK			1				
Carbon Conversations	UK			1				
Climate Change Fund (CCF)	UK				1			1
Government Energy Rebate	UK				1			1
Big Energy Vision	UK			1				
Transition Towns	UK			1		1		
Zero Carbon Homes	UK	1	1		1		1	1
StepGreen.org	Online, but worldwide			1				
Better Neighbours	UK			1				
Domestic Energy Advice	UK			1				
Eco Teams UK (1)	UK			1				
Green Streets UK	UK			1		1		
Eco Teams UK (2)	UK			1				
Manchester is My Planet	UK			1				1
Transitions Streets	UK			1		1		
Energy neighbourhoods	Europe-wide			1				
Wattbox	UK			1				
Relish, Worthing Homes	UK			1		1		
Affinity Sutton - FuturFit	UK			1		1		

Behaviour Change Initiative/Project	Country	Guidelines	Planning	Communication & Marketing	Legislation	Service Provision	Regulation	Fiscal Measures
Green Doctor Initiative - Southern Housing Group	UK			1		1		
Plugin (GAP)	UK			1				
Residents Energy Guide (ASFL)	UK			1				
Southway Housing Trust - residents Energy Guide	UK			1				
Washing in Wales	UK			1				
Energising London	UK			1				
Smart Homes	UK			1		1		
Warmer Homes Brent	UK			1				
E.ON pioneers smart home - The Thinking Energy	UK	1		1		1		
Eco Teams - GAP	UK			1				
SuperHomes Green Open House events	UK			1				
The Big London Energy Switch	UK			1				
The Smart Meter Project	UK			1				
NZEB Open Door Ireland	Ireland			1				
Cloughjordan Ecovillage	Ireland	1	1	1		1		
EcoTourism Ireland	Ireland	1		1				
Power Off Save	Ireland					1		
Energy Action	Ireland			1		1		
Power Of One	Ireland			1				
Transition Town Kinsdale	Ireland			1				
Future Proof Kilkenny	Ireland			1				
Transition Town Donabate/Portrane	Ireland			1				
Climate for Change - gender equality and climate policy	Italy	1			1			
Energy Roadmap Modena 2014 – 2050	Italy				1			
FarmduepuntoZERO	Italy		1			1		
M'illumino di meno	Italy			1				
No lift days Giornate senza ascensore	Italy			1				

Behaviour Change Initiative/Project	Country	Guidelines	Planning	Communication & Marketing	Legislation	Service Provision	Regulation	Fiscal Measures
SMARTinMED	Italy			1				
FIDIA sport	Italy					1		
Italia en Transition	Italy			1				
Biellese in Transizione	Italy			1				
Scandicci TT (Florence)	Italy			1				
Rubi Brilla	Spain			1				
Som Energia (generation kwh)	Spain					1		
Ni un Hogar Sin Energía	Spain			1				
Projecte Desendolla't	Spain			1		1		
Illa efficient BCN	Spain					1		
Carrega't d'Energia	Spain			1		1		
Red de Transcion Espana	Spain			1				
Ibiza Transition Island	Spain			1				
Barcelona en Transicio	Spain			1				
Nice Grid	France			1		1		
Darwin Ecovillage	France	1	1	1		1		
Familles à énergie positive	France			1				
AffichEco	France			1				
SQYen Transition	France			1				
Trieves en Transition	France			1				
Toulouse in Transition	France			1				

TOTAL COUNT OF POLICY CATEGORIES		6	4	61	5	22	1	4

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Behaviour Change Initiative/Project	Country	Restrictions	Education	Persuasion	Incentivisation	Coercion	Training	Enablement	Modelling	Environmental Restructuring
Green Doctors - Southway Housing Trust	UK		1				1	1		
Relish - Worthing Homes	UK		1							
Bexley Warm Homes Scheme	UK		1					1		1
EDRP	UK		1					1		1
Smart Meters & Smart People	UK		1		1				1	
Stockbridge Village Energy Champions	UK		1	1			1	1		
Carbon Conversations	UK		1	1				1	1	
Climate Change Fund (CCF)	UK				1			1		
Government Energy Rebate	UK				1					
Big Energy Vision	UK		1					1		
Transition Towns	UK		1	1			1	1	1	1
Zero Carbon Homes	UK							1		1
StepGreen.org	Online		1					1		
Better Neighbours	UK		1							
Domestic Energy Advice	UK		1							
Eco Teams UK (1)	UK		1							
Green Streets UK	UK		1							1
Eco Teams UK (2)	UK		1							
Manchester is My Planet	UK		1	1			1	1	1	
Transitions Streets	UK		1	1			1	1	1	
Energy neighbourhoods	Europe-wide			1						
Wattbox	UK		1					1		
Relish, Worthing Homes	UK		1							1
Affinity Sutton - FuturFit	UK		1							1
Green Doctor Initiative - Southern Housing Group	UK		1				1	1		

