

A Cooperative Business Model for Self-Sustainable Energy Communities Based on an Autonomous Negotiation Protocol

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Abstract—The paper presents a cooperative business model for autonomous, self-sustaining, and self-organized smart grids and energy communities. It applies a multi-agent, multi-lateral, and multi-criteria negotiation protocol where consumers are involved on one side and electricity suppliers participate on the other. The model maximizes the utility functions of both sides, so that supply is negotiated dynamically between customers and suppliers with the highest potential. The model is based on the principles of Energy 4.0 and 5.0. It applies appropriate intelligent techniques to analyze data from distributed sources. It is evaluated based on the simulation study and SWOT analysis. The key contribution of the research is an original approach to incorporate multi-lateral integrative negotiations into electricity supply models for self-sustainable energy communities.

Index Terms—Autonomous negotiation protocols, cooperative business models, energy communities, multi-attribute utility theory, self-sustainable electricity grids

I. INTRODUCTION

Despite advances in intelligent technologies adopted in the energy utility sector, considerably less effort has been invested in approaches that aid, automate, or structure energy supply processes based on multi-criteria negotiation protocols and negotiation support systems. For this reason, the presented research aims to establish and validate a cooperative business model for autonomous, self-sustainable, and self-organized energy communities. It follows the presumption that we can utilize an automated multi-criteria negotiation protocol and integrate it with a distributed ledger to develop communities.

The approach builds upon our previous research work [1], [2]. It advances it through a cooperative business model, application in the Energy 4.0 and 5.0 domains [3], and the assessment of energy market equilibrium. We aim to assess the efficiency of the proposed cooperative energy supply model and its equilibrium with a simulation study, in which we consider simulated metering data of consumers and prosumers in the community to perform the evaluation. We also show the

characteristics utilizing the SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis.

The rest of the paper is organized as follows. In Section 2, we present theoretical foundations and provide the literature review. Section 3 introduces the cooperative business model and the underlying negotiation protocol. The model is evaluated in Section 4. Finally, Section 5 concludes the paper.

II. THEORETICAL FOUNDATIONS

The research covers several areas, including energy supply and sustainability models, IT (Information Technology) and OT (Operational Technology) integration, big data, artificial intelligence, blockchain technology, statistical analysis, multi-criteria decision analysis, multi-objective optimization, negotiation theory, economic models, and Industry/Energy 4.0 and 5.0. The overall complexity of the subject is presented in Figure 1. It identifies five areas of approaches, methods, and technologies that can be applied to establish the Energy 5.0 system, support smart grids, and introduce original business models in the energy and utilities sector. At the core, big data on electricity production and consumption is collected. All other approaches utilize and process the available big data.

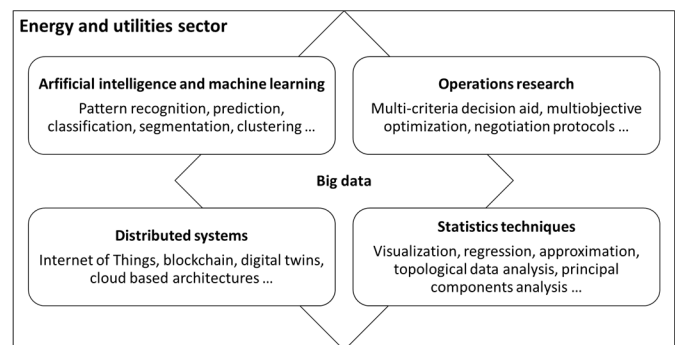


Figure 1. Intelligent approaches for Energy 5.0 and smart grids [2].

A. Multi-Criteria Negotiation Systems

The presented research introduces an original approach to incorporating negotiation protocols into Energy 4.0/5.0 supply models. The motivation is that non-routine business tasks, such as providing services and products customized to the needs of individual clients, require negotiations that credibly capture the preference structures of all involved stakeholders. For this reason, negotiation theory is the foundation of this work.

In the negotiation process, a group of people or autonomous agents cooperate to reach common goals that can overcome incompatible individual goals. Different negotiation strategies and multi-criteria models can be applied to reach an agreement on transactions that maximize the utility of all involved parties [4], [5]. Figure 2 presents the approaches and characteristics by introducing a taxonomy of negotiation systems.

