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Published in:
Energy Informatics

Publication date:
2021

Document version:
Accepted manuscript

Citation for pulished version (APA):
Christensen, K., Ma, Z., Demazeau, Y., & Jørgensen, B. N. (2021). Agent-based simulation framework for evaluating energy flexibility solutions and adoption strategies. *Energy Informatics*, *4*(Suppl. 1), [P11]. https://energyinformatics.springeropen.com/articles/10.1186/s42162-021-00145-9#Sec45

Agent-based simulation framework for evaluating energy flexibility solutions and adoption strategies

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Abstract: To achieve national and international climate goals, huge investments are expected in the transition to a low carbon society. Due to large investments and high failure rates, avoiding risks (especially the value chain risk) evaluating the energy flexibility solutions and their impact on the energy ecosystem is essential. This PhD research project aims to develop an agent-based simulation framework for evaluating energy flexibility solutions and adoption strategies in a given energy ecosystem. The simulation framework consists of two sub-frameworks. One identifying and implementing energy flexibility solutions to the agent-based simulation. Another for identifying and implementing adoption strategies to the agent-based simulation. To show proof-of-concept of the developed framework, agent-based simulations of a case study are developed based on the model framework. The case study is an investigation of electric vehicle charging in a Danish electricity distribution grid. The research project's outcomes of evaluations and recommendations of energy flexibility solutions will contribute to the climate goals.

Keywords: energy flexibility solutions, agent-based simulation, innovation adoption, generic framework

Motivation

Grid balancing becomes more and more challenging due to the increasing share of non-dispatchable energy production from renewable energy resources, e.g., wind and solar [1]. One of the solutions is to utilize the energy flexibility on the consumption side [2]. New energy flexibility solutions are introduced to the market to activate the flexibility potentials, e.g., virtual power plants and distributed energy resources [3]. However, there are many kinds of solutions, and some are more efficient but also more complex than others [4]. The failure rate to launch new products/solutions to the market is still high, and the energy flexibility solutions usually require large investments [5, 6]. The market adoption rate is also usually slow and depends on different market segments and business models that companies apply [6, 7].

Therefore, to avoid the risk (especially the value chain risk) and to evaluate the impacts of energy flexibility solutions on the energy ecosystem, this research project aims to develop an agent-based simulation framework for evaluating energy flexibility solutions and adoption strategies in a given energy ecosystem.

This research applies agent-based simulation to evaluate energy flexibility solutions, adoption strategies, adoption rate, and business opportunities in a given energy ecosystem. The research project outcomes will support the ambitious climate goals for Denmark [8] and the Paris Agreement [9] [10]. The developed agent-based simulation framework will also assist the understanding of what-if scenarios, e.g., how to positively affect the adoption of smart energy solutions by overcoming the adoption barriers and turning their solutions/innovations into adoption triggers [7]. Consumers' behaviors, including the adoption rates and adoption speeds and their differences and similarities in the different energy ecosystems (e.g. USA and Denmark), are also investigated in the project.

Research Objectives

With a case study of the Danish electricity ecosystem, the research objectives are:

1. Develop a generic agent-based simulation framework for energy flexibility solutions in a targeted energy ecosystem
2. Design a generic agent-based simulation framework for adoption strategies of energy flexibility solutions.
3. Evaluate the adoption of energy flexibility solutions' impacts on the energy ecosystem

The planned research process to achieve the above research objectives is illustrated in Figure 1. The first objective requires methodologies for energy flexibility selection and implementation in agent-based simulation. The development of a methodology for selecting relevant solutions starts by identifying the energy ecosystem and its CSTEP ecosystem factors [11, 12]. CSTEP factors cover Climate & environment, Social culture, Technology, Economy & finance, and Policy & regulation. The next step is to investigate the State-of-the-Art (SoA) solutions. Last, the SoA solutions are evaluated and selected. The development of a methodology for implementing the solutions into an agent-based simulation starts by selecting the energy ecosystem and implementing it to the simulation model. Next, the agent-based model is designed and solutions are implemented. Last, a generic agent-based simulation framework for algorithm implementation is developed.

