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General Considerations About Simulating Energy Communities

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***Abstract* — Collective action and citizen involvement in the energy sector represent the new platform upon which the novel energy communities are developed. From a scientific point of view, we consider modeling and simulation represent important instruments to shape the future energy communities and assess their impact on the society. In this context, this paper presents an initial conceptual analysis upon the most important requirements and challenges that can be expected in this new research direction, where human actors must be directly involved in the technical solution. We also propose a general model of an energy community, emphasizing the key entities and limitations, along with a concept for modeling the human behaviour. Furthermore, we consider several metrics for assessing the impact of the community with respect to the internally consumed energy.**

Keywords* — *energy community; modeling and simulation; human behaviour; self-consumption

I. Introduction

The novel *energy community* concept investigated in recent years [1] might represent a key solution in achieving net zero carbon emissions by year 2050. This is mostly because in recent decades the increasing number of appliances and electronic devices market had placed people in a position in which they rather have an important role then simply be an external factor in an energy efficient system. More specifically, it is now important to focus on energy efficient systems that take into account human behaviour as a complement to the conventional energy efficient solutions.

Moreover, through energy communities, we may discover a new way to understand energy consumption in a more profound manner, but this aspect also applied to energy production. There are intelligent solutions nowadays with photovoltaic plants and energy storage systems that may be too expensive for a singular household, but from a collective point of view it would be interesting to consider solutions for several households, some of them being investors, some of them being simple users. Thus, it is important to involve people in energy management solutions, but also to increase the reach towards a larger number of citizens involved.

Therefore, from a scientific point of view, it is imperatively necessary to properly understand the problem before providing the solution. This aspect is related to investigating frameworks used in collective-related notions such as energy markets and residential districts and identify the key simulation tools that may be used in the novel paradigm. Furthermore, solutions that involve and investigate human behaviour must be analysed in order to see what are some possible variants for modeling and simulating human involvement. It is also important to transpose the main characteristics of energy communities in a formal way and to identify the requirements and challenges that are important to address in future research directions by the scientific community.

In this context, the paper presents the first steps in formalising the platform for investigating and simulating energy communities, focusing on stating the initial problem and several theoretical and practical considerations.

II. State of the art related research

First, we have to consider several collective management solutions and approaches that have been proposed recently by the research community, with respect to the energy sector. In this matter, several collective solutions that involve multiple actors are currently represented by peer-to-peer trading, energy services or intelligent recommendation systems.

By analysing peer-to-peer energy trading, a recent review paper [2] indicates two possible approaches for simulating a system of such complexity: game theory approach [3] [4] and optimisation models [5]. Through game theory, users can increase their own benefits in terms of profit in a non-cooperative trading game, or they can act in a collective manner (cooperative game) and increase the global benefit of the community. This second principle represents a key aspect of energy communities (as it can be interpreted from the main characteristics [1]). However, as stated in [2], the main difficulty resides in modeling human behaviour in such a context. Another interesting solution for modeling peer-to-peer trading is represented by multi-agent simulations [6], where the trading mechanism is modeled with several agents types and scenarios. Even if the main objective is the maximisation of own benefit, the multi-agent framework presents an interesting approach that can be a possible solution in the energy community context. Moreover, an optimisation model relies on the assumption it is possible to collect all the problem data in a single problem, but human actors use to have lots of implicit knowledge and information. From this perspective, game theory and multi-agent do not rely on this assumption and are more relevant.

On another hand, an important aspect of energy communities is the possibility to request members to act in a certain manner through load shifting mechanisms or consumption increase/decrease to achieve a certain objective. This would represent a significant contribution in demand side management, were the aim is to provide flexibility in the usage of energy through various methods such as integrating electrical vehicles or using several transportation systems in the peak shaving process [7]. It is important to note here that energy communities would represent thoroughly complex systems, were a wide range of appliances and consumer could play a certain role. Therefore, another challenge is to conceptualise that role with respect to the community. However, very few works take into consideration the impact of humans in relation with the technical solution.

