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Addressing Behavioural Technologies Through the Human Factor: A Review

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ABSTRACT Energy-efficiency related research has reached a growing interest in recent years due to the imminent scarcity of non-renewable resources in our environment and the impending impacts their usage have on our environment. Thus, facing the reduction of energy waste and management has become a pivotal issue in our society. To cope with energy inefficiency, the scientific research community has identified the promotion of people's behaviour change as a critical field to foster environmental sustainability. However, the body of literature shows a lack of systematic methods and processes to reach a common ground when designing technology for promoting sustainable behaviour change. Therefore, this paper contributes with a thorough review and analysis of state of the art. Firstly, theoretical works related to behaviour change are collected and studied to clarify their main concepts and theories. Secondly, the different technologies, processes, methods and techniques applied in the field are reviewed to find diverse strategies in the application of the previously explained theoretical domains. Moreover, a wide range of systems developed to improve energy efficiency through human behaviour change is analysed (from augmented objects to the Internet of Things, digital applications or websites). Finally, the detected research gaps are listed to guide future research when aiming to raise the awareness of individuals through Information and Communication Technologies.

INDEX TERMS Behaviour change, Internet of Things, sustainability, sustainable behaviour change, ICT.

I. INTRODUCTION

The industrial development and the fast proliferation of Information and Communication Technologies (ICT) and electronic devices are some of the wide amount of factors that have increased energy usage in the current years [1]. To avoid massive exploitation and waste of natural resources, a sustainable approach must be implemented in all the stages of the value-support chain. There are 2 common approaches to tackle energy efficiency through technological systems, which can be used in an isolated or complementary way: 1) *With Technology*: this approach involves technology-based solutions, like automation or Artificial Intelligence. This idea puts the focus on the devices or systems themselves. Thus, the responsibility of being efficient lies in the technology. Although this can be a powerful strategy, it presents some negative effects when individuals are involved: the automated processes may cause distrust, and a rebound effect may appear when the technological aspect is removed due to the disassociation of the user [2]. 2) *Through Technology*: This approach uses technology as a way to influence on the individual. For that, the Human-Computer Interaction relies on the user side to improve awareness about energy efficiency and sustainable behaviour through methods and techniques that focus on the human factor.

To understand human behaviour towards waste of energy, the context is a key factor that presents specific challenges. In scenarios where the individual is not involved (like in some industrial processes) "*With tech*" approach can be feasible. However, the individuals behave differently depending on the context and therefore, the context-related factors must be taken into account when the user is involved in a specific

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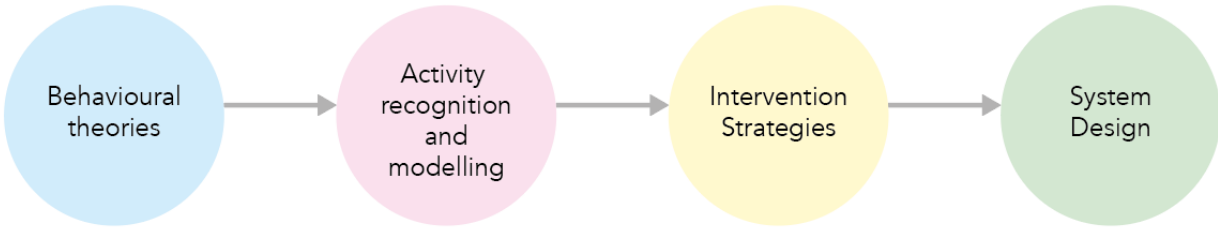

FIGURE 1. The basic workflow of the development of Behavioural Technologies is followed in this work to review the different works in the field.

strategy or interaction. The physical environment where sustainable behaviour is performed is directly related to this context [3]. At private spaces, like home, the individual is more aware of their own energy consumption since they are the one in charge of managing the energy-related issues and paying the fees. In shared or public spaces, like the workplace, the responsibilities are diluted and the behaviour is less strict as a consequence. Thus, the awareness about energy consumption in workplaces is poorer than in private spaces due to the third party management and payment, and therefore, energy waste is higher in this type of contexts. Although the awareness of the individuals through sustainable behaviours and efficient energy management should be improved and fostered in every context and moment, the gap to improvements is higher in contexts managed by third parties.

While awareness is always linked with consciousness, the behaviour change can be performed avoiding the conscious actions and decision-making processes. Some strategies and tools to foster the change can not influence the individual, but most of them address the rational side, improving the awareness to raise the change subsequently. Therefore, both ''awareness'' and ''behaviour change'' concepts are closely related, but it is important to recognise the differences. In fact, they should be taken into account to understand the implications and correlations between both concepts in order to target each strategy.

Following the lines proposed by a previous works in the field [4], this paper offers an overview of the different concerns related to energy-efficient behaviour. Furthermore, it covers a significant number of relevant pieces of research from different scholars, ranging from the theoretical issues to the final applications and systems. Hence, the main contributions are, i) to collect relevant works from the body of literature; ii) to analyse the current status of the research topic; iii) to find gaps and the uncovered issues in the literature; and iv) to set future research lines and shed light on how the research field may evolve. To address these objectives, we provide a structured analysis to offer researchers and practitioners a guide of the different concerns related to the development of technologies to foster the energy-efficiency addressing the human factor. The structure of this paper follows the work-flow of the ideation and development of Behavioural Technologies (BT) (see Figure 1). For additional clarification, BT are understood as technological strategies and systems addressed to target the behaviour change.

For selecting the works presented in this article, we applied the following methodology: mainly works related to the energy efficiency have been analysed, and the theoretical approach has been delimited to this area to avoid losing the focus from the target topic. From this selection criteria, the most recent works have been prioritised. The included information has been extracted from the main scholarly research databases, including Google Scholar, Scopus or IEEE Xplorer. These databases were queried using a combination of keywords such as ''Behavioural Technologies'', ''Sustainable Behaviour Change'', ''Eco-feedback'' or ''Activity Recognition Model''.

From the large number of works included in those categories (e.g. 2750 results for ''Eco-feedback'', 1270 for ''Sustainable Behaviour Change'' or 1160 for ''Activity Recognition Model'' in Google Scholar), every search was redefined using secondary keywords such as ''sustainability'' or ''energy-efficiency'' to find the best combination. Those with the main keyword in the title or the abstract and containing the secondary ones in the rest of the paper were pre-selected and categorised according to the different topics they were related to. However, in section III some other works non-related to the energy have been added in order to show examples of works using advanced behaviour recognition techniques for behaviour change in other fields.

The most relevant papers were then carefully reviewed to determine the final eligibility, and its bibliography was also analysed in order to extract relevant references which could enrich our study. As a result of this process, this work includes a selection of almost 150 papers, most of them recently published, on a wide variety of topics around energy-efficiency and behaviour change.