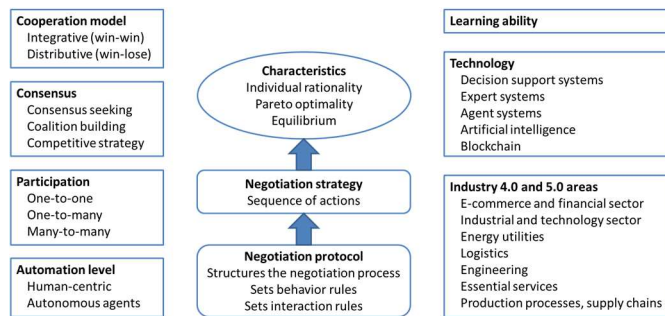


Figure 2. Taxonomy of negotiation systems.

Our taxonomy systematizes negotiation types on the left-hand side of Figure 2, the relations to supporting technologies and applications in Energy 4.0/5.0 on the right-hand side, and the building blocks and key characteristics of the negotiation process in the middle. Similarly, the Montreal taxonomy [6] characterizes web-based electronic negotiation systems. The key concepts of negotiation processes include multi-criteria preference modeling, preference compensation, and iterative improvements of the collective solution. Several methods and types of analyses exist to operationalize these concepts. The most frequently used is the monotonic concession protocol [7]. It uses the utility function to reduce preferences to a single value and can be applied for one-to-one or one-to-many negotiations. Other significant approaches are relational analysis, dynamic coalition building, and consensus-seeking. Bregar [8] proposed a consensus-seeking negotiation procedure that generalizes different preference models, including the utility function [9] and pseudo-criteria [10], and enables constructive learning.

B. Cooperative Business Models and Equilibrium

Cooperative business models are derived from the general field of cooperative economics [11]. The benefit of their use is that they can guarantee the energy market equilibrium. This is a key concept in energy economics. Electrical power markets should achieve efficient operational levels for the power system by matching the required electricity generation and demand at each point [12]. Therefore, supply and demand should result in a balanced relationship between benefits and costs. Well-behaved supply offers and demand bids need to maximize net benefits and social welfare [13].

Lee and Angeli [14] proposed a cooperative economic model for linear systems in various business domains. They suggested a feedback strategy, which can converge to a set of Nash equilibria. Fan et al. [15] introduced a market transaction optimization model that maximizes social benefits, considering constraints that balance supply and demand. Gao and Sheble [16] argue that an electricity market equilibrium model can help system operators and regulators analyze market performance. It can also allow all market participants to define optimal bidding strategies based on microeconomic analysis.

Electricity markets must be designed to provide reliable energy at the least cost to consumers [17]. The best designs satisfy the goals of both short-run and long-run efficiency. Risk management is essential for decision-making, as stakeholders can face price and delivery risks due to energy allocation. Liu and Wu [18] addressed risk as a portfolio optimization problem.

C. Energy 4.0/5.0 and Supporting Technology

The key drivers of change in energy transmission, supply, selling, production, and consumption in the electricity utility sector are the elements and components of Industry 4.0 [19]. Combined with IT/OT integration architectures, AI (Artificial Intelligence), big data, blockchain, and other contemporary technologies, they can optimize existing energy supply models and introduce new sustainability models. Industry 4.0 is based on four principles [20]. The aspect of interconnection enables machines, smart devices, sensors, and people to connect and communicate with each other. It applies to smart grids, M2M (Machine-to-Machine) protocols, and IoT (Internet of Things) supported communication. Information transparency relies on big data, sensors, metering devices, distributed architectures, and regulatory standards to collect vast amounts of data from all points of manufacturing processes. The technical assistance principle pertains to the ability of systems to support people in cognitively demanding, unpleasant, exhausting, repeating, or unsafe tasks. It also facilitates decision-making and problem-solving. It builds on intelligent technologies, visualizations, and information aggregation techniques. Finally, the principle of decentralized decision-making introduces systems that perform tasks autonomously by utilizing negotiation protocols, multi-criteria decision analysis, and intelligent agents.

