A Framework for Behavioural Change Through Incentivization in a Collaborative Virtual Power Plant Ecosystem

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Abstract. The penetration and growing diversity of Distributed Energy Resources in Renewable Energy Communities (RECs) are currently on the rise. The challenge with these emerging ecosystems is that their effective integration and management are becoming increasingly complex. The Collaborative Virtual Power Plant Ecosystem (CVPP-E) concept was proposed as a contribution to their effective management using a collaborative approach. Here, the CVPP manager promotes collaborative behaviour such as collaborative consumption by influencing the consumption behaviour of members through incentives. The objective is to influence community members to "delegate" their "deferrable loads" for effective management by the manager. In this work, a framework for modelling and simulation of incentivization and related behavioural intervention, adapting the CVPP-E as a digital twin model of a REC is described. The architectural structure, context of incentivization, behavioural change techniques, modelling methodology and expected outcomes of the model are outlined. Some key definitions for the model and future works are also introduced.

Keywords: Collaborative Networks · Collaborative Virtual Power Plants · Incentives · Behavioural change · Demand Response

1 Introduction

Incentives have been used in diverse sectors of society as a means to influence behavioural change. Many successful cases have been recorded in areas such as health [1], agriculture [2], natural resource conservation [3] waste management and recycling [4], as well as transportation [5]. Transposing this idea into the domain of energy is rare [6] and relatively contemporary, although tariff-based approaches have always been the dominant norm in the past [6]. Influencing behavioural change through incentives is nevertheless promising for the energy industry, particularly at the consumer end of the grid. This is because consumers' behaviour has been found to impact energy consumption in a very significant way, therefore, it is anticipated that, by altering the way consumers use energy at the household level, significant gains could be made in terms of energy conservation [7–9]. For instance, works such as [10–12] confirm the strong

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synergy between consumer behaviour and energy consumption. Further, works such as [13] revealed that there is a gap between people's desire/intentions towards energy-saving behaviours and their actual behaviours, therefore various forms of interventions including incentives are being considered to help fill this gap. For instance, works such as [6, 14, 15], describe cases where incentives have successfully been utilized to effect behavioural change in domestic energy use. Other works have also demonstrated diverse approaches and campaigns to behavioural change using various incentive models with the ultimate aim of inducing energy saving behaviour among users at the household's levels.

In this work we borrow and utilize three theories/models from the behavioural science/economics to help model behavioural change induced by incentives in a Renewable Energy Community (REC). A digital twin of a REC, called *Collaborative Virtual Power Plant Ecosystem (CVPP-E)* [16, 17], is modelled, using the combination of System Dynamics, Discrete Event and Multi-agent System (MAS) technology, thus a multi-modelling method approach. In the model, we test the effectiveness of "one-size-fits-all" and "customized incentives" (different incentives for different categories of community members, in this case households) in a REC. In order for our model to mimic the real world, we introduced other primary influences that are likely to come to play in real life scenarios. The model is also linked tightly to agents' behavioural change, resulting from incentives, to their decision to delegate. Therefore, at the global/community level, it is possible to analyse the aggregated effect and dynamics of incentives on the community as a whole (community behaviour), and also determine which kind of incentive has the prospect of being used as a more effective Incentive-based Demand Response Management technique. In this particular work, the general conceptual framework for the model and related definitions are described and defined respectively.

2 Contribution to Life Improvement

The need to provide a sustainable future with the highest level of quality life begins with the environment [18]. The ongoing discourse on climate change within the research, political, social and economic echelons of society are all intended to advance the livelihood and quality of life of earth's inhabitants. In the case of energy, the generation, transmission and consumption, are major contributors to environmental degradation in diverse forms and shades. In [19] the authors confirmed that energy consumption is inherent to quality of life and population growth. They further described some indices such as human development index of the United Nations (UNDP, the human welfare index of Meadows and Randers) etc. to measure quality of life in relation to energy consumption. In this context, the introduction of sustainability in the domain of energy was aimed at ensuring universal access to modern energy without compromising the environment. As it has already been established, energy is required to sustain and improve quality of life globally, therefore it is in the right direction to ensure it is generated, transported and consumed in a sustainable manner.

