

UNIVERSIDADE FEDERAL DO PARANÁ

KRISTIE KAMINSKI KÜSTER

CONTRIBUTIONS ON IMPACTS OF LOCAL PEER-TO-PEER ENERGY MARKETS
ON UTILITIES

CURITIBA

2022

KRISTIE KAMINSKI KÜSTER

CONTRIBUTIONS ON IMPACTS OF LOCAL PEER-TO-PEER ENERGY MARKETS
ON UTILITIES

Trabalho apresentado como requisito parcial
para a obtenção do título de Doutora em En-
genharia Elétrica pelo Programa de Pós Gra-
duação em Engenharia Elétrica do Setor de
Tecnologia da Universidade Federal do Paraná.

Orientador: Prof. Dr. Alexandre Rasi Aoki
Coorientador: Dr. Germano Lambert Torres
Coorientador: Prof. Dr.-Ing. Daniel Navarro Ge-
vers

CURITIBA

2022

DADOS INTERNACIONAIS DE CATALOGAÇÃO NA PUBLICAÇÃO (CIP)
UNIVERSIDADE FEDERAL DO PARANÁ
SISTEMA DE BIBLIOTECAS – BIBLIOTECA CIÊNCIA E TECNOLOGIA

Küster, Kristie Kaminski

Contributions on impacts of local peer-to-peer energy markets on utilities
/ Kristie Kaminski Küster. – Curitiba, 2022.

1 recurso on-line : PDF.

Tese (Doutorado) – Universidade Federal do Paraná, Setor de
Tecnologia, Programa de Pós-Graduação em Engenharia Elétrica.

Orientador: Prof. Dr. Alexandre Rasi Aoki

Coorientador: Dr. Germano Lambert Torres

Coorientador: Prof. Dr.-Ing. Daniel Navarro Gevers

1. Energia Elétrica - Comercialização. 2. Energia Elétrica – Viabilidade
econômica. I. Aoki, Alexandre Rasi. II. Torres, Germano Lambert. III.
Gevers, Daniel Navarro. IV. Universidade Federal do Paraná. Programa de
Pós-Graduação em Engenharia Elétrica. V. Título.

Bibliotecária: Roseny Rivelini Morciani CRB-9/1585

TERMO DE APROVAÇÃO

Os membros da Banca Examinadora designada pelo Colegiado do Programa de Pós-Graduação ENGENHARIA ELÉTRICA da Universidade Federal do Paraná foram convocados para realizar a arguição da tese de Doutorado de **KRISTIE KAMINSKI KÜSTER** intitulada: **Contributions on economic impacts of local peer-to-peer energy markets on utilities**, sob orientação do Prof. Dr. ALEXANDRE RASI AOKI, que após terem inquirido a aluna e realizada a avaliação do trabalho, são de parecer pela sua APROVAÇÃO no rito de defesa.

A outorga do título de doutora está sujeita à homologação pelo colegiado, ao atendimento de todas as indicações e correções solicitadas pela banca e ao pleno atendimento das demandas regimentais do Programa de Pós-Graduação.

CURITIBA, 06 de Junho de 2022.

Assinatura Eletrônica
07/06/2022 18:25:28.0
ALEXANDRE RASI AOKI
Presidente da Banca Examinadora

Assinatura Eletrônica
07/06/2022 17:45:44.0
THELMA SOLANGE PIAZZA FERNANDES
Avaliador Interno (UNIVERSIDADE FEDERAL DO PARANÁ)

Assinatura Eletrônica
22/06/2022 16:38:14.0
RUTH PASTÔRA SARAIVA LEÃO
Avaliador Externo (UNIVERSIDADE FEDERAL DO CEARÁ)

Assinatura Eletrônica
29/06/2022 09:58:08.0
EDSON PINHEIRO DE LIMA
Avaliador Externo (PONTIFÍCIA UNIVERSIDADE CATÓLICA DO PARANÁ)

ACKNOWLEDGMENTS

First of all, I would like to thank my supervisor Alexandre Rasi Aoki. I have a deep personal and professional respect and admiration for Prof. Aoki, for his technical competence and the generosity of his guidance style, always present and focused on results, and with respect and empathy for the challenges faced.

To my co-supervisors Prof. Germano Lambert Torres and Prof. Daniel Navarro Gevers. Prof. Germano contributed to the work by helping me identify the knowledge gaps that were worth publishing and insights to delineate the research path. Prof. Navarro opened many doors for me in Germany and provided great feedback sessions on the research results.

To my former doctorand colleague Luciano Cavalcante Siebert, who was the one who suggested the topic of this research to me, and helped me along to better define it.

To the company LACTEC and to the Agência Nacional de Energia Elétrica R&D Project No. 2866-0444-2016 and Coordenação de Aperfeiçoamento de Pessoal de Nível Superior for the support of this project.

To the company OLI Energy, especially to Mukund Wadhwa and Godwin Okwuibe, with whom some discussions on the potential advantages of local energy markets against other approaches provided a spark to this research direction.

To the InES colleague Katharina Bär, we had several conversations and shared with each other our experiences on pursuing a Ph.D, and whose advice helped me figure out the steps that I needed to take to build a model and find results.

To my colleague and friend Daniel Gebbran Cons Bacilla Ferreira, whose cooperation partnership was fundamental for the research final course. Gebbran made an important technical contribution and friendly support, which gave me motivation to keep getting results and finish.

To my partner and husband Nicolas for embarking on this journey with me with unconditional support. During the doctoral period, we had two children and made changes to jobs and even countries. Our mutual love, respect and trust help us overcome challenges and add sweetness to our lives. To our children, Otto and Anna, the most incredible human beings I have ever met. The love I feel for them gives me strength to do better every day. To everyone else that contributed towards enabling me to do this work I am profoundly grateful.

RESUMO

Os mercados de energia peer-to-peer (P2P) são uma abordagem promissora para coordenar localmente a quantidade crescente de recursos energéticos distribuídos (DERs) nos sistemas de distribuição. Quando projetados adequadamente, eles podem moldar o comportamento dos prosumidores para corresponder à operação segura da rede. No entanto, embora os benefícios dos mercados P2P para os prosumidores já sejam bem conhecidos, pouco se sabe sobre seus impactos nas concessionárias. Até agora, não há regulação em país algum que permita a adoção generalizada de mercados de energia P2P devido a essa incerteza. O presente estudo visa desenvolver uma avaliação abrangente e quantificação dos impactos dos mercados de energia locais P2P nas distribuidoras. Primeiramente, é traçado um *roadmap* para analisar benefícios, vantagens e desafios como estratégias para a adoção de mercados P2P. Propõe-se que os critérios atribuídos a este *roadmap* sejam quantificados em termos de desempenhos técnicos e econômicos e comparados aos atuais modos de operação de medição líquida e autoconsumo. Para executar essas avaliações sob diversos cenários, uma plataforma de co-simulação é desenvolvida, que conecta um modelo de mercado a um modelo de rede elétrica. O modelo de mercado consiste em um esquema de negociação bilateral de leilão duplo pago por demanda. Os fluxos de receita são avaliados para quantificação da perda líquida, e taxas de rede e de transação são introduzidas como possíveis mecanismos de compensação de perda de receita. O modelo da rede é estabelecido no OpenDSS para analisar o fluxo de potência em série temporal. O desempenho da rede é avaliado por seus impactos nos indicadores de operação. Todas as avaliações são verificadas sob a variação das taxas de rede, do número de agentes, PV e armazenamento. Como resultado, um equilíbrio de benefícios para todos os *stakeholders* é alcançável se as métricas não financeiras forem levadas em consideração em uma análise de viabilidade integrada; se houver um desenho adequado de estruturas de mercado, tarifas e taxas para o equilíbrio econômico-financeiro de todos os *stakeholders*; e se o projeto dessas estruturas for sensível a diferentes configurações de rede e penetração de DERs. Os resultados contribuem como primeiros passos para compreender como as concessionárias podem adotar os mercados P2P como uma solução viável e lucrativa para seus desafios de coordenação de rede, mantendo os benefícios e a soberania dos prosumidores. Esses primeiros passos já dão direções iniciais aos reguladores, mas também abrem um conjunto de novas questões que devem ser abordadas por pesquisas futuras.

Palavras-chaves: co-simulação; recursos distribuídos de energia; análise de viabilidade; análise de impactos; mercados locais de energia; microrredes; transações peer-to-peer.

ABSTRACT

Peer-to-peer (P2P) energy markets are a promising approach for locally coordinating the increasing amount of distributed energy resources (DERs) at the edge of the power system. When properly designed, they offer a way of shaping the prosumers behavior to match the secure operation of the grid. However, although the benefits of P2P markets for the prosumers are already well understood, little is known about their impacts on the utilities. So far, no regulatory framework in any country allows for the widespread adoption of decentralized energy markets due to this incertitude. The present study aims to better understand these impacts through a comprehensive evaluation and quantification of P2P local energy markets' impacts on power distribution utilities as primary stakeholders. First, a qualitative roadmap is outlined to analyze benefits, advantages and challenges as strategies for the adoption of peer-to-peer markets by utilities. It is proposed that the criteria assigned to this roadmap be quantified in terms of revenue performance and network operation performance. The technical and economic performances of a P2P market are compared to the current net-metering and self-consumption operation modes. These evaluations are carried out through scenarios analysis, where a co-simulation framework connecting a market model to a power flow model is set up. For the market model, a double-sided pay-as-bid peer-to-peer trading scheme is developed. Revenue streams are evaluated for net loss quantification, and grid fees and transaction fees are introduced as possible compensation mechanisms for the net revenue loss. The power flow model is established in OpenDSS to analyze time-series power flow within the chosen circuit. The grid performance is evaluated for its impacts on the grid operation indicators. The performance of the stakeholders is not only quantified under the variation of network fees but also under variation in the number or agents, PV and storage penetration. As a result, an equilibrium in benefits for all stakeholders is achievable if non-financial metrics are taken into account and properly quantified economically in an integrated feasibility analysis; if there is a proper design of market structures, tariffs and fees for the financial economic balance of all stakeholders; and if the design of these structures are sensitive to different network configurations and DER penetration. The results contribute as first steps toward comprehending how could the utilities embrace P2P markets as a feasible and profitable solution for its grid coordination challenges, while keeping prosumers' benefits and sovereignty. These first steps already give initial directions to the policymakers, but they also open a set of new questions which must be taken upon by further research.

Key-words: co-simulation; distributed energy resources; feasibility analysis; impact; local energy markets; microgrids; peer-to-peer energy trading.

LIST OF FIGURES

FIGURE 1 – Main problems caused by the drivers of change and their respective traditional solutions. Do they work? Source: the author based on the study (KOK, 2013)	22
FIGURE 2 – Drivers of change shift the focus to the edge of the grid - a prosumer-centric system. Source: (PINSON et al., 2017)	22
FIGURE 3 – Distributed Energy Resources overview. Source: (SIEMENS, 2016)	25
FIGURE 4 – Classification of distribution-level energy management approaches Source: (KOK; WIDERGREN, 2016)	27
FIGURE 5 – Decentralized Market Layouts. Source: (BAROCHE et al., 2019) .	28
FIGURE 6 – Merit order and equilibrium for an electricity pool. Source: (PINSON, 2019)	29
FIGURE 7 – Trading periods as they approach time of delivery.	32
FIGURE 8 – Strategy spectrum of bidding. Source: (KOK, 2013)	33
FIGURE 9 – Layer platforms of a P2P energy framework. Source: (TUSHAR et al., 2020)	34
FIGURE 10 – Schematic representation of P2P adoption barriers and advantages for the utility	43
FIGURE 11 – Simulation Model Overview	46
FIGURE 12 – Example of a Two-Sided Pay-as-Bid Market Clearing within a Market Slot	47
FIGURE 13 – Example of bidding strategy from a consumer asset in a market slot	47
FIGURE 14 – Example of offering strategy from a generation asset within a market slot	48
FIGURE 15 – The utility enters the market as a price maker / inelastic demand and supply	48
FIGURE 16 – The hierarchical market structure	49
FIGURE 17 – IEEE European Low Voltage Test Feeder one-line layout	52
FIGURE 18 – Summed up demands of the 55 agents connected to the grid participating in the market	53
FIGURE 19 – Global horizontal Irradiance on the modeled photovoltaic systems	53
FIGURE 20 – Demanded Energy from Loads	56
FIGURE 21 – Energy supplied by the PVs	57
FIGURE 22 – Energy exchanged by the batteries	58
FIGURE 23 – Energy balance which will be required from by the utility as a sum of all agents - loads, PVs and storage systems	58

FIGURE 24 – Number of transactions as a function of participating agents	62
FIGURE 25 – Utility revenue variation as a function of participating agents (as a percentage of the revenue in the net-metering scenario	62
FIGURE 26 – Utility Revenue variation as a function of transaction fee price (as a percentage of the revenue in the net-metering scenario	63
FIGURE 27 – Participating agents' costs as a function of the transaction fee price	64
FIGURE 28 – Percentage of agents who are cost-wise worse off than net-metering scenario as a function of transaction fee price	64
FIGURE 29 – Variation in utility revenue as a function of PV Penetration	65
FIGURE 30 – Variation in utility revenue as a function of Storage Penetration . .	66
FIGURE 31 – Voltage profile on Transformer LV Side (full = net-metering; dashed = market)	67
FIGURE 32 – Voltage profile on furthest point from transformer (full = net-metering; dashed = market)	67
FIGURE 33 – Power on Transformer LV Side (full = net-metering; dashed = market)	68
FIGURE 34 – Power on Transformer LV Side for different PV penetration (full = net-metering; dashed = market)	69
FIGURE 35 – Voltage profile on furthest point from the transformer for different PV penetration (full = net-metering; dashed = market)	70
FIGURE 36 – Power on Transformer LV Side for different load demands (full = net-metering; dashed = market)	71
FIGURE 37 – Voltage profile on furthest point from transformer for different load demands (full = net-metering; dashed = market)	71
FIGURE 38 – Energy balance which will be required by the utility as a sum of all agents - loads, PVs, and storage systems at 20% PV Penetration	72
FIGURE 39 – Energy balance which will be required by the utility as a sum of all agents - loads, PVs, and storage systems at 60% PV Penetration	72
FIGURE 40 – Energy balance perceived by the utility at the point of common coupling at 10% Storage Penetration	73
FIGURE 41 – Load loss as a percent from the no-DER deployment scenario for different PV penetrations)	74
FIGURE 42 – Load loss as a percent from the no-DER deployment scenario for different Storage penetrations)	74
FIGURE 43 – Mean purchase prices perceived by the prosumers at each market slot	75
FIGURE 44 – Mean sell prices perceived by the prosumers at each market slot	76

LIST OF TABLES

TABLE 1 – Different market pricing mechanisms for peer-to-peer markets. Source: adapted from (TUSHAR et al., 2020)	30
TABLE 2 – Summary of surveyed optimization methods	31
TABLE 3 – Main technical challenges for P2P energy framework. Source: summarized from (TUSHAR et al., 2020)	35
TABLE 4 – Research trends on P2P energy	36
TABLE 5 – Analysis Framework with Evaluated Criteria - P2P adoption roadblocks	44
TABLE 6 – Analysis Framework with Evaluated Criteria - P2P adoption advantages	44
TABLE 7 – Example of allocation for a match with multiple buyers and sellers within a market tick.	49
TABLE 8 – Agents' storage system configurations	54
TABLE 9 – Implemented Market Parameters	54
TABLE 10 – Revenue Streams for the different scenarios and stakeholders (in absolute values)	60
TABLE 11 – Revenue Streams for the different scenarios and stakeholders (as the difference in percent from the Base 2 scenario)	60
TABLE 12 – Number of prosumers who are in cost advantage or disadvantage in comparison to net-metering (Base 2) scenario	61
TABLE 13 – Transformer Load Factor for different scenarios	68
TABLE 14 – Total Circuit Losses in VA for different scenarios	69
TABLE 15 – Results summary from performance comparison for each analyzes criterion	80
TABLE 16 – Results summary of analisys from local energy markets advantages	81

LIST OF ABBREVIATIONS

COM	Component Object Model (®)
DER	Distributed Energy Resources
DG	Distributed Generation
DR	Demand Response
DSO	Distribution System Operator
ICT	Information and Communication Technology
IEEE	Institute of Electrical and Electronics Engineers
LEM	Local Energy Markets
LV	Low Voltage
MAS	Multi-Agent System
MV	Medium Voltage
OpenDSS	Open Distribution System Simulator (™)
P2P	Peer-to-Peer
PV	Photovoltaic
TSO	Transmission System Operator

LIST OF SYMBOLS

EP	Energy Purchased at market slot [kWh]
ES	Energy Sold at market slot [kWh]
E	Energy [kWh]
P	Power [kW]
b'	adjusted bid for fee accounting [kWh]
s'	adjusted offer for fee accounting [kWh]
b	bid [kWh]
C	cost of a given energy transaction [\$]
π	energy price [\$]
e	energy quantity per transaction [kWh]
FiT	feed-in tariff [\$]
α	grid fee ratio [-]
s	offer [kWh]
R	revenue of a given energy transaction [\$]
ω	revenue rate [\$]
T	transaction [-]
τ	transaction fee [\$]
f_{load}	transformer load factor [-]
ρ	utility tariff [\$]

SUMMARY

1	INTRODUCTION	14
1.1	Problem Definition	14
1.2	Objectives	16
1.3	Contributions	17
1.4	Document Structure	18
2	STATE-OF-THE-ART OF DECENTRALIZED AND PEER-TO-PEER ENERGY MARKETS	19
2.1	Concept of decentralized and peer-to-peer energy markets	19
2.1.1	Why towards consumer-centric markets	20
2.1.2	Types of markets	22
2.1.3	Desired characteristics for decentralized energy markets	23
2.1.4	Enabling technologies	24
2.1.4.1	Distributed Energy Resources	25
2.1.4.2	Advanced Metering and Energy Management Infrastructure	26
2.1.4.3	Information and Communication Technologies	26
2.1.4.4	Investment in technology roll-out	27
2.1.5	Market layouts	28
2.1.6	Pricing mechanisms	29
2.1.7	Trading periods	31
2.1.8	Bidding strategies	33
2.2	Peer-to-peer energy markets impact on distribution systems	34
2.2.1	Main technical challenges	34
2.2.2	Impacts of P2P energy in grid operation	36
2.2.2.1	Study of market's mechanisms impacts on the grid	37
2.2.2.2	Development of mechanisms for loss allocation and transmission rights	38
2.3	Feasibility of peer-to-peer energy models for the involved stakeholders	39
2.3.1	Feasibility for the prosumer	39
2.3.2	Feasibility for utility and retailers	40
2.4	Knowledge gap	40
3	METHODOLOGY	42
3.1	Research Strategy	42
3.2	Analysis and Evaluation Framework	42
3.3	Simulation Model Overview	45
3.4	Peer-to-Peer Market Mechanism	45
3.4.1	Market Timing	45
3.4.2	Two-sided pay-as-bid auction mechanism	46
3.4.3	Bidding/ Offering strategy	47
3.4.4	Trading Process	48

3.5	Grid Fee Calculation	49
3.6	Transaction Fee Calculation	51
4	RESULTS AND DISCUSSION	52
4.1	Case Study and Scenarios	52
4.1.1	Simulated Circuit Model and Input Data	52
4.1.2	Description of Simulated Scenarios	53
4.1.3	Detail of the storage system operation strategies	55
4.2	General simulation results	56
4.3	Revenue Stream Performance Comparison	57
4.3.1	Sensitivity to number of agents	61
4.3.2	Sensitivity to transaction fees	63
4.3.3	Sensitivity to PV Penetration	65
4.3.4	Sensitivity to Storage Penetration	65
4.4	Effects in grid operation	66
4.4.1	Voltage Profile	66
4.4.2	Transformer Load and Load Factor	67
4.4.3	Circuit Losses	68
4.4.4	Sensitivity to PV and Storage Penetration	69
4.5	Local energy markets as a non-wire alternative to infrastructure	70
4.6	Local energy markets as one of the approaches to locally coordinating DERs	73
4.7	Reducing costs for prosumers	75
4.8	Discussion	76
4.9	Outlook	82
5	CONCLUSION AND FUTURE WORK	83
	REFERENCES	86
	Appendix 1 - Scientific Contributions	97

1 INTRODUCTION

The power systems transition to sustainability is occurring mainly at the distribution grid, where growing participation of non-dispatchable renewable energy sources is occurring. The proliferation of distributed energy resources (DERs) aligned with consumer-level information and communication technology (ICT) propels the power systems toward a new reality, where the role of stakeholders within the energy value chain is redefined (JOGUNOLA et al., 2017).

Passive consumers are becoming “prosumers” – agents that flexibly consume and produce energy optimizing their electricity use to match their needs and preferences, including reduction of their electricity cost (PARAG; SOVACOOOL, 2016). This shift to a customer-centric vision of the power systems and the increasing proportion of generation and flexibility provided by DERs bring new challenges to the electricity infrastructure operation. To cope with it, a new paradigm of locally coordinated electricity systems is needed, where the prosumer takes active participation in operating their owned DERs (MORSTYN et al., 2020a).

Local peer-to-peer energy markets are emerging as a promising approach for locally coordinating DERs. Under the framework of peer-to-peer (P2P) energy markets, distributed flexible resources are directly controlled by their owners through a market-based operation. Each connected user (for example a smart home, building, industrial site, storage owner, electric vehicle, etc.) can engage in electricity demand and supply trade with one another, negotiating a transaction at the distribution system level (GWAC, 2013).

Such electricity markets, when properly designed, can tap into the consumption and generation flexibility of the participants and combine individual interests with grid operation objectives. The same concept already applies to the transmission and high voltage levels, where wholesale markets with trading and clearing mechanisms are used to manage and affect the grid operation (KOK; WIDERGREN, 2016).

1.1 PROBLEM DEFINITION

The framework and design of local P2P energy markets have attracted significant research attention in the past few years (KÜSTER et al., 2019). It is already well established in the literature that P2P local energy markets are technically feasible and bring benefits to the prosumer (PARAG; SOVACOOOL, 2016). The P2P markets are more beneficial to the consumers than the self-consumption operation because markets allow for a better allocation of resources to their highest value uses. In an efficient market,

where the social welfare is maximized and no one desires to unilaterally deviate from market outcome, even traditional consumers who do not own distributed generation can benefit financially from a market operation. However, none of the several small-scale initiatives and pilot projects for implementing local energy markets (TUSHAR et al., 2021b) has become system-wide adopted. This could be largely due to the uncertainty of impacts on the other stakeholders involved, namely power distribution utilities.