To achieve the second objective, methodologies for adoption strategy selection and implementation in the agent-based simulation are required. The methodology of adoption strategy selection is developed starting by conducting a SoA analysis of adoption strategies for energy-related solutions. Last, the adoption strategies are evaluated and selected for implementation. The adoption strategy implementation is developed by designing an agent-based model for implementing the strategies. Last, a generic agent-based simulation framework for adoption strategy implementation is developed.

The third and last objective is achieved by identifying the ecosystem impacts based on simulation results. This is done through the implementation of energy flexibility solutions and adoption strategies in the agent-based ecosystem model. The ecosystem for simulation is represented by a case study providing proof-of-concept of the developed frameworks. Next, an ecosystem impact indicator application is developed. Next, hypotheses and scenarios are designed to evaluate the ecosystem impacts. Next, the hypotheses are tested through scenarios. The results are generated for all scenarios and the raw results are interpreted through visualization in form of graphs and relevant figures. Last, the results are analyzed and CSTEP factor analysis is conducted based on the analyzed results.

The right-hand side of Figure 1 represents the three objectives. Their relations are shown with the arrows that the two first objectives can be made separately but are both implemented and tested to achieve the last objective. The same approach is used to describe the relationship of the small blocks on the left-hand side. The evaluation and selection of SoA solutions and adoption strategies are related to the development of the ecosystem impact indicator application. The same applies to the energy flexibility and adoption strategies implementation in the agent-based ecosystem model. This block is dependent on the agent-based modeling design and implementation of the solutions and adoption strategies.

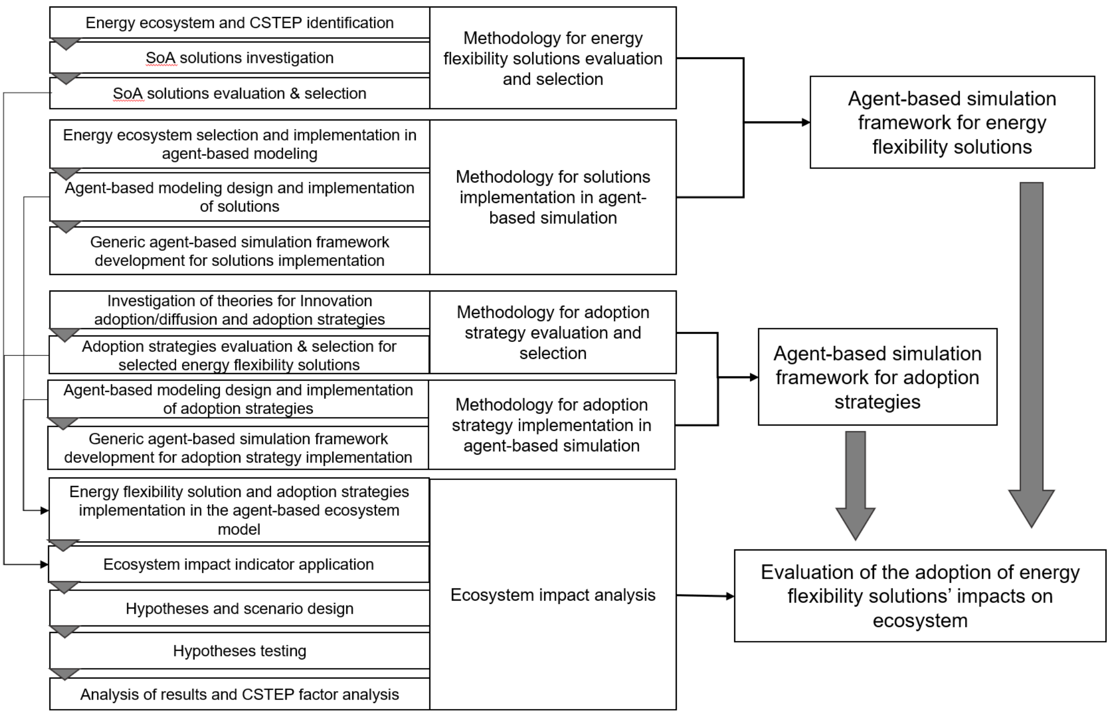

Figure 1. Research process to achieve the research objectives.

