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Decentralized Renewable Energy Trading Based on Blockchain Technology: Modeling a Microgrid Using the Design Science Research Methodology

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1 Introduction

Climate change and the dependence of democratic countries on fossil fuels, that are mostly imported from autocratic governed countries, pose challenges for the energy economy as well as for society. In order to prevent a drastic change of the earth and to reduce the probability of occurrence of natural disasters, solutions must be developed to reduce CO2 emissions especially in the energy sector.

The report of the Intergovernmental Panel on Climate Change (IPCC) highlights the urgency for change. It shows that the average global temperature between 2011 and 2020 was 1.09 degrees higher than in the period from 1850 to 1900. The IPCC indicates that also weather extremes like heatwaves and heavy precipitation as well as natural catastrophes are very likely human driven. Among other factors, there would have to be negative emissions of CO2 every year from around 2050 onward to meet the 1.5 degree target. And even if the target could be reached, the world's population would have to fight with harmful consequences. Besides disastrous environmental changes, research is projecting intensification of heavy rainfalls associated with flooding, as well as more frequent and severe droughts in comparison to 1850–1900. The researchers of the IPCC present a nearly linear relationship between cumulative CO2 emissions and the increase in global surface temperature and hence call for net negative CO2 emissions as quickly as possible.[11]

Moreover, representatives from 153 countries covering over 90% of the world's GDP committed to the 1.5 degree target at the UN Climate Change Conference 2021 (COP26) in Glasgow. Thereby, they particularly pointed out the importance of down phasing the use of coal and all other fossil fuels in the energy industry. On the other hand, they emphasized the importance of renewable energies as clean substitutes and agreed on scaling up green power by 2030 in advanced economies. The representatives also agreed on speeding up the process of decarbonization of road transport while shifting to electric vehicles (EV) with the perspective to reduce 2.6 gigatonnes of CO2 a year by 2030, as the transportation sector makes up for over 10% of global greenhouse gas emissions.[12]

Since raw materials are not evenly distributed around the world but are found in certain regions, entire communities of states like the European Union often depend on individual countries to supply them with fossil fuels in order to keep their industries running and the demand for various energy sources satisfied. Germany for example imports more than 40% of its natural gas and oil demand from only one country, Russia.[13] Often, exporting countries such as Russia are run autocratically, and crisis situations like the war against Ukraine highlight that such dependencies bring unpredictability and

[11] cf. Masson–Delmotte et al. (2021), pp. 5–11, pp. 16ff.
[12] cf. UN Climate Change Conference UK 2021 (2021), pp. 2-10, pp. 13–14.
[13] cf. German Federal Ministry for Economic Affairs and Climate Action (2018).

planning uncertainty for importing countries.
To reduce dependency, meet COP26 goals as well as strive for net negative CO2 emissions to limit the damage of climate change, renewable energy must be the tool of choice. Therefore, a rapid adaptation is necessary to meet the increasing demand for electricity and green hydrogen. However, there are some obstacles that make adaptation difficult. Besides respecting species protection, the construction of wind turbines near settlements often meets with opposition. In addition, without any legal changes many photovoltaic (PV) systems could no longer be profitable from as early as mid-2022, if the energy is not used by the producer itself, as operators of new systems will receive less and less compensation for the solar power they feed into the public utility grid (UG). The publicly guaranteed feed-in rate in Germany has fallen by 30% in the last two years.[14]
Decentralized microgrids (MGs) could possibly be a solution to these problems. Surplus from self-produced energy from distributed energy resources (DERs) like PV systems or wind turbines, which is not used by the producer itself, could be traded regionally in peer-to-peer (P2P) networks. Such energy suppliers which produce and consume energy, also called prosumers, would benefit if the MG price is higher than the remuneration they would get by feeding-into the UG. Buyers at the same time are better off, if the MG price is lower than the price of conventional energy providers. If the MG price including taxes is higher than the feed-in rate but lower than the market price, MGs could reduce reliance on the UG as well as on fixed feed-in rates and possibly incentivize renewable energy production due to higher revenues.
The deployment of decentralized MG trading would have to be simple and quick to implement for rapid adaptation, without having to make major adjustments on the technological infrastructure. Therefore, blockchain technology run by a decentralized network could agilely implement P2P trading by using smart contracts (SCs) enabling transactions between seller and buyer. Previously defined mechanisms in the SC are visible to every participant and create trust in the network. Conditions for every energy transaction made, are stored inside the blockchain. Hence, the effort for introducing P2P trading at the municipal level could be minimized with the use of SCs, since there is no need for additional IT infrastructure.[15]
This thesis will therefore address the following research questions (RQs):

> RQ 1: *What is the impact of decentralized energy trading in microgrids on renewable energy trading and prosumer costs, and how does it change the interaction with the utility grid?*
>
> RQ 2: *How can P2P energy trading in microgrids based on blockchain technology be enabled by smart contracts?*

[14] cf. Ritter et al. (2021).
[15] cf. Wörner et al. (2019).