From the utility's point of view, there is a competition between business interests involved in the mass penetration of DERs and prosumerism (ADAMS et al., 2021). Utilities may face prosumers as a threat due to net revenue losses caused by a decrease in electricity sales. In their current business models, they are expected to keep the task of ensuring energy reliability through operation and maintenance of grid infrastructure even in the presence of prosumers along with traditional final consumers (WITTMAYER et al., 2021).

Yet, prosumerism is already systemically wise tolerated by utilities in forms of self-consumption and net-metering regulatory schemes. Regarding its economic impacts on utilities, the available literature on the impact evaluation from mass penetration of distributed energy resources focuses on these current regulatory frameworks. In (ZINAMAN, 2020), a set of concepts and directions are given to elaborate tariff and revenue impact analysis studies regarding the emerging distributed photovoltaic programs. It elaborates a methodology that aims to quantify the expected changes in revenue collection, operational costs, and expenditures that served partly as a basis for this current study (TONGSOPIT et al., 2017).

An approach of local P2P trading would require regulatory reform. What would motivate the utility to adopt peer-to-peer energy markets as opposed to the business-as-usual prosumer integration? There are studies such as (BOTELHO et al., 2021) which focus on a qualitative analysis of the impacts, making an analysis of business models enablers and barriers for prosumer integration including business as usual and new regulatory frameworks such as local energy markets. A mainly technical approach on peer-to-peer impacts has also been studied (DUDJAK et al., 2021), focusing specifically on decentralized energy markets' impacts on grid operation.

However, it is still unsettled whether there is a scenario where both utility/-retailers and prosumers benefit from a peer-to-peer energy market business model. It is necessary to understand and quantify the mechanisms that positively influence the utility as a primary stakeholder in the process, as well as assess the risks and misunderstandings. An integrated view on technical and economical aspects of the impacts on both the utilities and retailers is yet to be done.

In other words, from the prosumer point of view, peer-to-peer local energy markets are beneficial in comparison to net-metering and self-consumption schemes. From

the utility point of view, revenue impact analysis on utilities by mass penetration of DERs is already well understood in current regulatory frameworks, such as self-consumption and net-metering. Technical and economic implications and opportunities for utilities in a P2P regulatory framework have been conjectured or approached qualitatively or isolated in previous studies, however, an integrated quantification of these impacts is still a knowledge gap.

1.2 OBJECTIVES

The main goal of this study is to provide a systematic and comprehensive evaluation of P2P local energy markets' impacts on power distribution utilities and retailers as primary stakeholders, and to quantify the challenges and opportunities for utilities in the adoption of P2P local energy markets.

This objective is translated into the following research questions:

- How do P2P markets compare to net-metering/self-consumption in economic and technical performance?
- What are the economic impacts of network fees as lost revenue adjustment mechanisms in peer-to-peer market schemes for utilities and prosumers?
- How do variations in DER penetration impact P2P markets in comparison to the net-metering/ self-consumption grid operation?
- And lastly, is it possible under the assumptions taken, that there is a scenario where both stakeholders - utility and prosumers - benefit more from peer-to-peer market schemes than from net-metering self-consumption regulatory framework?

To reach the general objective and answer the research questions, specific steps are assigned as follows:

- to review the concept of peer-to-peer energy markets and the respective up-to-date literature on impacts on power distribution systems;
- to assemble a feasibility overview on peer-to-peer local energy markets considering the primary stakeholders (utility and prosumers), based upon a review of up-to-date literature;
- to present a roadmap with an integrated evaluation platform of P2P energy markets roadblocks and opportunities for utilities;
- to set up a co-simulation framework to connect a market model to a power flow model;

- use this co-simulation framework to evaluate a case study and a specific set of scenarios for the stakeholder's revenue performance and grid operation performance;
- to interpret the results according to the evaluation platform's specific set of criteria guiding to answering the given research question.

1.3 CONTRIBUTIONS

By answering the posed research questions, the main contribution of this work is to provide a better understanding of the problem as a guide to outlining strategies for the adoption of P2P transactive markets by the distribution system operators (DSOs) and prosumers.

This study delineates a qualitative roadmap, considering roadblocks and challenges as well as advantages of the adoption of peer-to-peer energy markets by utilities, based on a review of up-to-date literature.

Considering the outlined roadmap, this study further provides a framework for quantification of the impacts of the adoption of peer-to-peer transactive markets by the DSOs.

A wide set of scenarios is organized to investigate the impacts and opportunities for utilities in the adoption of P2P local energy markets in a comprehensive framework. The stakeholders' technical and economical performances are quantified under the presence and variation of network fees, variation in number or agents, PV and storage penetration. A co-simulation framework connecting a market model to a power flow model is set up, which is then used to evaluate and quantify the stakeholders' revenue performance and grid operation performance. The results are discussed according to a specific set of criteria guiding to support policy makers' decisions.

This study results in:

- defining different structures for the operation between prosumers and DSOs, specifically net-metering operation and market operation.
- evaluating how adopting network fees can help recover the loss.
- analyzing how different levels of DER penetration (i.e., different proportions of PV and storage) affect the utility income.
- pointing to directions where P2P market implementation brings benefits for all stakeholders involved, prosumers and utilities alike.

The achieved results contribute as first steps toward comprehending how could the utilities embrace the approach of peer-to-peer energy markets as a feasible and profitable solution for its grid coordination challenges, all the while keeping prosumers' benefits and sovereignty. These first steps can already give initial directions to the policymakers, but they also open a set of new questions which must be taken upon by further research.

Further contributions in form of scientific production during this research duration are listed in Appendix A.

1.4 DOCUMENT STRUCTURE

This document is divided into five main chapters, where the first chapter presents the introduction of this study with the objectives and motivation that guide the author to research the related problem.

The second chapter discourses the state-of-the-art, bringing the concepts of decentralized energy markets, peer-to-peer energy impacts on distribution systems, and the feasibility of peer-to-peer models for the involved stakeholders.

The third chapter presents the methodology to develop the model and the analysis framework used to obtain the results. It details the developed market model and the chosen network model, and the co-simulation framework that links the two.

The fourth chapter introduces the simulated scenarios that will be used for performance comparison. It presents then the performed analyses results, with discussion and final considerations from the observed outcomes.

The last chapter presents the conclusion and proposes future research that are potential ramifications of this study.

2 STATE-OF-THE-ART OF DECENTRALIZED AND PEER-TO-PEER ENERGY MARKETS

This chapter presents the up-to-date literature on decentralized and P2P energy markets, P2P energy markets' impacts on distribution systems, P2P energy markets feasibility for the involved stakeholders, and the knowledge gap.

The first section (Section 2.1) is based on the work developed during this doctoral study that resulted in a published article with the title "Transaction-based operation of electric distribution systems: A review" (KÜSTER et al., 2019).

2.1 CONCEPT OF DECENTRALIZED AND PEER-TO-PEER ENERGY MARKETS

Electrical energy is a very particular type of commodity because it is inextricably linked its physical system which is faster than a market. Contrary to trading barrels or bushels, exchanging electricity can only function reliably on the notion that supply and demand must be balanced at each second, respecting the dynamics of power system operation. Nevertheless, it is possible to treat electricity as a good, service or commodity. As such, electricity can be traded in a market designed to abide mainly by two constraints: the generation limits of each generating unit, and the total balance between production and demand that must be held at all times. This is traditionally done by conceptually separating electricity market trade from the power network operation as the first step. Then, having a central "managing" authority (a power system operator) is present to conciliate market interactions and balance demand and supply on an almost instantaneous timescale basis to maintain the integrity of the power system (KIRSCHEN; STRBAC, 2004).

Trade and supply functionalities became then well-known and established as coordination mechanisms for bulk power systems. All around the world, power systems are organized into wholesale markets which are the basis for balanced power grid operations. However, given the rise of distributed generation and information and communication technology, the customer at the end of the distribution grid is now eligible for participating in electricity market trade. The so-called prosumer has now a value to offer: flexibility in energy production and consumption, which can be traded as a good or service.

A good starting point for the introduction to decentralized energy markets is the study from (WU; VARAIYA, 1999). This study defies conventional centralized electricity trading approaches to deal with the power system's shared resources with a new operating paradigm, where the decision-making authority and information are decentralized in a market-based operation of the electric power system. They introduce

a market design characterized by private multilateral trades between generators and consumers. As such, it established the groundwork for what is known today as peer-to-peer local energy markets for distribution networks, whose operation is based on this concept.

Local peer-to-peer (P2P) energy markets can be defined as a system where users (prosumers) at the edge of the distribution grid engage in an exchange of electricity with one another, based on their distributed energy resources (DERs). Distributed flexible resources are directly controlled by their owners through a market-based operation. Each connected user (for example a smart home, building, industrial site, storage owner, electric vehicle, etc.) can engage in market trade with one another, negotiating a transaction at the distribution system level (GWAC, 2013). The market participants exchange with a high degree of freedom according to their needs and preferences.

Local peer-to-peer energy markets can be seen, by definition, as the antithesis of the traditional electricity consumption model, in which consumers who want to buy electrical energy have little choice. They have to buy it from the utility that holds a monopoly on the electricity supply for that location or from a retailer at a predetermined tariff. In that sense, with decentralized energy markets, the operation of the distribution systems shifts to a new paradigm where they are not unilaterally controlled and supply-oriented, they are rather customer-centric and based on market transactions between its participants.

It is important to note that peer-to-peer trading is market-driven and not based on preset prices, in which introducing competition enhances the opportunity for the power system's economic efficiency.

2.1.1 Why towards consumer-centric markets

The study (KOK, 2013) details three major drivers that will bring technological changes to the electrical power systems: transition to sustainability, the electrification of every-thing, and the decentralization of generation.

The transition to sustainability refers to reducing fossil fuel utilization for electricity generation, in exchange for sustainable or renewable energy resources. This must happen because of climate change concerns (IPCC, 2021), global oil depletion (SORRELL et al., 2012) and diversification of energy sources (IEA, 2021). The main renewable energy sources for power generation which could largely substitute fossil fuels are wind and solar energy, which bring with themselves the intermittent problem. Unlike traditional generation, their power output can be discontinuous and not easily adjusted to electricity consumption. The traditional solution to this renewables problem has been to increase the regulation capacity for the power system (SCHNEIDER et al., 2013). Nonetheless, in a system overly reliant on intermittent sources, there can exist

periods where there is a high demand for electricity and low production, this can spike energy prices and lead to power outages (ALBADI; EL-SAADANY, 2010).

The electrification of everything regards the ever-growing consumption of electric energy. Besides the world population expansion, there is an increase in the development and the use of devices that rely on electricity. According to (IEA, 2019), "global electricity demand grows at 2.1% per year to 2040, twice the rate of primary energy demand". Ultimately, the electrification of mobility will require even more amounts of power and energy from the electrical power networks. The existing infrastructure not only won't be enough, it is also aging. Reinforcements of the grid surge as the traditional response, but this has impacts on the costs of energy for the final user (KIRSCHEN; STRBAC, 2004).

Finally, the decentralization of production regards the phenomenon of the growing proportion of generation capacity at the distribution system at the edges of the power grid. The declining prices of photovoltaic rooftops and storage systems and consumers' economic and environmental motivations have boosted the penetration of distributed generation (DG). Most of this distributed generation has been so far tolerated by the utilities, as in a small amount so far their impact was negligible. Terms such as "hosting" or "absorption" capacity were developed to describe the amount of DG that can be installed without the need to reinforce any segment of the distribution grid (ISMAEL et al., 2019).

Each of these drivers has main problems, and the traditional solutions which have been applied so far (Figure 1) were not able to completely resolve the situation as each has its limitations. The three drivers of change shift the focus of the electric power system to its edges (Figure 2), where new solutions are needed, in form of new smart paradigms and new coordination mechanisms.

The figure of the prosumer, defined by Eurelectric ((EURELECTRIC, 2015)) as "prosumer is a customer who produces electricity primarily for his own needs but can also sell the excess electricity", is at the heart of these transformation drivers. This player, which is driving the changes, can also be seen as part of the solution for a new paradigm, for it has an important value to offer: flexibility. Flexibility is understood as the ability to shape electricity consumption and production behavior according to the prosumers personal interests. It can be seen as an asset to the grid operation because it provides value in maintaining the balance of supply and demand in the power system. If it is an asset, it can be exchanged as a good or service.

In this way, new decentralized coordination mechanisms based on this prosumer flexibility find their way as technically feasible solutions to deal with the power systems' technological changes. Markets, as shapers of behavior, have the potential to act as a mechanism to tap into prosumer flexibility. The development of decentralized electricity

			
Transition to sustainability		Intermittency	More operating reserve?
Electrification of everything		Limit of electricity infrastructure	Reinforcement of the grid?
Decentralizing production		Unidirectional flow paradigm	Fit and forget?

FIGURE 1 – Main problems caused by the drivers of change and their respective traditional solutions. Do they work? Source: the author based on the study (KOK, 2013)

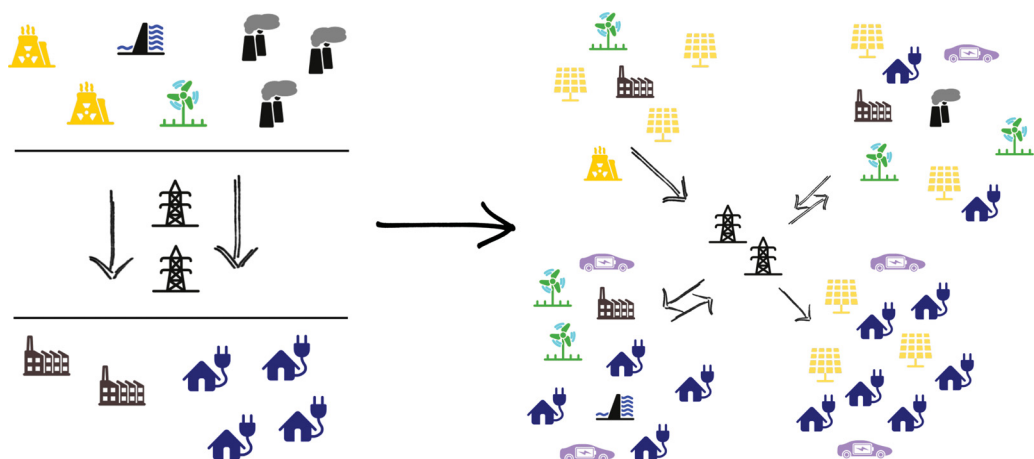


FIGURE 2 – Drivers of change shift the focus to the edge of the grid - a prosumer-centric system. Source: (PINSON et al., 2017)

markets offers, therefore, an opportunity to establish an economically efficient and technically feasible operation of a changing electric power system which slowly turns its emphasis to its fringes.

2.1.2 Types of markets

Transaction-based mechanisms can be in form of various grid services in energy and non-energy markets (ancillary services), such as power/capacity or ramping/regulation markets. In bulk power systems, depending on the regulatory framework of the country, Transmission System Operators (TSOs) award financially the ancillary service of balancing power. In Germany, for example, a market has been set via weekly and daily tender auctions, where the TSOs procure different kinds and amounts of active

power as an operating reserve (SCHNEIDER et al., 2013).

In distribution systems, although much of the literature on transaction-based systems is focused on energy markets, some studies look at other types of markets as well. (LIU et al., 2019) develops a two-stage optimal charging scheme for EVs based on transactive control, where the second stage is a regulating power market.

On the other hand, (CHASSIN, 2017) argues that, despite that energy and ramp markets are well separated in the frequency domain, the bids into each one of these markets are not independent. In that work, energy, power, and ramping are controlled jointly considering a unified price. It suggests that, unlike the common approach in the literature, the market mechanisms for energy and ancillary services are connected and therefore must be inter-coordinated.

2.1.3 Desired characteristics for decentralized energy markets

Overall, there is an assumption that the distribution markets should have interoperability, privacy protection, and scalability, which are often mentioned as features of proposed market designs.

Interoperability addresses the open communication and architecture of the applied technologies, which should allow interaction between its agents. Privacy protection is required once the information for market trade comes from “DER devices at the premises of electricity end-customers” (KOK, 2013) (p.6), which as it is argued, must be used “without infringing the privacy of the end-customer “ (p.6).

This study further proposes four criteria to indicate the desirability and completeness of a solution for distributed energy trading schemes: besides (a) scalable, as already mentioned, the designed market should be also (b) true cost-reflective, (c) present low overhead and (d) network constraints must be an integral part of market clearing.

Scalability is the quality a market should have to overcome the challenge of integrating an ever-increasing number of prosumer agents without collapsing due to heavy computational processing or reinforcements in the electricity infrastructure. Different market structures present different scalability, as showed in a recent study comparing the computational performance of three market structures (MORET et al., 2018).

Cost reflective pricing should result in charging accordingly who is imposing the costs and constraints on networks and generators in the grid. This is already a challenge in traditional power systems. Considering the ongoing transformation in electricity networks, new energy trading proposals must ensure that all stakeholders are being correctly charged and remunerated while making efficient choices, meaning that the

market should modulate prosumer behavior to a fair allocation of resources. For example, (MORET; PINSON, 2019) proposes a fairness assessment of the designed market based on indicators normally used in communication networks. Similarly, (FAQIRY; DAS, 2019) presents an auction model for energy markets where, after the auction termination, sellers' allocations are redistributed according to predetermined fairness criteria. Aside from that, there is a question on how the local P2P energy markets would impact traditional final consumers who do not wish to participate the market. How can we ensure that these customers still receive a fair tariff? The impact on electricity tariffs in the presence of local energy markets is evaluated in (ASKELAND et al., 2021). This study shows that the tariff value does not suffer increase in the presence of local energy markets due to the reduction in operation costs for the utility.

Another challenge is the computational overhead of implementing a distributed trading scheme. With a great number of small trades, any overhead for computing network constraints and market clearing must be very low. In this regard, designs proposing iterative negotiations in the search for a market solution may not be as effective as designs with a one-shot or aggregated communications (KOK et al., 2012). This also links to the scalability criterion, considering this feature is even more critical on the mass-application scale. Moreover, (ANDONI et al., 2019) discusses that blockchain-based market designs can present significant overhead due to the inherent mechanism of this technology, which may pose an impending challenge to blockchain-based energy trading implementation despite of its advantages.

Fourthly, a distributed energy trading solution should include network constraints as a part of market clearing. After all, markets for electrical energy can only function if they are supported by a reliable power system infrastructure, whose components must operate inside their safe range. Therefore, a network that uses price signals as a key operational parameter may consider not only imbalance issues between load and generation but also power transfer limits, voltage control, and reactive support services, stability services, and system restoration. This is already well understood in market mechanisms at the transmission level, a concept that now may be expanded into the distribution level of the electricity networks (KOK; WIDERGREN, 2016).

2.1.4 Enabling technologies

The legacy grid has been designed in such a way that would not allow by itself the trading between customers. The so far applied infrastructure consisted of a system operated vertically, powered by a few large power plants that are centrally monitored and controlled. The existing infrastructure should be re-engineered to an intelligent electricity system, one that facilitates full customer market participation. The main technologies which enable energy trading networks addressed in the literature are:

advanced metering and energy management infrastructure, information and communication technology (ICT), and distributed energy resources (DER). In (JOGUNOLA et al., 2017) a comprehensive overview of these technologies is provided, which is further detailed below.

2.1.4.1 Distributed Energy Resources

From the resources that play a role in distributed coordination tasks in this smart grid, distributed generation (DG) and demand response (DR) can be considered equivalent from the controllability perspective. Increasing production has the same effect on supply offer as decreasing consumption. Responsive energy consumption, therefore is also considered a resource. This has coined the unifying term “distributed energy resources, meaning the trinity DG, DR, and storage (KOK, 2013). The main characteristic of DERs, besides their distributed nature, is their flexibility in operation which allows their coordination into the smart grid. Figure 3 shows examples of grid assets with this shared characteristic. Electric vehicles serve as a two-fold type of DER, being a responsive load as well as storage on some occasions, besides having the feature of being a mobile DER. Due to these qualities, high penetration of electric mobility will play a significant role in the grid of the future. It is also relevant to notice that a shift from centralized generation to DERs transitions the electricity system to a more sustainable operation, once most DERs consist of clean energy technologies.

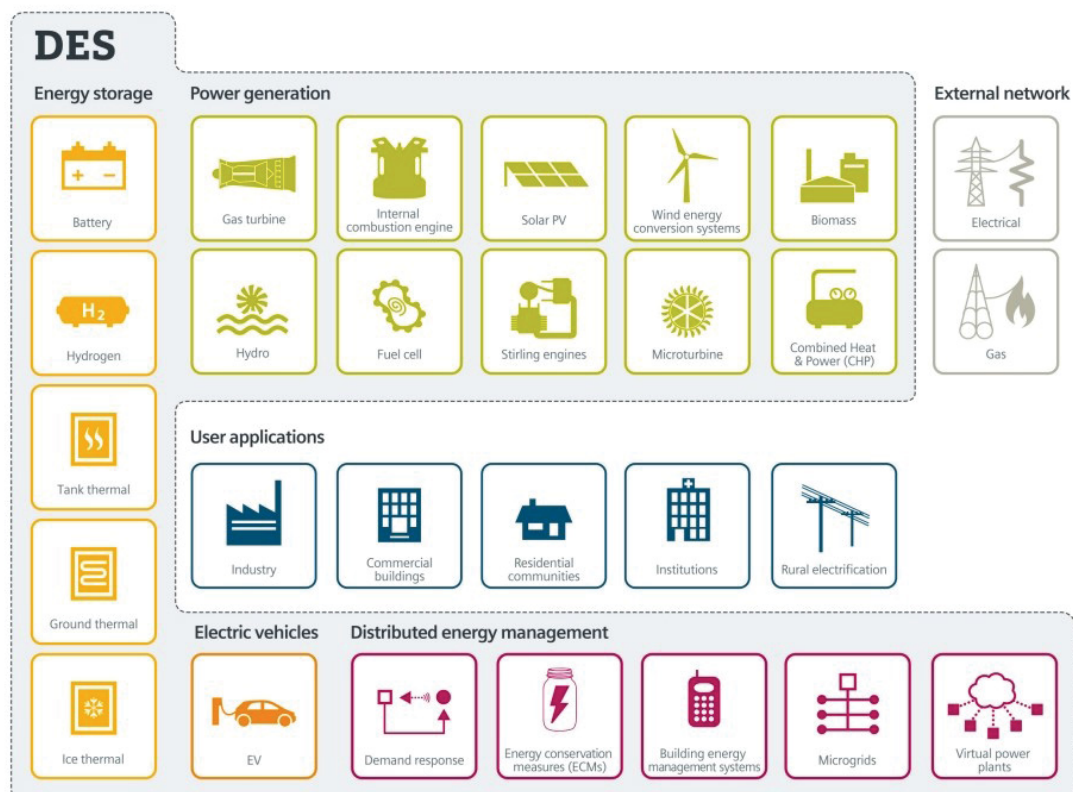


FIGURE 3 – Distributed Energy Resources overview. Source: (SIEMENS, 2016)

2.1.4.2 Advanced Metering and Energy Management Infrastructure

Although technically the concept of advanced metering infrastructure already integrates the communication technologies that enable two-way communication between utilities and customers, the author purposely categorized it apart from the ICT to include here the market-based control functions for responsive loads and other distributed resources, here called advanced metering and energy management infrastructure.