Regarding the relationship between human behaviour and energy consumption, several works show a common stochastic approach [8] to show correlation between certain human events and environmental context, or a human dynamics model is developed based on sequences of events [9]. Nevertheless, it is very difficult to determine the consumption related behaviour of people in the residential context, where there is a high degree of unpredictability.

Finally, intelligent recommendation systems have become increasingly important in the current technological context. In this way, citizens are actively involved in the energy sector through a specific set of recommendations, with the aim to reduce carbon emission and increase efficiency. However, as stated in [10], very few to none have real validation. Moreover, it is indicated that energy efficiency at collective level should be seen as an integration of social norms and technical ideals, thus potentially anticipating a key principle of energy communities. Another interesting study related to this matter involves a multi agent simulation for waste recycling [11]. Albeit the context is not related to energy management, the study emphasised that multi-agent systems may represent a way to emulate imperfection of citizens, with probabilities assigned for certain decisions. Also, people may willingly accept certain recommendations, however it is important to properly inform them and show the benefits of their change in behaviour.

To our knowledge at this moment, there are no solutions proposed to model and simulate an energy community using the aforementioned instruments and considering a proper human behaviour model. Therefore, we provide in this paper an initial step towards conceptualizing the community simulation framework by analysing and discussing a possible architecture, with related requirements and challenges.

III. Problem statement

The different energy scenarios, like for instance, Negawatt (*https://negawatt.org*) or the SHIFT project (*https://theshiftproject.org*), for complying with target adopted during the COP21 relies on 3 common levers: more renewable energies, better efficiencies of energy systems and more sobriety of energy users. Nevertheless, all these 3 levers have impacts on human behavior. The increased use of renewable energies, mostly producing intermittent electricity, leads to a less flexible production. As electrical energy can only be stored in small quantities, it is necessary to balance the energy produced with the one consumed, at any time. Therefore, until sustainable solutions for large energy storage means are found, flexibility of the energy use is required. "Demand side management" or "demand response" solutions are under development. A first approach is that electricity aggregator seeks to directly control the consumption of its customers. This is a problem that remains difficult when looking at the multiplicity of the types of consumption even if intervening on HVAC systems seems to offer interesting perspectives. In reality it only works in winter or in summer depending on the climate and this raises the problem of the rebound effect which is difficult to manage [12]. The direct control of the equipment poses real problems of acceptability by the inhabitants whereas the indirect control by the cost or by nudges such as SMS or other, is much more interesting but add complexity in the daily life for the human actors.

The second lever is to increase efficiency of energy systems. But, as shown in [13] for low consumption buildings, reducing waste increases the sensitivity of the energy consumption to human behavior; it yields problem regarding flexibility, which is less controllable and predictability issues for the energy consumption of buildings and, by extensions, to many energy systems (electric vehicles,...).

The third lever will have obviously the strongest impact on human behaviors. Consequently, automatized energy systems where human behavior could be considered as disturbances are going to become more sensitive to human behavior and we believe that the "doing instead" paradigm should evolve towards a "doing with" paradigm, with more involvement of human actors in the everyday energy management in order to develop awareness and responsibility regarding energy usage. Better integration of awareness of human behaviour in the design of energy systems has been highlighted as a requirement for energy efficiency solutions and associated regulations [14], [15]. Awareness and responsibility regarding sobriety and flexibility of human behaviour can be described, respectively and in this context, as the knowledge and perception of the impact of its own actions on energy performance. Numerous research works have been carried out to study the human behaviour influence on energy performance dealing with optimized energy management [16], modelling simulations of buildings and neighbourhoods, the transformation of building system models [17], methods for guaranteeing performances [18] or performance verification methods [19].

As pointed out by *Le Monde* [20], the major retrofitting effort carried out in Germany did not lead to any form of effective reduction in thermal consumption in private homes: in 2010, a household was consuming an average of 131kWh of primary energy ($kWhpe$) per square meter and, in 2018, it consumed 130 $kWhpe/m^2/year$. The cause is the rebound effect, i.e. after the retrofitting the inhabitants tend to increase their comfort requirements and become less careful about consumption which is supposed to be lower. The awareness and flexibility of human behaviour in order to favour low energy services and lifestyle must be taken into account.

