ABSTRACT

The increasing digitalization of the electricity grid into a Smart Grid implies the introduction of an increasing number of new digital energy solutions to the energy ecosystems. Digital energy solutions are expected to solve problems occurring, especially due to the transition to carbon neutrality. This is especially the case for sector coupling between the electricity grids and the transportation sector. However, the electrification of the transportation sector also introduces challenges to the energy system. The challenges relate to many ecosystem stakeholders, and the consequence of mass electric vehicle adoption is unclear. Furthermore, there is no sufficient method to identify and evaluate different digital energy solutions, such as electric vehicle charging algorithms, and their impacts on the energy ecosystem.

To address these challenges, this research proposes and develops an integrated framework consisting of three main parts: ecosystem modeling and multi-dimensional ecosystem impacts analysis, multi-agent based modeling and simulation, and multi-criteria decision-making for: 1) investigating the ecosystem dynamics with various scenarios of electric vehicle charging strategies and dynamic distribution tariffs, and 2) evaluating the impacts of electric vehicle charging strategies and dynamic distribution tariffs on related stakeholders.

Four main methods are applied in this research to develop the framework: Business ecosystem modeling and CSTEP multi-dimensional ecosystem impact analysis; Multi-criteria feasibility evaluation for assessing and identifying state-of-the-art technologies; Multi-agent based modeling and simulation; and Multi-criteria decision-making. A case study of a Danish radial distribution network with 126 residential consumers with increasing electric vehicle adoption is chosen to verify and validate the developed framework.

Based on the developed multi-dimension, multi-criteria feasibility method, three decentralized and four centralized electric vehicle charging strategies in the literature are identified and selected for evaluation besides the traditional electric vehicle charging strategy. Furthermore, various state-of-the-art dynamic distribution tariffs are evaluated, and the Time-of-Use distribution tariffs are evaluated as the most feasible in Denmark. The next generation Danish tariff model, Tariff Model 3.0, is a type of Time-of-Use distribution tariff.

From the multi-agent based simulation results, the main findings show that overload occurs in the grid in 2031 with the Traditional charging with a 67% electric vehicle adoption. Adopting other decentralized charging strategies results in faster and more frequent overload, e.g., 2028 with the Real-Time Pricing strategy. Meanwhile, by applying centralized strategies, overloads can be avoided with a limited impact on electric vehicle users' charging experience (with a 71-78% share of electric vehicles in the grid) in 2032. Overloads are also avoided with a 100% electric vehicle adoption in 2039; with the centralized strategies, electric vehicle users with electric vehicle models charging with 7.2 kW or more can reach the desired charging level before departure.

The multi-criteria decision-making evaluation results show that cost-oriented and environment-oriented electric vehicle users will most likely adopt the Real-Time Pricing and Time-of-Use Pricing charging strategies with the Tariff Model 3.0 and hourly electricity price scheme. The distribution system operator prefers the Traditional charging (under all price structures) for the electric vehicle users and is most likely to adopt the Round Robin and First-Come-First-Serve centralized charging strategies.

The evaluation of the combined strategies shows that the best combination is with the Real-Time Pricing and Round Robin strategies. The Round Robin is the best centralized strategy to manage the Real-Time Pricing and Time-of-Use Pricing decentralized strategies. Combining Real-Time

Pricing with Round Robin or First-Come-First-Serve significantly affects electric vehicle users. The users experience an increased frequency of not reaching their desired charging level before departure. The frequency increases by 42 times with Round Robin and 47 times with First-Come-First-Serve in 2032 (electric vehicle share of 71-78%) compared to Real-Time Pricing without centralized control. The combination of the Real-Time Pricing and Time-of-Use Pricing strategies results in overload in 2029 but with around 80% fewer overloads the year after (compared with the individual strategy experiments).

This research proposes a novel integrated framework that can capture the full ecosystem dynamics during a long-term period with a high resolution (hourly), therefore, a clear load profile of distribution grids in the future due to electric vehicle adoption can be captured. Meanwhile, this research introduces a systematic method that can be applied to investigating the impacts of increasing electric vehicle adoption or dynamic distribution tariffs in the energy system considering the ecosystem dynamics. Furthermore, the developed multi-agent based simulation can decode the complex behaviors and aggregated consequences due to the ecosystem dynamics. It is also applicable for investigating other future and what-if situations in similar energy ecosystems. Moreover, the multi-criteria decision-making model allows the evaluation of smart energy solutions and strategies considering individual stakeholders and ecosystem perspectives.