Industry 4.0 is a general term. Digital transformation in the energy and utilities sector specifically refers to Energy 4.0 [21]. It applies the advances of Industry 4.0 to build smart grids and communities, stimulate renewable energy management, and establish distributed energy resources. Following the Energy 4.0 paradigm, various blockchain applications are emerging in the utilities sector. Blockchain aims to guarantee a traceable and trusted consensus on sets of transactions, which are stored within finite non-modifiable blocks in a network of concurrent nodes [22], [23]. Blocks are secured and replicated for different owners so that transactions persist in a distributed manner. Smart contracts are used and signed to establish trust and cooperation rules among participating partners.

Kafol et al. [24] have correlated and integrated intelligent approaches and blockchain technologies. These mechanisms can be incorporated into various use case scenarios related to non-regulated or (partially) regulated business processes in the utilities sector. For example, a decentralized blockchain system

for internal energy trading has been implemented as a microgrid within a small self-sufficient community [25], which operates independently of the regional electricity network. It is fully responsible for producing and consuming electrical energy that comes from renewable sources. Transaction data is stored in the blockchain. A cryptocurrency is used as a method of payment.

Altogether, several scenarios are supported through Energy 4.0 technologies for smart grids and energy systems. For the scope of this paper, energy trading and consumer services are particularly relevant. An advancement of Energy 4.0 is Energy 5.0. It preserves all key technologies, concepts, and scenarios of Energy 4.0. However, it emphasizes and integrates human requirements, cognition, judgments, and decision-making [3]. It enables the implementation of autonomous processes but allows the human expert to contribute to the decision.

III. COOPERATIVE BUSINESS MODEL

A multi-lateral, multi-agent, and multi-criteria negotiation protocol is applied, such that electricity consumers are involved on one side and electricity suppliers, producers, and prosumers participate on the other. By maximizing the utility functions of both sides, each customer buys the cheapest and most suitable available electricity from the most preferred supplier. At the same time, the supplier is provided with directions to offer electricity and services to the most relevant consumers with the highest potential based on dynamically constructed marketing models. A related goal is to dynamically plan energy production in line with changing real-time demand and optimize contracts established between actors in the energy market.

A. Technology

The introduced cooperative business model requires that energy consumption patterns in metering devices are managed and recognized at all points of the electricity supply process. Therefore, the model is based on the principles of Industry 4.0 and utilizes appropriate intelligent techniques to process data from reliable distributed sources.

A multilayered decision system provides the technological basis for the cooperative model. Its architecture consists of several interconnected components depicted in Figure 3.

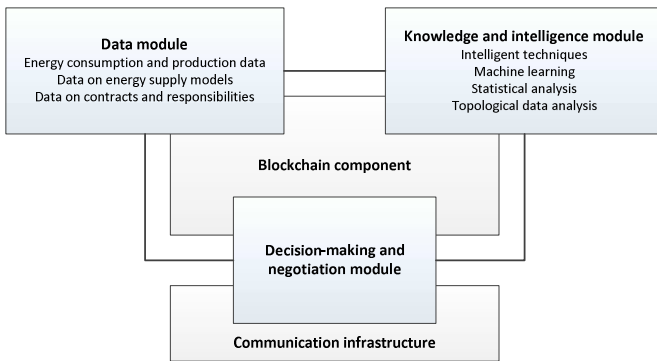


Figure 3. Technological components facilitating the cooperative model [1].

The key component is the decision-making and negotiation module. It is based on the multi-attribute utility theory [9] and negotiation concessions protocol [7]. Both negotiating sides

leverage the results from the business intelligence component. Their autonomous agents apply these results to dynamically form offers and counteroffers according to which they negotiate the optimal supply contracts. The energy consumer aims to select the most suitable supplier and its preferred supply model for an arbitrary period, considering multi-criteria projections of the required energy consumption for this period. The supplier performs multi-objective optimization to design and optimize supply models for existing and potential new customers. According to the classification of consumers, overall demand, market segmentation, and business strategy, the supplier can determine the most promising target groups of customers and make appropriate offer individualizations. The end effect is the ability to continuously adapt and optimize models for selling and buying electricity in self-sustainable smart grids.