This work makes a direct contribution to the provision of sustainable energy in communities and subsequently contributes to environmental sustainability and related quality of life in the context of a community. By influencing community member to delegate their deferrable loads, two significant implication could be derived. (1) In instances where there are excess generation of solar energy in the community, the manager could shift the use of these appliances to utilize the excess energy so that the energy is not wasted or sold to the grid as feed-in-tariffs for less returns. Furthermore, in instances where there is less generation of solar energy the use of these appliances could be shifted into the night where energy tariffs are much lower. (2) In the case of large communities, curtailing the use of these appliance or shafting the time of use could enable the community aggregate unused energy and strategically sell to the grid at peak times for higher gains. These dynamics could enhance the financial gains of community members, hence, a significant contribution towards the improvement of quality of life.

3 Related Works

In recent years, as mentioned in the introduction, various publications have analysed the determinants of incentives on behaviour change in relation to domestic energy use. In a comprehensive literature review conducted in [7], the authors reviewed different intervention methods and practices affecting energy use behaviour change in the built environment. The review covered key intervention techniques such as labels, energy performance certificates, energy auditing, prompts, norm appeals, commitments, economic incentives and disincentives, feedbacks, community-based initiatives, benchmarking, goal setting and gamification. In a similar work described in [12], the authors applied the Comprehensive Action Determination Model to investigate the relative influence of intentional, normative, situational and habitual processes on energy-saving behaviour. Another work described in [20] tested the influence of a private commitment strategy in which people pledge to change their behaviour towards energy-saving practices. The authors concluded that effortful commitment strengthens one´s personal norm to engage in the behaviour change. Other works like [21] and [22] considered various policy interventions in the form of tax incentives such as: private housing sector subsidies, grants, subventions, loans and moral suasion respectively, to influence consumers' behaviour. Financial incentives have also been found to feature prominently in this area. An investigative work conducted in [23] tried to find the motivation for participating in community energy initiatives that promoted sustainable energy use in communities. The authors' motivation was to enquire if peoples' motives for participating in such initiatives was due to money (financial component), environment, or community involvement. In the United Kingdom, a similar work [6], based on financial incentives, explored, through study trials, how financial payment and feedbacks facilitated load-shifting of residential energy consumption.

Complementarily, various forms of smart technologies are also being explored in this emerging area. For instance, a smartphone application called "Social Power App" which is a gamified digital app-based community challenge, designed to trigger electricity savings, is discussed in [21]. The concept of gamification is clearly demonstrated in this work. Another technological approach is seen in [10], where the authors adopted energy efficiency technologies described as "interactive" and "fixed" technologies, to influence residential energy consumption and householders' energy-related behaviours. An incentive-based optimization compensation scheme for demand management scheduling of appliances in a residential community is also proposed in [7]. The scheme is based on the level of inconvenience for participating in shifting of task-based appliances.

4 Modelling Framework

4.1 Categorization of Households in CVPP Ecosystem

In the considered CVPP-E, households are categorized into five distinct groups. The categorization is inspired by the Household Electricity Survey: A study of domestic electrical appliance usage that was conducted in the United Kingdom in 2012 [24], and considers: (a) Single pensioner household (b) Single non-pensioner household (c) Multiple pensioner household (d) Households with child/children (e) Multiple person households with no children living at home.

Categorization of Household Appliances. Household appliances in the model are aggregated and classified as shown in Table 1.

Table 1. Classification of household appliances.

	Appliance type	Aggregated classification
1	Washing machine, dish washer, washer dryer clothes dryer	Deferrable loads
2	Refrigerator, fridge-freeze Upright freezer, chest freezer	Cold appliance
3	Oven, cooker hob, microwave oven, kettle	Cooking appliances
4	CRT television, LCD television Plasma television, computer	Audio-visuals

Modelling Households in the CVPP-E. Each household in the ecosystem is modelled as an agent, using the AnyLogic platform [25]. Each agent goes through different states (stages) of behavioural change as they come under the effect of different kinds of state-specific influences. These influences could have negative or positive polarity. Negative and positive influences affect agents negatively and positively respectively. The polarity and intensity of influences are further explained in Sect. 4.5. Agents can also receive influences in the form of messages as well. These influences will cause agent to transition from one sate to another state. The more positive an influence the more it affects an agent's transition towards a positive behavioural change and vice versa. Table 2 shows the various sources on influence and their relative polarity in the model. The theories and models guiding this aspect of the work are discussed below, in Sect. 4.4.

