A Conceptual Model of a Multi-Agent System to Simulate Collective Behaviors in Renewable Energy Communities

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Abstract. The urgent need for a global energy transition towards sustainability has underscored the importance of Renewable Energy Communities (RECs) in promoting local green energy production and consumption. Managing these communities is complex due to the diverse behaviors of members influenced by various factors. This paper proposes a conceptual model of a multi-agent system that integrates the Theory of Planned Behavior and Activity Theory to simulate individual and collective behaviors within energy communities. By leveraging the psychological insights of the Theory of Planned Behavior and the socio-cultural perspective of Activity Theory, the conceptual model aims to enhance the understanding of behavioral dynamics within RECs, thereby informing management strategies and energy policies. The model is designed to simulate energy behaviors and interactions between agents and their environment. Agents, representing consumers and producers, make decisions based on attitudes, subjective norms, and perceived behavioral control as outlined by the Theory of Planned Behavior. The system's environment, structured by Activity Theory, organizes agents' interactions and incorporates tools, roles, rules, and norms governing the activities within energy communities. Future simulations under various scenarios will allow the evaluation of management strategies, facilitating the transition towards sustainable energy practices. This socio-technical approach offers a detailed framework for modeling energy community behaviors and demonstrates the efficacy of multi-agent systems in studying complex energy systems.

Keywords: Multi-Agent System, Conceptual model, Individual and collective behaviors, Theory of Planned Behavior, Activity Theory, Renewable Energy Community.

1 Introduction

The energy transition has become a global priority to mitigate the effects of climate change and promote energy sustainability. Following the adoption of the legislative package called the "European Green Deal", new forms of energy sharing have emerged almost everywhere in Europe [6]. The objective pursued by Europe is to accelerate the energy transition by placing the consumer and the decentralization of electricity production at the heart of the European energy strategy and developing new forms of energy sharing by participating in a renewable energy community (REC). These communities are legal entities (association, cooperative, etc.) based on open and voluntary citizen participation and must be managed by its members who can only be residential, small and medium sized enterprises (SMEs) and local authorities. The main goal of these RECs is to foster collective self-consumption of the produced green energy, thereby reducing the economic costs associated with grid energy consumption, decreasing carbon footprint, and promoting energy transition. They also aim to ensure inclusivity for people in energy poverty [Decree of the Walloon Parliament, 2022]. However, effectively managing these communities is a complex challenge [1]. The consumption behaviors of members are varied and influenced by numerous factors, making the optimization of collective self-consumption difficult [4]. In addition, the full operationalization of these communities in Europe is hindered by delays in the implementation of country-specific legislative decrees. In the absence of direct observation of these behaviors or the ability to conduct large-scale surveys, simulation emerges as a valuable alternative for understanding the impact of members' behaviors on the dynamic of these Renewable Energy Communities. Moreover, this simulation serves to assist managers in evaluating their energy management strategies and the effectiveness of distribution rules on members behaviors.

Multi-agent systems offer a promising approach to model and simulate these complex behaviors [3, 7, 9]. It is a simulation method that represents autonomous entities (agents) and their interactions within a system [11]. Multi-agent systems allow each member of the energy communities to be represented as an autonomous agent with specific behaviors and interactions with other agents. This enables to capture emergent dynamics of the overall system based on individual behaviors [7]. Each agent has specific characteristics and behaviors and can interact with other agents and the environment. Multi-agent system is used to study complex systems where individual behaviors and interactions can lead to non-trivial emergent phenomena [10]. The main objective of our multi-agent system is to enhance the understanding of behavioral dynamics within the energy communities to inform management strategies and energy policies.

However, multi-agent system modeling is often based on a techno-centric approach. However, multi-agent system modeling often adopts a techno-centric approach. Agents are typically programmed based on criteria such as load demands, preferred time-shiftable loads, thermal comfort, and external factors like retail prices and weather conditions [7, 9]. In this study, we built upon the agent architecture developed by Reis et al [9], enhancing the decision-making module by integrating theoretical models from cognitive, social, and human sciences.