Behaviour Change Initiative/Project	Country	Restrictions	Education	Persuasion	Incentivisation	Coercion	Training	Enablement	Modelling	Environmental Restructuring
Plugin (GAP)	UK		1							
Residents Energy Guide (ASFL)	UK		1	1				1		
Southway Housing Trust - residents Energy Guide	UK		1							
Washing in Wales	UK		1							
Energising London	UK		1							
Smart Homes	UK		1							1
Warmer Homes Brent	UK		1	1				1		
E.ON pioneers smart home - The Thinking Energy	UK		1							
Eco Teams - GAP	UK		1							
SuperHomes Green Open House events	UK		1						1	
The Big London Energy Switch	UK		1	1						
The Smart Meter Project	UK		1	1						
NZEB Open Door Ireland	Ireland		1						1	
Cloughjordan Ecovillage	Ireland	1	1				1	1	1	1
EcoTourism Ireland	Ireland		1							
Power Off Save	Ireland		1		1			1	1	
Energy Action	Ireland		1							1
Power Of One	Ireland		1	1						
Transition Town Kinsdale	Ireland		1	1				1	1	
Future Proof Kilkenny	Ireland		1	1			1	1	1	
Transition Town Donabate/Portrane	Ireland		1	1			1	1	1	
Climate for Change - gender equality and climate policy	Italy		1							1
Energy Roadmap Modena 2014 – 2050	Italy		1							
FarmduepuntoZERO	Italy									1

Behaviour Change Initiative/Project	Country	Restrictions	Education	Persuasion	Incentivisation	Coercion	Training	Enablement	Modelling	Environmental Restructuring
M'illumino di meno	Italy		1	1						
No lift days Giornate senza ascensore	Italy			1				1		
SMARTinMED	Italy						1			
FIDIA sport	Italy							1	1	
Italia en Transition	Italy		1	1			1	1	1	
Biellese in Transizione	Italy		1	1			1	1	1	
Scandicci TT (Florence)	Italy		1	1			1	1	1	
Rubi Brilla	Spain		1							1
Som Energia (generation kwh)	Spain				1					1
Ni un Hogar Sin Energía	Spain							1		1
Projecte Desendolla't	Spain									1
Illa efficient BCN	Spain									1
Carrega't d'Energia	Spain		1	1			1	1	1	
Red de Transcion Espana	Spain		1	1			1	1	1	
Ibiza Transition Island	Spain		1	1			1	1	1	
Barcelona en Transicio	Spain		1	1			1	1	1	
Nice Grid	France		1					1	1	
Darwin Ecovillage	France	1	1				1	1	1	1
Familles à énergie positive	France		1	1						
AffichEco	France		1							
SQYen Transition	France		1	1			1	1	1	
Trieves en Transition	France		1	1			1	1	1	
Toulouse in Transition	France		1	1			1	1	1	

Behaviour Change Initiative	Restrictions	Education	Persuasion	Incentivisation	Coercion	Training	Enablement	Modelling	Environmental Restructuring
TOTAL COUNT OF INTERVENTIONS	2	60	27	5	0	21	36	25	18