The rest of the paper is structured as follows: Section II reviews the most common and used theoretical approaches applied to energy efficiency, highlighting works that use and implement these frameworks in technological systems or interfaces. The objective is to offer a solid theoretical background to contextualise the technologies that address energy efficiency through the human factor. This section will help the research community to face the development of technological systems with the understanding of theoretical concerns that needs be taken into account to develop human-centric technologies and systems. Next, we put the focus on the behaviour recognition technologies in intelligent environments (Section III). Behavioural recognition involves technologies to gather and process data from the users in order to model and predict their activity. In this context, the existing approaches are reviewed to offer an overview of the current state of the art in the field: data-driven approaches, knowledge-driven approaches, and hybrid approaches. This section offers a summary of the current state of the art in behaviour modelling and recognition and may be helpful to the practitioners due to the review of the available approaches and technologies provided, which can guide the selection of technologies and the development of new ones. After the revision of theoretical concerns and the modelling and recognition technologies, the next step in the development of BT should be to select behaviour change strategies and methods. In Section IV, we offer a review of the most relevant guidelines, toolkits and empirical findings to provide an overview that aims at helping the researchers and practitioners in the strategy selection and implementation. Once covered the theoretical frameworks, behaviour recognition/modelling technologies and strategy selection, we put the focus in the technological systems intended to change the human behaviour to face energy efficiency. Therefore, Section V, tangible and digital systems that address the energy efficiency through human factor are reviewed, from energy consumption data to context-aware information and including other behaviour-related systems. Next, we propose a discussion to analyse the most controversial findings and different or complementary approaches that can be complex and diffuse. And finally, with the intention of offering valuable knowledge, we highlight the findings of the research work, providing a summary of the main conclusions. Besides, we summarise the main findings of the current state of the art, the main gaps that are uncovered and the future research lines that should guide the research work.

II. THEORETICAL APPROACHES FOR BEHAVIOUR CHANGE

As Hekler *et al.* [5] stated, BTs are gaining importance in the research community. Therefore, to develop successful systems and strategies it is crucial to understand human behaviour in its different phases. In fact, most of the behaviour change systems set their work upon theoretical models to sustain their research in a psychological background that contextualises the behavioural action and process. Nevertheless, the behavioural theories are not universal and they can present shortcomings. The researchers and practitioners should take this into account in the selection and analysis of the behavioural theoretical background.

In this section, we describe the most relevant theoretical approaches that have been implemented in BT addressed to promote energy efficiency. Firstly, we introduce the most used behaviour change theories and models. Secondly, we introduce Behavioural Economics, a field that emerged from economists that have been applied to improve energy-efficient behaviours. Finally, we summarise the main theoretical framework used for activity modelling and recognition. The explained theoretical models have significant differences taking into account the constructs used to frame the behavioural process. These differences can be used to choose the appropriate framework for each case. Besides, these can be combined and complemented to avoid the potential shortcomings derived from the static of the use of a single framework.

A. THEORETICAL MODELS FOR BEHAVIOUR CHANGE

In this review, we only put the focus on theoretical approaches and/or conceptual frameworks that are used to foster energy efficiency. This is important, as we only focus on these available theories that are being taken into account to develop BT. Hence, the main models of behaviour change applicable in the field of environmental sustainability are the following:

1) The Trans-Theoretical Model (TTM) [6] takes into account the different phases that occur in the behaviour change process: pre-contemplation, contemplation, preparation, action, maintenance and termination. Certain principles and processes to generate the desired behaviour change work best in each of the different stages mentioned. Based on this framework He *et al.* [7] implement different strategies based on the diversity of the individuals. In addition, Wising, Chirez and Adams [8] develop a proposal based on an adaptation of the Trans-Theoretical model to improve the industrial energy efficiency by changing the energy culture.
2) The theory of Values Beliefs Norms (VBN) [9], applies a value-based theory to a wide range of factors influencing the individual. Subjective norm is activated when individuals become aware that certain behaviour that they perform have adverse effects on issues they belief, and that behavioural action will have a positive and significant impact on the aspects the individual values. This approach is proposed by Stern *et al.* [9] and refined later [10], developing a framework of pro-environmental behaviour following the value-beliefs norms. Besides, [11] Petkov *et al.* proposed an interface offering feedback to different user types depending on the different values outlined by Stern's theory.
3) The Theory of Planned Behaviour (TPB) [12], is a conceptual framework that links beliefs, attitudes and behaviours with the intentions, which helps to understand how people's behaviour can be changed or directed with a series of predictable aspects that can influence the intended behaviour. This theory is based on the decision-making process (intentions) and the execution of the activity, and is conditioned by three factors: the personal evaluation of the behaviour (positive or negative), subjective norms and perceived behavioural control over the behaviour you want to change. In the same way as Petkov *et al.* applied the VBN, Coskun and Erburg [13] defined hypothetical user types for pro-environmental behaviour based on the variables defined by the Theory of

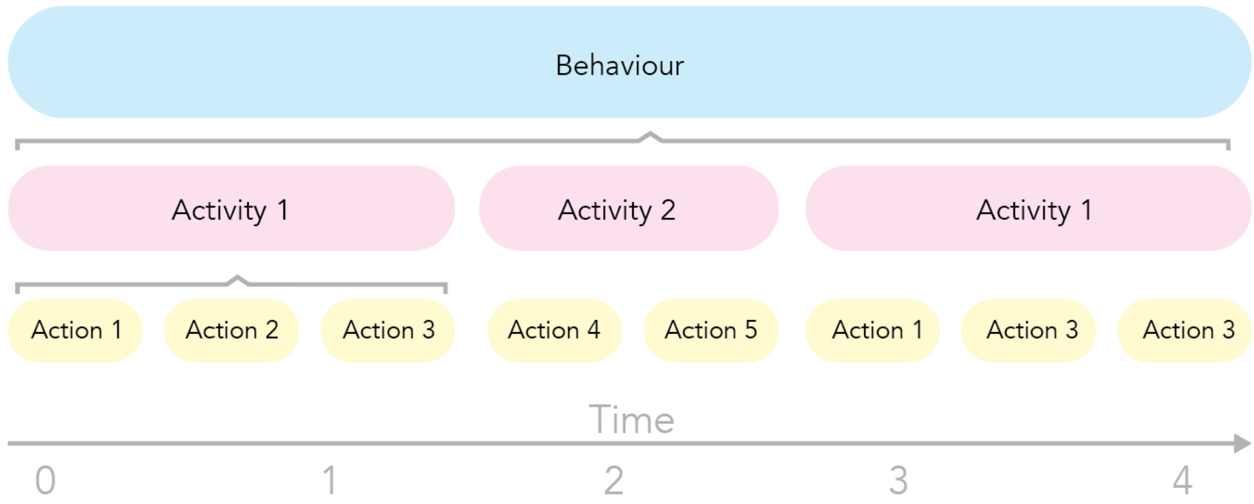

FIGURE 2. Activity recognition hierarchy model.

Planned Behaviour. In addition, Greaves, Zibarras and Stride explored the environmental behavioural intentions in the workplace using the TPB theory [14].

4) The Self-Concordance Model [15] is based on the idea that it is possible to improve the (sustainable) behaviour connecting specific behaviours with goals which are important to the individual. Although this model has been applied in another context, to the best of our knowledge there is only one related to energy efficiency: a recent study developed by Unsworth and McNeil [16] where an intervention is tested, validating the idea that connecting the goals and pro-environmental behaviour, the latter can be improved.