Table 2. Sources and polarity of influences

Source of influence	Polarity of influence
CVPP manager	Positive
Incentives	Positive
Community members	Positive or negative
Community/Social	Positive or negative

4.2 Configuration of CVPP-E (Configuring Community Size)

In order to be able to create different communities with diverse composition (varying number of each category of households) and also model different scenarios in the communities, the model is designed to provide dynamic community creation capabilities. For instance, in one instance, one could create a community with a tentative configuration of 20- Single pensioner household, 140- Single non-pensioner household, 10- Multiple pensioner household etc. In another instance, one could create another community with a tentative configuration of 5- Single pensioner household, 300- Single non-pensioner household, 150- Multiple pensioner household etc. These configurations can be done on the fly while the model runs. The Graphical User Interface (GUI) designed to achieve these configurations is shown in Fig. 1.

Fig. 1. Community configuration interface (GUI)

4.3 Incentivization

As mentioned in the introduction, incentives are introduced into the model as a means of influencing community members to delegate control of their deferrable loads to the CVPP manager. We consider two situations: one-size-fits-all and customized incentives. Table 3 illustrates the modes of incentives considered in this model and the respective target groups.

Table 3. Mode of incentive and target group in the model.

	Mode of incentive	Category of incentive	Target group
1	One size fit all	Monitory	All households
2	Customized incentives	Gamification	i. Multiple person households with no children ii. Single non-pensioner household
		Environmental	i. Single pensioner household ii. Multiple pensioner household
		Monitory	i. Households with child/children

4.4 Theoretical Framework of the Model

Behavioural science is addressed by various disciplines dealing with the subject of human actions [26]. Empirical evidence reveals several theories, concepts and models under this domain of science. These include: Social learning cognitive theory, Transtheoretical model, Theory of planned behaviour (Theory of reasoned action), Health action process approach, Fogg behaviour model, Diffusion of innovation theory and Social norm theory [26]. For the purpose of this work, three of these models/theories are adopted and merged into a single model dubbed the *Collaborative behavioural change and diffusion of innovation model (CoBeDim).*

The CoBeDim model is defined as the synergy of one or more behavioural change theories/models that integrates multiple dimensions of influences on members in a community as they endeavour to adopt a new innovation through behavioural change.

Aspects of the adopted models are briefly introduced below.

i. **Trans-Theoretical Model of Behaviour Change (TTM).** TTM is described in [27] and [28], and adopted as the main theory in which this work is grounded. It postulates that behaviour change occurs in five sequential stages. These are: (1) Precontemplation (not planning to change within the next 6 months), (2) contemplation (ambivalent or thinking about change), (3) preparation (taking steps towards changing), (4) action (attempting the change), and (5) maintenance (having been able to sustain behaviour change for more than 6 months and working to prevent relapse) and finally relapse (returning to any of the previous states due to failure to sustain the change). TTM is used to model the various transition of behavioural change of agents as they are influenced to incentives and other forms of influences.

ii. **Diffusion and Innovation Theory (DIT).** DIT is described in [29] and seeks to explain how, why, and at what rate new ideas and technology spread. The theory claims that diffusion is the process by which an innovation is communicated over time among the participants in a social system. With this theory, adoption (acceptance) means a decision to use an innovation and rejection is a decision not to adopt an innovation. The theory described five stages of the adoption process, and five adopter categories. The DIT would be applied as a guide to the rate at which "delegation" thorough incentives spread within the ecosystem. The model will adopt the various stages of the adoption process as well as the adopter category to facilitate the dissemination of the idea of "delegation".

iii. **Social Norm Theory (SNT).** A theory expounded in [30, 31], that describes situations in which individuals incorrectly perceive the attitudes and/or behaviours of peers and other community members. Social norm theory adds a social dimension to our model.