Smart meters that are fully capable of time-of-use contract types are already widely commercially available. However, in a transactive energy framework, the smart meter should also be able to act as an aggregator and engage in an automated market trade with a two-way communication of price/quantity bids (KOK; WIDERGREN, 2016).

In the Pacific Northwest Olympic Peninsula Project (AL; OLYMPIC PENINSULA PROJECT, 2007), where a field demonstration for transactive control was implemented, an advanced revenue meter was installed in every home and each responsive load was adapted to transact energy in real-time pricing mechanisms.

In the Brooklyn Microgrid, a field demonstration project in New York where a blockchain based peer-to-peer energy market was introduced (MENGELKAMP et al., 2018), TransActive Grid smart meters were implemented. To validate this new type of meter, it is mentioned that the previous analog meters were left installed. Even though no further comments are made on measurements comparison of this meter, the study identifies it as cryptographically secure, due to the use of blockchain technology.

2.1.4.3 Information and Communication Technologies

Communication is the underlying condition, based upon which all of the distributed energy market trade is built. In (KOK; WIDERGREN, 2016) it is shown that, not only communication is key in a transactive control, this control must be done in two-way and in a distributed manner (Figure 4).

Multi-agent system (MAS) technology emerges to integrate distributed communication among prosumers, where a system is implemented as a collection of autonomous software agents. Each agent is an encapsulated software that communicates with other agents, acts on its own goals, and interacts with its environment in order to achieve it. MAS theory allows an extensible form of communication operating in highly complex environments, providing an adequate paradigm for the design of distributed energy markets (KOK, 2013).

Besides approaches for inter-prosumer interaction, the communication infrastructure also deserves attention. Communication technologies and requirements that can be adopted for market-based and microgrid control are critically detailed in (JOGU-NOLA et al., 2017). It compares the characteristics and the possibilities for P2P energy

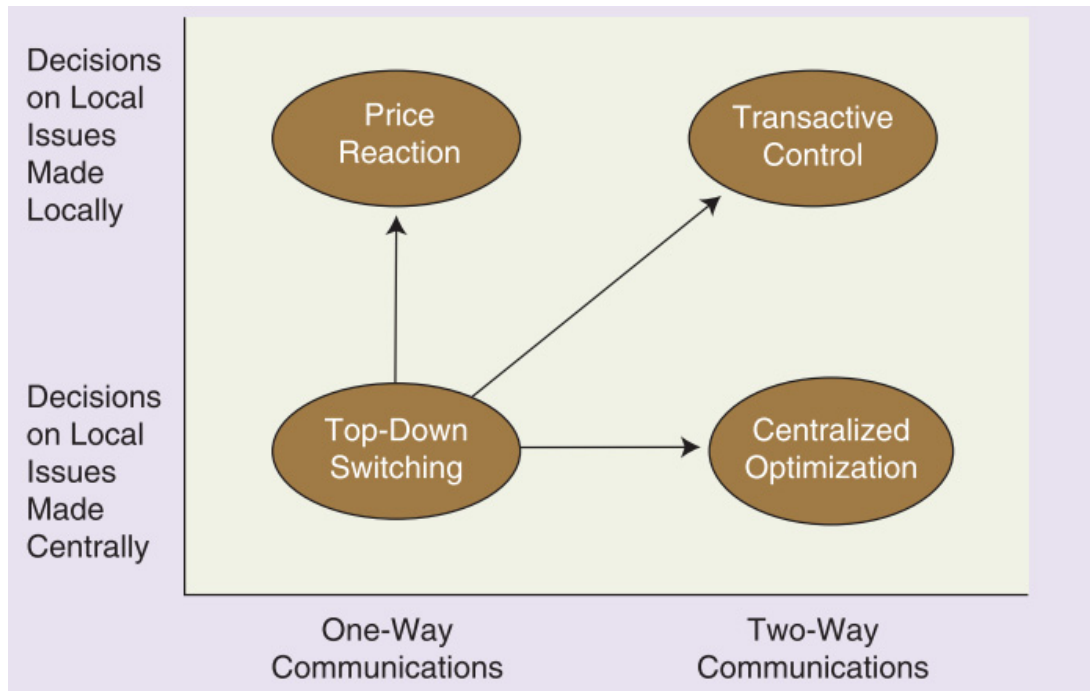


FIGURE 4 – Classification of distribution-level energy management approaches Source: (KOK; WIDERGREN, 2016)

trading of the following technologies: power line communication (PLC), optical fiber, digital subscriber line (DSL), Bluetooth, Zigbee, Wi-Fi, WiMAX, and 3G/4G.

2.1.4.4 Investment in technology roll-out

The base ground for the implementation of decentralized energy markets is the necessary information, communication, and metering infrastructure, as already presented above. A vast quantity of data is daily exchanged and produced in the operation of DERs in a market-driven framework. There are a variety of models in which this data can be managed, but in most of them, either the DSO or a grid operation-related third party is responsible. Currently, in many countries, the DSOs own the metering infrastructure. Improvements by the implementation of smart metering are seen as a key aspect to a more effective operation of the grid.

The study presented in (JOINT RESEARCH CENTER, 2019) shows the status of smart meters implementation in Europe and future planning based on a country-based cost-benefit analysis (CBA) performed in 2014. Of 20 countries, 13 countries gathered a positive outcome in their CBA, and based on these results, a wide-scale roll-out of smart meters was institutionally planned. The other countries which have had a negative result decide not to undergo massive smart meter roll-out or only selective smart meter implementation roll-out. In these countries, according to the study, "the delay of a widespread adoption of smart meters seems to be mainly connected to the lack of a clear definition of the requirements to ensure data protection and data

security".

In Brazil, there is no current regulatory requirement for the rollout of smart meters. However, the implementation of the white tariff and the establishing of technical requirements for distributed measurement systems (DMS) are important steps toward smart meter implementation (ALVES et al., 2022). This same study forecasts in a conservative scenario a level of insertion of around 50% of smart meters until 2030.

Many questions remain to be answered by these smart metering and communication infrastructure rollouts which will have a great impact on the regulatory decisions to implement decentralized energy markets and this aspect will be further on presented in the roadmap of challenges for the implementation of local energy markets (LEMs).

2.1.5 Market layouts

As detailed in (BAROCHE et al., 2019), there are three possible market layouts for decentralized energy markets (Figure 5). The nodes on the figures represent the possible market trades realized between agents.

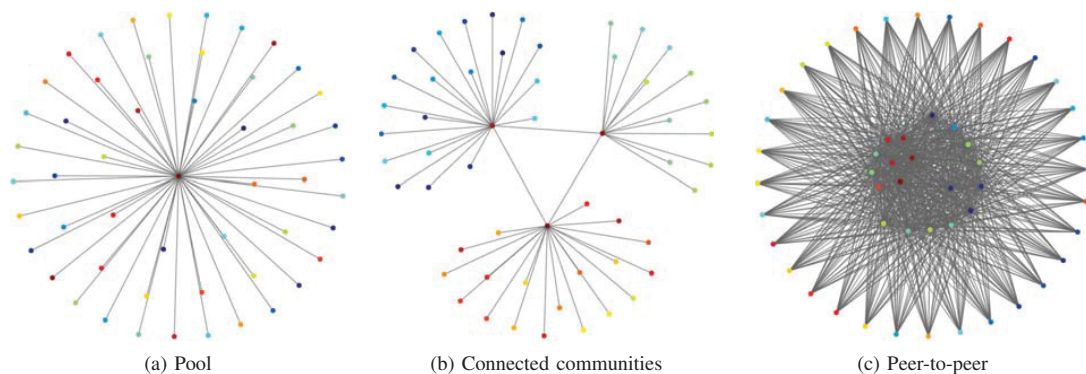


FIGURE 5 – Decentralized Market Layouts. Source: (BAROCHE et al., 2019)

In the electricity pool market layout, it resembles the physical functioning of the power system, as electrical energy is pooled as it flows from generators to loads ((KIRSCHEN; STRBAC, 2004). The pool is a mechanism where the market equilibrium is found systematically, by the hands of a central coordinator. There is no direct negotiation between agents, except with the central agent. All generators place their offers at the same time, and no one knows about others' bids and offers. The central agent runs the bids and offers through a market-clearing algorithm, which decides the bids and offers that are executed. Finally, the information about this decision is given to the system operator.

On the right side of Figure 5 there is the peer-to-peer market layout. This layout is completely based on bilateral trades, where each participant can establish trade with any other market participant. The contract made between two parties is made without

the involvement of a third party. The price of each transaction is set exclusively by the two involved participants.

As a third option, which appears as a combination of the previous two, is the aggregation of a small number of agents in communities which first pool their energy in order, and in a second step, its respective aggregators operate an interface where they communicate with each other for further energy exchanges. This aggregation can happen in an electrical and geographical manner, characterizing the formation of the grid as a collection of microgrids, or it can be made virtually, in form of virtual power plants.

In terms of scalability, with large number of participants, the pool layout can put too much strain on the central coordinator. The full peer-to-peer layout, in its turn, can strain too much the communication channels themselves. The organization in community layout has more potential for scalability due to its hierarchical form of aggregation.

2.1.6 Pricing mechanisms

In terms of electricity pools, the market-clearing algorithm will receive the consumption bids, which are ranked in decreasing price order, and the supply offers, which will be ranked in increasing price order. These price orders are also called merit order list. The systematical price for all market participants is a single price where the two curves of supply and demand meet, independent of individual price placements. This is called the system marginal price. The electricity pool can also be cast and solved as an optimization problem.

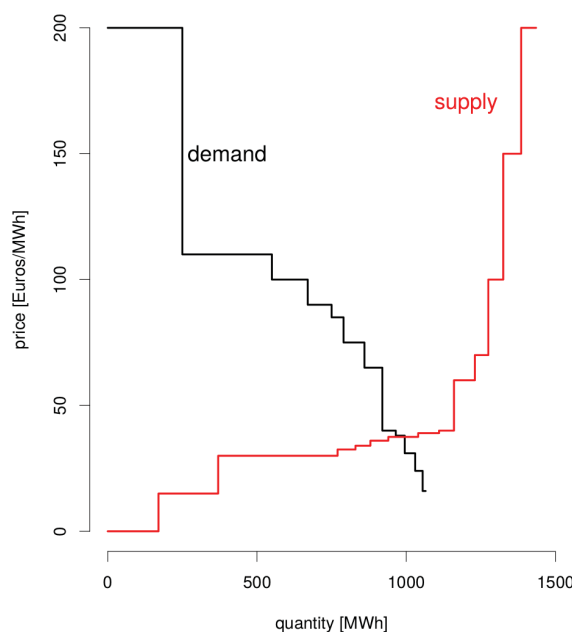


FIGURE 6 – Merit order and equilibrium for an electricity pool. Source: (PINSON, 2019)

In terms of bilateral trades, when in the case of customized long-term contracts or trading over the counter, the price can be directly established by the two parties involved, the buyer and seller. In a peer-to-peer market setting, where all participants are negotiating with one another even automatically, faster pricing algorithms are required. (TUSHAR et al., 2020) summarizes the different technical approaches that have been explored in literature in peer-to-peer pricing mechanisms. These approaches are shown in Table 1.

TABLE 1 – Different market pricing mechanisms for peer-to-peer markets. Source: adapted from (TUSHAR et al., 2020)

Mechanism	Description	Operation
Game Theory	Competition or cooperation to deliver a solution that is stable and mutually beneficial	Iterative decision-making process
Auction Theory	Interaction between a number of sellers and buyers in a step-by-step fashion	Like stock exchange. Needs a central platform
Constrained optimization	Mathematical programming where every agent solves a little piece of the puzzle	Optimizes parameters of P2P trading

Using game theory, the final price is achieved iteratively through several rounds of negotiations. In game-theoretic approaches, different types of players are trying to maximize their outcomes, mainly in a non-cooperative environment, and they bid based on the predicted strategy of their competitors. In the pricing mechanism designed by (COLLINS; MIDDLETON, 2019), the Nash equilibrium – “an equilibrium point at which no player can unilaterally reduce their costs” (p.4) – is mapped for 10 homogeneous players as the convergence of a “best response function” (p.4). In (VAKILI et al., 2018), a game is established between interconnected microgrids where they participate in a double-auction mechanism to satisfy their energy requirements and maximize their benefits. Each player provides the operator with its strategies and all scenarios are calculated to reach a stable outcome between the microgrids’ interactions, where the Nash equilibrium is reached. Cooperative game-theoretic approaches are also a possibility, as shown in the method developed by (TUSHAR et al., 2018). The social cooperation between prosumers in this study is achieved by behavioral models from motivational psychology, ensuring that the prosumers always find it beneficial to participate.

The double auction approach permits several buyers and sellers to interact to trade their goods. The potential buyers submit their bids and the potential sellers submit their offers to the auctioneer. The auctioneer is also seen as central management that can be an electronic platform. When, by order of arrival, a buyer’s price and a seller’s asking price match, a trade proceeds at the determined price, normally the bid

price (known as pay-as-bid schemes). It is shown in (GUERRERO et al., 2018) that trades within continuous double auctions, where bidders have rational goals, are always Pareto-improving. This guarantees that the outcome will be a Pareto-efficient allocation of resources.

TABLE 2 – Summary of surveyed optimization methods

Optimization solver	Objective function	References
Mixed-integer linear programming (MILP)	Minimize cost of energy for a time interval	(AKTER et al., 2018)
	Economic dispatch of thermal units considering the input from microgrid generation	(RENANI et al., 2018)
	Maximize social surplus	(FAQIRY; DAS, 2019)
Particle Swarm Optimization	Minimize cost function through balance of purchased and sold energy to the transaction market	(CHEN; HU, 2018)
Heuristic iterative method	Minimize current and future costs and grid losses	(DIVSHALI et al., 2017)
Forward-backward sweep	Minimize grid congestion	(FULLER et al., 2011)
Subgradient Methods	Minimize electric vehicles charging cost	(HU et al., 2017)
Predictor corrector proximal multiplier	Optimal power flow	(KIM et al., 2017)
Artificial Bee Colony	Minimize the forecasted power imbalance on microgrid	(NUNNA; SRINIVASAN, 2017)

Finally, in constrained optimization schemes, the idea of trading energy involves optimizing cost, being it “generation cost, transport cost, energy demand or profit maximization” (JOGUNOLA et al., 2017) (p.14). The problem generally takes the form of a multi-objective optimal power flow, one that may consider grid constraints along with the traded energy amounts. Many techniques have been applied to solve this optimization task, including methods based on game theory. Some other studies that present different optimization methods are presented in Table 2.

2.1.7 Trading periods

Electricity markets can be established in different periods for different purposes. Figure 7 illustrates these trading periods. Considering the date of delivery of the traded electricity, there are the forward or futures markets, which configure the trading period before or up to 48h of the date of delivery. These serve the purpose of price hedging

and risk management, and normally are long-term financial contracts. The day-ahead or spot market is characterized by the time up to around 24h to the moment of delivery and is the central instrument for everyday matching of electricity supply and demand. Intra-day markets are also spot markets, working to correct original schedules which are needed due to forecast uncertainties or contingencies. Finally, after gate closure for operation, which is in "real time", begins the market at post-operation or settlement process, where the executed net deliveries are verified with the previously established contracts and the imbalances are negotiated at spot market price.

Foward Markets	Spot Markets	Spot Markets	Settlement Process
	24h	1h	
	Day-ahead	Intra-day	

Time of Delivery →

FIGURE 7 – Trading periods as they approach time of delivery.

The study of decentralized energy markets has concentrated mostly so far in spot markets. Since most of the appeal of peer-to-peer energy has been the advantages of real-time dynamic pricing, spot markets within a time window from 5 to 15 minutes have been proposed and studied (FULLER et al., 2011) (HAO et al., 2017).

Day-ahead markets can also be implemented, being an important mechanism for coordinating small-scale and large-scale energy production. Also, it can work as risk mitigation for spot prices. DERs aggregated in a local distribution area participate in a day-ahead market which, through the DSO agent, exchanges energy with the transmission network in the wholesale power market in the study (RENANI et al., 2018).

Hierarchical optimization approaches also combine different time frames for the energy exchange. The study performed in 2010 (VYTELINGUM et al., 2010) had already envisioned and developed an online balancing mechanism following a day-ahead trading scheme. A similar concept was also presented in (ESFAHANI et al., 2019), an optimization approach that combines hierarchically a day-ahead market, an hour-ahead market, and a real-time market for multi-microgrid systems operation. This type of approach considers that a mismatch from the day-ahead procured energy can be corrected by bidding in the hour-ahead market and so on, ensuring the energy balance in a competitive environment for resource allocation.

2.1.8 Bidding strategies

In the scenario where every energy customer is actively participating on the energy market, each agent's decision has an impact in the market prices. Therefore, the bidding each agent submits to the market must be strategic assuming that each player is trying to maximize their welfare. Moreover, in order not to cause market distortions, bids must be regulated by the energy trading mechanism.

Depending on the designed market framework, bidding strategies will take on different forms. In a double auction mechanism, assuming that the desired goal is cost optimization and that the market takes the form of an economic dispatch problem, the supply bids can be done according to the marginal costs of operation. On the other hand, demand bids can be based on expected future prices, which in turn depend on the history of price dynamics. The resulting market clearing price will be a balance of all supply and demand bids.

In the study (KOK, 2013), a guideline for formulating an agent bidding strategy is suggested based on the placement of an agent on a bid strategy spectrum (Figure 8). In one extreme, the agent bids fully based on its marginal cost. This would apply as a good strategy for renewable power, for example, due to their very low marginal costs will generate electricity at almost any given price. On the other extreme, agents are dependent on price history and market dynamics. Storage would be an example of such an agent since it profits in the market through arbitrage: selling energy at high prices (concerning historical prices) and buying energy at low prices.

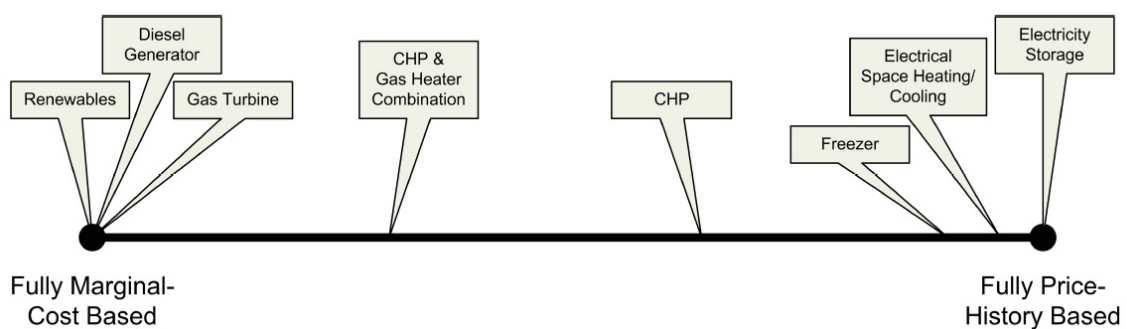


FIGURE 8 – Strategy spectrum of bidding. Source: (KOK, 2013)

Notwithstanding, (LIU et al., 2018) argue that operating costs of renewable generation are often neglected and propose that the generation uncertainties must be considered in the marginal cost model. This study also states that it is difficult to optimize energy storage bidding strategy, considering the action of charging and discharging to maximize profits must be made with uncertainty in the electricity price of the next

period. To solve this challenge, the paper proposes a new price function based on the state-of-charge and spot price.

2.2 PEER-TO-PEER ENERGY MARKETS IMPACT ON DISTRIBUTION SYSTEMS

2.2.1 Main technical challenges

To understand the main technical challenges to implementing P2P energy trading, it is necessary to classify the grid structure in terms of decentralized management and market-based operation principles. (TUSHAR et al., 2020) proposes a classification of P2P operating framework challenges in terms of the physical layer and virtual layer (Figure 9).

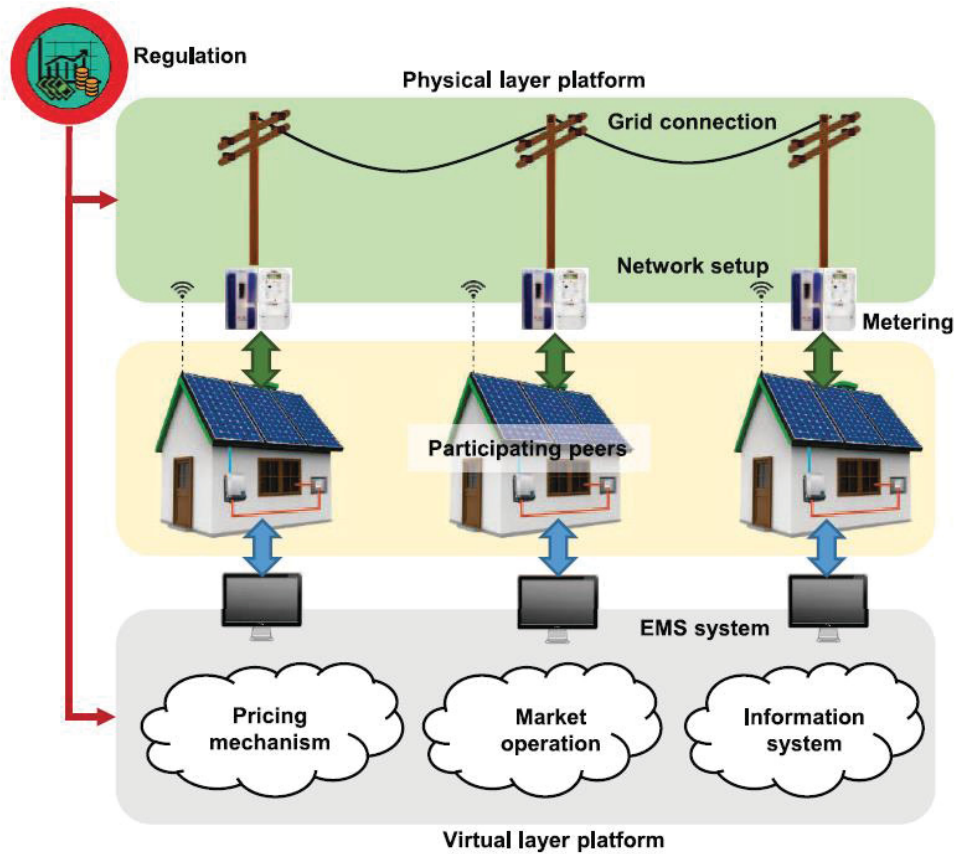


FIGURE 9 – Layer platforms of a P2P energy framework. Source: (TUSHAR et al., 2020)

The physical layer is composed of the electricity infrastructure and the connection of the participants to this grid; the metering infrastructure and the communication infrastructure. The virtual layer is comprised of the information system; the designed market and its respective pricing mechanisms, including taxes and surcharges; and finally the energy management system from the prosumer, which should ensure the energy supply.