Appendix 3

Commonly Adopted Technological Interventions – Residential Sector

Intervention	Broad category of intervention	Description of Intervention & How intervention is being used (Adoption)	Other features of interventions.	Complexity = Basic; Intermediate; advanced	Behaviour Change needed?	Indicative Cost Range (illustrative typical cost to install)
Condensing boiler (A++ rated)	Energy efficiency - Building Fabric - Heating system	Condensing boilers provide high efficiency water heating system fueled by gas or oil. Replacing an older boiler with condensing boiler(A++) is more efficient and costs less to run condensing boilers are more efficient than conventional ones; varying costs; retains cylinder using gas or oil; boiler efficiency is stated as a rating on a boilers ErP energy label from A-G. Nearly all modern gas condensing boilers get an A energy rating.	They achieve high efficiency (typically greater than 90% on the higher heating value) by condensing water vapour in the exhaust gases and so recovering its latent heat of vaporisation, which would otherwise have been wasted. This is often supported through financial incentives/subsidies	Advanced	No	€€€€
Combi Boiler	Energy efficiency - Building Fabric - Heating system	Combi boiler provides high efficiency water heating & central heating. Combi boilers are more efficient than conventional ones; with varying costs; boiler efficiency is stated as a rating on a boilers ErP energy label from A-G.	Combi boilers are considered every energy efficiency measure widely adopted; Using a timer on the thermostat is required to manage when it is being used or turned off.	Advanced	No	€€€€
Heating controls - thermostatic radiator valves (TRVs)	Energy efficiency - Building Fabric - Heating system	Heating systems controls enable correct temperatures without wasting fuel. TRVs are commonly installed alongside central heating radiators for heating rooms.	These are commonly found alongside central heating systems in households. Help with energy use management and saving money will depend on lifestyle	Basic	Yes	€€€
room thermostat or timer or programmer, including boiler thermostat/ smart heating controls	Energy efficiency - Building Fabric - Heating system	Room thermostats enable correct temperatures without wasting fuel. TRVs are commonly installed	These are commonly found alongside central heating or boiler systems in households. Help with	Medium	Yes	€€€

Intervention	Broad category of intervention	Description of Intervention & How intervention is being used (Adoption)	Other features of interventions.	Complexity = Basic; Intermediate; advanced	Behaviour Change needed?	Indicative Cost Range (illustrative typical cost to install)
		alongside central heating radiators for heating rooms and alongside boilers.	energy use management and saving money will depend on lifestyle			
Under-floor heating	Energy efficiency - Building Fabric - Heating system	Under-floor heating can be either a 'wet' system that pumps warm water through pipes under the floor, or 'dry' system of electric coils placed under the floor	It is considered an alternative to traditional radiators or hot-air heating systems. It offers energy efficiency in the home.	High	No	€€€€
Heat recovery systems and devices - Passive flue gas heat recovery systems	Energy efficiency - Building Fabric - Heating system	Heat recovery systems and devices - Passive flue gas heat recovery systems help to recover and re-use waste heat from boiler. These systems are a less common but gaining popularity for as a retrofit device	They are at best a retrofit devices for older boilers that capture waste heat from flue gases and reuse it, to improve the efficiency of hot water production and save fuel and money. It offers energy efficiency in the home.	Medium	No	€€€€
MVHR (mechanical ventilation with heat recovery) - whole house	Energy efficiency - Building Fabric - Ventilation	MVHR (mechanical ventilation with heat recovery) - are available as a single room or whole house option. They offer controlled ventilation; control the air flow by sealing up all those old air leaks, using mechanical ventilation instead. It is seen as complimentary system where there is a highly insulated home	It is effective and useful when there are high levels of insulation and airtightness. It improves the air quality and thermal comfort in home.	Medium	No	€€€€
Cavity wall insulation	Energy efficiency - Building Fabric	Insulating materials used to fill fills gaps often found between external walls. It is a common and low cost effective measure.	This is only appropriate for pre-1990's houses with gap between internal and external wall	Basic	No	€€€
Roof & Loft insulation	Energy efficiency - Building Fabric	Adding Insulation materials to reduce heat loss and reduce your heating bills. It is a common and low cost effective measure.	This insulation type is effective for at least 40 years after which it will need replacing or topping up. It improves the thermal efficiency of buildings.	Basic	No	€€€