In order to answer these questions this thesis is structured as follows. First, the basics of energy trading and blockchain are considered in Chapter 2. This is followed by a literature review of the current state of research in modeling MG energy trading in Section 3. Chapter 4 gives an explanation of the methodological approach using the design science research (DSR) method. In the main part of this thesis, first Section 5 introduces the Linear Programming (LP) model for representing MG trading. Afterwards the Mixed Integer Linear Programming (MILP) model extension including the supply of control reserve as a MG community is explained. A key focus is then the numerical results of various scenarios in both models, which will be evaluated in Section 6. Considering the second RQ in Chapter 7, the created SC is presented and its handling is analyzed afterwards in Chapter 8. The next Section 9 discusses the received results, whereas Section 10 addresses consequent implications for theory and practice. Chapter 11 suggests recommended actions based on the findings of this thesis and gives an outlook on future research fields, while Section 12 mentions existing limitations. The thesis closes with the main results being summarized in the last Chapter 13.

13 Conclusions and Outlook

Climate change is one of the challenges — if not the greatest challenge -– for humanity. In order to counteract the accelerating global warming, solutions must be found as quickly as possible to drastically reduce CO2 emissions. A switch from fossil fuels to renewable energies is essential. Particularly, the dependence on fossil commodity supply from authoritarian-led countries is also of great importance when considering the energy sector, as these increase uncertainty in the energy security.

In the scientific literature, P2P MG energy trading is seen as an approach that can lead to a more decentralized and interconnected energy supply and thus contribute to the transformation of the energy market. With the networking of smaller prosumers, the production of electricity from renewable energies is to be promoted in a local MG. This thesis builds on previous research and presents two mathematical optimization models based on it, which can be used to investigate MG energy trading. During the design process, attention was paid to ensure that the solution of the models would provide insight into the efficiency of MG trading and that different scenarios could be modeled.

The presented LP model can be used for the analysis of the findings resulting from different basic scenarios of MG trading. The introduced MILP model extension also includes the possibility to jointly offer CR as a MG community. Furthermore, in addition to the MG energy trading, the possibility of battery capacity trading between the participants is equally represented in the models, so that existing storage capacities can be lent P2P.

For the analysis of the models' solutions a baseline case and 8 realistic scenarios were developed. These differ in the maturity of renewable energy use, as well as the inclusion of electricity production by wind turbine besides the possibility of offering CR. All scenarios were assessed for the case with and without MG energy trading in the month of January and July, respectively. The models were implemented in MATLAB and the resulting 36 instances solved for two created MGs. While the first MG contains 20 households with different load profiles and living habits of the residents, the second MG comprises 7 institutions and companies.

The results demonstrate that MG trading can have an added value for the participants in the MG, thus providing an incentive for renewable electricity production and local energy trading. It is worth highlighting that the addition of a wind turbine leads to a strong cost reduction through MG trading. Local participation in the profits from wind power could lead to equitable remuneration of positive externalities and also provide more support for the construction of wind turbines near settlements. The analysis also emphasize that both MGs can benefit enormously from adding the option of offering CR. In this case, however, no amount of energy is traded P2P anymore but most of the energy produced is consumed by the prosumers themselves or used to provide CR. The numerical analysis also suggests that a joint MG that includes households as well as institutions and companies would run even more efficiently than two separate MGs.

In addition, this work presents an SC extension that allows P2P MG energy trading to be mapped based on a blockchain. The SC source code was written in the Solidity code language and is deployed on the Ethereum test network. The SC dictates that only registered prosumers can trigger functions of the SC, so a centralized entity like a regional administration would be needed here to handle individual user management.

The analysis of the SC functions proves that the basic processes of MG energy trading can be mapped decentralized and automated by means of a SC. Thereby, the most important data of energy offers and requests as well as completed trades are stored in the blockchain. The stored data could be used as certificates at the end of a billing period to confirm, together with smart meter data, that energy has been delivered within the MG.

Overall, by applying Hevner's DSR methodology, both the development and the analysis of the design artifacts are based on rigorous scientific principles and iterative evaluation processes. Therefore, this thesis can answer the 2 RQs posed in the introduction based on a sound scientific analysis. The results can certify that MG energy trading leads to cost reductions in the production of electricity from DER for the household MG in all scenarios. In the MG of institutions and companies, there are no savings compared to the case without MG trading in 2 of the 8 scenarios in January due to lack of enough self-produced energy. It can be concluded that MG trading subsidizes existing renewable energy production while incentivizing more locally produced energy from DER. Moreover, it was also emphasized that in the basic scenarios without CR, the dependency on the UG can be significantly reduced. In addition, implementing an SC can ensure that MG trading can be mapped decentrally on a blockchain database, which significantly reduces the technological requirements for feasibility on a municipality level.

For further research, a larger MG community could be explored that connects the two MGs under consideration and includes additional participants. Here, an analysis on a yearly basis would be interesting to investigate the changes in energy trading behavior even deeper. Also, by changing the Pareto condition, an analysis on the level of individual participants could be of relevance. Regarding the SC, a further development towards the mapping of CR would be promising, in line with the introduction of a fair market clearing mechanism.