The primary contributions of this paper are as follows:

- Modeling the decision-making processes of REC members to closely mirror real-world mechanisms.
- Modeling the influence of individual behaviors on one another and the interactions among different members of the REC.

This approach will contribute to the existing literature by providing a detailed framework for modeling behaviors within energy communities and demonstrating the effectiveness of multi-agent system in studying complex problems in the field of renewable energy.

The purpose of this work is to construct a conceptual model grounded in a robust theoretical framework, with the goal of subsequently developing a multi-agent behavior simulation system. We first present the theoretical framework underpinning the model, followed by an analysis of the REC system we aim to represent. Finally, we detail the two main stages of model construction: the architecture of the agents and the environment.

2 Methodology

2.1 Theoretical Framework

To develop our conceptual model, it is essential to rely on robust theoretical frameworks. In this research, we utilize Ajzen's Theory of Planned Behavior [2] and the Activity Theory as proposed by Leontiev [8] and Vygotsky [13], as they offer complementary perspectives for understanding and modeling human behaviors in complex contexts. Activity Theory, a socio-cultural approach, emphasizes the interaction between individuals and their environment, viewing human activity as a complex system mediated by tools [5]. Conversely, the Theory of Planned Behavior provides a psychological framework explaining human behavior based on three main determinants: attitudes, subjective norms, and perceived behavioral control. Therefore, while the Theory of Planned Behavior focuses on intentions and factors influencing individual behavior, Activity Theory puts the accent on the interaction between individuals and their sociocultural environment.

2.2 Renewable Energy Community overview

The conceptual model integrates elements of Renewable Energy Communities (RECs). In this model, residential and/or non-residential members comprise the REC, all located within a geographically local perimeter. Members can be either consumers or prosumers. Production means can be individual, such as photovoltaic installations owned by certain members, or common installations shared by the REC. Activities within the community include consuming, producing, selling, sharing, and storing produced energy. A community is managed by an individual or legal entity known as the manager, who is responsible for contract management and the implementation of rules for energy distribution among members, as well as managing energy and financial transactions. The collective goal is to ensure self-consumption of the produced energy to reduce consumption from the grid, avoid losses, and achieve autonomy for the community.

2.3 Objectives and Functional Specifications of the future multi-agent system

Before developing our conceptual model, it is essential to clearly determine the system's objectives and purposes by asking the following questions: What tasks should the system accomplish? What problems should it solve?
The purpose of this multi-agent system includes simulating energy consumption, sharing, and storage behaviors, as well as analyzing interactions between agents and their environment to improve the prediction of their individual and collective behaviors. The next step involves defining the necessary functionalities to achieve these objectives by identifying the end-users and their specific expectations and needs. These functional requirements primarily include the capability to simulate varied individual behaviors and manage collective self-consumption within a decentralized and intermittent energy resources.

2.4 Agent Modeling Based on the Theory of Planned Behavior

An agent is an autonomous entity capable of perceiving its environment, making decisions, and acting independently. These agents are reactive to external stimuli, proactive in pursuing their objectives, and can communicate and interact with other agents to coordinate their actions. They are also adaptable, modifying their behaviors in response to changes in the environment or interactions with other agents. In the context of simulating a Renewable Energy Community, the agents represent consumers, renewable energy producers, the community manager, and the network managers, each operating according to their own objectives and the common objective of the system, in addition to their action capabilities and predefined decision rules.
In this paper, we focus on modeling the consumer and producer agents of the community. These agents are considered the most complex and unpredictable in the simulation of the community. We first relied on Reis's agent architecture [9], which comprises three modules: (i) a communication component with introduced inputs from the environment with data on expected weather conditions (including photovoltaic generation and outdoor temperatures) and day-ahead retail pricing, (ii) a technical component includes loads and generation and storage equipment, and (iii) a decision-making component where the agent evaluates whether the information received from the communication component and the resources from the technical component enable it to act and achieve its goal or not. In our work, we focus on this third component to model in fine decision-making rules of the agent based on social approach of the Theory of Planned Behavior. This theory is particularly useful for modeling individual decision-making mechanisms as it captures the underlying motivations of individuals and external influences, providing a robust framework for predicting behaviors. According to Theory of Planned Behavior, an individual's behavior is determined by their intention to perform the behavior, which is influenced by three main factors: attitudes, subjective norms, and perceived behavioral control, as illustrated in Figure 1.

