Results report from SmartNEM project

Objectives and background.

The current electricity infrastructure in Norway lacks mechanisms for handling mass and concentrated energy demand primarily led by EVs charging requirements. Data-driven decentralized energy systems can address this gap through connection of household RES (Renewable Energy Sources) to the grid. However, this would disrupt the existing simple supply-demand market relationship between producers and customers. As a KPN project, the goal is to develop new knowledge and generate research competence needed to meet the above mentioned challenges. The consortium aims to achieve this with ICT based smart-solutions on a decentralized grid infrastructure integrating prosumers. Machine learning based methods are used to learn and predict household production and consumption behavior. Incentive systems and non-repudiation for energy trading are facilitated through the use of blockchains. Furthermore, edge and fog computing drive energy information solutions. Finally, all technical components are driven by data privacy and security elements.

An account of the results achieved under the project explained in the context of the project objectives.

Main objective

As the main objective, the project has investigated an ICT driven decentralized grid infrastructure supported by prosumers through the work of seven PhD scholars funded by the project and two PhD scholars funded in-kind by the partners. In particular, the project has been successful in designing energy trading mechanisms for local energy communities and microgrids while at the same time supporting DSOs and TSOs to achieve community level grid reliability, peak load reduction, load balancing, secure supply and increased economic benefits for the stakeholders, such as consumers and prosumers. In some of the works, game theory has been applied to maximize the benefits of all stakeholders.

Various trading platforms have been developed and experimented with, on different aspects such as performance, security and privacy. As targeted in the main objective of the project, a common characteristic of the trading platforms is that they are based on blockchain technology for the purpose of enabling distributed peer-to-peer (P2P) trading schemes. Furthermore, and in accordance with the main objective of the project, machine learning techniques have been utilized for preserving security, such as attack detection, and privacy, exploiting distributed deep reinforcement learning, and for predicting household loads, renewable energy production, electricity prices, and charging demand for EVs.

A community level information intensive data hub was developed based on token mechanisms allowing prosumers to share information about their production and consumption behavior. It creates a decentralized virtual neighborhood where each household operates autonomously and trades energy with other households and communities, in which case, the central authority or the main grid only act as a facilitator for maintaining supply/demand balance.

Secondary objectives.

The secondary objectives have been achieved by the collective contributions of the PhD students.

1. **Investigation on a role for managing the system**: Various approaches to the management of energy neighborhoods have been investigated by the PhD students. A common approach has been to introduce the role of a coordinator (e.g., in the form of an aggregator) that manages the energy sharing and trading inside the community and with the main grid (selling surplus energy from the community, or buying at times when the locally generated energy is not sufficient for satisfying the demand). The coordinator itself can be realized in various ways, e.g., as a trusted single entity such as the owner of an apartment building, or as a consortium of stakeholders exploiting blockchain technology. Furthermore, it has been investigated how the coordinator can apply the principles of energy justice to sharing and trading of energy in apartment buildings. Experiments were conducted, using real data to perform thorough simulations and numerical results in every work. Various aspects of the proposed algorithms were investigated including analysis of their performance.
2. **A scalable energy information solution driven by fog/edge computing.** The use of fog and edge computing has been investigated in several scenarios, including in the context of detecting novel cyber-level attack scenarios in P2P energy trading among home energy management systems, and in consumption load scheduling among households without the need to share information with each other. In the latter case, edge devices, referred to as Energy Consumption Controllers, in each home are used to schedule the consumption in real time. In addition, we studied and demonstrated how concepts and techniques from graph theory, machine learning can be applied to solve some of the Smart Grid challenges. Optimal design of wind farm collector systems for integration in Smart Grids is investigated. The model is applicable in the planning and installation stages of wind farms and particularly relevant in the current scenario with increasing focus on integration of renewable sources of Energy in Smart Grids.
3. **Real time monitoring of prosumption and the grid supply/demand:** Related to monitoring, and grid supply and demand, results have been achieved on applying generative adversarial networks and transfer learning for non-intrusive load monitoring, as well as on applying combinatorial auctions and graph neural networks for local flexibility markets to achieve a better utilization of the offered flexibility. The works on energy sharing and trading have all included solutions for balancing supply and demand, possibly with the assistance of the main grid. Machine learning techniques are also investigated for anomaly detection in smart meter data with generative adversarial networks based techniques. Machine learning based power forecasting techniques are proposed on the demand side power management. Moreover, different factors influencing most on various load consumption profiles at the household level are identified with studies, and performance evaluation of the most common algorithms in short-term load forecasting at the building level. Different approaches to improve short-term load forecasting at household and small community levels respectively are aslo investigated. We also investigated the influential factors on the micro-power generation of households.