Although there is a slight difference in human influence between commercial and residential buildings, the solutions for helping people to become more aware are different: the former can be based on automation because the companies can support the often-large investments and the diversity of activities is often low, while the latter remains problematic. The INVOLVED project considered in [21] and [22] has provided responses by developing concepts for Persuasive Interactive Systems (PIS). It aims at supporting sustainable behaviours while involving the occupants in daily decisions that have an impact on consumption and comfort. This PIS focus on the perception, understanding and action capabilities of the inhabitants, thus avoiding the pitfall of excessive automation. Beliefs, resistance to change, perception and misunderstanding were taken into account by the PIS in generating reports [16] and advice after the inhabitants specified their expectations [23]. There is no references to aware human practices insofar since the comfort requirements are specific to each household, but above all, the inhabitant's intentions remain inaccessible to the PIS. Mirroring, replay, explanation, focus and advising services have been developed and tested [24].

Consequently, several requirements for an energy community are:

- people should understand the impact of their actions
- people should trust the PIS
- people should have support to tackle the increased complexity in everyday energy management
- interactive services and mixing system data and human knowledge should be used to get good solutions
- people should obtain a form of profit for changing their behaviour in the desired way

There are solutions for involving households in the everyday energy management but local renewable plants and storage systems may require a size which is not affordable for a single household but are relevant for a group of people both users and investor. Consequently, we consider the energy communities to be a potential solution to this challenges, by both focusing on citizen's behaviour towards energy consumption and opening the idea of renewable energy to almost all types of residences through a collective approach.

IV. Modeling and simulation requirements

Considering the previous problem setting, we further establish the necessary requirements for properly modeling and simulating an energy community. We focus on designing the community as a collection of individual autonomous entities, the requirements for the most important actors and other relevant issues such as privacy.

Regarding the organisational form of the community, an intuitive approach would suggest a structure focused on members, with a community manager that represents an informational entity responsible with understanding the dynamics of the community at every step, and also with providing a certain support for community members in their everyday decisions. The technical nature of this manager would also allow optimisation models to be implemented, based on different criteria: community satisfaction, community performance in terms of economical and environmental issues, involvement of members etc. The organisation form will also provide roles for each member, according to their profile, involvement or capabilities. For example, we might have a community with or without electric vehicles, and so it is important to take into account this aspect in the simulation process.

A special focus must be placed upon the community members. More specifically, members should be simulated as individual autonomous entities, having specific actions and attributes. This aspect is available for both households and small to medium sized businesses as well. Moreover, each member must have a specific attribute (or set of attributes) to represent the level of satisfaction. In this way, the focus will not only be to integrate humans in the energy technical domain, but also on the level of satisfaction with their respective involvement. However, people are complex and guessing people intentions could be a challenge. From this perspective, a stochastic approach might be used to model the inclination of agent towards a certain action or sequence of actions.

Nevertheless, the communication side in an energy community is complex. A typical community member must be designed in a way to depict a certain level of intelligence and reactivity to the interactions with other members, the interaction with the manager and also the social, economical and environmental performance of the community. The member must understand the energy performance of the community and has the possibility to act, with support given by the manager, to improve the community performance. On the other side, the community manager must be able to send different messages to the members in an effective way, with the aim to develop and improve the behaviour regarding energy consumption.

Seasonality and daily routine play an important role from the simulation point of view. There are different time periods of the day when the consumption or the production is higher then the other one, so it is important to adapt the community dynamic to these periods accordingly.

Finally, the privacy issue must be considered as an important issue. The necessity for the community manager to understand the community dynamic might lead to intrusive measurements, so it is important to adopt a moderate approach in measuring energy consumption and understanding human behaviour.

V. Proposed concept-architecture

Considering the aforementioned aspects, we propose a general concept architecture for a simulation model of the physical system of an energy community (Fig. 1).