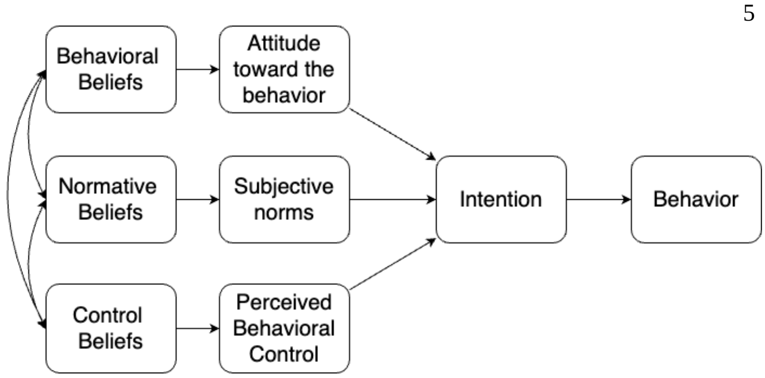

Fig. 1. Theory of Planned Behavior Model (Ajzen, 2015)

We present below the definitions of these factors and their interpretations in defining the decision-making rules of the agent-members of the community.

Attitudes. These are the positive or negative beliefs and perceptions towards a particular behavior and its consequences. Agents evaluate a behavior positively or negatively based on:

- Loads: refer to consumption habits or regular practices of individuals concerning the use of electricity at specific times of the day or week. Loads can also be urgent or imperative;
- Perceived benefits: financial savings, contribution to environmental sustainability;
- Perceived costs: initial investment, equipment maintenance;
- Personal comfort: refers to thermal and physical comfort specific to each individual. Comfort tolerance varies from one individual to another.

Subjective Norms. These norms include social and cultural pressures and expectations. Agents can be influenced by the expectations of other community members, reinforcing or moderating their intentions and behaviors:

- Peer pressure: influence from neighbors or community members on the individual's behaviors. It can take the form of direct suggestions, explicit requests, criticism, mockery, or social exclusion. It can also be more subtle, like the desire to fit in or not feel different from others;
- Community rules and policies: such as local regulations, incentives for the consumption and production of renewable energy.

The agent's degree of influence plays a significant role in conforming to these norms. It refers to the agent's likelihood of changing their attitudes, beliefs, or behaviors in response to external stimuli or pressures. Several factors can influence this degree, including personality, level of knowledge and expertise, type of relationships, source of influence, need for recognition, and past experiences.

Perceived Behavioral Control. This concerns the individual's perception of their ability to act and the ease (or difficulty) of performing the behavior. Agents' perceptions concern their ability to manage energy based on available means and resources:

- Available means: Produced green energy, IoT, connected equipment, presence at home, financial capabilities;
- Access to and ease of use of these means.