Related Literature and Theories

The main literature and theories identified to be related to this research are described in this section. The literature and theories are mainly in the subjects of energy ecosystem, energy flexibility, energy flexibility solutions, and innovation adoption.

Energy ecosystem

In this research project, the concept of energy ecosystem is used to investigate the complex social energy system [12]. The research in the energy ecosystem has been mainly discussed by the SDU Center for Energy Informatics, and applied in the fields of energy in buildings and microgrids, e.g., [1, 13, 14].

According to [15], ‘a targeted ecosystem is a completed business ecosystem within a defined boundary, with elements of actors, roles, and interactions, and actors create values and interact with others to complete value flows’. Therefore, the energy ecosystem in this Ph.D. research project refers to distribution grid ecosystem including actors of the Transmission System Operator, Distribution System Operator (DSO), electricity supplier, and domestic consumers; objects of the electricity grid, DataHub, EVs, and EV charging boxes; and including all five interactions of monetary, data, information, and good/product flows, and intangible interactions between actors and objects.

Energy flexibility

Energy flexibility is a key element in this research. Energy flexibility on the demand side means that the energy consumers shift their consumption from one period to another period that has more electricity production by renewable energy sources [16]. These periods are related to the periods where the price is the cheapest [17]. The prices give the consumers incentives to move its load to periods with lower prices, hence, helping the grid and achieve an economic benefit. This is called Demand Response (DR) which is defined by the European Commission as “voluntary changes in consumers’ electricity usage patterns – in response to market signals”.

Energy flexibility solutions

Energy flexibility solutions are in this research considered as solutions that activate potential flexibility at the consumers. This could be smart meters together with an hourly price scheme allowing the consumer to do DR or an algorithm that automatically utilizes the flexibility to benefit consumers. The term “solution” covers algorithms/software/service, regulations, and business models.

Innovation adoption

Several innovation diffusion/adoption theories exist, such as “Diffusion of Innovation Theory” by Rogers 1960, “Inter-organizational relationship theory” by Clark 1965, “Theory of Reasoned Action” by Fishbein and Ajzen 1975, etc. This research currently uses Rogers' innovation diffusion theory [18] to identify consumers' adoption behaviors and to find the adoption rate of new energy flexibility solutions, e.g., [19, 20]. According to [18], the adoption rate is defined as: “the relative speed with which an innovation is adopted by members of a social system. It is generally measured as the number of individuals who adopt a new idea in a specific period, such as a year. So, the rate of adoption is a numerical indicator of the steepness of the adoption curve for an innovation.” The adoption curves can be seen in Figure 2. There are many factors have been shown that influence consumers to adopt energy flexibility [21].