Two additional submodules are designed for:

- Dynamical calculation of energy prices based on supply and demand (production and consumption), availability of services and energy resources in the community, real-time consumer demands, assessment and prediction of future consumption, patterns in past and current consumption data, environmental factors (such as time, location, and weather), etc.
- Advice and optimization of energy consumption and supply based on customer segmentation, electricity utilization within segments, identification of energy savings, optimization of production capacities, etc.

Blockchain technology [24] ensures the required reliability. It provides a solid foundation for smart contracts between the collaborating parties. It enables the system to automate the secure management of relationships between the actors in self-sustainable energy communities or the broader energy market. Encrypted metric data on electricity consumption is stored in distributed nodes. The supplier is granted access to metering data by signing a smart contract with the consumer. This supplier can then use data to dynamically form optimal supply models, thereby maximizing its utility by considering multiple criteria when competing with other suppliers for consumers. Similarly, the consumer can select the best possible supplier and negotiate the optimal energy supply model. This approach is depicted in Figure 4.

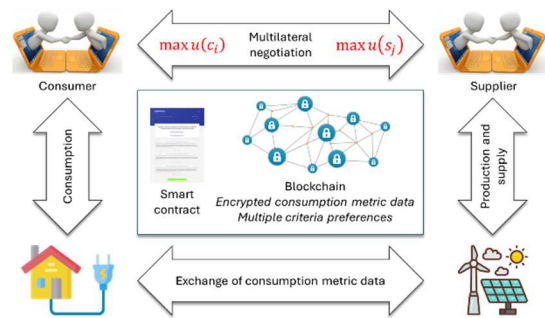


Figure 4. Energy supply market model.

B. Negotiation protocol

The cooperative model aims to maximize the benefits of all participating stakeholders. For this purpose, a multi-criteria

negotiation protocol must be applied in a multi-agent setting. The cooperative electricity supply negotiation mechanism is shown in Figure 5. The entire ecosystem involves consumers, suppliers, underlying data processing technology, and the implemented negotiation protocol. This ecosystem enables the autonomous processing of the best electricity supply offers and facilitates trustworthy contracts between consumers and suppliers. It utilizes mechanisms for consumer segmentation and consumption prediction from past consumption data. It can be further enhanced with the principles of Energy 5.0 [3]. In this case, human stakeholders – consumers and suppliers – can verify initial automated decisions inferred by autonomous agents and enrich them with subjective judgments, preferences, requirements, and expertise. The Energy 5.0-compliant group decision process is defined in Figure 6.

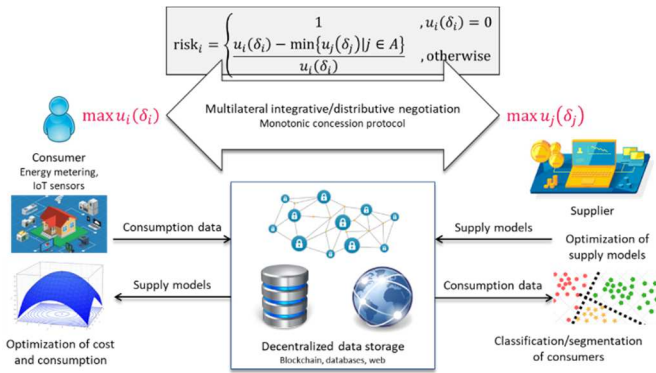


Figure 5. Negotiation mechanism.

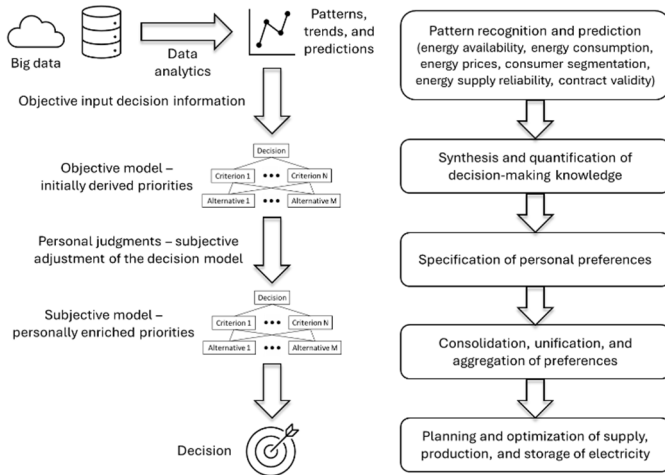


Figure 6. Energy 5.0 decision process.