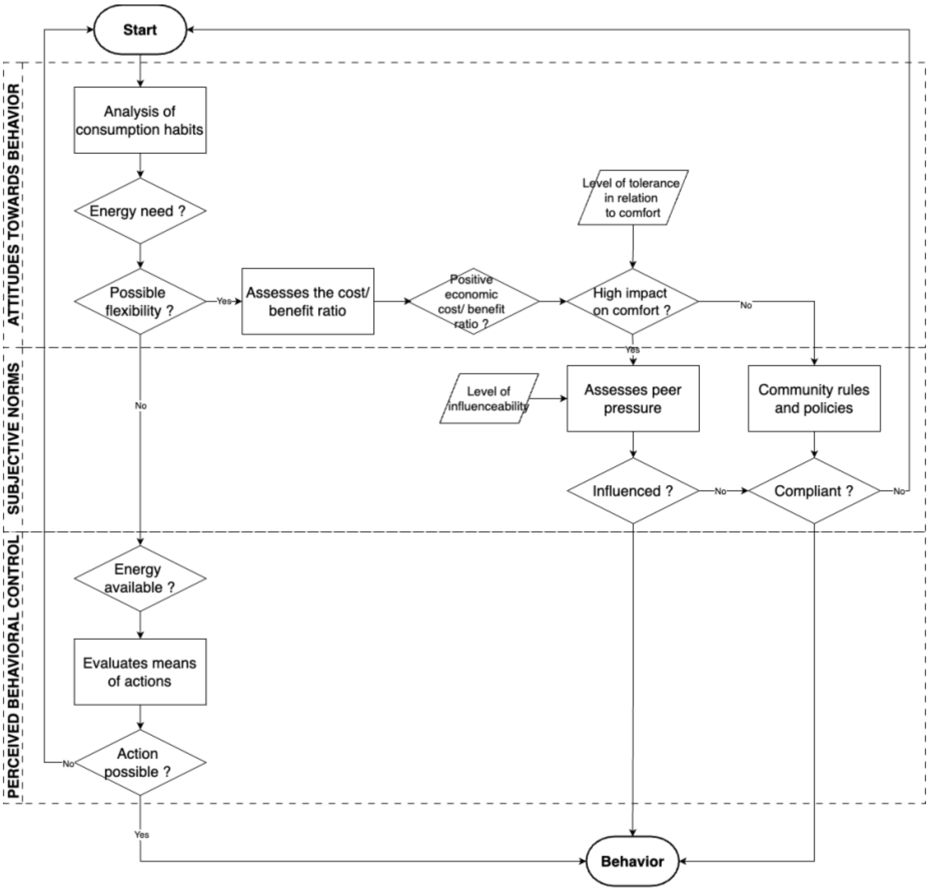

Fig. 2. Flowchart diagram of decision-making process of an agent.

In Theory of Planned Behavior, attitudes, subjective norms, and perceived behavioral control are evaluated in an integrated manner. The sequential order is not strict; it depends on the agent's characteristics and the type of behavior to be performed. For consistency with the base model, we illustrate the decision-making process of an agent in the diagram in the figure 2. Each agent will then be programmed using these decision rules, taking into account interactions with other agents and the environment. The simulation environment, in which the agents will operate, is created to reflect the real conditions of the REC, including available energy resources, infrastructures, and regulatory constraints.

2.5 Designing the environment of agents following the Activity Theory

The design of the agents' environment involves determining agent interactions and communication and coordination structures. It also entails defining the internal structure of agents, including the decision modules presented in section 2.4. The Activity Theory model, developed by Engeström and depicted in figure 3, provides a framework for organizing interactions between individuals and their environment.
This theory focuses on human activities as goal-directed processes, instrumented by artifacts (technologies), and influenced by social structures. The organizational structure of agents, based on this model, aims to form a coherent system reflecting the structure of the energy community thus ensuring effective cooperation among them to achieve the objectives defined in section 2.2.

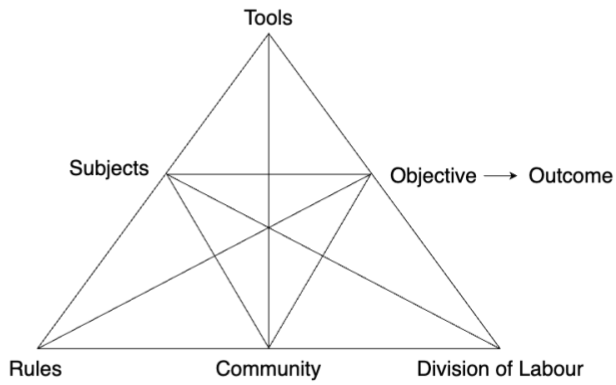

Fig. 3. Engeström's model of the structure of human activity (Adamides, 2022)

Each element of the model is translated into a component of conceptual model's architecture by integrating the agent's architecture.
Object (Goal). The object in Activity Theory represents the goal of the activity. Agents work towards a common goal, which is the optimization of collective self-consumption to reduce energy costs and maximize the use of renewable energy sources. Each agent may also have activities motivated by individual goals.