B. BEHAVIOURAL ECONOMICS

Behavioural Economics is a field that analyses the effects of psychological and cognitive factors in the decision-making process of individuals [17]. It aims at guiding the conduct of the individuals covering the discrepancies among the perceived behaviour and the real conducts and actions. Behavioural economics is based on the limitations and barriers that influence the decision-making process and consequently in the behaviour. For that, this approach is focused on the heuristics and biases that influence the individual's choices. In recent work, Sorrell exposes a review of issues, challenges and approaches to address the energy efficiency, including behavioural economics as a field that provides a more robust understanding of economic decision-making [18]. Besides, Frederiks, Stenner and Hobman apply the behavioural economics to understand the consumer decision-making and behaviour in the household energy-use [17]. The role of Behavioural economics in Energy and Climate Policy has been explored by Pollit and Shaorshadze [19]. They analyse the three areas of impact: consumption and habits, investment in energy efficiency and provision of public goods and support for pro-environmental behaviour. Nevertheless, they conclude that behavioural economics seem unlikely to provide the solution to massive energy consumption problematic.

C. BEHAVIOURAL THEORIES FOR ACTIVITY RECOGNITION

From the point of view of the activity recognition, the behavioural theories are understood as conscious movements developed in a determinate frequency. Multiple authors have introduced several definitions for human conduct in intelligent environments, conditioned by the complexity and granularity of the modelled conduct. Chaaraoui *et al.* [20] propose a model with three levels of conduct: actions, activities and behaviours. In this model, each of the levels is composed by conduct instances of the previous level, i.e. activities are composed by actions and behaviours are composed by activities. Almeida & Azkune [21] extended and formalised this model, providing definitions of each level and distinguishing two types of behaviours, intra-activity behaviours and inter-activity behaviours (Figure 2). Authors propose the following definitions:

- Actions are temporally short and conscious muscular movements made by the users (e.g., taking a cup, opening the fridge, etc.).
- Activities are temporally longer but finite and are composed of several actions (e.g., preparing dinner, taking a shower, watching a movie, etc.).
- Behaviours describe how the user performs these activities at different times. They have identified two types of behaviours. The intra-activity behaviours describe how a single activity is performed by a user at different times (e.g., while the user is preparing dinner, sometimes they may gather all the ingredients before starting, while on other occasions, the user may take them as they are needed). The inter-activity behaviours describe how the user chains different activities (e.g., on Mondays after

having breakfast, the user leaves the house to go to work, but in the weekends, they go to the main room).

III. BEHAVIOUR MODELLING AND RECOGNITION IN INTELLIGENT ENVIRONMENTS

Human behaviour modelling and recognition is an active area of research for promoting behaviour change in intelligent environments. To do so, several behaviour modelling approaches have been employed. For instance, Carulla *et al.* [22] proposed the modelling of higher-level conducts, starting from the behaviour. The authors proposed a hierarchical structure that includes behaviours, habits (repeated behaviours that have been internalized) and lifestyles (groups of habits). They model a taxonomy of six higher level habit categories (diet/exercise, vitality/stress, sleep, cognition, substance use and other risks).

In this direction, other authors have also created several ontologies to describe human behaviour. Chen & Nugent [23] propose an ontology modelling the Activities of Daily Living [24] to be used for activity recognition. Similarly, Nevatia *et al.* [25] created an ontology to model actions in videos. While Latfi *et al.* [26] propose an ontological architecture of a telehealth-based smart home aiming at high-level intelligent applications for elderly persons suffering from loss of cognitive autonomy. Azkune *et al.* [27] propose an ontology to model actions and activities based on their type and the sensors used for their detection. Riboni *et al.* [28] use a detailed ontology of possibles behaviours to recognize them. Finally, Almeida & López-de-Ipiña [29] propose a model that considers uncertainty and fuzziness when modelling intelligent environments.

Behaviour recognition in intelligent environments is divided into two significant approaches, data-driven and knowledge-driven approaches, with the hybrid approaches that combine both of them gaining popularity in the last years. Data-driven approaches use annotated datasets to apply machine learning and data mining algorithms to learn models able to recognize the target behaviours. Several examples of the data-driven approaches exist in the literature. Brand *et al.* [30] present a Hidden Markov Model based system to recognize the activities that the users are performing. Hayashi *et al.* [31] use deep neural networks for activity recognition based on accelerometer data and environmental sounds. Moreover, Almeida *et al.* [32] represent user actions using Word2Vec embeddings and then apply multi-scale convolutional neural networks (CNN) to predict the user behaviour based on the previously executed actions. To conclude, Guan & Plötz [33] use ensembles of LSTMs to recognize activities of daily living in smart-homes, based on sensor data.

In the case of the knowledge-driven approaches for behaviour recognition, prior domain-specific knowledge is used to create behaviour models that are compared with the captured data. To do that, Chen *et al.* [34] propose a logical framework for cognitive behavioural modelling, reasoning and assistance based on a logical theory of actions, which they refer to as Event Calculus. In COSAR, Riboni & Bettini [35] use ontologies and ontological reasoning combined with statistical inference. The authors use structured symbolic knowledge about the environment to infer which activities among the candidates identified by statistical methods are more likely being executed. Chen & Nugent [36] also propose another different system, based on multi-sensor data streams in smart homes, which exploits semantic reasoning and classification for activity recognition, enabling both coarse-grained and fine-grained activity recognition. Finally, Noor *et al.* [37] present an algorithm that integrates OWL ontological reasoning mechanism with Dempster–Shafer theory of evidence to provide support for handling uncertainty in ontology-based activity recognition.

Hybrid approaches combine both data- and knowledge-driven solutions for behaviour recognition. For example, Ye *et al.* [38] present a hybrid activity recognition system named USMART, where ontologic models define the sensors measures that compose an activity. In order to detect the sensor patterns that need to be mapped, they propose a semantic similarity metric. Azkune & Almeida [39] propose an easily scalable activity recognition systems named HARS, which uses an unsupervised pattern recognition algorithm to detect possible activities and using minimal activity models to recognize them. Riboni *et al.* [28] first model the behaviour knowledge using an ontology which later is mapped to a Markov Logic Network, an approach that requires very detailed models of the users' behaviour.

A more in-depth analysis of behavior recognition can be found in the surveys by Lara & Labrador [40], Shoaib *et al.* [41], Chen *et al.* [42] and Wang *et al.* [43].

Following this trend, different works have applied behaviour recognition and modelling techniques to improve energy efficiency through behaviour change. Casado-Mansilla *et al.* [44] model and predict specific energy-related behaviours (i.e. usage of specific devices) using ARIMA to foster more sustainable behaviours. Fabi *et al.* [45] modelled human window opening behaviour in residential buildings in order to reduce levels of buildings energy consumptions. Nguyen *et al.* [46] present an ontology-based activity recognition system in office environments in order to serve as input for building energy and comfort management systems. The proposed system handles multiple-user, multiple-area situations, rapidly recognizing office activities. Cottone *et al.* [47] propose an hybrid activity recognition model based on the SAIL [48] and MDL [49] algorithms in order to predict energy consumption.

IV. METHODOLOGIES TO DEVELOP BEHAVIOUR CHANGE TECHNOLOGIES

Behavioural theories and frameworks may be abstract and complex to be implemented when developing BT to improve energy-efficiency. To address this challenge, several pieces of research offer different proposals. Empirical findings and the design hypotheses are the typical starting point to guide the design of strategies. Many different approaches and works can be found in the literature that offer guidelines to address the energy waste through behaviour change: 1) Persuasive Technology, 2) Design for Sustainable Behaviour (DfSB) and 3) Nudging are some of the fields that focus on the improvement of the energy-efficient behaviour. Besides, there are other tool-kits and proposals that offer guidelines and methods to face energy efficiency through the human factor. In the following lines, we highlight the most relevant proposals in this field according to the authors' criteria.