Intervention	Broad category of intervention	Description of Intervention & How intervention is being used (Adoption)	Other features of interventions.	Complexity = Basic; Intermediate; advanced	Behaviour Change needed?	Indicative Cost Range (illustrative typical cost to install)
Internal wall insulation	Building Fabric	Internal wall insulation requires fitting by trained professionals rigid insulation boards to the wall, or by building a stud wall filled in with mineral wool fibre. It is expensive but gaining wider social acceptance.	Numerous materials are available on the market as a solution for solid walled older housing. It improves the thermal efficiency of buildings.	Medium	No	€€€€
External wall insulation	Energy efficiency - Building Fabric	External wall insulation requires fitting by trained professionals and requires fixing a layer of insulation material to the wall, then covering it with a special type of render (plasterwork) or cladding. Internal wall insulation requires fitting by trained professionals rigid insulation boards to the wall, or by building a stud wall filled in with mineral wool fibre. It is expensive but gaining wider social acceptance.	Numerous materials are available on the market as a solution for solid walled older housing. It improves the thermal efficiency of buildings.	Medium	No	€€€€
Draught proofing	Energy efficiency - Building Fabric	Often undertaken as a low cost DIY measure to prevent heat loss. Can be utilised in older homes or where replacing glazing is too expensive	It is a well-established action that can be effective as a short term measure. Professional services which cost more than DIY are available. Some of these measures are available free with community energy projects.	Basic	No	€€
Floor insulation	Energy efficiency - Building Fabric	Floor insulation is used to seal the gaps between floors and skirting boards to reduce draughts. It is used to prevent heat loss via the floor where there is a raised floorboards or solid floors. Its adoption is prevalent in older housing.	The costs vary significantly depending on work. Numerous materials are available on the market as a solution for solid walled older housing. It improves the thermal efficiency of buildings. It is seen as an insulation	Advanced	No	€€€€

Intervention	Broad category of intervention	Description of Intervention & How intervention is being used (Adoption)	Other features of interventions.	Complexity = Basic; Intermediate; advanced	Behaviour Change needed?	Indicative Cost Range (illustrative typical cost to install)
			measure alongside wall and roof insulation.			
double glazing (A+)	Energy efficiency - glazing and doors	Two sheets of glass with a gap in between, usually about 16mm, to create an insulating barrier that keeps heat in. It is a relatively affordable and common measure.	The costs vary significantly depending on the number of windows. It improves the thermal efficiency of buildings and seen as an insulation measure alongside wall and roof insulation.	Basic	No	€€€€
triple glazing (A+)	Energy efficiency - glazing and doors	Triple glazing uses three sheets of glass to keep heat in. It is an expensive yet growing in popularity in adoption.	Triple glazing is not always considered better than double glazed windows. It improves the thermal efficiency of buildings and seen as an insulation measure alongside wall and roof insulation.	Basic	No	€€€€
secondary glazing	Energy efficiency - glazing and doors	Secondary glazing requires the addition of a pane of glass fitted over the window internally increasingly used in older historic houses/buildings where it is too costly to replace existing frames or because of planning restrictions.	It is seen as a cheaper option to double glazing. It may cause condensation, and the efficiency is not as good as they are not sealed units.	Basic	No	€€€
Ground source heat pumps (GSHP)	Microgeneration - Room heating	Ground source heat pumps captures warmth from below ground and used as a reliable, renewable heat source to run central heating systems. They are expensive and less commonly adopted renewable technology	Cost is the biggest deterrent for its adoption although the RHI is available. Its distinctive feature is the pipework, usually about 100m of it, which is buried in loops in trenches (photo, below) or in one or more vertical boreholes. However, this may not be an option with those with little garden space and lack of knowledge can hinder its social acceptance.	Advanced	Yes	€€€€
Air source heat pumps	Microgeneration	There are Two types: Air	Cost is the biggest	Advanced	Yes	€€€€

Intervention	Broad category of intervention	Description of Intervention & How intervention is being used (Adoption)	Other features of interventions.	Complexity = Basic; Intermediate; advanced	Behaviour Change needed?	Indicative Cost Range (illustrative typical cost to install)
(ASHP)		to Air or Air to Water. They work in reverse to a refrigerator - the air is drawn into pump where it meets liquid refrigerant which turns into gas, which is compressed, raising temperature and producing heatpumps extract heat from below ground for use in heating and hot water; offers renewable heat source to run central heating systems for our homes.	deterrent for its adoption although the FiT available. Finding the space for the device and lack of knowledge can hinder its social acceptance. A lack of the appropriate roof orientations can hinder its adoption for some homes.			
Solar thermal hot water heating	Microgeneration	Solar thermal uses free heat from sun, and panels to generate heat and hot water. This is slightly less common than Solar PV but still widely adopted renewable technology. Prices are lowering and driven by incentives	It is regarded as a key renewable heat source with FiT incentives available	Advanced	Yes	€€€€
Solar PV	Microgeneration	Solar PV uses free heat from sun, and PV panels to generate electricity. One of the most common and widely adopted renewable technologies. Prices are lowering and driven by incentives	It is regarded as a key renewable heat source with FiT incentives available. A lack of the appropriate roof orientations can hinder its adoption for some homes.	Advanced	Yes	€€€€
Domestic biomass boiler	Microgeneration	Domestic biomass boilers are stand-alone stoves or offer back boilers to heat hot water. They are used in homes as wood burner/stoves where fuels include recycled wood or wooden pellets and other organic material products. They are expensive and yet increasing in popularity and adopted. They are seen as a sustainable	This is seen as carbon neutral as it still burns fossil fuels but seen as sustainable alternative as new trees can be re-planted; It contains complexity in its fuel options from many different technological products. These are not feasible options for flats and can be expensive to run.	Advanced	Yes	€€€€