Subject (Agent). The agent, represented by the subject in Activity Theory, represents a member of the energy community. It can be an individual or an entity actively involved in the consumption, production, storage, or sharing of energy within the energy community. Subjects can be homeowners, local small and medium sized enterprises, or public institutions. A coordinating agent represents the community manager and is responsible for managing interactions and communications with and among the community members. Agents integrate attitudes, subjective norms, and perceived behavioral control into their decision-making. For example, a homeowner evaluates financial benefits (attitudes), feels influenced by neighbors (subjective norms), and considers their ability to install photovoltaic panels (perceived behavioral control).

Community (members and stakeholders in REC activities). The community consists of agents interacting within the system. It represents individuals, groups, and organizations involved in collective self-consumption activity. Community dynamics incorporate subjective norms, influencing agent behaviors.

Tools (Technologies and equipment). Tools are the technologies and equipment used to mediate the activities of agents (REC members) within the system to achieve their goals. They include consumption equipment, generation equipment (solar panels and wind turbines), storage devices (domestic batteries and community storage systems), energy management systems (energy management software and real-time monitoring platforms), sensors and meters, and energy and information communication infrastructures. Agents make decisions based on data provided by these tools. Observation and communication modules are integrated into the system to enable agents to perceive and react to environmental constraints and opportunities, thus facilitating optimal energy management. Depending on the accessibility and effectiveness of the tools, agents' perceived behavioral control may increase or decrease.

Roles and Division of Labor. This component describe how tasks are distributed among community members. In a Renewable Energy Community, each agent has a specific role: energy producers (those who generate energy from renewable sources), consumers (those who use energy for domestic or industrial purposes), storers (those who manage energy storage), and the manager who coordinates all these activities among the different community members. Task allocation among agents is based on their roles, abilities, and responsibilities. Roles must be clear, and agents must follow role-specific interaction rules.

Rules and Norms. These are the protocols and standards governing agent interactions and energy practices. Rules and norms govern interactions between agents and structure activity. In a Renewable Energy Community, they encompass regulations such as energy policies, safety standards, environmental norms, social norms such as attitudes and shared expectations regarding renewable energy consumption, energy conservation practices, and local agreements such as distribution rules and contracts between community members for energy sharing and exchange.

Outcomes. These are the consequences of activity. They represent the outputs of the system and are evaluated in terms of :

- collective self-consumption rates: increase in the use of locally produced energy ;
- financial savings: expenses related to purchasing energy from the grid ;
- environmental impact: carbon emissions, promotion of green energy production ;
- member satisfaction: equity and inclusivity of members in energy poverty.

These simulation results are analyzed to assess the effectiveness of collective self-consumption strategies and system performance. A conceptual model is proposed in Figure 4 to illustrate the interaction of all these elements.