1) Fogg [50] defines Persuasive Technology as ''the class of technologies or interactive computing systems that are intentionally designed to change a person's attitude or behaviour''. There is a wide amount of literature on persuasive technology and its review is out of the scope of this paper. Therefore, we highlight some of the most significant proposals to better contextualise the field. According to Fogg, the functional triad is a framework that illustrates the three roles computing technology can play: tools, media and social actor. As tools, persuasive technologies make users' activities easier or more efficient to do, e.g. by performing calculations or providing guidance that leads users through processes in a step-by-step manner. As media, persuasive technologies provide interactive and engaging experiences. Finally, as social actors, persuasive technologies attempt to mimic a living entity, e.g. by providing feedback or social support. The Persuasive Systems Design (PSD) [51] discusses the process of designing and evaluating persuasive systems and describes which kind of content and software functionality may be found in the final product. Persuasive systems are defined as ''computerised software or information systems designed to reinforce, change or shape attitudes or behaviours or both without using coercion o deception''.
2) Design for Sustainable Behaviour (DfSB) [52] is a field that aims at reducing the environmental impact intervening people's everyday activities through the design of interfaces and systems. It takes into account the different impact-types throughout the product (or system) lifecycle [53]. This field focuses on the system-design to influence the improvement of human behaviour. The DfSB covers the main areas of influence on user decision-making: eco-feedback, which guides change, behaviour steering, which maintains change and Persuasive Technolgy, which ensures change. DfSB, therefore, provides a framework for acting in all areas of influence when designing products and systems that promote energy efficiency. Michie proposes specific strategies and techniques for this task, offering a taxonomy of techniques applicable to the process outlined in the DfSB [54]. Besides, in other relevant work, the author proposes a mapping of behaviour change techniques to behaviour determinants [55].
3) Following the behavioural economics' theoretical approach, a relevant part of the literature has emphasised Nudging as a method to guide energy-efficient behaviour [56]. Nudges are strategies to steer individuals while preserving freedom of choice. The key concept is to facilitate the most sustainable decision and make the unwanted choice more difficult, without cutting options and offering choices. Newell and Siikamäki applied nudges to evaluate the impact of energy-efficient labelling in the user-decision making process, finding that economic-related simple information was the main element that guided the decision [57]. Ölander and Tøgersen analysed the impact of both informational and nudging strategies, concluding that only educational approaches had limited success at changing behaviour. Besides, the environment-related choices include some conditions (as the delayed effect of the choices, the difficulty of these, the poor feedback…) that obstructs the decision-making at the cognitive level being necessary behaviour steering tools and techniques. Therefore, following the authors' conclusion, the researchers and practitioners should ensure that informing and nudging strategies are applied in a simultaneous and complementary way [58]. Nudging has become a key term to encompass techniques that work through the automatic decision-making system (for example the setting of defaults as pre-set flows of an action). Therefore, it should be understood as an empirical application of behavioural theory, and more research is needed to define a more elaborated and solid framework, offering defined and validated guidelines.

Once reviewed the most relevant research fields that tackle the implementation of the theoretical background presented above, there are some other relevant works that should be included. These studies present empirical findings that guide the design phase and offer complimentary strategies to develop systems, technologies and interfaces that address energy efficiency through the human factor. Besides, other specific tool-kits and frameworks are reviewed to offer a summary of the most relevant methods and tools. Finally, other relevant empirical insights are exposed to offer an overview of papers that cover other types of research work, aiming to address the plurality of the available methods and points of view.

- The Behaviour Change Wheel (BWC) [59] is a methodology that includes a synthesis of 19 frameworks of behaviour change. It includes 3 main dimensions of behaviour, providing a simple framework to contextualise the behaviour. Capability, opportunity and motivation are presented as 3 key conditions for behavioural activity. Moreover, sources of behaviours, intervention functions and policy categories are included to facilitate the application across levels from individuals to groups. This framework has been used to design energy interventions [60] and as a methodology to guide the systematic review of the available evidence on interventions to change behaviour and save energy in the workplace [61].

- The Theoretical Domain Framework (TDF) [62] provides a method for conducting a more elaborate behavioural analysis. The 14 domains of the TDF can be mapped onto the Capability, Opportunity and Motivation components of BCW. Although this framework seems very relevant to develop a structured implementation of behavioural strategies to foster sustainable behaviour, to the best of our knowledge, it only has been applied to foster the recycling behaviours [63].
- The Design with Intent method proposes a tool for influencing user behaviour through different perspectives [64]. This approach is contextualised within the concept of Persuasive Technology and offers complimentary and specific interventions to this field [65]. The Design with Intent method includes a tool-kit composed by a card deck to facilitate the design and implementation of behaviour change strategies [64]. This method has been applied to energy efficiency [66] and offers practical guidance, based on the theoretical background, that can enhance the design of Behavioural Technologies. In this context, Morgan *et al.* [67] used this tool in their studies to face energy efficiency in a large organisation.

Finally, to cover the different areas and other research works in the field, we review the studies that provide empirical findings on how to address the design and development of Behavioural Technologies.

Lockton *et al.* exposed the relevance of the DfBS and User-Centered design as a methodology to allow to develop energy-efficient systems and products [53]. Kuijer and Jong [68] and Wever, van Kuijk and Boks also worked in this idea [69]. In a later work, Lockton *et al.* [70] delve deeply into the study of the user diversity, proposing three different user profiles according to the behavioural traits of the individuals. For each profile, the authors suggest strategies and ideas to develop sustainable behavioural systems, technologies and products. In this line, Coskun explores user diversity analysing the dimensions of the users according to the Theory of Planned Behaviour [13], [71]. The authors also offer design ideas, guidelines and recommendations to address the heterogeneity of human behaviour. Besides, Petkov *et al.* [11] and He *et al.* [7] face user diversity purposing a user differentiation based on the constructs extracted from different Theoretical Frameworks, as exposed previously, offering suggestions and recommendations for each user type.

Morgan *et al.* explore the role of co-design in a large organisation through a Living Lab [67]. The authors extract insights and findings from workshops and develop an initial prototype to foster energy efficiency in the workplace. Yun, Aziz and Lasternas [72] explore the online feedback and control strategies for sustainability in the work environment and Bao *et al.* [73], [74], explore the impact of the quantitative and emotional feedback in the displays, finding that both aspects were relevant to improve the awareness in the individuals.

Cor and Zwolinski [75] exposed a procedure to select the intervention strategy on a product or system, offering a model that can guide the researchers and practitioners in the development of Behavioural Technologies.

V. TANGIBLE AND DIGITAL SYSTEMS

In a society where the proliferation of electronic devices leads the rising demand for energy, it seems paradoxical that the same cause of the problem, that is using even more electronic devices, could be part of the solution [76]. However, technological advances are enablers to contribute to a more environmental-friendly energy management [77] and to optimize the performance of electricity distribution and consumption [78]. Additionally, they can also to cover the lack of awareness of the individual about energy-related matters and its influence on the ecological footprint [79]. Under this context, technology can play an essential role in the reinforcement of energy efficiency relevance while increasing awareness through sustainable behaviours (i.e. monitoring which habits need to be changed and providing information about the consequences of the energy use). In this regard Pierce *et al.* [80] stated that technology based-solutions should undertake an optimal combination of measurement systems, a timely delivery of relevant information for personal control and the right design of interfaces to interact with the users.