Intervention	Broad category of intervention	Description of Intervention & How intervention is being used (Adoption)	Other features of interventions.	Complexity = Basic; Intermediate; advanced	Behaviour Change needed?	Indicative Cost Range (illustrative typical cost to install)
		technology				
Micro-CHP boilers	Microgeneration	Micro-CHP boilers are stand-alone stoves or offer back boilers to heat hot water. They are expensive and less commonly adopted renewable technology	This is seen as carbon neutral as it still burns fossil fuels but seen as sustainable alternative as new trees can be re-planted. Fuel costs may vary dramatically but will generally cost less per kilo depending on the size of the order.	Advanced	Yes	€€€€
Micro Wind turbine	Microgeneration	Micro Wind turbines use dual energy system to generate heat and hot water and same time produce electricity. It uses free wind power; there are two types: roof mounted or stand alone; they connect directly to national grid or the energy can be stored in a battery. They are expensive and less commonly adopted renewable technology	Renewable heat source because of the way it re-uses waste heat to generate electricity; for the average home will cost between €14,000 and €19,000 including installation, flue, fuel store and VAT at 5%.	Medium	Yes	€€€€
Smart meters with in-home display	energy management B21	Smart meter devices are gas and electricity meters with accompanying in-home displays which help keep track of energy use in homes. Individuals can find out daily and weekly costs, identifying periods of time that are energy intensive and those appliances that use significant amounts of energy.	Smart meters have become successful in particular areas of reducing energy consumption, although this is dependent upon individual attitudes towards energy consumption. It has been recorded that individuals whose homes equipped with a smart meter do monitor their energy consumption and attempt to reduce their energy use to minimise energy costs. Studies have shown that this is particularly identifiable in both affluent and socio-economically	Basic	Yes	Free

Intervention	Broad category of intervention	Description of Intervention & How intervention is being used (Adoption)	Other features of interventions.	Complexity = Basic; Intermediate; advanced	Behaviour Change needed?	Indicative Cost Range (illustrative typical cost to install)
			deprived areas.			
reduced flow shower head - Saving Water	Water saving devices	A reduced flow shower head helps save water use and can produce water flows that feel far higher than they actually are. These are normally installed as new build buildings, yet often undertaken as retrofit measure. available free from water companies	This is an easy low cost-effective measure, that can be completed professionally or as DIY. Often something that is actively promoted by Water Authorities the suppliers of water to consumers.	Basic	Yes	€€ and free
Water efficient taps	Water saving devices	Water efficient devices with low flow rates can be fitted cheaply and as DIY measure. These are normally installed as new build buildings, yet often undertaken as retrofit measure. available free from water companies	This is an easy low cost-effective measure, that can be done professionally or as DIY. Often something that is actively promoted by Water Authorities the suppliers of water to consumers.	basic	Yes	€€ and free
reduced flow cisterns - Low-flush and dual-flush toilets	Water saving devices	Reduced flow cisterns and low flush toilets are designed to reduce the volume of water used for flushing and save water. These are now installed as standard practice in new builds, or can be retrofitted when replacing an old toilet system	It is culturally acceptable to find dual flush toilets	Basic	No	€€
Energy Efficient Appliances	Energy Efficiency - Appliances	Buying A+ energy ratings labelled appliances, *e.g.,* LED lightbulbs, washing machines, fridge freezers. Typically all new 'white' goods such as washing machines, dishwashers have a mandatory energy label from A-G on the package	The A rated labels are useful when replacing appliances	Basic	No	€€€
Lighting fittings -Light Emitting Diodes (LEDs)	Energy Efficiency - Lighting	Lighting fittings (LEDs) are simple solid state electronic devices that allow electricity to flow	are more efficient than CFLs and will save you more money in the long term	Basic	No	€€