Table 3 summarizes the main technical challenges detailed in the study (TUSHAR et al., 2020). In the challenges from the virtual layer, the first approach is reducing the

cost for prosumers. Indeed, making electricity less expensive is one of the main motivations for the adoption of local electricity markets by prosumers. This connects with the challenge of engaging and incentivizing prosumers, including prosumers who do not invest in distributed generation, but are willing to offer flexibility in modulating their consumption. Significant work has been done to explore the cost optimization and empowerment for P2P market participants in previous studies (KÜSTER et al., 2019).

The P2P energy framework must also be able to balance local generation and demand if possible intrinsically by market design. The whole point of market-based operation is not only to guarantee economic efficiency but also reliability in energy supply.

The challenge of developing pricing mechanisms connects directly to the design requirement of true cost reflectiveness explored in Section 2.1.3. The study in (TUSHAR et al., 2020) mentions the importance of cost allocation in the engaging of prosumers, it fails to mention that this must be true for all stakeholders, including the utility. The adoption of P2P energy markets by utilities will be deeply linked to the successful development of pricing mechanisms, as we will further explore in the model elaborated in this dissertation.

TABLE 3 – Main technical challenges for P2P energy framework. Source: summarized from (TUSHAR et al., 2020)

Challenges in the virtual layer	Challenges in the physical layer
Reducing cost of energy	Violation of capacity and voltage constraints
Balancing Local Generation and Demand	Network Power Loss
Incentivizing and Engaging Prosumers	Loss of system strength
Developing Pricing Mechanism	
Computational Issues	
Securing Transactions	

The challenge in dealing with computational issues also connects to the market requirement of presenting low overhead. This will directly reflect the capacity of the information and processing systems to deal with communication failures and delays. Attention must be given to both developing market frameworks that do not add to communication complexity issues and to developing robust information and communication networks.

Finally securing transactions as a challenge in the virtual layer refers to transferring what happens in the market to the physical operation of the grid, which links directly to the P2P energy main challenges in the physical layer.

TABLE 4 – Research trends on P2P energy

Research trends	Publications
Focus on market mechanism development	See references published in (KÜSTER et al., 2019).
Effort to map and classify all the different mechanisms	(KÜSTER et al., 2019), (TUSHAR et al., 2020), (GUERRERO et al., 2020)
Attention to the study of impacts of the mechanisms in the physical network operation and infrastructure	(HAYES et al., 2020), (GUERRERO et al., 2020), (AZIM et al., 2019), (AZIM et al., 2020), (JENKINS; KOCKAR, 2020), (MORET et al., 2021)
Mechanisms development with special focus on loss allocation and transmission rights	(PAUDEL et al., 2020), (VILLIERS; CUFFE, 2020), (NIKOLAIDIS et al., 2019), (MORSTYN et al., 2020b), (MORET et al., 2021)

From the side of the physical layer, the main challenges regarding how the P2P market will impact the reliable operation of the grid, and studies have been aiming at trying to quantify impacts on capacity, and voltage constraints, network power losses and loss of system strength. These impacts have already been extensively analyzed in literature for high DER penetration under different regulatory frameworks, such as net-metering or self-consumption schemes, or in proposals for optimal operation of DERs that are not market-driven (PASSEY et al., 2011)(WECKESSER et al., 2021)(CIOCIA et al., 2021).

However, studies on the particularities of P2P energy on the physical layer are only a recent trend. The next section of this document is dedicated to better understanding the state of research on the impacts of decentralized energy markets on the distribution systems.

2.2.2 Impacts of P2P energy in grid operation

From the publications and studies analyzed so far, some research trends and knowledge paths were recognized, which are described below and summarized in Table 4 .

In an initial approach to the literature, lots of proposals for market design, structures, and mechanisms showed up, addressing the main motivations for the future of electrical power systems. Different approaches and techniques were sought to develop decentralized energy markets.

A second pathway is identified, comprising the efforts to map, classify and define categories for the different approaches. Aside from the author's own effort (KÜSTER et al., 2019), other publications also undertook this task, as seen in (TUSHAR et al., 2020) and (GUERRERO et al., 2020).

The newest trends for research direction in this topic lie within the objectives of this Ph.D. study, which is to investigate and evaluate the impacts of the market-based operation and decentralized energy markets, or to develop mechanisms with a special focus on grid constraints, such as transmission rights and loss allocation. This is very well marked considering that among the most cited works within the most recent are papers on this subject, such as (BAROCHE et al., 2019), (HAYES et al., 2020), (NIKOLAIDIS et al., 2019), (AZIM et al., 2019) among others. These studies will be better detailed in the next subsection.

2.2.2.1 Study of market's mechanisms impacts on the grid

For P2P energy trading to gain acceptance on a larger scale, it will be necessary for utilities to model its impacts on the distribution networks. In (HAYES et al., 2020), a co-simulation methodology is presented to evaluate these impacts. The approach is based on coupling the blockchain market layer simulation with the time series simulation of a modeled unbalanced 3-phase LV network. The software choice for the power flow studies was OpenDSS, which interacts with the energy trading software through Python code. The results are then processed and analyzed within MatLab.

The study (GUERRERO et al., 2020), besides providing a literature review, also researches the impacts of different DER integration approaches on the distribution grid. Not only the P2P market is tested, but also an uncoordinated approach (home energy management systems) and coordinated approaches (optimal power flow and virtual power plant). The approaches are compared regarding voltage levels, transformer capacity, and energy exported, among others. It concludes that a high penetration of DER needs a coordination approach, and it shows the challenges and drawbacks of each coordination method.

The paper (AZIM et al., 2019) highlights the possible network issues associated with the P2P energy trading market by addressing the same market mechanism with and without network constraints and then comparing both. Even though P2P trading brings economic benefits to both buyers and sellers, the study finds that voltage levels are violated and power losses are burdened onto the utility without proper financial return.

In (AZIM et al., 2020), a similar comparison is done, this time addressing the same grid operation with and without P2P trade. They aim to answer what is the repercussion of P2P trading on the power losses in grid-connected electricity networks? Through the simulation of an LV test feeder, the study concludes that the power dispatch through P2P transactions changes the loss outline on the grid at some moments of the day, but the 24h-long period remains similar to the dispatch without any P2P trading.

Regulation can also play a role in the P2P market impacts on the distribution system, as analyzed by (MORET et al., 2021) and (JENKINS; KOCKAR, 2020). In the latter, a regulatory particularity of the UK power systems is explored, where distributed generation classical access rights compete with P2P markets for power injection. This particular operation causes a curtailment of distributed generation assets, as is studied in the presented article. In (MORET et al., 2021), a comparison study on different loss allocation policies including agents both in transmission and distribution level is performed. Special attention is given to the fact that different methods have different impacts on customers according to their geographical location, and proper policies are needed to guarantee fairness and cost-reflectiveness among market participants.

2.2.2.2 Development of mechanisms for loss allocation and transmission rights

Market mechanisms should be designed in such a way that the agents' interests should not conflict with system objectives, and it should be fair to all agents, including prosumers, traditional consumers without DG and the network operator. Only recently the proper framework for the P2P energy trading, which considers the network usage during P2P energy transactions has received relevant research attention.

The electrical distance can be a potential approach to calculating the network fees for the P2P energy trade. The network fees are proportional to the electrical distance between producers and consumers. In this approach, longer-distance transactions become more expensive because of higher network fees, so consumers are encouraged to trade with producers at a shorter electrical distance. In (PAUDEL et al., 2020) the network owner provides the charging rate for network utilization in advance before the P2P negotiation starts. Similarly, (VILLIERS; CUFFE, 2020) proposes a P2P tokenized energy trading with an electrical distance-based tax, using the calculation of Klein resistance as a method of evaluating the electrical distance between parties. In both studies, as well as in (BAROCHE et al., 2019), it is highlighted that the network fees, if too tough, can discourage P2P trading participation.

It is also important to highlight the radial and unbalanced nature of the 3-phase LV distribution network. The study published in (NIKOLAIDIS et al., 2019) tackles this problem by proposing a graph-based following of the transaction's paths.

In another approach, P2P energy trading is integrated into probabilistic distribu-

tion locational marginal pricing (MORSTYN et al., 2020b). This paper considers a DSO that is responsible for setting locational import and export prices, based on day-ahead three-phase probabilistic dispatch, and P2P transaction fees. Local P2P energy trading platforms allow prosumers to negotiate bilateral energy transactions.

2.3 FEASIBILITY OF PEER-TO-PEER ENERGY MODELS FOR THE INVOLVED STAKEHOLDERS

2.3.1 Feasibility for the prosumer

So far the foundation and motivation for research of P2P energy trading have been the feasibility for prosumers to actively engage in local markets which by design directly benefits its participants while ensuring a balanced supply and demand coordination. Many studies that focus on market mechanisms development have the increased economic welfare for the prosumers as a prerequisite for market modeling (PENA-BELLO et al., 2022).

Considering P2P energy as not the only but one of the possible regulation frameworks to increase penetration of DERs, up-to-date research has also been dedicated to evaluating the rise of prosumers in different business models. For example, (BOTELHO et al., 2021) study the enablers and barriers to increased participation of small consumers in power systems. The main barriers explored in this work are a lack of regulations to better define prosumers' rights and obligations, technology-related issues such as the mass roll-out of infrastructure for real-time data and privacy concerns, high upfront investment price of the necessary equipment for energy generation, and finally a lack of information and awareness of the meaning of being a prosumer.

This last barrier is more deeply explained in (PRESSMAIR et al., 2021) as the feelings of the end-users towards new technologies and what they mean in their daily lifestyle and decision-making. This study goes ahead in quantifying these barriers for local energy markets and local flexibility markets adoption, with a focus on the prosumer.

Going back to (BOTELHO et al., 2021), the authors also argue that the feed-in-tariffs, self-consumption, and net-metering frameworks were important to initially enable the growth of the domestic PV prosumer. Now that the technology is well established, countries are beginning to move away from subsidies. A potential substitute business model is the market-driven mechanisms (also presented by (RÖVEKAMP et al., 2021)). Besides the economic benefits, the author cites other enablers in the prosumer feasibility assessment: reduced environmental impacts (in comparison to centralized fossil-based generation), self-empowerment and energy autonomy, and prosumer-friendly regulation.

2.3.2 Feasibility for utility and retailers

Once it is clarified that peer-to-peer markets are beneficial to prosumers, another part of the path to adoption of such markets is the technical and economical feasibility of the utility.

From the technical feasibility stand, Section 2.2 already shows some of the relevant research on the impacts of decentralized energy markets in grid infrastructure. Further on, (DUDJAK et al., 2021) and (DYNGE et al., 2021) also provide in-depth reviews of research to understand this impact, including impacts on control, operation, and planning of power systems. Besides classifying the most common benefits and issues of local energy markets on power systems, (DUDJAK et al., 2021) also categorizes different methods to include physical constraints in market models and different methods to allocate network tariffs and power losses. From the conclusions of this study, it is important to mention that to counter the negative impacts on the grid, the DSO must be actively involved in the market mechanism developed, once variations in market design influence what kind of impacts are perceived.

Regarding the quantification of revenue impact for the utility, (ZINAMAN, 2020) offers a guide for quantification of utility revenue impacts for the case of distributed PV deployment. It is a useful guide, but it primarily focuses on current regulation frameworks such as self-consumption and feed-in tariffs. It does not mention DER deployment in market-driven regulation schemes.

Regarding the economic feasibility of utility, (ASKELAND et al., 2021) developed recently a study on DSO income effects and feedback effects of grid tariffs on grid development in the presence of local energy markets. They vary grid tariffs with the objective function of minimizing and recovering costs with the income of the DSO. It concludes that the local energy markets defer some investment in infrastructure, although a too big of a tariff increase can motivate the neighborhood to disconnect from the grid altogether.

(TUSHAR et al., 2021a) establishes original work by analyzing the role of retailers in decentralized trading. It discusses the feasibility of retailers' involvement in peer-to-peer energy markets. It proposes a form of inclusion of the retailers into the market, as a way of enabling the feasibility for retailers in such a regulatory framework.

2.4 KNOWLEDGE GAP

From the analysis of the up-to-date literature, it is possible to see that the market-driven operation of DERs is more beneficial for the prosumer in terms of economic welfare in comparison to current regulation schemes.

On the other side, feasibility and revenue impacts for the utility are already well

known for current regulation scenarios. The study of market-driven feasibility for the utility has started recently and has taken important steps, however, quantification of revenue impacts in comparison to current scenarios is still unclear.

Some examples of studies that were analyzed which leave open gaps:

- (PRESSMAIR et al., 2021) overcomes barriers for prosumers, but leaves explicitly open the questions on the cost allocation of DSOs for further investigation.
- (RÖVEKAMP et al., 2021) brings market-driven models as post-feed-in-tariff solutions and analyses these models from a renewable energy source owner's perspective. The study does not address the impacts on other stakeholders in the power system and states the need for quantifying economic potential and impacts not only from renewable generation owners' perspective but also from "new actors" providing energy services.
- The inclusion of grid and transaction fees are studied in (HEO et al., 2021), including grid and transaction fees, named "network usage charges" and "platform service charges". This study quantifies the impacts of these charges on the buyers and sellers, but not specifically on the utility.
- (ASKELAND et al., 2021) is very correlated to this study in the variety of scenarios and DER deployment profiles, however, it focuses on the effects of varying grid tariffs in the presence of local energy markets. Since it focuses on comparing DSO costs, from this point of view it concludes that the highest value of implementing local energy markets is on investment deferral of infrastructure.
- (TUSHAR et al., 2021a) establishes a model where the retailers are a direct part of the negotiation, to better comprehend and enable feasibility for this stakeholder in decentralized energy markets. However, the quantification offered in the study is a small example case, which opens the potential for more research in this area.

In summary, a broader analysis on the overall impacts considering all stakeholders, with a special focus on the utility, is the gap this study intends to explore. An overall view of the role of utility in the presence of decentralized market regulation and how this compares to the DER deployment in other regulation scenarios with regards to a holistic view of revenue and grid operation impacts, is still uncertain. This is the contribution this current study aims at making, having in mind the furthest goal of contributing to clarifying the path towards the adoption of peer-to-peer local energy markets as solutions for some of the challenges of the power systems.

3 METHODOLOGY

3.1 RESEARCH STRATEGY

The strategy to answer the research questions is outlined in this section, with an overview and explanation of the specific steps to achieve the answers that are sought. In order to provide a comprehensive evaluation of P2P energy markets, the current research relies on the approach described in the sequence.

First, an evaluation framework is developed by listing a set of potential barriers and opportunities for utilities which were identified during the literature review presented in the previous chapter. To evaluate if these P2P market's potential barriers and opportunities (fully detailed in the Section 3.2) apply to utilities, a quantification method is needed. With that purpose, a specific set of criteria is assigned to quantify each potential barrier and opportunity.

The established evaluation criteria comprehend both economical aspects of revenue generation by the market and technical aspects of its impacts on grid operation. All criteria can be calculated and quantified through the modelling and analysis of a P2P market operating on a distribution network. The construction of this model is the following step of this research. A co-simulation platform is built, which is able to couple the model of a designed P2P market to the actual power flows across a low-voltage distribution network (detailed in Section 3.3).

After the simulation model overview description, the rest of this chapter is dedicated to describe the features, particularities and limitations of both market and grid models.

3.2 ANALYSIS AND EVALUATION FRAMEWORK

Central to the research in this thesis is the understanding and quantification of local P2P energy markets on utilities. Hence, the main research question can also be formulated as:

Is there a scenario where P2P Local energy markets bring a “win-win” situation for both prosumers and utility concerning current regulation frameworks?

Starting from the finding that P2P local energy market benefits are well known for the prosumers, the focus of this study is on the utility's point of view. Based on the literature review and state-of-the-art analysis, a schematic representation of a map to explore the P2P local energy markets' possible challenges and advantages for the utility is outlined in Figure 10.

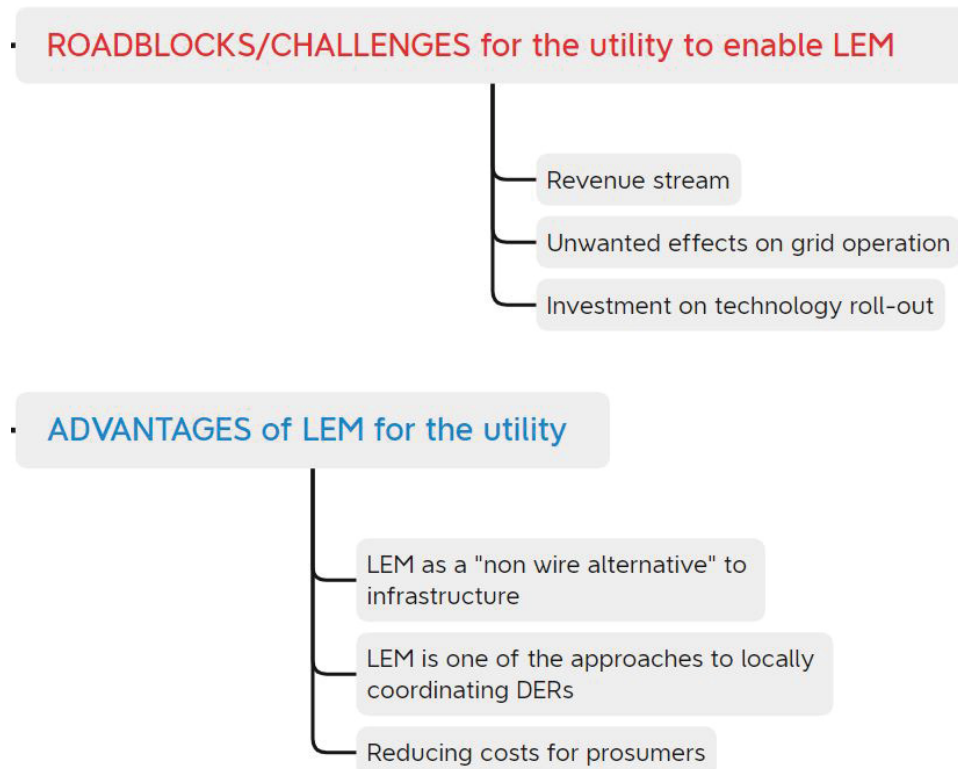


FIGURE 10 – Schematic representation of P2P adoption barriers and advantages for the utility

Three main barriers to the adoption of P2P energy markets by the utilities are established. First is the revenue stream. It can be easily concluded that local energy markets negatively impact revenue streams, but a better quantification is still unclear. Second is the unwanted effects in grid operation, or how the grid performance will be affected by the DERs operating in markets as opposed to their business-as-usual operation mode in the current regulatory framework. The third is the amount of investment in ICT infrastructure needed to cover and implement P2P local energy markets, such as the mass roll-out of smart meters among others. From the advantages that local energy markets could bring to the utility, we establish mainly three. First is local energy markets as a “non-wire alternative” to improving electricity infrastructure. If local energy markets could positively impact network usage, this could lead to investment deferral in grid reinforcements. Second, local energy markets could be a promising approach to locally coordinating and operating DERs connected to the grid, which could bring benefits in avoiding interruptions and improving interruption indexes. Third, bringing benefits for the prosumers is also valued by the utility as a way of discouraging these prosumers from defecting the grid.

Based on these mapped opportunities and obstacles for the adoption of P2P local energy markets by the utilities, the research of this thesis was structured into an analysis and evaluation framework, which was designed to quantify each of the roadmap elements with a set of specific criteria. This analysis and evaluation framework is shown

in Tables 5 and 6.

The "Investment in technology rollout" barrier present on the roadmap was not added to the evaluation framework of this study. The evaluation of this barrier is out of the current study's scope which is more focused on analyzing the challenges and opportunities of network operation. Nonetheless, it is an important part of grid planning within the framework of P2P energy markets, which have been briefly discussed in Subsection 2.1.4.4. Its proper quantification is suggested for future work.

TABLE 5 – Analysis Framework with Evaluated Criteria - P2P adoption roadblocks

RoadBlocks	Analysis	Criteria
Revenue Streams	Revenue Stream Performance Comparison	Revenues from the utility X revenues from the prosumers in all scenarios
		Sensitivity to number of agents
		Sensitivity to network (grid and transaction) fees
		Sensitivity to PV / storage penetration
Unwanted Effects in Grid Operation	Grid Performance Comparison	Voltage profile
		Transformer load factor
		Circuit losses
		Sensitivity to PV / storage penetration

TABLE 6 – Analysis Framework with Evaluated Criteria - P2P adoption advantages

Advantages of LEM for the utility	Analysis	Criteria
LEM as a non-wire alternative	Qualitative analysis of investment deferral - comparison between net-metering x P2P	Sensitivity to PV and Storage Penetration
LEM as one of the approaches to locally coordinating DERs	Qualitative analysis of alleviating curtailment	Operation of microgrid in islanded mode - comparison of shedded load net metering x P2P
Reducing costs for prosumers	Revenue Stream Performance Comparison	Revenues from the utility X Revenues from the Prosumers in all scenarios
		Proportion of prosumers who are better / worse off
		Transaction Prices
		Sensitivity to number of agents
		Sensitivity to network fees

3.3 SIMULATION MODEL OVERVIEW

To execute the analyses and evaluation shown in the previous section, a simulation framework was developed. This simulation framework consists of an energy trading algorithm connected to a power flow calculation model.

The energy trading model consists of a double-sided-pay as bid auction scheme which is implemented in the MatLab environment. The power flow calculation is carried out as three-phase time-series using the OpenDSS distribution network simulator. Open Distribution System Simulator (OpenDSS) (EPRI, 2021) is an open-source, comprehensive electrical system simulation tool for electric utility distribution systems. It is capable of modeling three-phase networks in LV e MV in detail. Many of the features found in the program were originally intended to support distributed generation analysis needs. It can also interact with MatLab via an in-built Component Object Model (COM) interface.

The implemented framework works as a co-simulation approach (Figure 11). In the first step, a market simulation is run in the energy trading model for the desired time interval. The input data for this market simulation are load profiles, PV generation profiles, storage limits and dimensions, size of market time steps, users' trading strategies, and utilities tariffs and fees. The results from this energy trading simulation in form of traded amounts of energy for each connected participant are fed as input data for the OpenDSS simulation via the COM interface inside MatLab. The OpenDSS also receives the network model data as input. The results of the time-series power flow calculation are returned to MatLab for post-processing.