In this particular, the Internet of Things (IoT) is emerging as a new paradigm in the ICT sector that aims to build up a dynamic worldwide infrastructure by connecting a variety of physical and virtual things [81]. The potential of IoT to provide appropriate solutions for energy awareness resides on its ubiquitous services. These services seek to convert the world in a global network of connected people and devices, enabling them to interact, collect and exchange data, make measurements and perform automatic analysis of the obtained data. Therefore, the pervasive nature of the Internet of Things can be considered a suitable tool to mediate the relationship between humans and their motivation towards energy-efficiency.

In essence, technology for energy-efficiency needs to put the focus on how data is obtained and how this data can be analyzed to extract relevant information in order to infer peoples' behaviours. These objectives range from the design of appropriate instruments and electronic devices for energy measurements (Smart Metering) to the use of advanced techniques for data processing and representation (Data analytics and Eco-feedback). Furthermore, this process should not oversee the promotion of technology adoption while achieving an appropriate user experience at the same time [82].

A. FROM ENERGY CONSUMPTION DATA TO CONTEXT-AWARE INFORMATION

One of the main requirements to foster energy efficiency through behaviour change is to initially collect data about the energy consumption of the users in different contexts. Data is usually obtained through smart gadgets such as wearables, and in particular to the case of energy with smart meters. This equipment facilitates the communication and data exchange among the users and the energy supply chain. For this reason, it provides additional capabilities for demand response techniques, managing the load shifting of the power grind [83]. As a consequence, the deployment of smart meters allows to monitor consumer usage, adjust prices according to the hour and season and provide detailed information that helps users to identify power-saving opportunities.

Regarding the user, the primary purpose of smart metering techniques is to obtain enough data to illustrate energy habits in different everyday live contexts, particularly in contexts where individuals choices and behaviours have a more significant impact on the energy consumption [84]. Different research works have approached smart metering technologies to monitor electricity usage, presenting architectures for data acquisition through IoT objects, a combination of these devices with big data analytic, or ubiquitous sensor-based systems. In 2016, Spanò el al. [85], presented a customer-centric architecture for the smart grid infrastructure, embedding smart home applications for energy monitoring in an IoT platform. Other works combine big data analytics with intelligent systems designed to provide information to the utility and the customers [86]. Other approaches allows to remotely monitor and control devices to better manage energy consumption according to user demands [87]. On the basis that sensorization is not enough to properly develop final energy-aware services, Terroso-Saen *et al.* [88] presented an accurate monitoring and control system for a large variety of energy-related agents, dealing with energy quality insurance and support for data analytic. Other approaches address the challenges for near real-time energy-related data processing towards developing energy management strategies [89]. In this direction, a ubiquitous sensor-based platform for tracking user' relevant actions was introduced by Jahn *et al.* [90]. Moreover, Al-Turjman *et al.* reviewed advanced metering infrastructures for power quality and reliability monitoring, highlighting IoT-related challenges for providing efficient control of the current power grids [91].

However, data itself is not enough in order to change the energy consumption patterns. Additionally, information needs to be clearly presented in a contextualized way that helps to associate this information to everyday practices [92]. This involves interacting with the users to show them data about their energy-related performance and corresponds to the concept of Eco-feedback [93], [94]. Eco-feedback has the potential to transform users' decision-making style from a habit-driven mode to a deliberate thinking mode [95]. To that end, two main aspects need to be taken into consideration to increase the feedback effect: which information is given to the user and how it is presented.

In this regard, in 2016 an analysis of energy consumption saving through real-time in-home displays feedback compared two approaches, one in which users learn about the energy consumption versus a one having a constant nudge or reminder of energy use [96]. In this work, real-time information was found more effective in the long term when introducing the learning factor. Other strategies focus on the nature of the information, where electricity consumption can be associated with other factors, such as price visualization. In this sense, a pricing-based interactive control strategy was designed [97]. The idea behind this work was to remove the peak loads on the smart grids and match the energy supply with demand. By the same token, Nilsson *et al.* [98] analyzes the effect of real-time price visualization in overall household electricity consumption level. The results showed a load shifting of approximately 5% of the total daily electricity consumption from peak hours to off-peak hours. Other visualization strategies rely on showing the consequences of the energy-related behaviours on the environment [99] and appealing to the attitudes and determinants of more environmentally friendly behaviour [100].

The way in which feedback is framed must also be carefully considered. This corresponds to the visual methods employed to display energy-related information and feedback. In this category, ambient displays and other digital approaches such as web user interfaces are common visualization interfaces [101]. The visual delivering of energy-related information has been the subject of study from a design point of view in which the visual forms that are used in current research are reviewed [102]. In this work, Castelly *et al.* pointed to the adoption of more advanced visualization and analytic techniques to identify strategic goals. Another study addressed the key design components of eco-feedback interfaces and showed that historical comparison and incentives-based information worked as engagement tools for these platforms [103]. Visualization interfaces have also be harnessed to work as a tool to implement web-based intervention programs [104] and real-time monitoring [105]. Mobile phone applications also stand out as a suitable medium to provide behaviour-influencing feedback [106]. PowerPedia is an illustrative example of an application designed to better understand the energy usage metrics and to identify the energy consumption of different domestic appliances [107]. Peer-to-peer comparative approach and the social dimension is another strategy that directly correlates with existing social media initiatives [108]. In this regard, Petkov el Al. presented EnergyWiz [109], a mobile application that enables comparative feedback supported by a community where participants can compare themselves with the rest of the users. More innovative approaches include enhanced variations, such as an interactive agent to operate the washing machine by booking time slots in order to minimize the cost of a wash by charging a battery at times when electricity demand is low [110] and a conversational agent for energy feedback [111].

Although previous works offer promising insights for encouraging energy conservation, new visualization platforms need to be studied [112]. For this reason, a wide range of augmented devices seeks to directly interact with the user and offer new ways to deliver information [113]. Tangible visualization through augmented everyday objects emerge