Intervention	Broad category of intervention	Description of Intervention & How intervention is being used (Adoption)	Other features of interventions.	Complexity = Basic; Intermediate; advanced	Behaviour Change needed?	Indicative Cost Range (illustrative typical cost to install)
		through them in one direction to produce a small amount of light. They offer energy efficient lighting in homes.				

Indicative Cost Range
€€ - less than 100 Euros
€€€ - hundreds of Euros
€€€€€ - thousands of Euros
free - no charge

Appendix 4

Characterisation of Behaviour Change Interventions

Intervention	Category of intervention	Description of Intervention	Use of technology in intervention	Complexity of implementing intervention	Evaluation of intervention
Awareness raising	Antecedent method, Informational strategy	Used to increase awareness of policy, practices and solutions at a very general level. Can be done via leaflets or posters *etc.*	Often disseminated through paper-based, online or media outlets	Straightforward intervention: considerations revolve around messages and dissemination pathways	Does not lead to behavioural change and is viewed as an ineffective method to garner changes in pro-environmental attitudes and concerns. Impact is limited
Information	Antecedent method, Informational strategy	More specific than awareness raising yet not individually tailored. Often used to draw attention to policy and how practice can make positive changes	Often disseminated through paper-based, online or media outlets - dependent on whether information is sought or provided	Straightforward intervention: considerations revolve around messages and dissemination pathways	Rarely leads to behaviour change, but evidence shows that it can lead to concern and higher levels of knowledge and awareness of policies and practices. Impact is limited
Tailored information	Antecedent method, Informational strategy	Applied at a local level providing information on energy use and changes individuals can make to their lifestyles to reduce energy consumption	Often disseminated through computerised and online media tools, can be applied through billing also	Straightforward intervention: considerations revolve around identifying specific information to include, how to disseminate and how to appeal to different publics	More successful in leading to direct behavioural changes than generic information. Can be used flexibly to encourage energy consumption reduction and in conjunction with other methods
Mass media campaigns	Antecedent method, Informational strategy	Used to raise awareness of numerous environmental policies and/or solutions to addressing sustainability related issues	Often disseminated through paper-based, online or media outlets	Straightforward intervention: considerations revolve around which policies to advertise to public	Does not lead to behavioural change in most circumstances. Minimal impacts on influencing concern for sustainability related issues.
Kick-starter events	Antecedent method, Informational strategy	Applied at a local level (sometimes national) to provide more tailored	Minimal, depending on information provided, usually through paper-	Straightforward intervention yet requires planning and community	Can garner support for local initiatives and builds upon concern and

Intervention	Category of intervention	Description of Intervention	Use of technology in intervention	Complexity of implementing intervention	Evaluation of intervention
		information, appliances and activities at the start of local projects. Frames projects and stimulates enthusiasm	based methods but can be signposted to online material. Appliances are often small-scale technical interventions	engagement skills and experience to effectively involve local residents	knowledge for local sustainability issues. When applied continuously, can provide foundations for behavioural change. Moderate impact, short term if not applied continuously
Incentives and rewards	Consequence method, Structural strategy	Financial rewards are provided on the basis of "good behaviour" whereby rebates or vouchers are provided when people reduce their energy consumption or recycle, for example	Minimal technology involved	Challenging intervention to incorporate incentives and rewards to maintain specific behaviours long after intervention has ended	Can lead to behavioural change yet when the financial reward is dis-continued this leads to people associating the behaviour with a reward. When the reward stops, so does the action
Feedback	Consequence method, Structural strategy	Applied daily individuals are provided with feedback on energy consumption that is designed to identify usage patterns, costs and areas of saving energy	Often provided via computerised or online information while other types provided via smart technologies	Requires technical skills and insights to effectively determine what feedback is required to meaningfully engage individuals with behaviour change	Proved to be a successful intervention, particularly when used in conjunction with other informational strategies such as tailored information. Does lead to behavioural change, and can last up to 2 years following action
Workshops	Antecedent method, Informational strategy	A focus on the "how to do" rather than the "what to do". Specific training or activities illustrating how to do particular actions that can reduce energy consumption	Moderate use of technology dependent upon how information is disseminated, often via face-to-face methods illustrating how to use technologies or change practices	While community engagement practices	The provision of practical information and applications can lead to minimal changes in behaviour, depending on the targeted action. Used minimally, yet has potential to support local transitions with practical changes
Continuous feedback	Consequence method, Structural strategy	Feedback is provided on a continuous basis that	Often provided via computerised or online	Requires technical skills and insights to effectively	The most successful type of feedback is that which