A similar co-simulation approach can be seen in (HAYES et al., 2020).

3.4 PEER-TO-PEER MARKET MECHANISM

The implemented peer-to-peer energy market consists of a continuous two-sided pay-as-bid auction mechanism, which was based on the Grid Singularity Exchange's technical approach (GRID SINGULARITY, 2021).

3.4.1 Market Timing

The desired electricity market exchange must balance the grid in terms of demand and supply, efficiently accounting for the physical energy production and consumption. To achieve that, the selected market mechanism for this study is a spot market, where short-term trades are made for immediate delivery or near-term delivery. The energy amounts are divided within 15-minute time slots, within which transactions can take place. Here is important to define the concepts of market slots and market ticks.

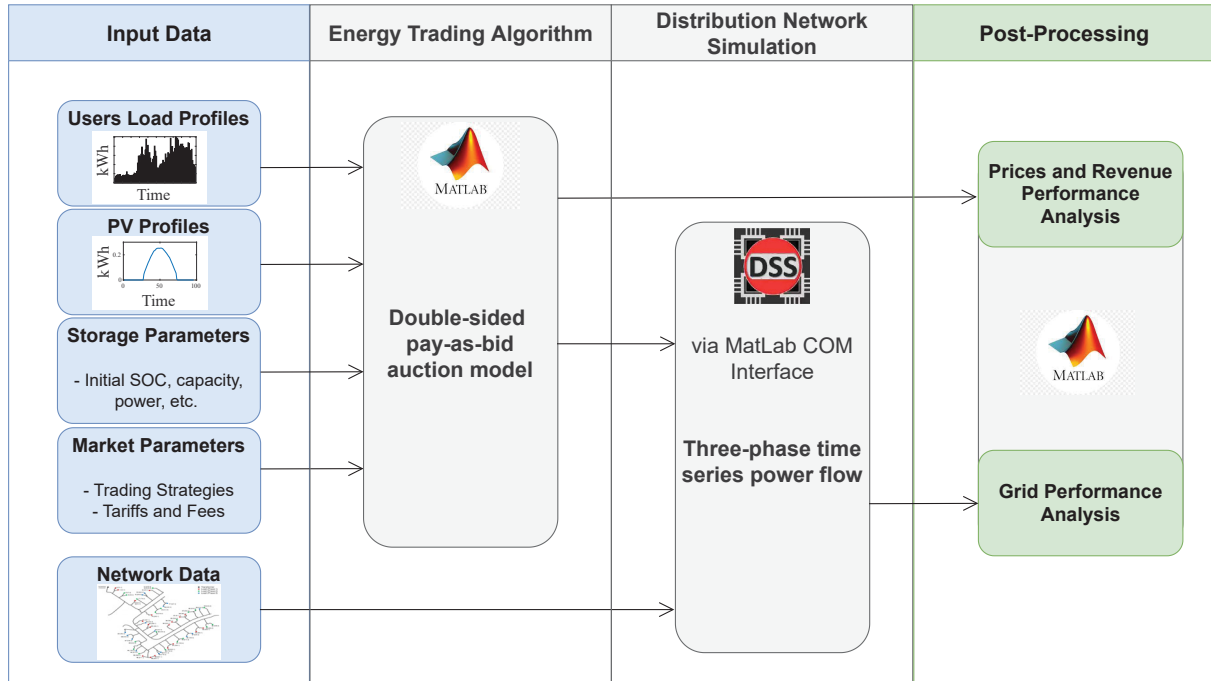


FIGURE 11 – Simulation Model Overview

Market slots are blocks of time where the participants have defined quantities of energy to trade. For the chosen 15-minute time slot size, in a one-day simulation, there will be 96 market slots.

Each slot is further divided into market ticks. For the chosen tick of 15 seconds, each market slot is made up of 60 ticks. Each market tick is an opportunity for the participants to place or renew their bids and offers. We will further see that, for the chosen mechanism, the market is cleared at the end of each tick.

3.4.2 Two-sided pay-as-bid auction mechanism

In the Two-Sided Pay-as-Bid market, buyers can place bids in the market, alongside the offers placed by sellers. The market matches bids and offers issued by the trading agents. The auction is continuous, so the market will trigger a clearing right away if a bid is matched to an offer in the current tick. The clearing price is the bid price. If the bid/offer is not matched, or if some of the bid/offered energy amounts remain available, a new bid/offer must be made at the next market tick, as seen in the example in Figure 12. In case there are remaining energy amounts left unmatched after the last tick at the end of the market slot, it will be annulled. That means, for example, that any unmatched amount of PV generation will be curtailed, or an unmatched amount of load will be shed. Or it can mean, in practice, that any amount of energy which was not traded at the market level will be absorbed by the main grid and valued at the utilities tariffs.

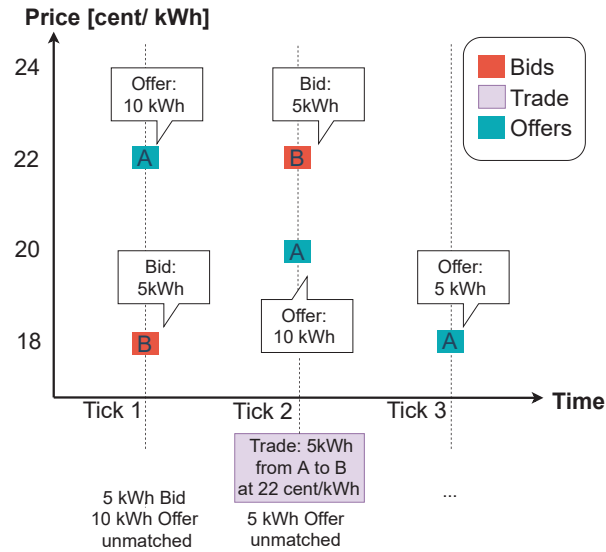


FIGURE 12 – Example of a Two-Sided Pay-as-Bid Market Clearing within a Market Slot

3.4.3 Bidding/ Offering strategy

The implemented bidding/offering strategies for this study are linear and deterministic. Each agent or asset will first try to buy at a low price, and if not cleared, the price will increase linearly during the market slot until the maximum is achieved. On the other hand, producing assets will try to offer at a high price, and if not cleared, will reduce their offer rate until a minimum is achieved.

For the bids, the following setting must be given by the bidding agents: initial buying rate and final buying rate. Then, a rate increase is calculated to linearly adjust the buying rate at each market tick, setting the limits of initial and final rates to the first and last market ticks, respectively (Figure 13).

Similarly, the offering agents will provide their settings from the initial and final selling rate. From these values, a rate decrease is calculated to fit the time limit of the market slot (Figure 14).

In this scheme, the utility itself acts as a price maker negotiating agent, keeping the bidding and offering prices constant during the whole market slot (Figure 15).

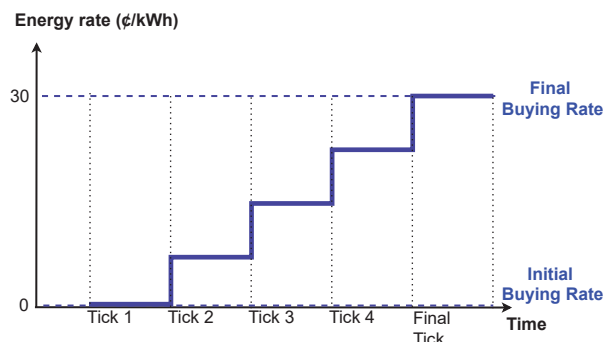


FIGURE 13 – Example of bidding strategy from a consumer asset in a market slot

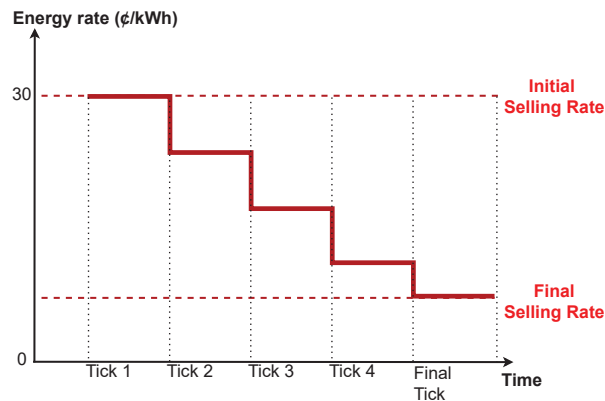


FIGURE 14 – Example of offering strategy from a generation asset within a market slot

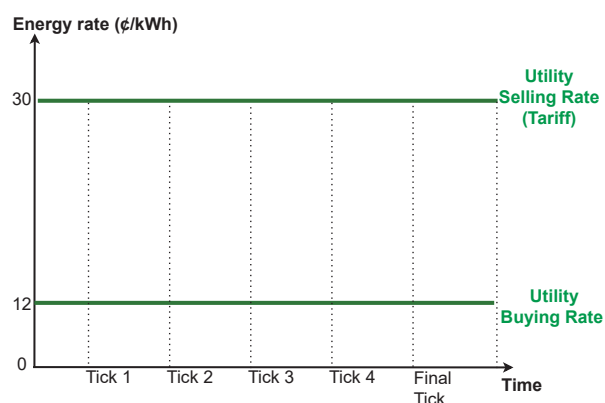


FIGURE 15 – The utility enters the market as a price maker / inelastic demand and supply

3.4.4 Trading Process

Once the market slot opens, the bids and offers are put in each tick for the negotiation and bilateral trades start to happen when there is a match. When more than one match is possible for the same bids or offers, then the market engine must prioritize the most local trades. To process this prioritized matching of bids and offers, a market hierarchy in three levels is developed. The first level is the negotiation between assets of the same household. The second level is the negotiation between households within the same low voltage network. The third level is the negotiation between the households and the grid. Figure 16 depicts this hierarchy setup. Practically, this hierarchy effect is accomplished by delaying the matching possibilities of sequential levels by two market ticks. If multiple matches per buyer or seller happen inside the same trading level at the same tick, then an allocation procedure takes place for equal distribution of the matched bids/offers into a series of bilateral trades. This allocation procedure is based on the equal rights of multiple buyers to acquire energy from a seller at the same price, leveling the quantities at the lowest bid amount. In the same way, multiple sellers have an equal right to sell to a certain buyer at the offered price, leveling the divided quantities at the lowest offered amount. An example of the allocation procedure is given in Table 7.

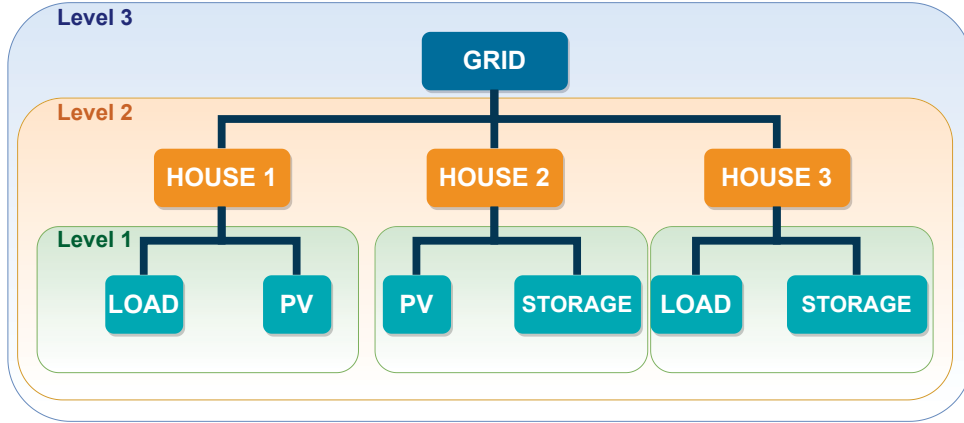


FIGURE 16 – The hierarchical market structure

TABLE 7 – Example of allocation for a match with multiple buyers and sellers within a market tick.

Case 1 - Equal Supply and Demand					Case 2 - Excess Demand					Case 3 - Excess Supply				
				Bids					Bids					Bids
				A	B					A	B			
				9	15					12	15			
Offers	X	4	2	2	Offers	X	4	2	2	Offers	X	4	2	2
	Y	8	4	4		Y	8	4	4		Y	10	5	5
	Z	12	3	9		Z	12	6	6		Z	12	5	5
Result: 6 trades, no unmatched supply/demand					Result: 6 trades, Buyer B has 3 kWh unmatched demand					Result: 6 trades, Seller Z has 2 kWh unmatched supply				

3.5 GRID FEE CALCULATION

The grid fee calculation is also based on the D3A (GRID SINGULARITY, 2021) market engine. The adopted grid fee for this study is a percentage grid fee, where the fee is a ratio in (%) of the negotiated transaction.

In the first level of the market hierarchy setup, there are no grid fees involved, as the trades happen between assets of the same household. If a bid propagates to the second level, where households trade with each other, the bids b and offers s will be modified by the grid fee ratio α . The new bids and the new offers will be accounted for as follows:

$$b_{after_fee} = b(1 - \alpha) \quad (3.1)$$

$$s_{after_fee} = s(1 + \alpha) \quad (3.2)$$

When there is a match between the new bids and offers, the actual fee rate of

this transaction will be:

$$fee_b = b - b_{after_fee} \quad (3.3)$$

$$fee_s = s_{after_fee} - s \quad (3.4)$$

$$fee_rate = fee_b + fee_s \quad (3.5)$$

The paid price π for the energy is equal to the original bid from the buyer since this is a pay-as-bid model. The revenue rate ω for the seller is the original price discounted from the fee.

$$\pi = b; \quad (3.6)$$

$$\omega = s - fee_rate \quad (3.7)$$

In a numerical example, supposing the bid is 20 *cents/kWh*, the offer is 16 *cents/kWh* and the Grid Fee Ratio is 10%.

- $b_{after_fee} = 20(1 - 0,10) = 18 \text{ cent/kWh}$
- $s_{after_fee} = 16(1 + 0,10) = 17,6 \text{ cent/kWh}$
- $fee_s = 20 - 18 = 2 \text{ cent/kWh}$
- $fee_b = 17,6 - 16 = 1,6 \text{ cent/kWh}$
- $fee_rate = 2 + 1,6 = 3,6 \text{ cent/kWh}$
- $\pi = 20 \text{ cent/kWh}$
- $\omega = 20 - 3,6 = 16,4 \text{ cent/kWh}$

The actual fee rate is calculated for every transaction and in percentage will be higher than the grid fee ratio. The grid fee ratio is the given modifier of the bids and offers. By this procedure, the grid fee accounting ensures that the buyer does not pay more than what she bid, and the seller does not receive less than what she offered. But in practice, when the grid fee is applied, the market participants have to adjust their bidding/offering strategies to keep finding bids and matches that are more beneficial than buying directly from the utility at tariff price (Eqs. 3.8 to 3.11). This means that the market participants feel the impact of the grid fee on their costs and revenues.

$$b'_{initial} = \frac{b_{initial}}{1 - \alpha} \quad (3.8)$$

$$b'_{final} = \frac{b_{final}}{1 - \alpha} \quad (3.9)$$

$$s'_{initial} = \frac{s_{initial}}{1 + \alpha} \quad (3.10)$$

$$s'_{final} = \frac{s_{final}}{1 + \alpha} \quad (3.11)$$

where $b'_{initial}$ and b'_{final} are the adjusted initial and final buying rates bid by the buyer, respectively, once the grid fee is applied; and $s'_{initial}$ and s'_{final} are the adjusted initial and final selling rates offered from the seller, respectively, to account for the application of the grid fee.

Finally, for the transactions between market participants and utility at tariff prices, the grid fee rate is not applied as it is already imbued in the tariff price. This would relate to the level 3 of negotiation, according to the market hierarchy presented previously.

3.6 TRANSACTION FEE CALCULATION

To compensate for the expenses incurred by establishing a P2P local energy market, such as ICT and transaction platform infrastructure and maintenance, a per-transaction fee is included in the analyzed scenarios. This per-transaction fee is implemented as a flat fee, in other words, the same fixed charge that every market participant pays every time a transaction is processed, no matter the amount of energy traded.

In the developed model, the per-transaction fee will be subtracted from the revenue R in [\$] of the seller, and added to the cost C in [\$] of the buyer once a transaction T is set (Eqs. 3.12 and 3.13). If the revenue R of a possible match is lower than the sum of the per-transaction fee τ and the grid fee (Eq. 3.14), this transaction will not take place and the unmatched energy quantities e will be carried on to the next market tick. This is implemented to make sure the revenue of a transaction is never negative, that is, the seller does not pay to sell her energy surplus.

$$C = \pi e + \tau \quad (3.12)$$

$$R = \omega e - \tau \quad (3.13)$$

$$\exists T \iff R = \omega e - \tau > 0 \quad (3.14)$$

4 RESULTS AND DISCUSSION

According to the evaluation framework proposed in Section 3.2, the current section presents the results from the carried simulations in form of energy balances, and each evaluated item and its respective criteria.

4.1 CASE STUDY AND SCENARIOS

4.1.1 Simulated Circuit Model and Input Data

The revenue performance analysis and the grid performance analysis proposed by this study are carried out through a case study using the IEEE European Low Voltage Test Feeder (IEEE, 2016). This model consists of a radial distribution feeder with a base frequency of 50Hz and a voltage level of 416V (phase-to-phase). Its one-line diagram layout can be seen in Figure 17. The model provides load shapes with a one-minute resolution for 24h for time-series simulation.

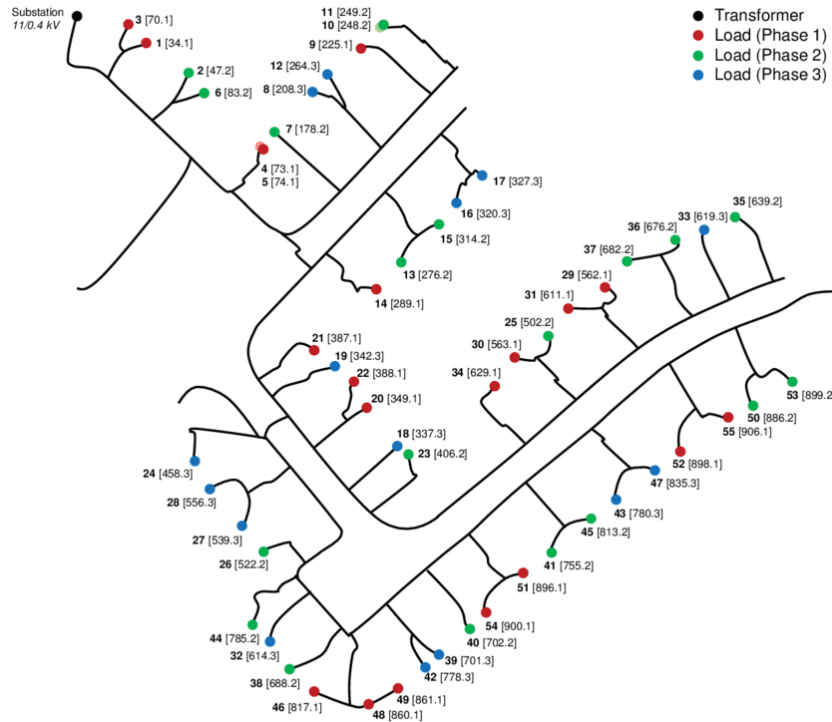


FIGURE 17 – IEEE European Low Voltage Test Feeder one-line layout

In the developed case study, 55 households are connected to the grid and participating in the market, each with a load, a photovoltaic rooftop, and a battery. The load curves used are the ones present in the IEEE LV test feeder data (Figure 18).

The radiation profile is given as a sunny day at a subtropical latitude (Figure 19). Each agent has $1kW_p$ of photovoltaic installed.

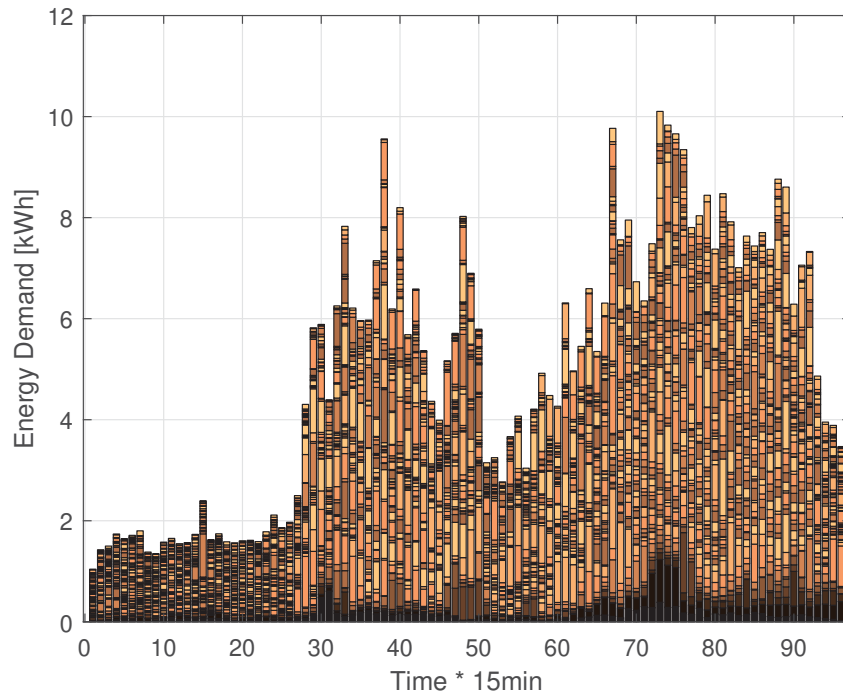


FIGURE 18 – Summed up demands of the 55 agents connected to the grid participating in the market

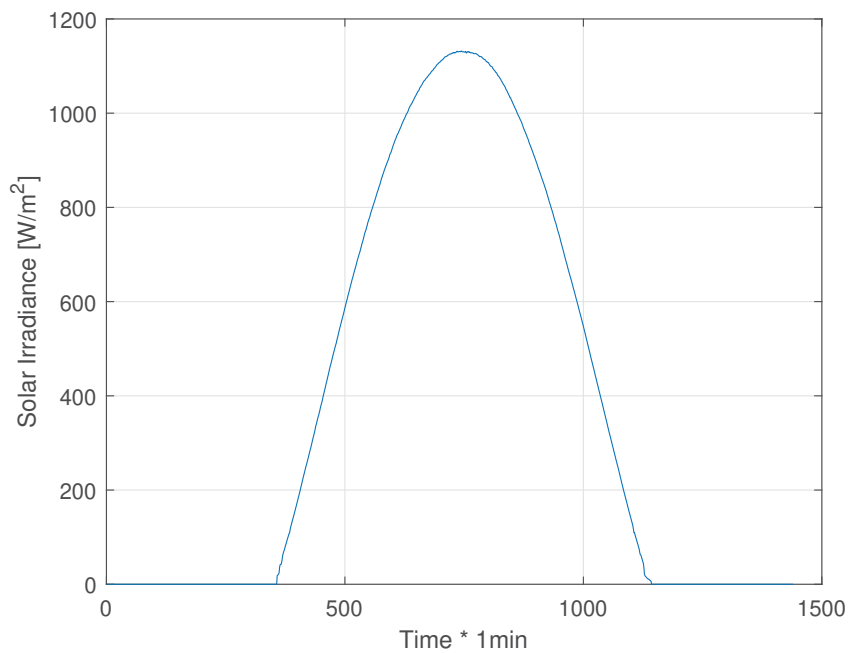


FIGURE 19 – Global horizontal Irradiance on the modeled photovoltaic systems

The storage system's configuration is given in Table 8.