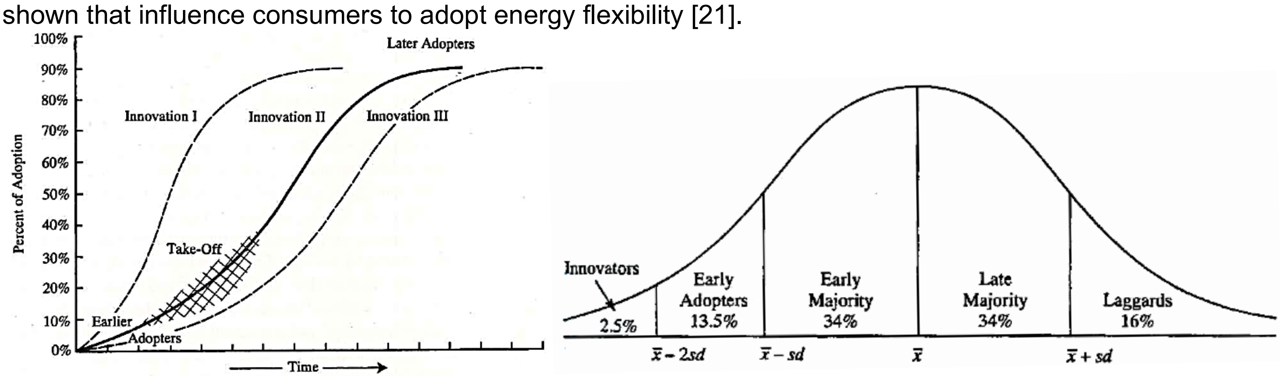

Figure 2. Rogers’ adoption curves *[18]*.

Methodologies

The methodologies used in this research project can be divided into sub-sections: Scoping review, Agent-based simulation, and case studies. The methodologies are what are used to conduct the research and to achieve the expected results.

Scoping review

The scoping review methodology is used to identify the SoA solutions both in energy flexibility solutions and adoption strategies. Based on the scoping review result and CSTEP ecosystem factor analysis, this project also develops a methodology to evaluate and select the SoA solutions and adoption strategies that match the needs and criteria of a targeted energy ecosystem, e.g., [22].

Agent-based simulation and modeling

This research uses agent-based simulation as the main method for developing, testing, and validating the model framework. Agent-based simulation is a relatively new method to simulate real-life systems compared to system dynamics and discrete event modeling. The increased use of agent-based simulation happens due to the desire to get deeper insights into simulated systems. Furthermore, the growth in CPU power has influenced the increase as agent-based models demand high CPU power capacity. Agents can represent many different things in an agent-based model such as energy market stakeholders which represents agents in this research [23].

An agent-based simulation is an artificial intelligence method that allows software agents to behave close to real-life entities. Agents operate in an environment and behave and react to different external events. This behavioral knowledge is fed into the agent logic through data (e.g. historical data for how an agent reacts to specific changes in the environment) [24]. The software used for the agent-based simulation is called AnyLogic and is a unique simulation software tool that supports system dynamics, discrete event, and agent-based modeling as simulation modeling methods [23].

In this research project, agents represent actors in an energy ecosystem such as a DSO [15]. The agent-based simulation method makes it possible to study the collective behaviors of agents [25]. Hence, identifying emergent behavior and interference. Emergent behavior is behavior that arises out of the interactions between parts of a system. This behavior cannot easily be predicted or extrapolated from the behavior of those individual parts. Emergent interference is an undesirable behavior that arises out of the interactions. Emergent interference is important to identify as this can lead to dysfunctional system behavior and in the worst case cause a severe system failure.

Case study

To show proof-of-concept of the developed frameworks a radial distribution grid below a 10 kV transformer of 137 domestic consumers in Denmark is chosen as the case study EVs are chosen in the case study due to the DSOs' concern regarding the impacts of EVs on the distribution grid stability. Therefore, this research aims to investigate how the adoption of EVs affects the grid.

In this research project, Electric Vehicles (EVs) are considered as a flexible demand. The EV is considered as having high potential as a flexible load due to its high consumption [26]. EVs are flexible as they do not need to charge immediately when the owners arrive home, and the EVs' charging can be shifted to times when the electricity price is low [27]. It is expected that the number of EVs will increase over time due to the goal of having one million EVs in Denmark by 2030 [28]. This calls for a solution that can utilize the EVs' flexibility to balance the power grid. Furthermore, flexibility should be utilized to avoid overload in the grid.