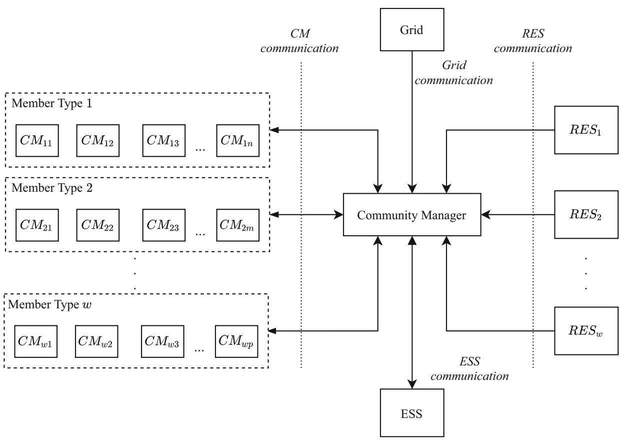

Figure 1. General architecture for simulating energy communities

A. The community manager

The main entity in this architecture is represented by the Community Manager. By analysing the general characteristics of an energy community [1], we consider an intuitive solution to be of centralized nature, where for each energy community we have an assigned entity (possibly an automatic service) that is the community manager. However, this entity should be limited in control - even though in [25] people could agree to accept external control of residential appliances to some degree, in an energy community the focus is represented by the human behaviour.

To assess the economical performance and environmental impact of the community, the manager must use a series of data-related specific instruments. A first such instrument might be, considering the basic principles of energy communities [1], self consumption [26] which represents how much of the internal production is used internally through consumption. Another metric that can be used to assess the performances of the community is represented by self-sufficiency [27] which represents the degree of autonomy of the system, with respect to the produced renewable energy.

The presented metrics are frequently encountered in specialised literature [28], [29], however there may be other metrics for evaluation the performances of communities. The list is also open for metrics that evaluate environmental benefit or the social impact. The only requirement here is to properly show the citizens the benefit of their active involvement and the collective satisfaction level in a quantifiable manner.

Given the limited role of the community manager, we consider that the communication side with community members and other entities is crucial. Therefore, as emphasised in Fig. 1, we consider there may be several types of communication channels:

- **bidirectional communication** - we consider that this type of communication must be established between the manager and community members and also between the manager and the potential energy storage system. This is because in this new paradigm, empowering citizens with information is essential. We consider that this communication aspects should be thoroughly clarified for each community type, given the importance of information transfer.
- **unidirectional communication** - between the manager and renewable energy sources and between the manager and the grid. This aspect is important since the manager must always quantify the energy that is used from RES and the energy used from the grid in order to evaluate the performance of the community.

B. Renewable energy sources and storage systems

From another point of view, a renewable energy community can be connected to several renewable energy sources (RES), while a citizen energy community is electricity based [1]. Thus, in Fig. 1, we provide a global view of this aspect by defining several renewable energy sources types: RES_1, RES_2, ...Therefore we consider a general case, but this proposed solution can be easily adapted for only one renewable energy source.

Also, we may consider communities with extended flexibility, in the form of energy storage systems (ESS). In this way, surplus renewable energy can be stored and used at a later time.

C. Community members

In order to formalise the complexity of a generic community, we consider several types of members. Thus, we consider set $\mathcal{A} = \{CM_{11}, CM_{12}, CM_{13}, ..., CM_{1n}\}$ to be the set of n community members (CM) of type 1, another set of m community members $\mathcal{B} = \{CM_{21}, CM_{22}, CM_{23}, ..., CM_{2m}\}$ of type 2 and so on. The criteria for classifying community members may be related to either the amplitude of consumption, the willingness to modify the load profile or even the time period in which the member can modify the consumption. The main idea here is to conceptualize several possible communities:

- an energy community with only one CM type - this community may be represented by a residential district with houses, thus developing a community with members having similar levels of consumption (to a certain degree).
- an energy community with two CM types - this community may also consider (besides the residential CMs) electrical vehicles as another form of flexibility to the overall community consumption. Here, the predictability given by the period of battery charging may represent an important information for the community manager.
- an energy community with three or more CM types - were other possible entities that are part of the urban power grid may join. In this case, we may consider residential members with similar amplitude but different willingness to shift the consumption, small to medium sized business with a particular load profile and so on - excluding large enterprises [1].