For the market model, the following configurations in Table 9 were adopted.

4.1.2 Description of Simulated Scenarios

The envisioned scenarios to generate research data and provide an opportunity for the intended assessment of this study are described in the sequence. The simulations

TABLE 8 – Agents' storage system configurations

Power	1.5 kW_p
Capacity	1.8 kWh
Minimum state-of-charge	20%
Initial state-of-charge	20%
Round-trip efficiency	90.25%

TABLE 9 – Implemented Market Parameters

Market Slot's Size	15	min
Market Tick's Size	15	sec
Market Slots	96	steps
Market Ticks per Slot	60	steps
Grid fee ratio	10	%
Per-transaction fee	0.05	cents/kWh

all last 24 hours and are made in 15-minute steps. Five cases are analyzed:

- **Base 1:** this is the base situation of the IEEE test feeder, where the agents have only loads and no DERs present. All households buy energy from the utility at the tariff price.
- **Base 2:** in this scenario, the distributed energy resources are introduced. Each household possesses now a PV system and a storage system. These systems work in self-consumption and net-metering mode. Each storage system can only be charged by the respective household's PV surplus. In the same way, the storage system only discharges to feed the household's energy demand. When there is surplus energy from the PV that surpasses both load and storage charging, this surplus will be fed into the grid at a feed-in-tariff price.
- **Market 1:** in this scenario, the DERs can exchange energy between themselves and the grid according to the market rules described previously.
- **Market 2:** the same market rules operation, with the presence of grid fees as described previously.
- **Market 3:** the same market rules operation, with the presence of both grid and transaction fees as described previously.

The definition of net-metering used for the "Base 2 "scenario is the one given in (ZINAMAN, 2020):

"net-metering is a type of metering and billing arrangement, where the customer's gross [...] generation within a predefined period [...] is subtracted from the customer's electricity consumption within that same predefined period, and any [...] generation in excess of consumption can [...] be compensated at a predefined rate [...]."

For the purposes of this study, the mentioned predefined rate is the feed-in tariff.

4.1.3 Detail of the storage system operation strategies

In scenario Base 2, the storage system is present and operates on a net-metering and self-consumption mode. This storage only works within the energy balances of the household where it is installed and does not interact with the grid. It will present the following operating conditions:

- when there is surplus PV energy after the load demand is met, the battery will charge until it reaches maximum state-of-charge;
- if there is no surplus PV energy, the battery does not charge;
- when there is load demand greater than PV production, the battery will provide energy to the load until it reaches minimum state-of charge.

In scenario Market 1, 2, and 3, the storage system can operate in a wider range within the established market and interacts with the local grid in terms of energy balances:

- if the battery is not at the minimum state-of-charge, it will make an offer to the market to sell energy;
- if the battery is not at the maximum state-of-charge, it will make a bid to the market to buy energy for charging;
- in theory, one battery can make both bids and offers at the same market slot, but in practice, due to rates adopted in the bidding strategies, the battery will either buy or sell at one market slot, according to the best offer;
- due to the bidding strategies, a battery does not trade with other batteries, or with the utility. It will either sell to loads on different households, or buy from PV surpluses from different households.

4.2 GENERAL SIMULATION RESULTS

The energy balances that resulted from the carried simulations are presented in the following figures. Each scenario is presented for comparison purposes.

Figure 20 shows the sum of demanded energy by the loads, which were completely supplied. This depiction demonstrates that no matter the grid operation scenario, the load demands are always met and none of the variations in operating the DERs cause load shedding. As follows, the scenarios don't differ in terms of residential consumers' comfort or convenience, considering electricity a commodity regarded as always available.

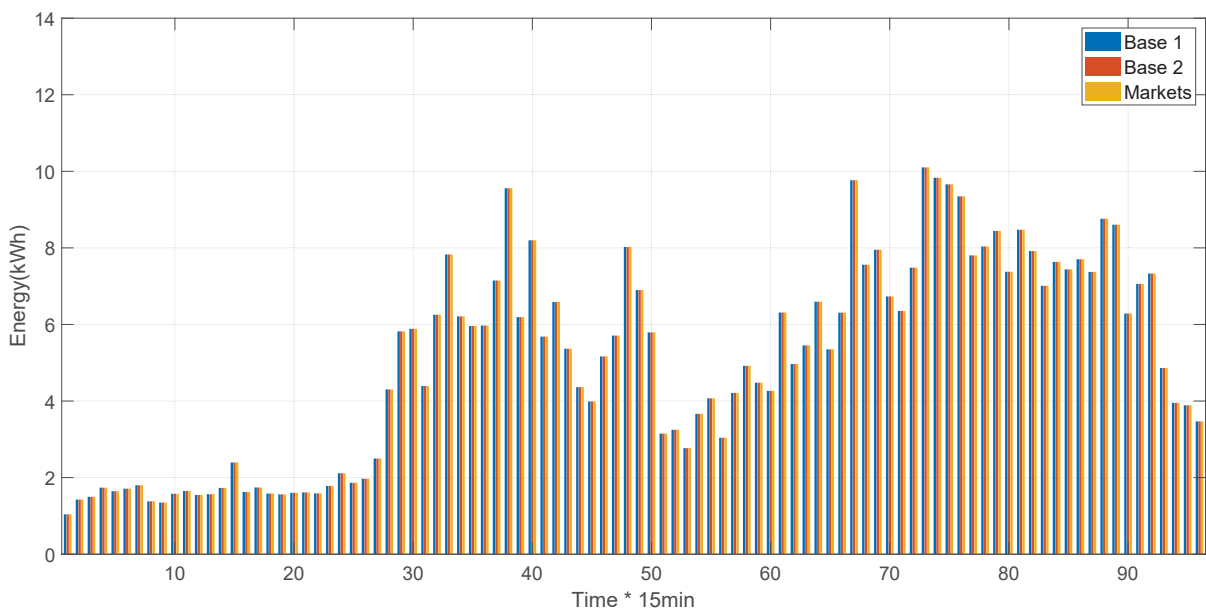


FIGURE 20 – Demanded Energy from Loads

The same is valid for the PV operation, as seen in Figure 21. Regardless of the DERs operation, the available energy which the PVs can supply will not be curtailed. This is important both for the economic feasibility of the PVs, as well as for the sustainability of the proposed operation schemes, to maximize the PVs' energy yield.

The storage system, on the other hand, offers the flexibility needed to change the aspects of grid operation according to each scenarios' regulations. The sum of the exchanged energy by the batteries in each operation step during the day is shown in Figure 22. During the sun hours in the net-metering scenario (Base 2), the batteries start charging as soon as there is a PV surplus from each agent since in this scenario only self-consumption is allowed. On the other hand, in the market scenarios, the PV surplus is firstly exchanged between agents, and only when there is a systemic PV surplus will the storage systems start charging on market scenarios (Market 1, 2, and 3), but then at a higher rate. This also can be seen in Figure 23, which shows the net

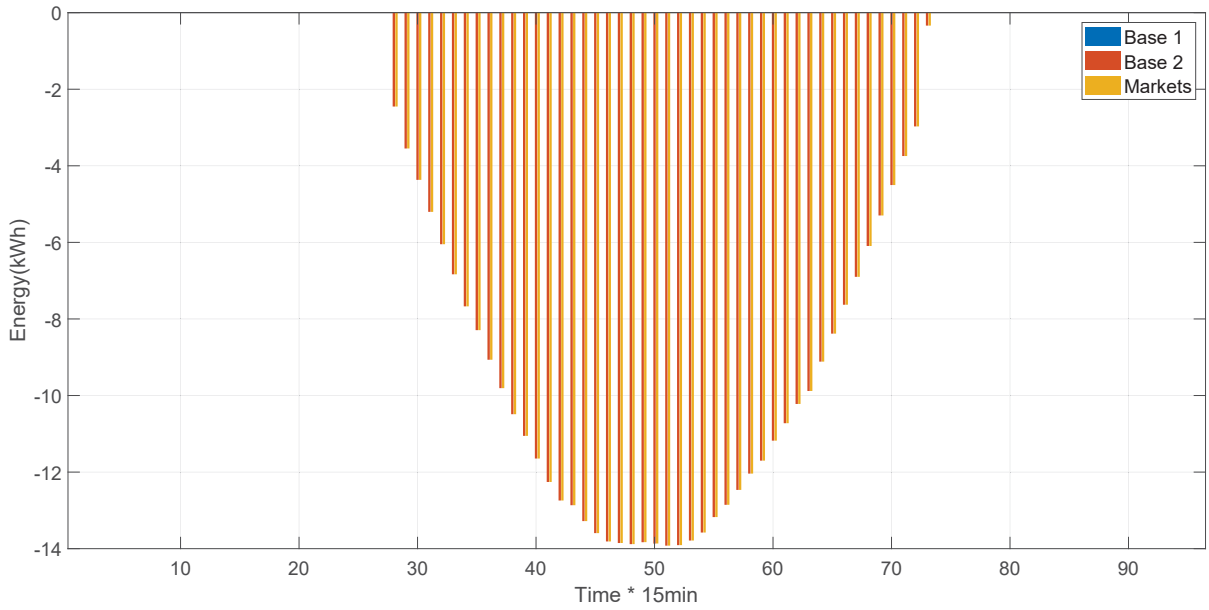


FIGURE 21 – Energy supplied by the PVs

energy amounts which will be requested from/injected into the utility.

By breaking away from restricting to self-consumption in the net-metering scenario (Base 2), the agents can enter into a form of collective self-consumption. This can also be noticed by the beginning of night time which coincides with the end of PV production and a spike in demand. In the net-metering scenario, the batteries discharge at a lower rate because they can only supply the energy to their respective household. In the market scenarios, the storage systems contribute to eliminating net demand at peak consumption time by being able to exchange their energy between consumers. It is interesting to notice that this collective self-consumption effect is not from any schedule or optimization method but is totally defined by market rules, with energy prices as key operational parameters at each time step.

Despite showing the sum of all energy surpluses and demands from each agent, Figure 23 does not mean the actual energy demand and surplus perceived by the utility at the point of common coupling to the grid. This value will be better detailed further on by the power flow calculations.

4.3 REVENUE STREAM PERFORMANCE COMPARISON

To calculate the revenue streams from the energy transactions for each stakeholder, the following equations (Eqs. 4.1 to 4.4) are used:

$$R_{utility} = \sum_{i=1}^M (\rho \cdot ES_i - FiT \cdot EP_i) \quad (4.1)$$

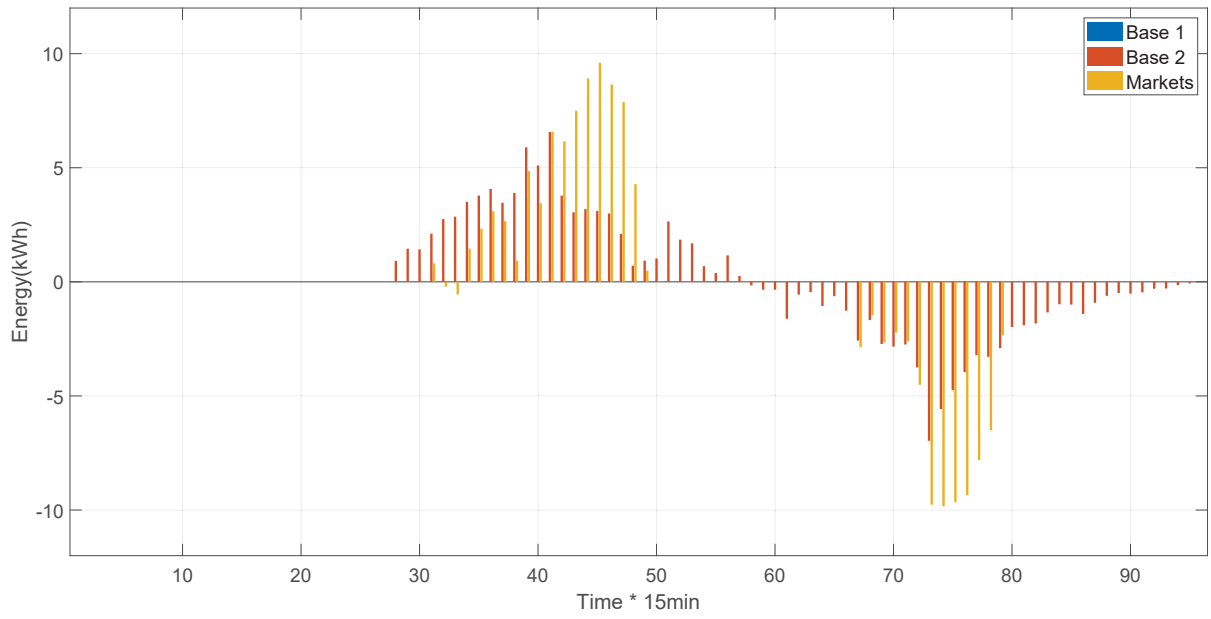


FIGURE 22 – Energy exchanged by the batteries

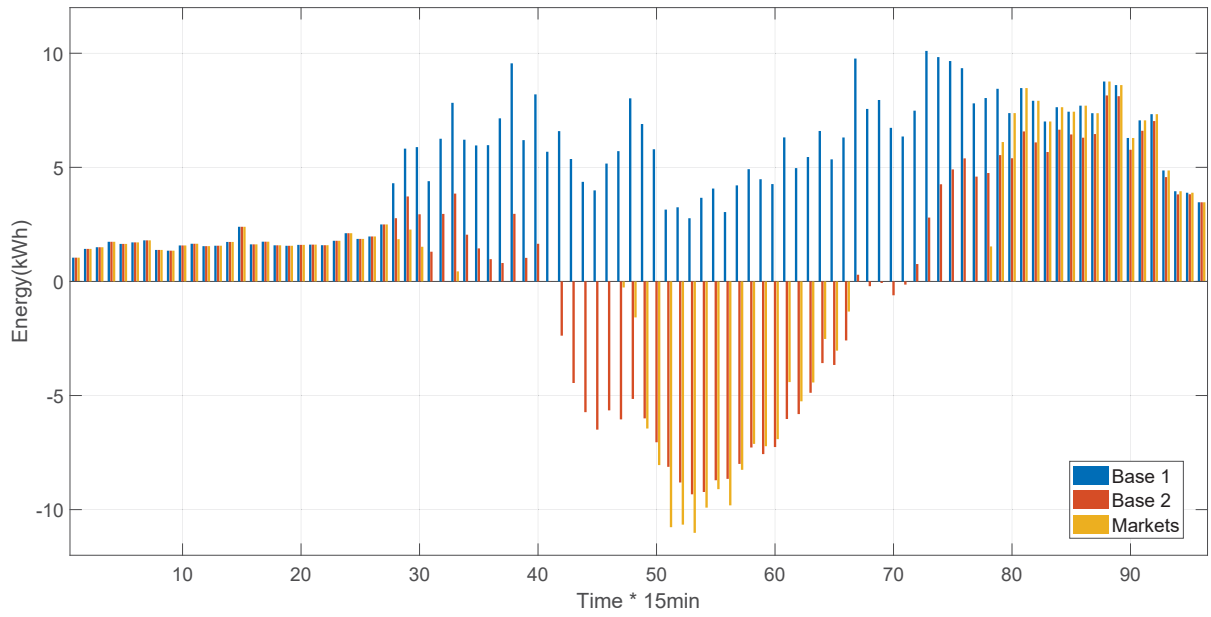


FIGURE 23 – Energy balance which will be required from by the utility as a sum of all agents - loads, PVs and storage systems

$$R_{grid_fee} = \sum_{i=1}^M \sum_{t=1}^T (fee_rate_{i,t}) \quad (4.2)$$

$$R_{trans_fee} = \sum_{i=1}^M \sum_{t=1}^T (2 \cdot \tau) \quad (4.3)$$

$$R_{total_utility} = R_{utility} + R_{grid_fee} + R_{trans_fee} \quad (4.4)$$

Where $R_{utility}$, R_{grid_fee} and R_{trans_fee} are the revenues of the utility with energy sales, grid fees and transaction fees, respectively. Other variables are:

- M is the number of market slots accounted
- ρ is the utility tariff for energy sale
- ES_i is the energy sold at market slot i
- FiT is the feed-in-tariff at which the utility buys energy back from the prosumer
- EP_i is the energy bought by the utility from the prosumer
- T is the total number of transactions

The prosumers revenue is calculated by:

$$R_{total_prosumers} = \sum_{n=1}^N \sum_{i=1}^M \sum_{t=1}^T (R_{n,i,t} - C_{n,i,t}) \quad (4.5)$$

Where N is the total number of prosumers, $R_{n,i,t}$ is a match t of energy sale inside a market slot i for a prosumer n , and $C_{n,i,t}$ is the cost of an energy purchase t inside a market slot i for a prosumer n .

Table 10 shows the calculated value streams. To further the comparison, Table 11 shows the same values expressed as a percentage of the difference from the revenue in scenario "Base 2", as stated in the equation below:

$$Value_{percent} = 100 \cdot \frac{Value_{scenario} - Value_{Base2}}{Value_{Base2}} \quad (4.6)$$

As expected, there is a significant decrease in revenue for the utility by DER deployment, from the no-DERs scenario (Base 1) to the presence of DERs in net-metering mode (Base 2). This revenue loss in energy sales is further deepened by the market operating mode scenario (Market 1). In the market scenarios, the revenue was as much as 23% further reduced for the utility in reference to the net-metering operation mode (Base 2).

This happens due to the collective self-consumption effect created by the market rules, which can allocate more effectively the energy exchanged by the DERs through the interaction of the market participants. In terms of revenue, this impacts the utility negatively. The grid and transaction fees are introduced then as a way for the agents or market participants to absorb these revenue losses associated with market-based operation. By the given values used in this case study, the introduction of grid fees is

TABLE 10 – Revenue Streams for the different scenarios and stakeholders (in absolute values)

	Base 1	Base 2	Market 1	Market 2	Market 3
Utility Energy Sale Revenues	14,517.42	4,785.35	3,696.98	3,696.98	3,649.99
Total Fee Revenues	0.00	0.00	0.00	488.92	1,757.51
Utility Energy + Total Fee Revenues	14,517.42	4,785.35	3,696.98	4,185.90	5,407.50
Total Welfare Prosumers	-14,517.42	-4,785.35	-3,696.98	-4,185.90	-5,407.50

TABLE 11 – Revenue Streams for the different scenarios and stakeholders (as the difference in percent from the Base 2 scenario)

	Base 1	Base 2	Market 1	Market 2	Market 3
Utility Energy Sale Revenues	203.4%	0.0%	-22.7%	-22.7%	-23.7%
Fee Revenues	0.0%	0.0%	0.0%	10.2%	36.7%
Utility Energy + Fee Revenues	203.4%	0.0%	-22.7%	-12.5%	13.0%
Total Welfare Prosumers	-203.4%	0.0%	22.7%	12.5%	-13.0%

able to alleviate revenue loss by up to 10% in reference to the net-metering revenue. The further introduction of the transaction fee can even reverse revenue loss, positively impacting utility revenue in comparison to net-metering scenario.

In the proposed values used in this case study, the introduction of transaction fees comes at a negative for the prosumer. With such fees, the market is no longer as beneficial for the participants as the net-metering scheme. Table 12 shows the number of market participants who are better/worse off net-metering scenario in terms of energy costs. The market was beneficial for all prosumers in comparison to the net-metering scenario, up until the implementation of fees. By the grid fee proposition, some of the prosumers already start to be cost-disadvantaged in regard to the net-metering framework. With transaction fees on top, almost all prosumers are worse off in the market framework.

This draws to a very important remark, which is that cost- and revenue-wise, the implementation of market-based operation of the grid by peer-to-peer local energy markets is a "zero-sum game" in regard to net metering. If the prosumer is benefited in revenue gains in comparison to the net-metering scenario then the utility will suffer

greater revenue loss. On the other hand, if the utility switches from net-metering to the market-based scenario and tries to recover their extra revenue loss by trying to heavily allocate fees to prosumers, the prosumer perceives no motivation in joining a local energy market as opposed to staying in a net-metering regulation.

TABLE 12 – Number of prosumers who are in cost advantage or disadvantage in comparison to net-metering (Base 2) scenario

		Base 1	Base 2	Market 1	Market 2	Market 3
Prosumers Better off		0	0	55	48	5
Prosumers Worse off		55	0	0	7	50

Even in a scenario where the market is not more beneficial to the prosumer than net-metering schemes, it does not mean that this market implementation is not beneficial at all for the prosumer. A full net present value analysis considering the initial investment in the installed DERs could still render positive for the prosumer if the investment costs are low enough, considering that no matter what scenario, the prosumers are still better off with such a peer-to-peer energy market than in the scenario where no DERs are in place (Base 1). This analysis is out of the scope of this current study, though, and is suggested for future research.

4.3.1 Sensitivity to number of agents

To investigate further trends in revenue performance, a set of variations in the values of the base case study is executed in the form of sensitivity analyses. First, the variation in the number of agents participating in the market is presented.

The number of market participants varied from 4 up to 55 agents. Figure 24 shows that the number of transactions' growth rate accelerates with the increase of participating agents. This can be explained by considering that the more agents participating in the market, the bigger is its liquidity, or in other words, there are more opportunities to execute transactions due to the higher number of bids and offers.

The increase in transactions count leads to an increase in transaction fee revenue, as can be in Figure 25, which shows the percent variation of utility revenue from the net-metering scenario as a function of the number of agents. The utility revenue from energy sales decreases with the number of participants in the market because there are more opportunities for the agents to consume collectively. But the total revenue is increasing due to the higher collection of transaction fees, which are directly proportional to the number of transactions.