A multi-lateral negotiation protocol involves autonomous intelligent agents, which are not depicted in Figure 5 but are necessary for the negotiation process to sign efficient smart contracts without manual involvement of stakeholders. Each consumer is represented by a personal agent (supporting only this consumer), which simultaneously negotiates with all agents of electricity suppliers. On the other side, each independent supplier's agent negotiates with many decision-making agents that support individual consumers. The goal of an agent is to maximize its multi-attribute utility function and to minimize the risk that pertains to the utilities of all competing agents:

$$risk_i = \begin{cases} 1 & , u_i(\delta_i) = 0 \\ \frac{1 - (u_i(\delta_i) - \min\{u_j(\delta_j) | j \in A\})}{u_i(\delta_i)} & , \text{otherwise} \end{cases} \quad (1)$$

In eq. (1), u_i and u_j denote the utilities of the consumer δ_i and the supplier δ_j , respectively. The greater the utilities of the competing suppliers' agents, the higher the risk considered by the consumer's agent. Instead of the minimum operator, the maximum or averaging operators can be used to increase risk.

The criteria of the utility function include electricity cost, supply availability, contract validity, and quality of service. The calculated risk may refer to the unavailability of supply or non-optimal utility compared to competing agents.

The negotiation protocol for a single consumer is described with the algorithm in Figure 7. The consumer's agent negotiates with suppliers only. It never negotiates with other consumers. An analogous assumption holds for suppliers or producers engaged in negotiations with consumers. The negotiation process is cooperative because it aims to maximize the utility of both sides. The supplier's negotiation protocol is similar and is therefore omitted from the paper.

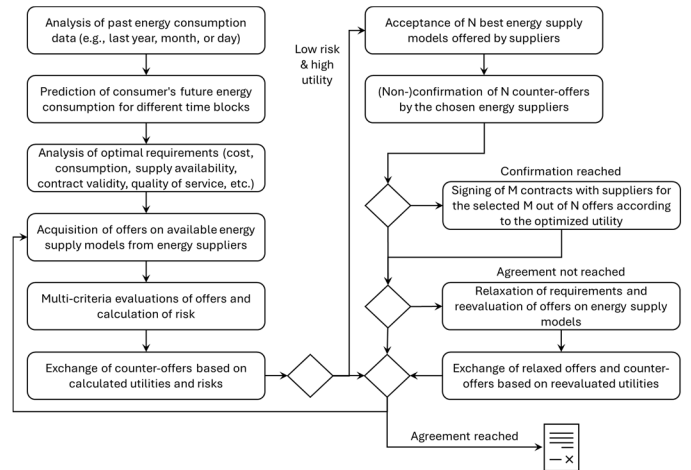


Figure 7. Negotiation protocol for the electricity consumer.

In Figure 7, diamonds represent decisions. Due to the space constraints, questions are omitted. The outcome of one branch is written for each decision on the branch arrow or action. The other result is a negation and is not explicitly presented.

IV. EVALUATION OF THE MODEL

We evaluate the cooperative negotiation model for self-sustainable energy communities with a simulation study and SWOT analysis. In the next phase, we will also perform a case study. This is research in progress, so we present only the model of the simulation study in Figure 8. Simulation is currently in execution. We will publish its results in a follow-up paper.

The simulation study has a comprehensive and complex design. It assesses the market equilibrium by considering two groups of output variables (orange shading). The first group observes the efficiency of the negotiation process and protocol. The second group aims to determine the balance of supply and consumption. Overall, 12 output variables are considered.