4. **A blockchain based incentive system for prosumers:** The RenewLedger is suggested as a framework for renewable energy transaction, storage management and direct-to-consumer demand response incentivization and gamification for peak shaving. The demo system was designed and implemented using Hyperledger Fabric with benchmarking performance in experiments under different conditions using Hyperledger Caliper. Two versions of the system were implemented on Hyperledger Fabric. Assets encapsulating an identifier or unique information along with value are modeled as non-fungible tokens (NFT), while those representing value only are modeled as fungible tokens (FT). We developed the associated algorithms for token lifecycle management, analyzed their complexities and encoded them in smart contracts for performance testing. The results show that performance of both implementations are comparable for most major operations. Detailed comparison of FT and NFT implementations are investigated based on use-case, design, performance, advantages and disadvantages. Furthermore, a data driven approach for incentive-based peak mitigation based on user energy profiles is also tested and verified by extracting aggregated user energy behavior in temporal contexts and semantic linking and contextual clustering give us insight into consumption and rooftop solar generation patterns.
5. **A cyber-secure and privacy-preserved solution to address data collection obstacles:** TOTEM (Token for controlled computation: Integrating Blockchain with Big Data), granted as a US patent and product of this project, is a framework allowing the users to analyze the data without moving the data from the data owner´s environment. It ensures the security and privacy of the data. A Proof-of-Concept (PoC) has been developed showing how the TOTEM architecture can be adapted into a smart community neighborhood for data analysis in a secure manner. An extended version of the TOTEM architecture is also proposed as a solution if the data consumer demands a combined result from data providers as a part of data analysis. The Software Development Kits (SDK) is developed for the TOTEM framework, along with the deployed smart contracts in the network, from a pre-monitoring system that keeps track of totem entity value associated with each users' submitted codes using an estimator table.
6. **A community level intelligent battery management system:** Battery management has been addressed in the context of optimal scheduling of EV (fast) charging, in the distribution grid utilizing the concept of virtual power plant and applying game theory to reduce peak loads and maintain power quality. In the proposed system. EVs can be charged at high charging rates without affecting the operation of the power grid by purchasing energy through a cloud-based virtual power plant based market that aggregates energy offered by users with storage devices. The latter kind of users sell their stored energy in the same market. The experimental results show that users with storage devices can obtain much higher revenue than the baseline solutions by participating in the market, while EV owners can reduce their charging costs correspondingly.

A description of the most important R&D tasks that have been carried out and the groups that have played a key role in the project implementation.

To date, the project has produced nine PhDs (7 funded by project and 2 funded in-kind) with high quality publications and several more are already submitted and waiting for evaluation, including e.g., edge computing for real time monitoring and distributed microgrid resilience, machine learning for energy forecasting, security and blockchain solutions for local and community level energy trading, applications of the principles of energy justice to sharing and trading of energy in apartment buildings, integration of local energy sources at homes, neighborhoods and communities into the grid. Finally, one patent has been granted in the USA for her innovation.

Research stays abroad during the project period

Due to COVID-19, many planned mobilities were canceled and meetings were moved to online. One of the PhD students from UiO stayed 3 months at the Technical University of Munich (TUM) working with the Energy Informatics team on conducting experiments on P2P energy trading with Hyperledger blockchain. This stay resulted in a joint paper in an IEEE Transactions journal. Another PhD student from UiO stayed at the Technical University of Berlin (TUB) for 3 months working with the Electrical Engineering group on issues of scheduling EV fast charging supported by decentralized energy generation aggregated as a virtual power plant. This stay resulted in two joint papers both published in IEEE Transactions journals. These mobilities were not funded by overseas research grants.

Dissemination of the results.

The results of the project have been published widely in both academic and non-academic channels as summarized below. Since not all PhD students have completed their studies, some further academic publications are expected. The results of the project will be utilized and leveraged in future research projects.

Annual workshops have been held with the project´s industrial partners. During COVID-19 the workshops were held online. The last workshop held in October 2022, was hybrid with video recording of presentations. In this meeting the results from the project were summarized, and all PhD students presented their particular research results. All material (slides, videos) from the meeting has been shared with the stakeholders.

Several summer schools have been organized with physical presence in collaboration with the two RCN INTPART projects LUCS and PACE.

Results that are expected to be finalized after the completion of the project.

Some further results from one of the UiO PhD students are expected on applying self-determination theory in prosumer-centric P2P energy trading. Furthermore, another UiO PhD student will develop a more lightweight model for NILM using a Tsetlin Machine.

Further validation and verification projects with industrial stakeholders are needed to utilize the results. The current EU TradeRES project is considering verifying some of the relevant results on blockchain based trading in the local market. The current PriTEM project at UiO on privacy preserving transactive energy management will further leverage results from SmartNEM, in a collaboration with the Social Sciences and Law faculties. The underlying research question is how perspectives from social sciences and law can lead to new approaches to the design of (transactive) energy systems.