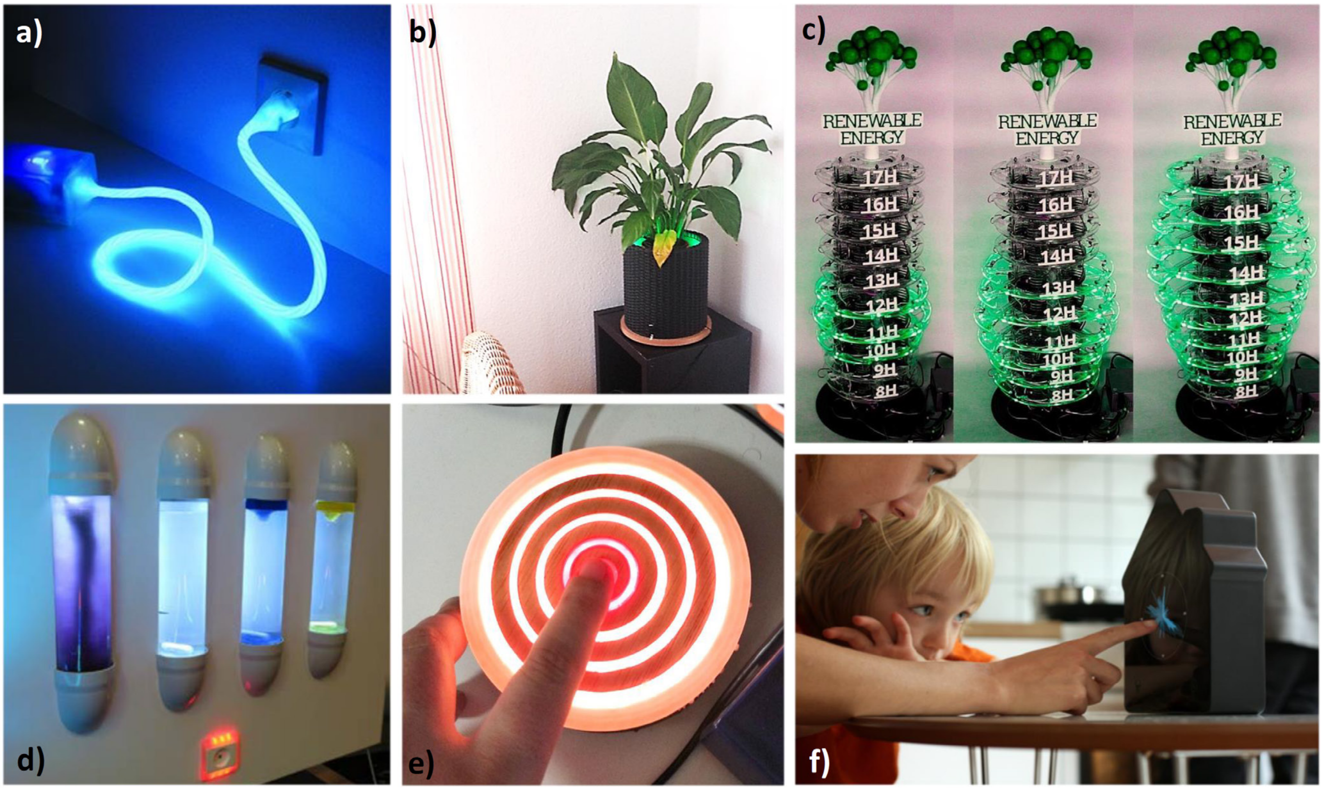

FIGURE 3. Examples of different augmented objects designed to display energy consumption: a) PowerCord b) InfoPlant c) CairForm d) Watt-i-see e) The Interactive coaster and f) The energy aware clock. Images ow of their corresponding authors. All images included are the property of their respective Authors.

as a very illustrative and innovative option to perform this user-level interaction by reinterpreting the functionality of a common object. In 2005, Gustafsson *et al.* presented the 'Power-Aware Cord' [114], a re-design of a common electrical power strip modified to displays the amount of energy passing through it at any moment. The main purpose of this strategy was to resemble the energy flow and make people aware of the level of energy needed at a given time. The idea behind this concept was studied by Backlund *et al.* [115], who analyzed how energy-related issues could be made tangible through form and the different aspects of energy feedback in objects. Following this path, other works have explored the possibilities of different attention-catching devices for energy awareness. Daniel *et al.* [116] presented a shape-changing interface using illuminated disks for representing physical histograms. Likewise, Heller *et al.* designed a power socket that visualizes the power consumption directly on the outlet [117]. In 2010, Broms *et al.* presented an approach to display the history of electric consumption through different patterns [118]. Furthermore, Schrammel *et al.* introduced a watch that provides the current status of the power supply grid [119]. The idea behind this work is to align users' behaviour with the dynamics of the energy generation and promoting the time slots where green electricity is available. Other tangible visualization interfaces can serve to display which ratio of available energy comes from a green source, as Quintal *et al.* illustrated using four glass pipes containing a coloured vortex and coloured power sockets [120].

Other approaches go even further and use different metaphors that resemble the environment and increase energy awareness. This is the case of InfoPlant, a living plant augmented through technology. This plant was designed to provide unobtrusive feedback and make users aware of their electricity usage [121]. Moreover, Hammerschmidt *et al.* propose using waterdrops falling sounds to inform about resources consumption while taking a shower [122]. Common shared places have also been the subject of attention for this kind of interaction. The workplace stands out as appropriate places to increase energy awareness and to guide workers in their routine. With this in mind, Irizar-Arrieta and Casado-Mansilla proposed a digital interface [123], and in the context of H2020-GreenSoul project [124] an Interactive Coaster was designed for office environments. The idea of this device is to persuade workers to be more aware of their energy consumption related to the electrical devices surrounding them in their desktop. Besides of this individual approach, improving energy efficiency from a general perspective via behaviour change in a large organization has also been addressed. Tho that end several strategies have been implemented, from measuring shared lab equipment usage [67] to projecting real-time energy statistics of a factory in the physical environments [125] and convert work equipment into persuasive devices to motivate green behaviours and raise eco-awareness [126].

To illustrate how everyday objects can be augmented and enhanced with new functionalities to foster energy awareness, figure 3 shows some of the examples mentioned above.

VI. DISCUSSION

As has been observed in this manuscript, there is a common agreement on the need for taking into account the behavioural theories when designing energy-related interventions. However, this presents several shortcomings that deserve discussion. Firstly, the wide range of models and theories covers different aspects of the individual (as norms or attitudes). These aspects can be useful depending on the context, the target behaviour or the user dimension. Nevertheless, the selection of what theoretical frame to apply in each occasion can be difficult and complicated. Besides, there are existing research that only address some constructs of a model instead of applying the whole framework. This presents some problems since the omission of the global framework can involve a misusing and understanding of the whole model and causal factors. Secondly, the behavioural models are theoretically validated, yet they should not be assumed as an ''universal truth''. Thus, the contextual factors and barriers should be studied carefully in order to avoid shortcomings when bring then to the field environments. Finally, due to the limited amount of research methods and the difficulty of implement and measure the behaviour change, there is a lack of solid and triangulated data that supports the effectiveness of the implementation of behavioural theories.

Another key point that emerges from the development of this work is the involvement of the ethics in BT. Whereas the existing research in the field seemed to be ethically adequate, the usage of behaviour change strategies often involves a more thorough review of the ethics of each developed system. The freedom of choice should be allowed, informing the user and avoiding coercive strategies. This idea is in line with the difference between behaviour change and awareness. While behaviour can be a consequence of the high awareness of the individual, the behaviour change may be generated through other strategies that might not involve a conscious decisions-making. This can be achieved through coercive strategies or not, but the framing of the behaviour should be placed in second place and always having ethics in mind. The priority should be to raise the awareness of the individual informing and motivating about the decision-making process, and to support this with other complementary strategies to facilitate the most sustainable choice. Besides, the lack of informational strategies can involve negative effects and other context-related implications.

The complexity of the individuals is another relevant factor when implementing BT. The literature agrees on the fact that users have different needs and motivations and on the importance to face this heterogeneity. Although there are some studies covering this topic, to the best of our knowledge, there are no gold standards to address the heterogeneity of the individuals. There is neither a flexible nor a multi-dimensional user taxonomy applied to the sustainable behaviour change. The reviewed works present specific classifications and design recommendations based on their empirical findings, which presents valuable knowledge. However, the idea about how to address the user heterogeneity is still controversial and faced in different ways.

The need for a global approach when addressing sustainable behaviour change is another relevant idea. A wide range of the corpus reviewed present isolated findings, being difficult to locate them in the real world, where are a lot of contextual factors that have an impact on the final result. The implication of different factors in the behavioural process presents a hard challenge, and the study of them involves a difficult work. Nevertheless, more multidisciplinary experiments and studies are needed to find the relation between the theoretical approaches and the final systems and to find how they work in the real world.