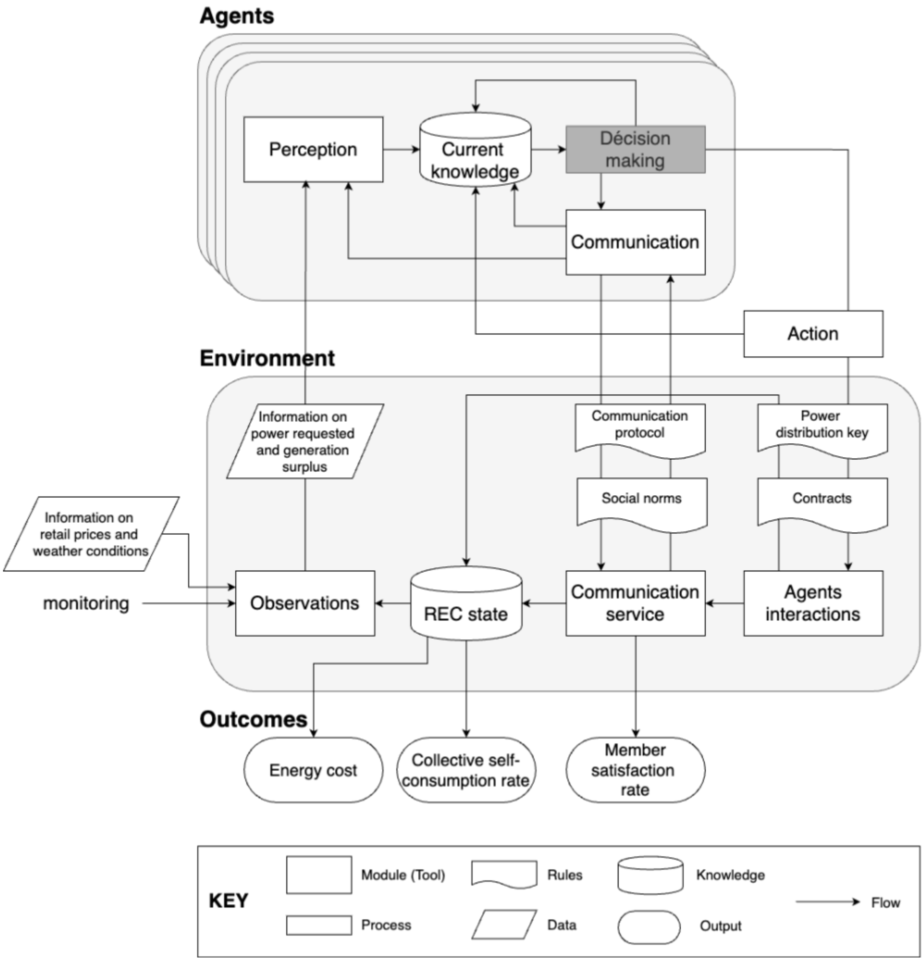

Fig. 4. Conceptual model of the Multi-Agent System

3 Discussion of the Conceptual Model

This conceptual model presents the Renewable Energy Community's system structured into two main levels: the individual level of agents and the collective level of the community. Each agent is equipped with different components, including communication, which allows them to gather information on energy retail prices and weather conditions. Agents use a knowledge base to store and update this information, then make decisions based on this data and the behavioral model explained in section 2.4. They also exchange information among themselves to coordinate their actions effectively.

At the community level, the system integrates several processes and interactions, including monitoring the system's state, including power demands and generation surpluses. This centralized state is maintained to integrate agent data. A communication service manages communication protocols between agents, including social norms and contracts. Agent interactions are governed by power distribution rules, contracts, and social norms. The system aims to optimize energy costs, maximize collective self-consumption rates, and improve community member satisfaction, using autonomous agents that perceive and react to their environment, make decisions based on real-time updated knowledge, and interact in a coordinated manner.

Simulations will be conducted under two main scenarios: (1) Agents intentionally configured with pre-defined choices to obtain desired state of optimized collective self-consumption. The aim of this scenario is to evaluate whether the self-consumption objective is counterintuitive to the satisfaction rate of the members and energy costs. (2) the second scenario is to trace decision-making of agents and see whether their individual goals correspond to the collective goal of self-consumption. These scenarios may also include variations in individual behaviors (different levels of attitudes, subjective norms, and perceived behavioral control, etc.), variations in environmental conditions (renewable energy production, weather conditions, etc.), and management strategies (modification of energy distribution rules, local rules and intervention of incentive policies, etc.).

Analysis of simulation results and interactions between agents and their environment identifies actionable levers to improve collective self-consumption, such as strengthening pro-environmental social norms or improving access to energy management technologies.

4 Conclusion

Our approach, combining the theories of planned behavior and activity, enables the capture of individual and collective emergent behaviors within a Renewable Energy Community. By integrating the individual and sociocultural dimensions of human behavior, the proposed conceptual model aims to accurately model the complex dynamics of the Renewable Energy Community and better predict emergent behaviors. Autonomous agents perceive their environment, make decisions based on real-time updated knowledge, and interact within a community structure governed by communication protocols, social norms, and contracts. The simulation results allow for the evaluation and validation of management strategies, thus facilitating the transition towards more sustainable and collaborative energy practices.

Disclosure of Interests. The authors have no competing interests to declare that are relevant to the content of this article.
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