D. Human Behaviour Simulation

Given the difficulty of simulating human behaviour, it is important to consider as a starting step a simple stochastic approach. This interaction can be conceptually explained by a sequence diagram (Fig. 2).

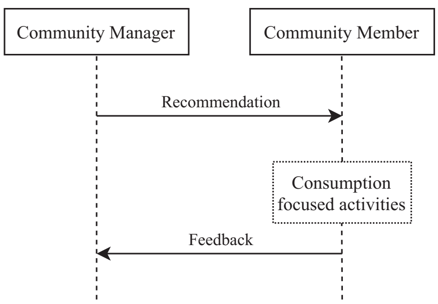

Figure 2. Interaction between Community Manager and Member

More specifically, we consider the case where the manager gives a recommendation to a community member in order to modify his consumption, thus providing specialised support. In this case, a stochastic model of the member may be developed since he may or may not follow the recommendation while doing certain consumption related activities. After that, a specific *feedback* must be sent to the community manager.

If the member follows the recommendation, then the stochastic model may be developed in a way to introduce and investigate incentives: *what are some meaningful ways to motivate community members to modify their consumption?*. Some interesting solutions here revolve around developing reward systems, where the involvement of citizens in the collective energy dynamics is appreciated in a certain manner, either economical or social. On another hand, if he does not follow the recommendation, it is important to investigate the factors that led to this decision and also take into account the satisfaction of the citizen.

Finally, the feedback mechanism is very important in the whole behaviour model, since it is imperative that the community manager understands the dynamics of the community given his recommendations. The feedback may be given by the community members individually (in order to understand the degree of trust in the process), or it may be computed through consumption measurements and comparison with an expected consumption profile (which acts as a reference). Each measure, however, must be taken considering privacy issues.

Given the available instruments for modeling and simulation discussed in section 2, we therefore some possible implementable solutions are:

- multi-agent with a peer-to-peer organisation
- an optimization model to provide suggestions from partial knowledge to human actors
- a game theory model to represent the behaviour of human actors
- a mechanism guaranteeing convergence to a better solution then now
- a model with performance criteria evaluating people satisfaction and profits

Furthermore, dynamic simulations with stochastic models for human decisions would also be possible. A challenge here would be in terms of simulation speed, where languages like Python and Matlab would be relatively slow for long simulations. A better alternative would probably be Java.

VI. Conclusions and ongoing work

In this paper we presented an initial step in modeling and simulating energy communities, in the novel paradigm proposed by the European Union. The proposed analysis focused on properly stating the problem and identifying the requirements and challenges that may be identified, from a scientific point of view. A formalism was proposed, along with several metrics for performance evaluation of the community. A special focus is placed on human behaviour modeling and a recommendation mechanism

We highlighted the importance of accurately predicting the consumption of the community, along with frequently and accurately informing community members about the collective dynamics of consumption and other relevant metrics. Furthermore, the unpredictable and autonomous character of community members represents a key requirement. The identified requirements allowed us to propose a conceptual architecture of an energy community, emphasising the communication between the entities and also the stochastic approach with could be a key solution.

There are many interesting directions that can be investigated from this point forward. For example, the dynamics of a multi-agent based energy community with residential houses, where agents may cooperate between themselves for the overall community benefit. Also, a community with residential houses and electrical vehicles may also be investigated, where agents charge the vehicles based on recommendations from the community manager.

Currently, our work is focused on developing an energy community model with residential houses, through a multi-agent approach and considering the concepts proposed in this paper. The idea is to implement an intelligent recommendation system that would actively influence the consumption behaviour of community members and will also take into account the imperfections of citizens through a stochastic approach.

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