Even though modern behaviour modelling and recognition approaches offer powerful analysis techniques to automatically model people's behaviour and detect potential behaviour changes, it is a research field that has not been deeply explored. Most of the behaviour recognition approaches used to foster energy efficiency has been focused on applying learned behaviour models to later build energy-efficient machines which use previous knowledge to adapt their behaviour to users habits. However, there is still a lot of work to do on using behaviour modelling and recognition techniques in the promotion of human behaviour change to foster energy efficiency.

Moreover, behaviour recognition approaches could offer a new method for evaluating behaviour change methodologies to foster energy efficiency using other metrics than the amount of saved energy, comparing the initial behaviour of the users with their behaviour after applying behaviour change methodologies. In some cases, improved action or behaviour may generate little energy savings over the previous behaviour. While this may be a limitation, it is important to bear in mind that these residual savings can be extrapolated to other contexts, settings and behaviours. This is why it is essential to maintain the consistency of the strategy/intervention, even if the quantifiable results are apparently small, given that the impact of energy-saving can grow exponentially. Besides, although the quantitative data can be an indicator of the energy savings, other qualitative information about the impact on the awareness and behaviour change can be relevant to find the effectiveness of the decide.

The technology and in particular ubiquitous devices are the tools in charge of interacting with the user and guiding their behaviours to more sustainable ones. Therefore, particular emphasis should be given to increase the attachment to this new landscape of devices. Ensuring its efficacy may depend on different factors that focus on user engagement, technology acceptance, and adoption [127], [128]. Furthermore, the main challenge is to motivate end-users to feel willing to invest time in the technology upkeep through technology appropriation and ownership while creating an emotional bond [129], [130]. These aspects become crucial when technology guide users behaviours through the process of bringing energy awareness of their own everyday habits. In this sense, Eco-feedback and Smart metering allows receiving (and sharing) information related to energy use. These techniques require users to interact with the energy providers, something that may create more psychological connections between the utility and the users [131]. However, this connection depends on perceived technology attributes such as usefulness, cost, privacy risks or the emotional response [132]. Perceived usefulness of technology is a strong predictor of the adoption intention of technology for energy usage measurement [133], where the factors influencing users' intentions can be measured applying the Theory of Planned Behavior (TPB) and the Technology Acceptance Model (TAM) [134]. Moreover, cost becomes an important variable when expensive devices are needed to obtain real-time information regarding the quantity and the quality of the power supply [135]. Privacy concerns arise as a consequence of the growing awareness about the amount of data collected by the ubiquitous devices and the treatment that is made of this information. As a consequence, monitoring technology needs to overcome additional barriers regarding perceived privacy concerns about the potentially sensitive personal information [136], [137]. Finally, to boost the efficacy of energy-related interventions, an emotional response is particularly important to engage users in the long term and to increase the links between emotions, motivations and users' sustainable behaviours [73].

The potential of the feedback provided through technology is another essential factor to consider. In a conducted study to measure the potential for demand-side management to reduce peak load, Laicane *et al.* [138] concluded that the household consumption level decrease only was able to occur by changing user behaviour. In this case, the feedback and the information provided in the context of smart metering was found mainly effective as far as it acts as a reminder and motivator. For this reason, the authors put the focus on how to get users' attention and educate them to increase customer awareness and participation in demand management. Accordingly, Bastida et al. [139] analyses the role of the consumers' behaviour with respect to the potential of ICT-based interventions to decrease electricity usage in households. In this work, they addressed motivating, reinforcing and enabling factors to encourage lasting behaviours and analysed their impact on the efficacy of ICT approaches to mitigate CO_2 emissions. By the same token, Buchanan et al. [140] presents a critical analysis of the effectiveness of the energy-feedback through smart meter devices and in-home-displays. These findings sustained the statement that existing display interfaces may not induce the desired energy-reduction response if new feedback devices are not designed with user engagement in mind. Three main problems where addressed: i) the limited evidence of efficacy in the reviewed works and the difficulty of validating this results, ii) the need for user engagement to avoid technology uptake and iii) the potential for unintended consequences due to a meaningless presentation of the data. These results reinforce one of the cornerstone ideas that articulate this article: innovative feedback mechanisms are needed to actually engage users taking into account the individual differences and giving importance to "the human factor" [141], [142].

VII. CONCLUSION

In this section, the most relevant findings are summarised. In Table 1, we analyse the extracted insights and we propose future research gaps and lines aiming at offering some guidance in the development of this research area.

A. THEORETICAL FRAMEWORKS FOR SUSTAINABLE BEHAVIOUR CHANGE

The need to rely on theoretical foundations approaching the human factor is widely recognised by the research community. The most relevant findings obtained throughout this manuscript are exposed below:

- The **importance** of using **behavioural theories** as a guide when developing technologies **is commonly accepted**. However, **understanding** their **limitations** is a key point that the researchers and practitioners should take into account, being contextual factors carefully analysed. These shortcomings or limitations can be further investigated to extract valuable insights to apply to the upcoming works and studies.
- There is a wide range of valuable and diverse studies referring to behavioural theories. However, the **lack of validated studies and measurements** makes it difficult to ensure the impact and effectiveness of the different behaviour change frameworks. Besides, it is difficult to replicate the specific studies due to the lack of systematisation and scalability. Thus, it can be difficult to find validated data and extrapolate those findings. Taking this into account, future research lines should work in this line to ensure replicability.
- The different **theoretical models** or frameworks **should be understood as a global** approach. There are some works that breakdown the frameworks in different parts. This practise seems to be right isolating the study of one factor. However, it may present shortcomings in some contexts as there are confounding and hidden factors overlooked. Having said that, we argue that isolated determinants or constructs can be addressed in a specific way, yet understanding the main framework is a must in order to contextualise the determinants that are in relation to others. Therefore, addressing some parts of the behavioural theories can be adequate, while understanding and contextualising the strategy in the global context of the theory. In this way, the importance of the relations of the constructs will not be overlooked. The global approach of the behavioural strategies can be a future line of research to fill the shortcomings emerged from the closed and specific perspectives.

TABLE 1. Summary of the insights obtained from the conducted review containing the current status, found gaps and guidelines for the future lines of work.