4.5 Demonstration of the Modelling Technique

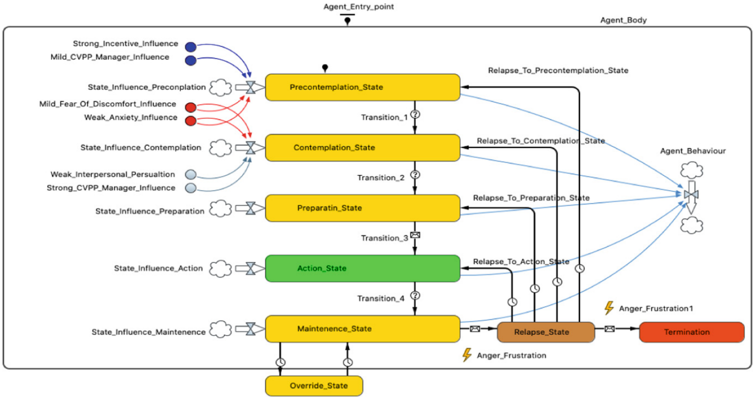

Fig. 2. A sample model of influences and rated effect on agent behaviour

The "agent body" represents the embodiment of the agent, and within the agent body lies the various states of transitions conforming to the various stages of behavioural change as borrowed from the TTL model. These states start from the precontemplation state and end at the maintenance state, with relapse and termination as possible options. At each state, an agent experiences an inflow of secondary influence called "State + Influence + Sate name", e.g. State Influence Precontemplation, which constitute an aggregation of primary influences such as Strong Incentive Influence, Mild CVPP Manager Influence, Mild Fear of Discomfort Influence, and Weak Anxiety Influence that affect the agent in the precontemplation state as shown in Fig. 2. These primary influences can carry a negative polarity as shown in red or positive polarity, shown in blue. Besides the polarity, an influence can also have intensity, which can be described as either strong, mild or weak. The intensity and polarity of influences are modelled using stochastic numbers generated within a predefined range. For instance, the model generates stochastic numbers between 10….14, which is the defined scale for positively strong influence. For weak and mild influences, the model generates stochastic numbers between 5….9 and 0….4 respectively. On the other hand, influences like

Anger/Frustration or Fear of discomfort are modelled as negative influences. A strong negative influence is modelled by generating stochastic numbers between (−14) …. (−10). Again, the model generates stochastic numbers between (−9) …. (−5) and (−4) …. (0) for negatively mild and negatively weak influences respectively. The transition from one state to the other is also conditional and is usually triggered when the "state + influence + sate name" influence acting on the agent in that particular state generates its highest possible number, resulting from the sum of all the primary influence acting on the agent in that state. In the relapse state, an agent can relapse to any of the previous states. Relapse is triggered by a message such as Anger/frustration. Termination state is a state of failure and is also triggered by a message. The final agent behaviour is the aggregation of all the "state + influences + State name" influences. Override is a temporal state where agents can opt to temporarily control their deferrable loads for a short period and return control to the manager afterwards.

5 Conclusions

This work forms part of an ongoing research work intended to implement Key Performance Indicators (KPIs) in a REC as they are incentivised to delegate control of their deferrable loads to a community manager. This is a collaborative approach which is intended to promote a collaborative behaviour in an energy ecosystem. We adopted knowledge and concepts from two disciplines: (a) Collaborative Networks [32–34] and (b) Virtual Power Plants [18]. Details of the proposed KPI are described in [35]. The main contribution of the developed framework includes: (a) Integration of multiple behavioural change models into a single model called-*CoBeDim* and its subsequent application in a REC, (b) Introduction of multiple incentives, targeting different category of agents, (c) Multimethod approach to modelling multiple incentives in a REC. The expected outcomes are: (i) Identify the kind of incentive that is suitable in a community such as a REC. (ii) Influence consumption behaviour of prosumers using the appropriate kind of incentives. (iii) Influence prosumers to delegate the control of their deferrable loads to the community manager thorough incentives. (iv) Study the aggregated behaviour/dynamics of deferent kinds of incentives on a community at the global level.

Ongoing and next stages of the work will focus on the development and implementation of this CVPP-E framework using the Anylogic platform. The proposed analysis discussed in this framework will also be performed. The outcome is anticipated to be published as an extended version of this work in a peer reviewed journal. Currently, the one size fits all model has successfully been completed. Significant progress has also been made towards the development of the customized model.

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