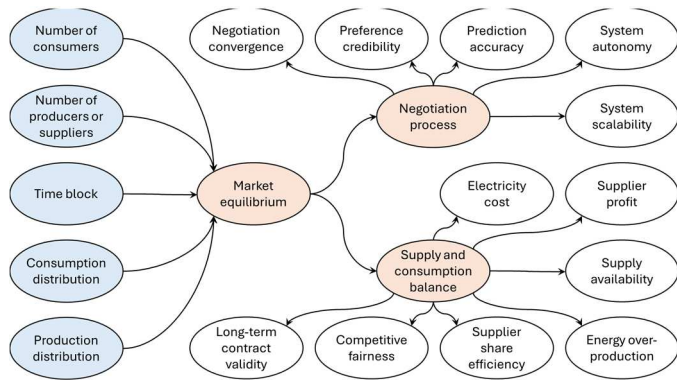


Figure 8. Simulation model.

We control the simulation experiment with 5 independent variables (blue shading). The most crucial variable determines specific time blocks during which electricity consumption exhibits common patterns. This implies that consumption varies significantly between different time blocks. In the first setting, we use time blocks from the national electricity distribution system [26]. In the second setting, we sample blocks arbitrarily. We also sample the amounts of energy produced and consumed by different stakeholders in various simulation settings based on the normal statistical distribution.

Additionally, we performed a SWOT analysis to identify the characteristics of the proposed cooperative negotiation model. We summarize it in Table 1. We use a modified format due to the two-column layout.

TABLE I. SWOT ANALYSIS

<i>Strengths and opportunities</i>
Reduced energy consumption in self-sustainable and self-sufficient communities
Optimization of energy consumption costs
Lower transaction costs due to direct energy supply without the need for large intermediate suppliers
Reduction of electricity prices by balancing real-time demand and supply
Reduced electricity prices due to the improved transparency of transactions within valid regulations
Better insight into transactional data on consumers and resources based on decentralization within valid regulations
Optimization and simplification of business domains, rules, and processes
Improved self-sufficiency of smart energy communities
Improved energy supply for households and e-mobility
Flexible and new models and services for the energy market
Improved security, verifiability, and integrity of data on energy consumption and production
Common autonomous consensus mechanisms that do not require a central authority to build trust
Flexibility of energy networks, production and supply of electricity, and energy services for customers
Balancing of (smart) energy networks
Improved economic equilibrium

Environmental benefits and green energy based on the transformation of processes in energy utilities
Autonomous and efficient alignment with consumers' needs

Weaknesses and threats

Potential problems with low scalability, low speed, and high costs of transactions
Large amounts of data from metering devices
High flexibility of networks is required
Regulations might be too restrictive and should be adapted
Functional disadvantages and security risks might appear due to possibly inappropriate standardization and regulations
Problems in existing (regulated) processes can occur
Adoption of technology may cause problems and errors
Users might not accept the adopted technology due to its complexity and the lack of trust and information
No central authority exists to resolve disagreements
Cybersecurity risks on the network level might exist, particularly related to smart metering devices and sensors
Business models might not be in full accordance with real-life requirements and business domains
Intelligent analysis techniques, machine learning, and negotiation protocols might be biased because of learning samples and business characteristics
Possibility of inaccurate and inefficient predictions, assessments, analyses, and decisions

V. CONCLUSION

The key contribution of the research we presented is that it developed an approach to incorporate multi-lateral integrative negotiation protocols, cooperative autonomous agents, and automated decision-making into energy supply models and business models for electricity grids based on the principles of Energy 4.0 and Energy 5.0. In particular, the monotonic concession protocol is utilized to optimize costs. The approach aims to dynamically specify the conditions of energy consumption and production in self-sustaining electricity grids and energy markets according to supply and demand. In addition to improving economic efficiency, it also addresses environmental requirements. As it considers fundamental aspects of business, technology, security, regulation, and contractual responsibilities, it lays the foundation for achieving a high degree of autonomy and automation of self-sustainable energy communities according to the concepts of Energy 4.0 and 5.0. It distinguishes itself from the existing approaches by incorporating negotiation mechanisms and multi-criteria methods at the core of business models. This means that the presented research attempts to introduce the theory of multi-criteria and multi-agent negotiations into business processes underlying self-sustainable energy communities and electricity grids, as well as into business models for the supply and demand of electrical energy.

The research work exhibits several practical implications, as shown in the SWOT analysis. However, they are generic and will be fully validated after the simulation study is completed and through a follow-up case study.

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