Intervention	Category of intervention	Description of Intervention	Use of technology in intervention	Complexity of implementing intervention	Evaluation of intervention
		indicates past energy consumption and cumulative data on reduction of energy use.	information while other types provided via smart technologies	determine what feedback is required to meaningfully engage individuals with behaviour change	is provided continuously and not discontinued allowing for comparisons to be made with previous behaviour. Allows for substantive behaviour change
Comparative feedback	Consequence method, Structural strategy	Feedback on energy consumption is provided along with that of another, to illustrate wider energy consumption. Elements of competition, social pressure and norms are used to enact behavioural changes	Often provided via computerised or online information while other types provided via smart technologies	Requires technical skills and insights to effectively determine what feedback is required to meaningfully engage individuals with behaviour change	While useful for high and medium consumers of energy, this can lead to reductions in behaviour yet when withdrawn consumption remains higher than baseline levels. Intervention is more effective if comparisons are made with others who are known
Sanctions	Consequence method, Structural strategy	Limits to accessibility of unsustainable products or services such as personal transport options and wasteful products where sustainable options exist are promoted through fines, limited options, reduction in service provision and investment in sustainable alternatives	Minimal use of technology	Challenges involve how to effectively implement such an intervention against challenging public acceptability and an appetite for developing such interventions	Can be successful in directing individuals to sustainable alternatives dependent upon how the intervention is set up and communicated. Higher taxes do have support from the public, yet changes to service provision and redirected investments to sustainable alternatives gain higher acceptability.
Fines	Consequence method, Structural strategy	A financial disincentive whereby individuals receive a fine to pay for breaching a predefined limit of waste, resource use, or carbon emissions. Price defined by market	Minimal use of technology	Challenges involve how to effectively implement such an intervention against challenging public acceptability and an appetite for developing such interventions	Not considered to be an effective intervention for changing behaviours, in the similar way as rewards. Viewed as an extreme forcing mechanism to the polluter pays principle that is

Intervention	Category of intervention	Description of Intervention	Use of technology in intervention	Complexity of implementing intervention	Evaluation of intervention
		per tonne or kg etc			unpopular to implement from policy perspectives
Pricing policies	Antecedent method, Structural strategy	Changes in pricing can affect the products that people buy *e.g.,* energy efficient technologies and appliances such as washing machines, boilers and cars. Often applied to encourage ownership and use of sustainable models	Minimal use of technology yet these can be advertised via marketing campaigns to support changes in pricing	Challenges revolve around how to shift the burden of taxes from unsustainable products to sustainable alternatives as well as implementing the policy effectively	Behavioural economists have shown that changing pricing structures have resulted in changing behaviours where sustainable alternatives are often more pricier than unsustainable products. Reducing the costs of sustainable alternatives and increasing the costs of unsustainable products leads to price-based market interventions that do lead to lifestyle changes
Infrastructural changes	Antecedent method, Structural strategy	Changes to local infrastructure may encompass building pavements along country roads or including cycle lanes to encourage more sustainable transport methods at a local level	Substantial use of technology to change infrastructure itself and depending on scheme could lead to permanent technological structures to support behavioural changes	Complexity involves planning permission and the development of sustainable alternatives to make full use of infrastructural changes	Positive impacts can result from infrastructural changes to the local environment to support alternative approaches for transport and consumption particularly. Moderate impact if used with other interventions
Pop-up shops	Antecedent and consequence method, Informational and structural strategy	A source of information and feedback, often delivered through a face-to-face and peer-to-peer approach. Provision of meaningful and accessible information on solutions and activities in communities	Moderate use of technology dependent upon how information is disseminated, often via face-to-face methods illustrating how to use technologies or change practices	Requires a flexible and constantly evolving process of updating material, feedback and teaching residents how to use technologies	Have the potential to provide on the spot advice, support and tailored feedback to those who need it. Immediate and accessible as an intervention. Trusted by the community with immediate impact to support continued behavioural changes