The EV types are represented by the top five EVs sold in Denmark in 2019. The types are important as they vary in battery capacity, mileage, and charging rate. The energy flexibility solutions are represented by smart charging algorithms. The evaluation is made from the DSO's point of view, hence keeping grid stability instead of minimizing consumer cost is prioritized. To evaluate energy flexibility solutions and adoption strategies several hypotheses are designed. Two hypotheses are tested through scenarios designed to answer the hypotheses.

Data for the research is mainly obtained from the Danish DSO – TREFOR [29]. Household consumption data including grid constraints are given from their distribution grid. Data for EVs and consumers' driving patterns are obtained from the literature. Furthermore, data is going to be obtained using qualitative and quantitative interviews used to identify consumer adoption behavior.

Results

Accomplished results

The energy ecosystem built up around EV home charging is created. The stakeholders' logic, communication flows, and the environment are identified and implemented into a model in AnyLogic. The model comprises the fundamental agent-based model that is going to evaluate the energy flexibility solutions. The adoption rate in the fundamental model is based on historical data for EV adoption in Denmark. The results generated by the model so far are the times when the EVs are expected to overload the transformer with and without the use of smart charging. The smart charging in the fundamental model makes sure the EVs are charging when the electricity price is lowest within the time it is connected to the charger. When using simple charging, the charging starts when the EV arrives home which is based on the domestic consumption pattern. A large increase in consumption after 12 noon is indicating that the EV has arrived home. Furthermore, the results show how many EVs the current grid can handle with simple and smart charging. The result can be seen in Table 1. The results show that smart charging can have more EV charges simultaneously. However, the overload occurs much faster and more frequently as the EV consumption is placed in the same period. Hence, this strategy is not durable in the long term. Suitable smart charging strategies are identified and several are implemented in a newer version of the fundamental model.

Table 1. Generated results from the current agent-based model.

Results of the first overload occurrence	**Simple charging**	**Smart charging**	**Difference**
Time	October 12, 2031	February 04, 2030	1 year, 8 months, and 8 days
Total EVs	70	45	25
Simultaneously charging EVs	37	45	-8
Size of overload (the grid capacity is 474 kW)	18.07 kW	7 kW	11.07 kW
Days with overload after the first year	11	235	224

Future works

The future work consists of developing frameworks for implementing energy flexibility solutions in the model and for identifying and implementing adoption strategies. The framework is designed to develop a generic model that can be adjusted for a given energy flexibility solution in a targeted energy ecosystem. The framework includes methodologies for adjusting the model for different energy flexibility solutions and adoption strategies in a defined ecosystem. This is done by use of a modular setup approach. Each module represents a part of the ecosystem e.g. an electricity consumer. The modules have some defined inputs and outputs making it possible to add and remove modules relatively easy to reflect a specific ecosystem, solution and adoption strategy. The methodologies should be the fundamental parts for developing the frameworks in objectives 1 and 2. The model is going to be modified to enable consumers to choose between available energy flexibility solutions in the same simulation. This should reflect a future in which the consumers can choose between more than one solution and how this is going to impact the grid.

The results from the case study simulations are expected to be a variety of dates when the first overload is expected. With the current grid, it is not expected to be able to handle 100% EV adoption without a compromise of the consumers' convenience. The results will show the best charging strategy to prolong the period it takes before overloading the grid. Meanwhile, the charging algorithms' performance will be evaluated, such as the computation cost and number of EVs to support, etc. The adoption strategies are evaluated based on how the adoption rate impacts the ecosystem. The results can help the DSO choose its strategy to how and when to improve the grid. Furthermore, it is expected that the results will suggest possible regulation changes to improve strategies.

The developed agent-based simulation framework can be modified to apply to different energy ecosystems, e.g., district heating or sector coupling, for different solutions and business models, e.g., photovoltaic and heat pumps. Meanwhile, the developed framework can be applied to other geographic-different energy ecosystems, and also be possible to support the cross-national comparisons.

Acknowledgments

This work is part of the national project- Flexible Energy Denmark FED funded by Innovation Fund Denmark.

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