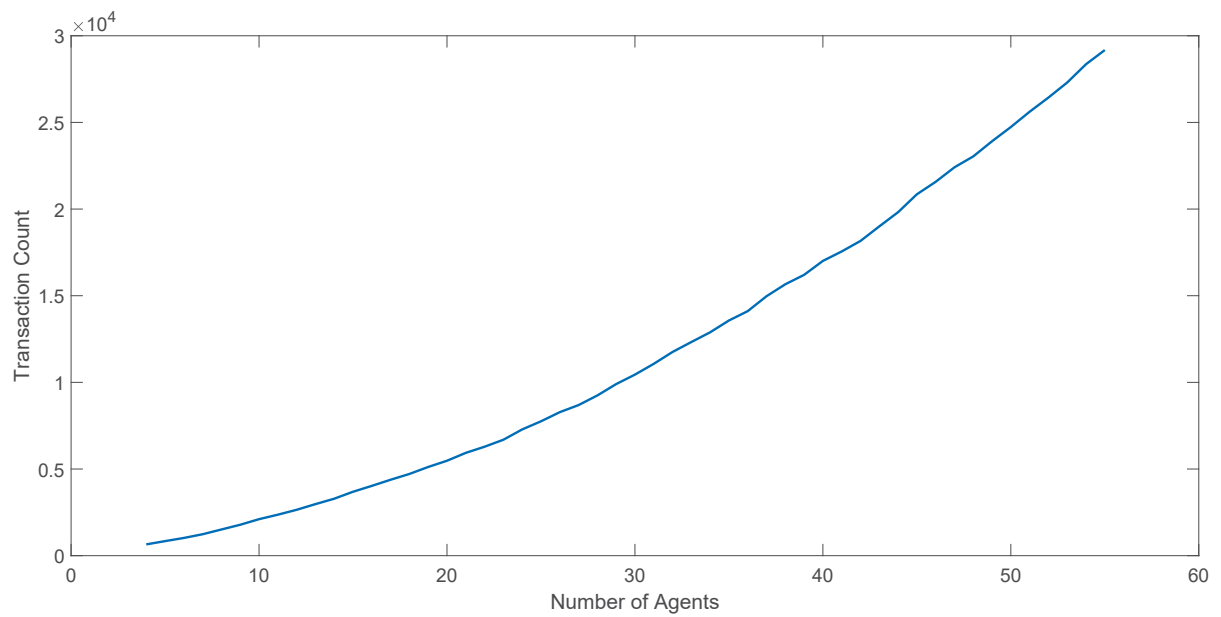


FIGURE 24 – Number of transactions as a function of participating agents

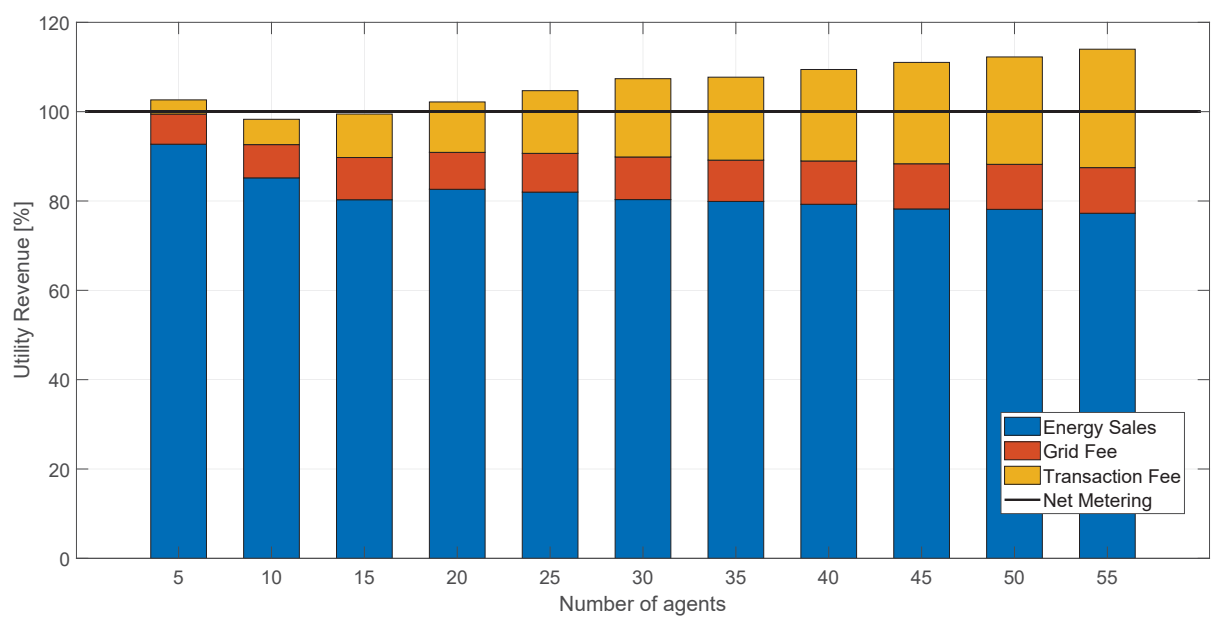


FIGURE 25 – Utility revenue variation as a function of participating agents (as a percentage of the revenue in the net-metering scenario)

The impact of the number of participants in the transaction fee revenue could suggest to the policymakers that, in local market regulations, transaction fee values could suffer adjustments as the number of market participants increases to balance economics for all stakeholders.

4.3.2 Sensitivity to transaction fees

The impact on utility revenues caused by the modification of transaction fee values is looked into in this section. Figure 26 shows utility revenues percent variation from the net-metering scenario as a function of transaction fees. Even if the energy sales revenue in market-based scenarios stays below the income in the net-metering scheme, there is a certain transaction fee price up from where the total income surpasses net-metering earnings.

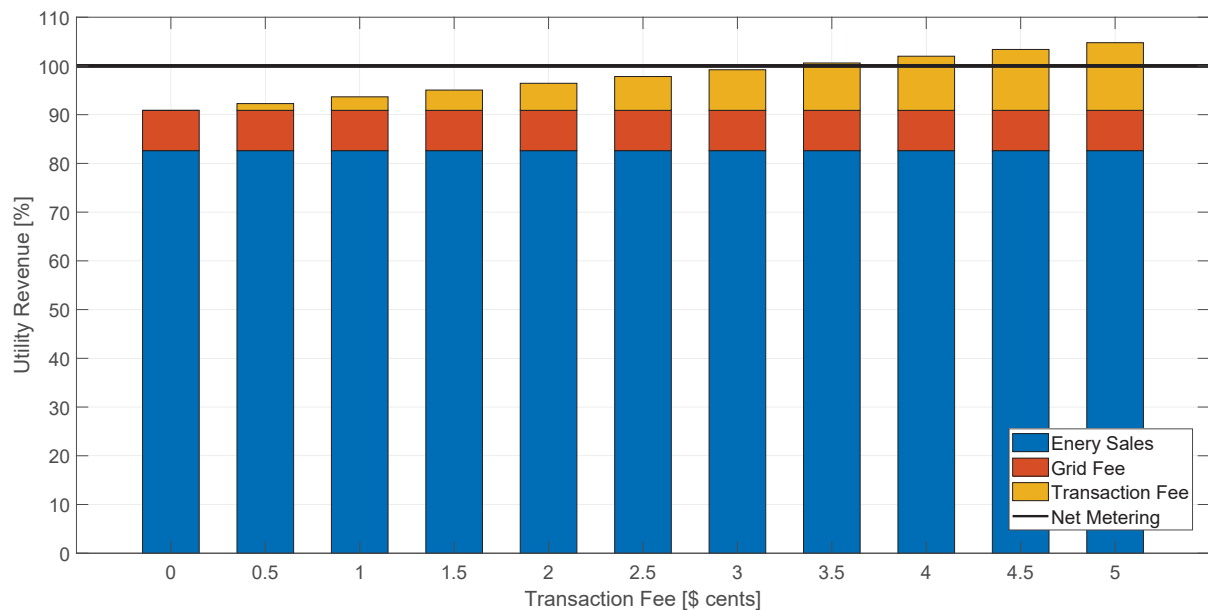


FIGURE 26 – Utility Revenue variation as a function of transaction fee price (as a percentage of the revenue in the net-metering scenario)

If a value of transaction fee is considered such as it balances off the revenue loss in comparison to the net-metering framework. This is also seen in Figure 27, which shows the agents' total cost variation as a function of transaction fees. There is a value of the transaction fee which equals the threshold of net-metering cost. This value could be a compromise point for the utility to feel motivated enough to implement peer-to-peer local energy markets, provided that other non-financial aspects of this implementation are beneficial (which will be further explored in the following evaluation criteria). Studies (HAIDER et al., 2021; HERENCIC et al., 2021) also see how the economic benefits for prosumers affect the system operators negatively and speak for a "golden mean" where the profits are divided, however, they do not evaluate other possible advantages for the utility as a form of compensation for the revenue loss in a more comprehensive analysis.

It is worth noticing that the values depicted in Figure 27 are the sum of all agents' costs. Some of the agents will still perceive lower costs even with the increase in transaction fees. However, as the transaction fee goes up, the proportion of market participants who are cost-wise disadvantaged in regard to the net-metering will go up,

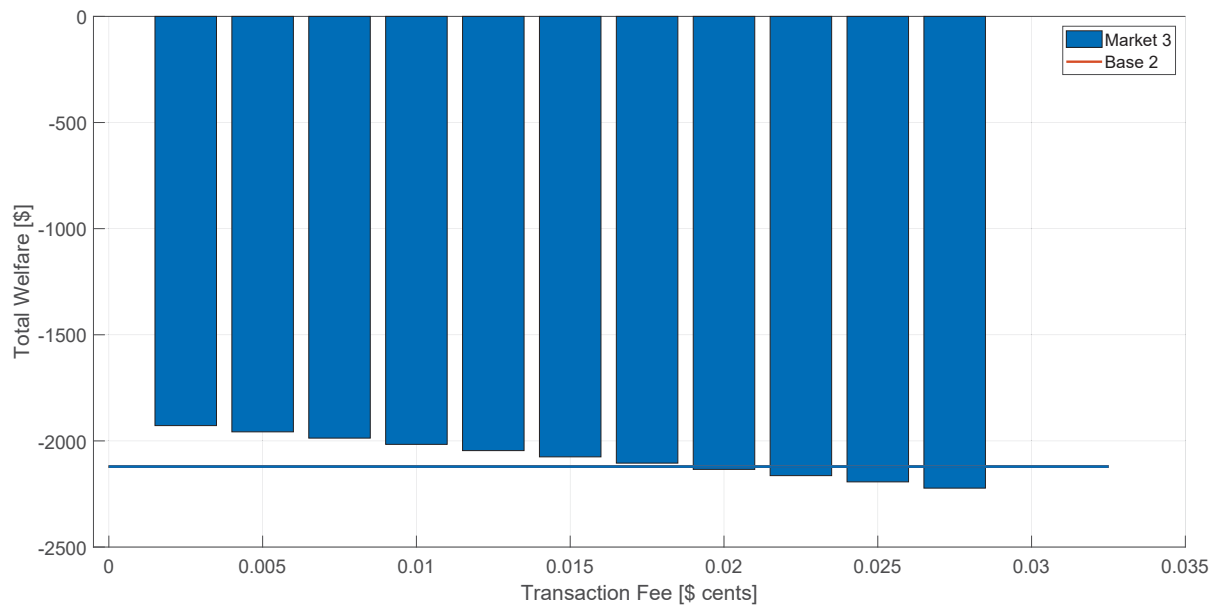


FIGURE 27 – Participating agents' costs as a function of the transaction fee price

as seen in Figure 28. Some of the agents will always be negatively affected by the market due to particularities in their electricity consumption amounts and patterns. This could be changed or reversed by adapting consumption behavior to perceived average electricity prices, for example. The impact of consumers changing behaviors is, however, out of the scope of this study and is suggested for future research.

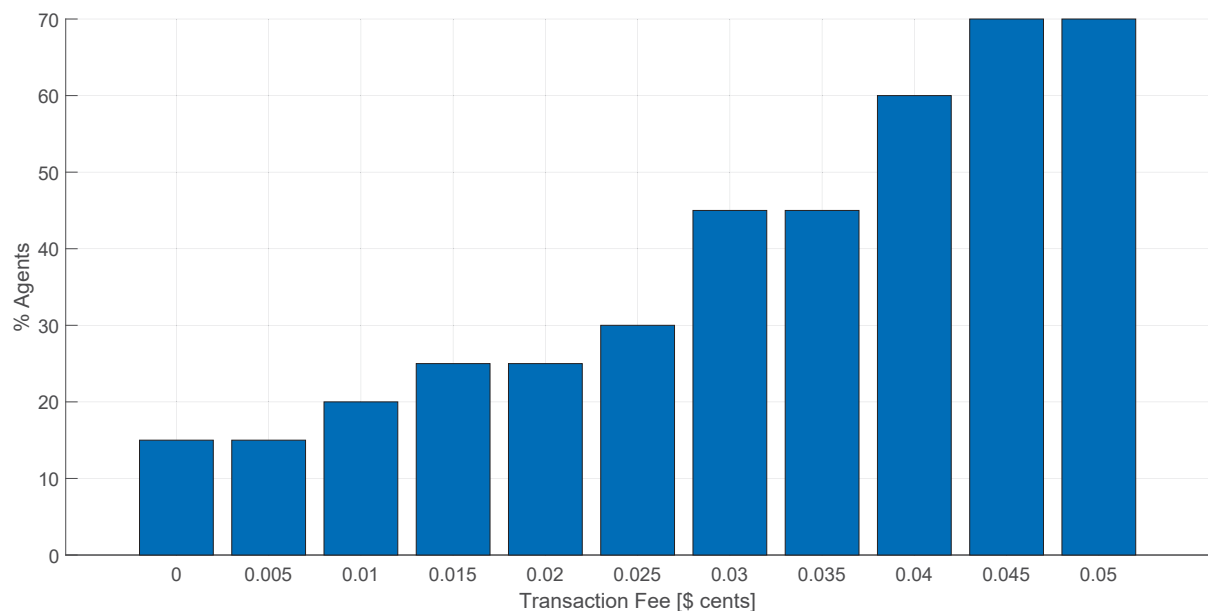


FIGURE 28 – Percentage of agents who are cost-wise worse off than net-metering scenario as a function of transaction fee price

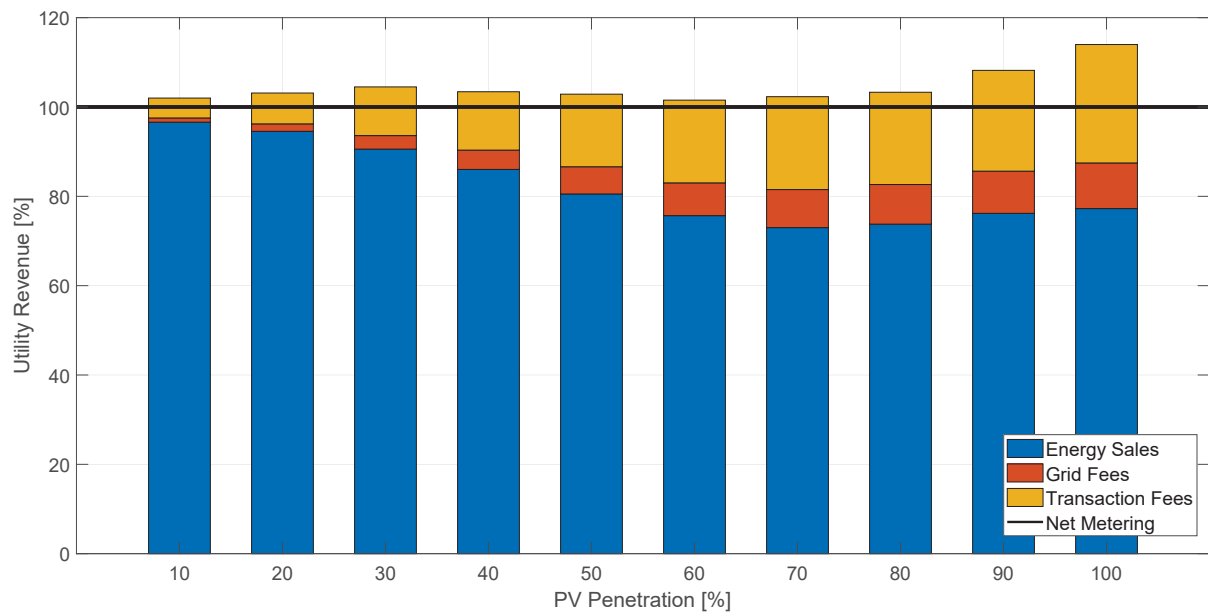


FIGURE 29 – Variation in utility revenue as a function of PV Penetration

4.3.3 Sensitivity to PV Penetration

The impact of PV penetration on utility revenue for the different scenarios can be seen in Figure 29. The PV penetration varied from 10% to 100% of the participating agents having a PV rooftop. As the PV proportion in the system increases up to 70% penetration, a decrease in energy sales revenue for market scenarios in comparison to net metering earnings for the same amount of PV is perceived. Further 70% PV penetration, the income in market scenarios goes back up in regard to net metering income.

It is also seen in Figure 29 that the revenues from grid and transaction fees increase with the higher proportion of PV in market scenarios, which can counter the revenue loss from increasing PV deployment. As long as there is more PV energy available, more offers are made and more transactions are established, generating more income in the form of fees. This suggests that the market operation is a better suit than net-metering in terms of revenue in systems with a very high penetration of PV.

4.3.4 Sensitivity to Storage Penetration

The same impact analysis is performed on storage penetration in different scenarios, where the proportion of agents with storage systems is ranging from 10% to 100% of the market participants. Within Figure 30 it is observed that the presence of batteries does not affect energy sales revenue in market scenarios.

When comparing net-metering to market schemes by reduced presence of storage, the utility is suffering revenue loss in energy sales. There is an increase in

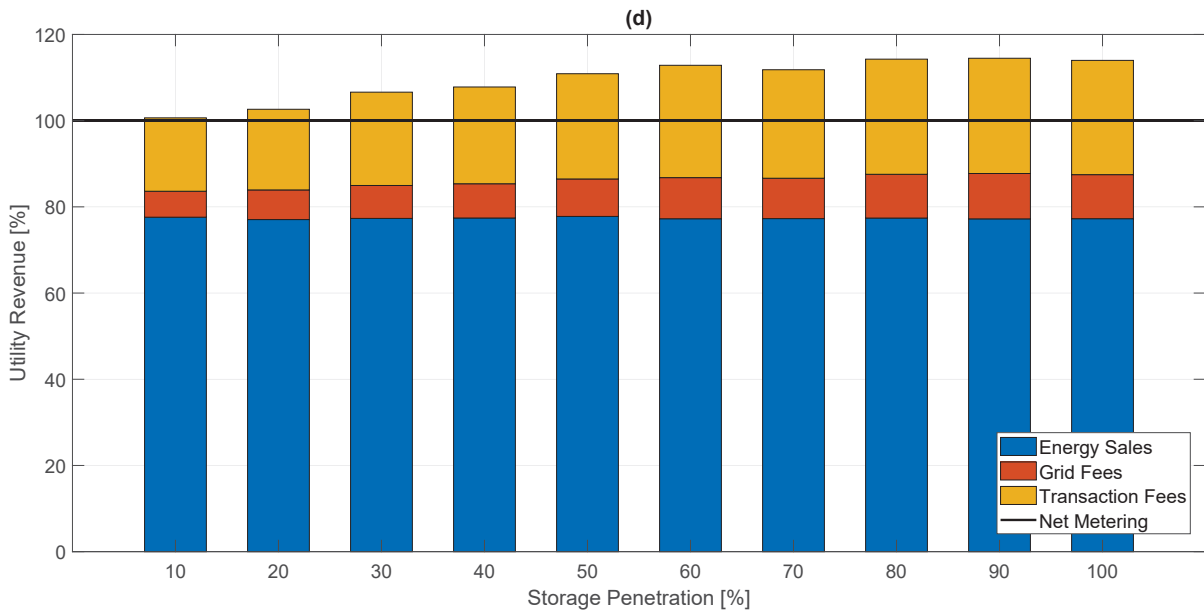


FIGURE 30 – Variation in utility revenue as a function of Storage Penetration

revenue from fees, though. This suggests to the utility that the presence of storage is to be motivated since it has the potential to improve grid performance and increase income in the form of fees in market operation.

4.4 EFFECTS IN GRID OPERATION

This section is dedicated to looking at the time-series power flow results of the simulated scenarios, to better understand and compare the impacts on the grid operation regarding the net-metering against local market scenarios.

4.4.1 Voltage Profile

Figures 31 and 32 show the 3-phase voltages on the low-voltage side of the feeder transformer and the voltage on the furthest point in electrical distance from the mentioned transformer. Full lines show the voltages in net-metering operation, and dashed lines show market-based operation. It is observed that no voltage in the worst case has broken the limits between 0,95 and 1,05 *pu*. However, in the market scenario, the voltages tend to deviate more from the target value of one *pu* during sunny hours. Similar results regarding higher voltage fluctuation were found in (DYNGE et al., 2021), a study that compares the grid performance for P2P and no-P2P scenarios. At the traditional peak load time in the beginning of the evening (around 6 PM), the market operation is benefiting the grid by presenting less voltage drop.

It is difficult to make a statement about the impacts of market-based operation on the voltage profile, once this analysis is highly situational. But we can affirm that

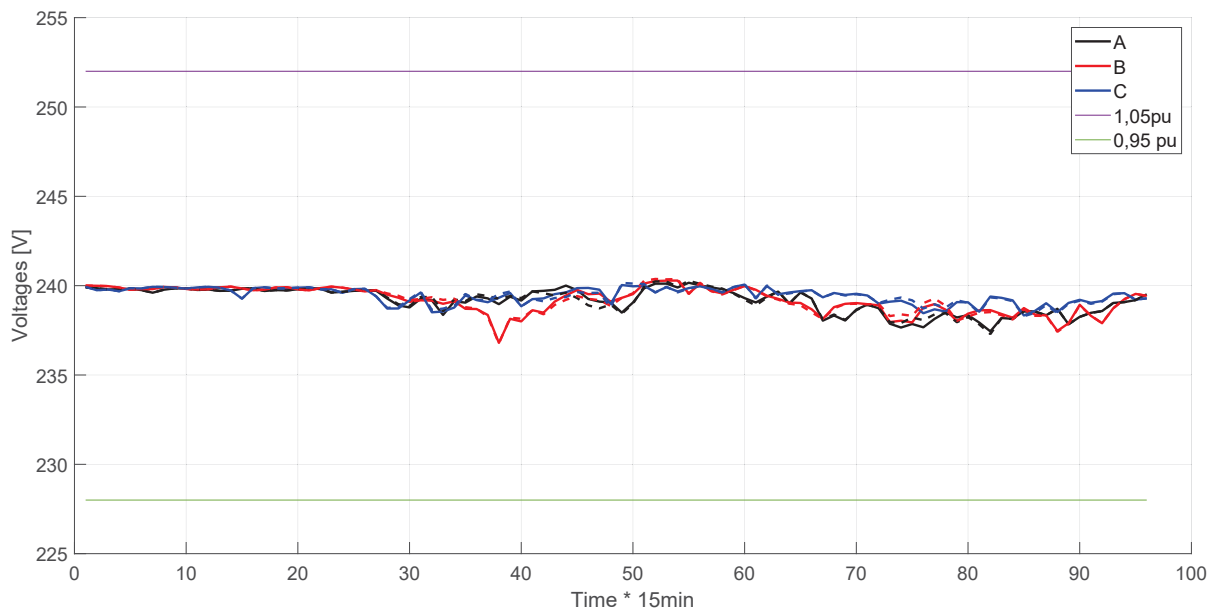


FIGURE 31 – Voltage profile on Transformer LV Side (full = net-metering; dashed = market)

the peer-to-peer operating scheme does not bring an obvious improvement to the voltage profiles, nor does it show a clear degradation of grid status in voltage values in comparison to net-metering operation.