	Summary and Finding Insights		
	Current Status	Gaps	Future Lines
Theoretical models and frameworks	Theories are widely used with the understanding that they have limitations and ambiguous aspects.	The shortcomings of the theories are not properly analysed and measured.	More research is needed to find knowledge and understand the limitations and shortcomings of theoretical models and frameworks.
	There is a variety of different and diverse studies involving a wide range of theories and approaches.	Lack of validated, systematic and scalable studies.	An effort should be made to systematise, validate and measure the impact of behavioural theories.
	The theories are applied in a diverse way.	The use of certain parts of the theories can be a limited approach if it is not understood in a global and contextualised manner.	Global approach is needed to contextualise a specific strategy avoiding the shortcomings deriving from excessively specific interventions.
Behaviour recognition and modelling	There is a wide range of applicable behaviour modelling and recognition techniques.	Lack of behaviour change works using behaviour recognition techniques for its evaluation.	It should be concisely analysed how behaviour recognition techniques could help in the evaluation of behaviour change techniques.
	Most of the works are focused on using behaviour modelling and recognition techniques to create automated processes to foster energy efficiency.	Lack of behaviour modelling and recognition techniques to foster energy efficiency through behaviour change	It should be analysed if behaviour modelling and recognition techniques could be used to cause a behaviour change on people
	Very few works use behaviour modelling approaches to address or evaluate their behaviour change methodologies.	It is not clear yet which are the best behaviour modelling and recognition techniques for the promotion of behaviour change.	An analysis of which behaviour modelling and recognition are the most appropriates for the promotion of behaviour change.
Methods, guidelines and toolkits	There is a wide range of techniques and methods to develop behavioural interventions.	Lack of studies that bring together the variety of methodologies available.	Classify, analyse and measure the different methods and guidelines to find which can be more adequate in each case.
	Some recent works offer guidelines and ideas on how to develop the strategy selection.	The intervention selection remains being complicated as the impact is neither fully measured nor validated.	Develop intervention selection guidelines taking into account the wide range of them.
	There is an excessive focus on informational strategies, forgetting other kinds of strategies and techniques.	Lack of interventions applied in a global and complementary manner and addressing the heterogeneity of people.	Implement strategies and interventions addressing the heterogeneity of the individuals' behaviour and providing different and complementary strategies to avoid the "One size does not fit all" issue.
Tangible and digital systems	Ubiquitous computing, together with visualization interfaces, represent the core of energy-related information channels	Limited evidence of Eco-feedback efficacy in the reviewed works and the difficulty of validating its results	Increase the attachment to the intelligent system and engage users in the long term through a sense of perceived usefulness of technology
	Smart Grinds and Demand-side management have the potential to make more efficient usage of the resources, aligning users' behaviour with the dynamics of the energy generation.	Technology-based behaviour change interventions suffer from a recurrent problem of lack of continuity and follow-up where the devices employed end up being forgotten and unnoticeable elements	Designing easy to use, secure and trusted systems to boots the motivating, reinforcing and enabling factors that lead to technology upkeep and acceptance.
	Existing approaches tend to move this core to innovative feedback mechanisms, redesigning and augmenting everyday objects.	Representation methods and strategies can lead to unintended consequences and low income due to a meaningless presentation of the data.	Investigate in in-depth how eco-feedback information should be presented to increase the efficiency of energy-monitoring applications

B. BEHAVIOUR RECOGNITION AND MODELLING TECHNOLOGIES

The following conclusions can be drawn from the current use of behaviour modelling and recognition techniques applied to foster energy efficiency through behaviour change:

- Modern behaviour recognition could enrich the way in which behaviour change researchers could evaluate their behaviour models and methodologies, allowing the **automated detection of minor changes in user's behaviours**.
- Even though there are several behaviour recognition approaches, **it has not been made yet a deep analysis of which approaches are better** qualified for this task.
- Although behaviour recognition techniques' performance has drastically improved during the last years, there are **a small number of research works combining advanced behaviour recognition techniques with behaviour change approaches**. Moreover, the amount of work focused on behaviour change to foster energy efficiency is even lower since most of the approaches goal is to foster energy efficiency through automated processes.

C. METHODS AND GUIDELINES AND OTHER FINDINGS

The amount of different guidelines and recommendations makes difficult to decide which strategy has a best fit in specific contexts. Thus, following a specific selection criteria is important to make feasible the process. Besides, the audience should be studied carefully to adequate the strategies to the specific target users. Other relevant conclusions are presented hereafter:

- Taking into account the review done in this work, one of the main conclusions that emerged is the **variety** and large amount **of methods**, **frameworks and findings** that are focused on offering Behaviour Change interventions. These isolated works are usually implemented independently and, to the best of our knowledge, **is hard to find studies grouping these works**. Hence, researchers may find it difficult to identify all existing methodologies that can be applied. For this purpose, further research on the **methodology classification** can be a promising future line of work.
- It remains to be difficult to select the best intervention strategy to each context albeit we have performed a thorough review of the body of literature in behaviour change techniques. One reason (in addition to the many strategies available) may be **the lack of validated and measured frameworks** which implies uncertainly when selecting the one which may have a higher impact. To cope with this issue, future research can explore the study and comparison of the different strategies and methods, **measuring their impact to extract validated data**.
- Finally, once reviewed the core corpus of the literature we highlight the **importance of the informational strategies** over another type of interventions. Eco-feedback technologies have been widely implemented with interesting results, but as a conclusion we can argue that there is a raising **need to complement the only informational strategies with other complementary techniques** to target the heterogeneity of the individuals and to avoid the shortcomings derived from the "one size does not fit all" approach [7]. Besides, there is a lack of interventions applied in a global and complementary manner and addressing the heterogeneity of people. Future research lines can study the implementation of interventions addressing the heterogeneity of the individuals and providing different and complementary strategies.

D. DIGITAL AND TANGIBLE SYSTEMS

The conclusions that can be derived from the process of acquiring the data to displaying the information to the user are provided next:

- Smart grids, demand response management systems and monitoring platforms **are not enough to reduce energy consumption** or to change load shifting if a proper analysis the energy consumption patterns is not made beforehand. An **improved understanding of how users interact with the power grid and the influence of Eco-feedback** is needed to develop energy-aware services to pursue the energy efficiency goal.
- System interfaces need to **avoid meaningless representations of the data** through energy metrics. On the contrary, **information needs to be clearly presented** in a contextualized manner. To increase energy-awareness more effectively, research should put the focus on the implications of **Eco-feedback presentation methods and strategies**, as long as evaluating the usability of the interfaces.
- Current trends indicate a shift from traditional feedback devices (such as in-home displays) to new innovative ones based on **tangible visualization interfaces**. Redesigning and **augmenting everyday objects** to provide a more natural interaction may be the way to increase the potential of the feedback. Above all, the design need to **overcome barriers regarding the uptake, lack of attachment or the distrust of technology** to actually engage users in the long term.

To conclude, a few concerns extracted from the research work are exposed as a final remarks. Whereas there is a wide amount of literature facing the behavioural aspects of technologies to raise the energy efficiency, across the present work we discovered the main shortcomings and gaps that should be targeted to improve the accuracy and the impact of them. In addition to the stated specific findings and conclusions, there are two main key points that the research community should take into account. Firstly, the diversity of behavioural theories and their implementations present shortcomings due to the specificity of the implementation of a given model based on a single theory and approach. However, this presents an interesting research line where the different theories can be analysed in conjunction, finding common determinants and relations to map and link the most common behaviour change theoretical models for sustainable behaviour, and enriching the isolated approaches. In this way, the shortcomings of each model can be avoided or minimized fulfilling the gaps presented by each theory with complementary theoretical approaches.

The second key point derived from the conclusions is the need to implement global and cross-cutting strategies beyond a specific approach. All the reviewed approaches tackle sustainable behaviour through a mostly rigid or static strategies. Besides, most of the reviewed works implemented their strategies through technological devices without complementing or reinforcing these approaches through other channels. Due to this, the responsibility is, in most cases, relegated to the autonomous piece of technology, so that capacity for sustainability falls on it and the user tends to become left apart. Both physical and digital devices, as well as recognition and modelling tools, should be part of a global strategy and should not be dependent on the device. In addition, people's needs and the emotional/psychological aspect of behaviour change must be implemented in technological systems to develop effective strategies that truly improves the awareness, attachment and the acquisition of the responsibility.

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