Intervention	Category of intervention	Description of Intervention	Use of technology in intervention	Complexity of implementing intervention	Evaluation of intervention
Balancing communication	Antecedent method, Informational strategy	Eradicating the false balance in climate change communication at a national and local level to mirror (un)certainties in climate science. Focus on media outlets and publications	Moderate, often used to communicate messages are now disseminated through online and electronic communication	Challenges associated with willingness of particular press outlets to incorporate recent scientific updates with respect to climate science. Challenges revolve around freedom of press status	Improves public understanding of climate science and the consensus on climate change. Challenges exist around press regulation and reporting of accurate facts where scientific principles are concerned.
Local food production	Antecedent method, Structural strategy	Production of food via allotments or other means to support local food growth. Encourages development of knowledge and action around self-sufficiency	Moderate, depending on food production system outlined for project	Complexity of this intervention revolves around space for growing locally produced food as well as participation in such a project	Increases knowledge and practices of food production for self-sufficiency, drawing attention to food miles and carbon footprints. Meaningful behavioural changes result, yet limited uptake by population
Local energy generation	Antecedent method, Structural strategy	Focus on microgeneration of renewable energy such as solar, wind or biomass. Accompanied by changes in pricing structures and physical infrastructure of homes and communities	Substantial use of technologies including smart technologies, heating and cooling systems and energy systems	Challenges revolve around feed-in tariffs, development of locally acceptable generation of renewable energy sources and integrating changes within the homes of residents	Supporting a decentralised and renewable energy future at a local level, tailoring community transitions and producing self-sufficient communities. Often expensive to introduce and maintain
Community-based carbon reduction projects	Antecedent and consequence method, Informational and structural strategy	Local projects, often incorporating multiple interventions, to stimulate, increase and maintain sustainable lifestyles. Key aspect of intervention is collective action rather than individual practices	Moderate use of technology dependent upon how information is disseminated, often via face-to-face methods illustrating how to use technologies or change practices. Use of renewable energy technologies substantial	Complexity includes turning initial excitement to sustained participation, developing funding for activities and integrating multiple interventions and activities as part of a wider strategy for community sustainable living	Meaningful lifestyle changes have been observed in existing examples with substantial environmental, economic and social outcomes. Yet lack of funding and support available from areas of government. Continuous activities support long-term lifestyle

Intervention	Category of intervention	Description of Intervention	Use of technology in intervention	Complexity of implementing intervention	Evaluation of intervention
					changes.
Regulation	Antecedent method, Structural strategy	Implementation of regulations such as congestion charges and plastic carrier bag charges that make travelling or wasteful behaviours undesirable through additional charges. Encourages behavioural changes	Dependent upon regulation - often minimal to moderate use. For example, congestion charging may require mobile applications and specific websites to register vehicles on	Complexity of this intervention is visible in the design of this intervention rather than its conceptual planning *e.g.,* practicalities of establishing congestion zone charging and sustainable alternatives	Successful, if applied correctly. Substantial impacts on behavioural change *e.g.,* Stockholm congestion charge and Welsh plastic bag charge. Can also influence spill-overs to other behavioural and attitudinal change. Minimal appetite for regulation on energy use by governments
Personal Carbon Allowances	Antecedent method, Structural strategy	A Personal Carbon Trading scheme where a predefined cap on emissions is determined and individuals monitor and reord their carbon footprints and seek to reduce them through lifestyle changes	Moderate to high use of technology including carbon credit cards, smart technologies including smart phones, applications and smart meters to monitor and track carbon footprints	Very complex system to implement with considerations revolving around best ways to implement intervention i.e. credit card system, reporting, carbon trading markets and prices. Complex practicalities involved requires technical skill set to implement	Provides a framework for reducing carbon footprints. Very successful with long-term impacts, particularly on high and medium energy consumers. Redirects emphasis towards carbon capability of individuals. Limited appetite for implementation by governments
Intervention	Category of intervention	Description of Intervention	Use of technology in intervention	Complexity of implementing intervention	Evaluation of intervention