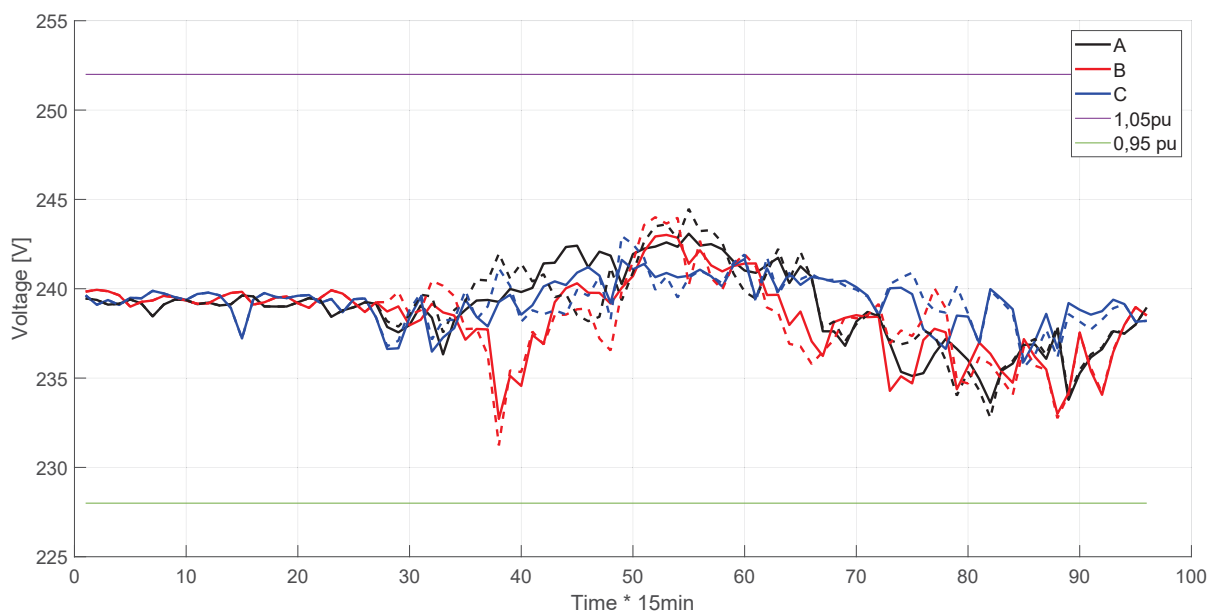


FIGURE 32 – Voltage profile on furthest point from transformer (full = net-metering; dashed = market)

4.4.2 Transformer Load and Load Factor

By analyzing the transformer load in Figure 33, it is observed that the peak power in one moment reaches its highest in the market scenario during sunny hours.

Even though the transformer is less solicited in market operation than in net-metering operation at the beginning of evening time, the highest peak during night hours also occur during market operation.

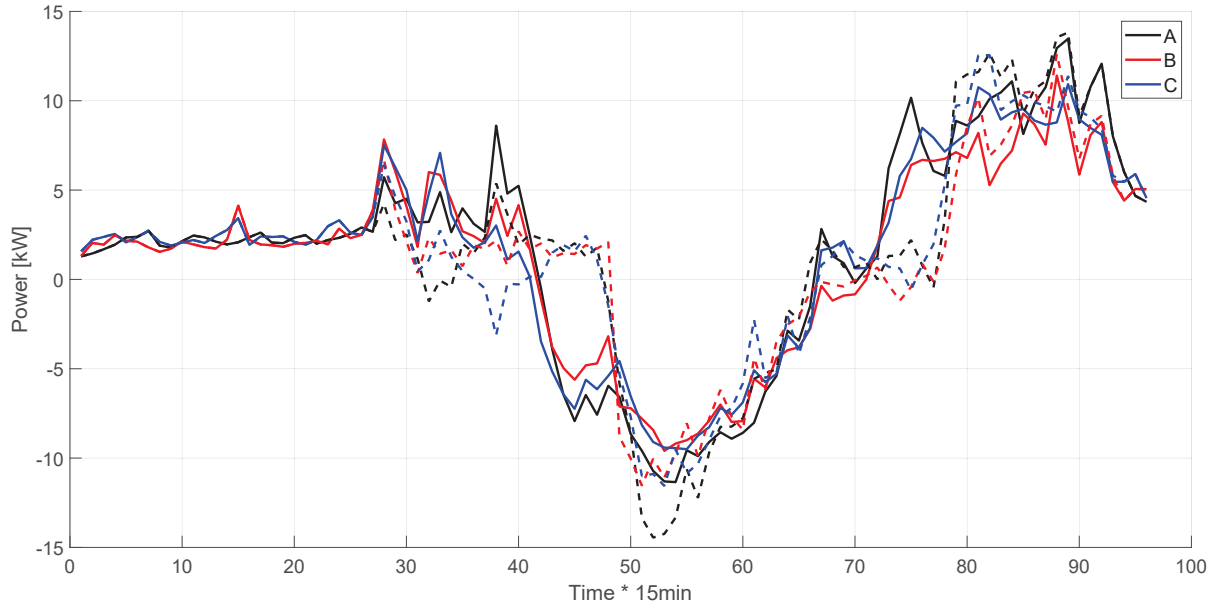


FIGURE 33 – Power on Transformer LV Side (full = net-metering; dashed = market)

Looking into the transformer load factor, which is expressed in Eq. 4.7 and shown in Table 13, it is seen that the load factor deteriorates for the market-based scenario. In this situation, the load factor worsens in the market-scenario because the transformer is on average less solicited, but when solicited it is then at a higher peak.

$$f_{load} = 100 \cdot \frac{\sum_{i=1}^{24} (E_i [kWh])}{P_{max} * 24} \quad (4.7)$$

TABLE 13 – Transformer Load Factor for different scenarios

Base 1	Base 2	Market 1	Market 2	Market 3
50%	45%	35%	35%	35%

4.4.3 Circuit Losses

The sum of all circuit losses is shown in Table 14. There are no significant changes in circuit losses from one scenario to another, showing the change in regulatory scenarios does not impact the grid in terms of energy loss. This is an opposite finding than (DYNGE et al., 2021), where P2P trading scenario present significant more losses than the no-P2P scenario. In that study the batteries are designed to engage in arbitrage, which provide a substantial difference in operation.

TABLE 14 – Total Circuit Losses in VA for different scenarios

Base 1	Base 2	Market 1	Market 2	Market 3
134.4927	134.4950	134.4904	134.4904	134.4904

4.4.4 Sensitivity to PV and Storage Penetration

The impact of PV and storage penetration in grid performance for the different scenarios is evaluated in this subsection. When varying PV deployment, by around 60% PV penetration, the market-based operation can eliminate the reverse power feed into the main grid, considering the effect of the market-ruled collective self-consumption. This is confirmed by evaluating the power at the transformer, as seen in Figure 34. This is why the overvoltage at the peak PV surplus by 60% penetration is managed better in the market-based scenario than in net-metering operation (Figure 35). By 100%, however, the market scenario has higher overvoltages at peak PV surplus than on net-metering scenarios. This means that the P2P energy impacts on the grid depend not only on market designs, but also on the proportion of DER deployment.

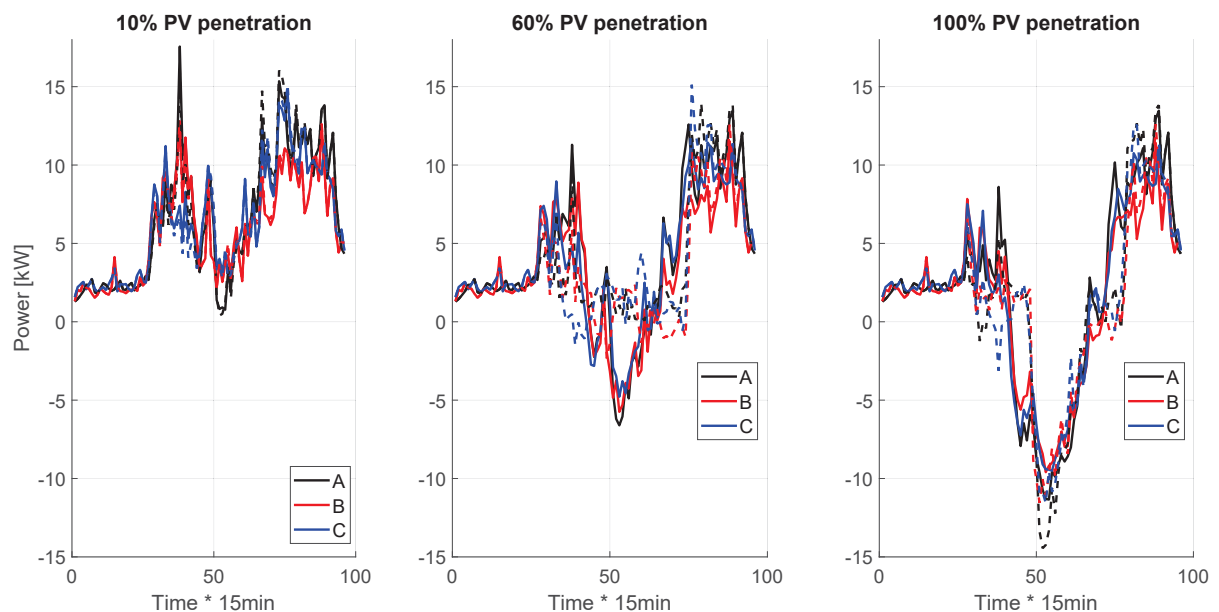


FIGURE 34 – Power on Transformer LV Side for different PV penetration (full = net-metering; dashed = market)

The observed impacts and effects on grid operation for the storage variation did not show significant divergence from the results of the base case.

Regarding the overall grid performance comparison of net-metering versus market-based scenarios, one can affirm that though the market-based scenario performed worse for the implemented case study, it showed more flexibility to find more beneficial operating points in terms of the number of market participants and DER penetration that can counter unwanted effects on grid operation.

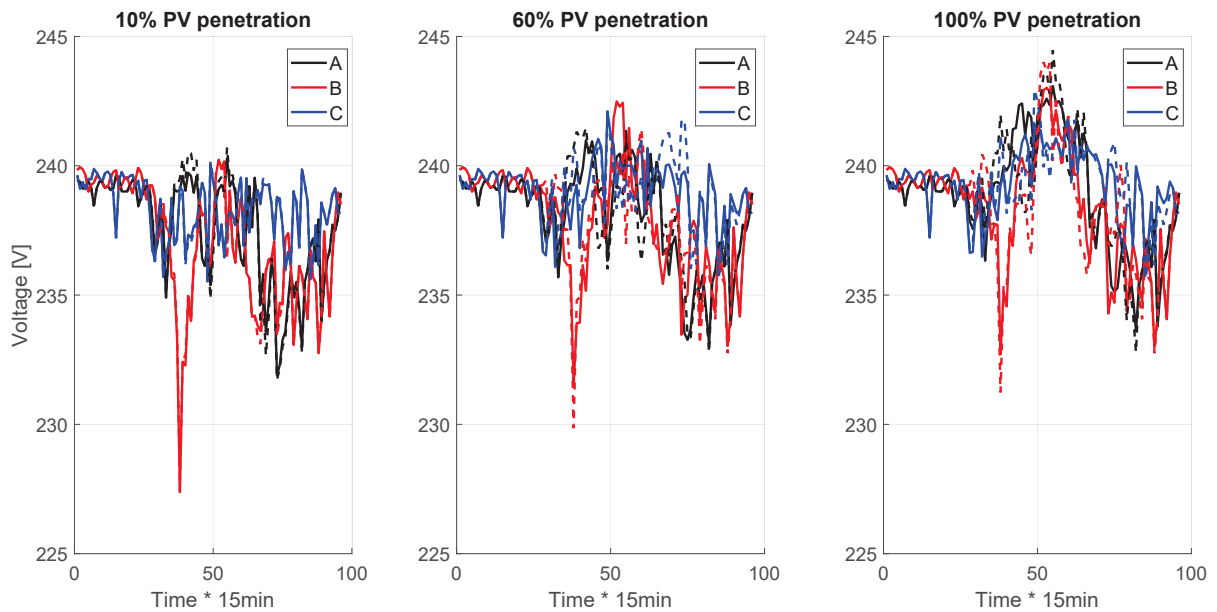


FIGURE 35 – Voltage profile on furthest point from the transformer for different PV penetration (full = net-metering; dashed = market)

4.5 LOCAL ENERGY MARKETS AS A NON-WIRE ALTERNATIVE TO INFRASTRUCTURE

To look into the possibility of using local energy markets as non-wire alternatives, first the load is increased up to 3 times its normal size to observe the impacts on the grid. The PV and storage sizes were raised proportionally.

For this simulation, the base voltage on the main transformer was raised to 1,03 *pu* to counter the effects of the voltage drop due to higher loading.

Figures 36 and 37 show the comparison of transformer load and voltage profile, respectively, for different load demands and net-metering *versus* local-market operation schemes. The depictions show that the local-market scenario was not able to alleviate voltages or peak power in comparison to net-metering. Rather, it has shown an increase in peak values for both measurements.

There is also no significant loss difference for the different operation scenarios either, also considering operation without DERs (Base 1).

Considering load increase, local energy markets are not advantaged in regard to net-metering to possibly counteract the need for further investments in grid infrastructure.

The case is different when PV deployment is varied. Figures 38 and 39 present the energy balance for 20% and 60% PV deployment in reference to the base case. By 20% market and net-metering behave similarly in operation. However, by 60% PV penetration, the market operation can eliminate reverse flow, as opposed to net-metering.

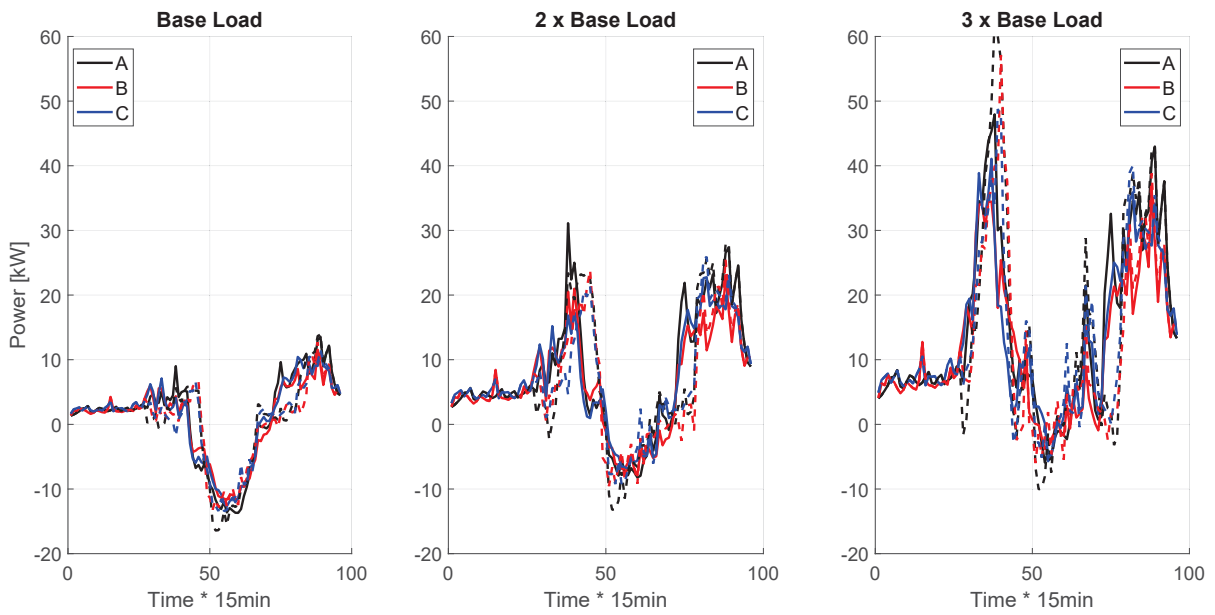


FIGURE 36 – Power on Transformer LV Side for different load demands (full = net-metering; dashed = market)

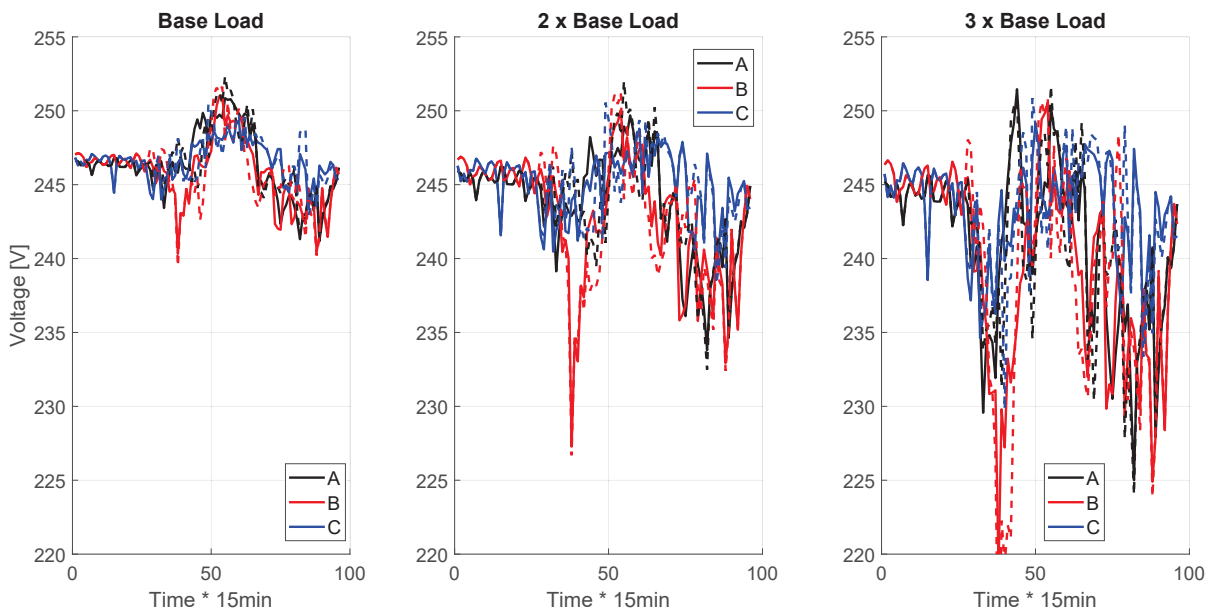


FIGURE 37 – Voltage profile on furthest point from transformer for different load demands (full = net-metering; dashed = market)

This is what causes the effect of relieving the transformer load seen previously. In this case, the market operation is more capable of using PV and storage deployment to counteract the need for grid reinforcement because it offers more flexibility to affect grid operating points.

It is important to note that this effect is only possible due to the presence of storage. If storage is not present, there is little effect on the outcome from the compared

operating strategies. It is seen in Figure 40 that the grid operation in market regulation (Markets 1, 2 and 3) with very little storage does not differ from operation as net-metering (Base 2).

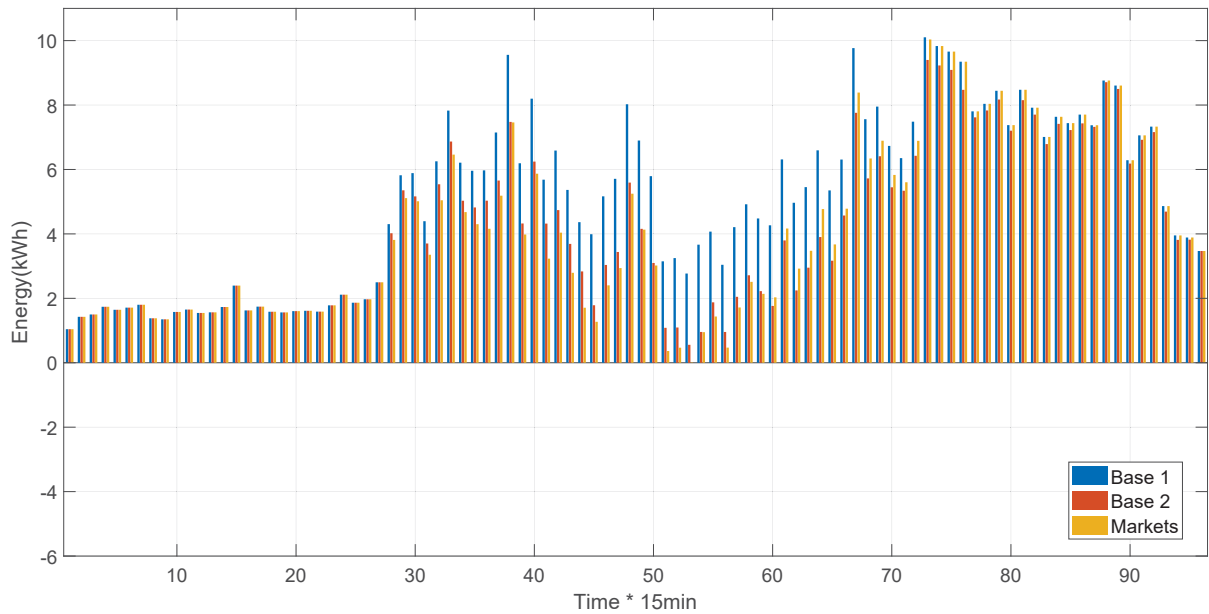


FIGURE 38 – Energy balance which will be required by the utility as a sum of all agents - loads, PVs, and storage systems at 20% PV Penetration

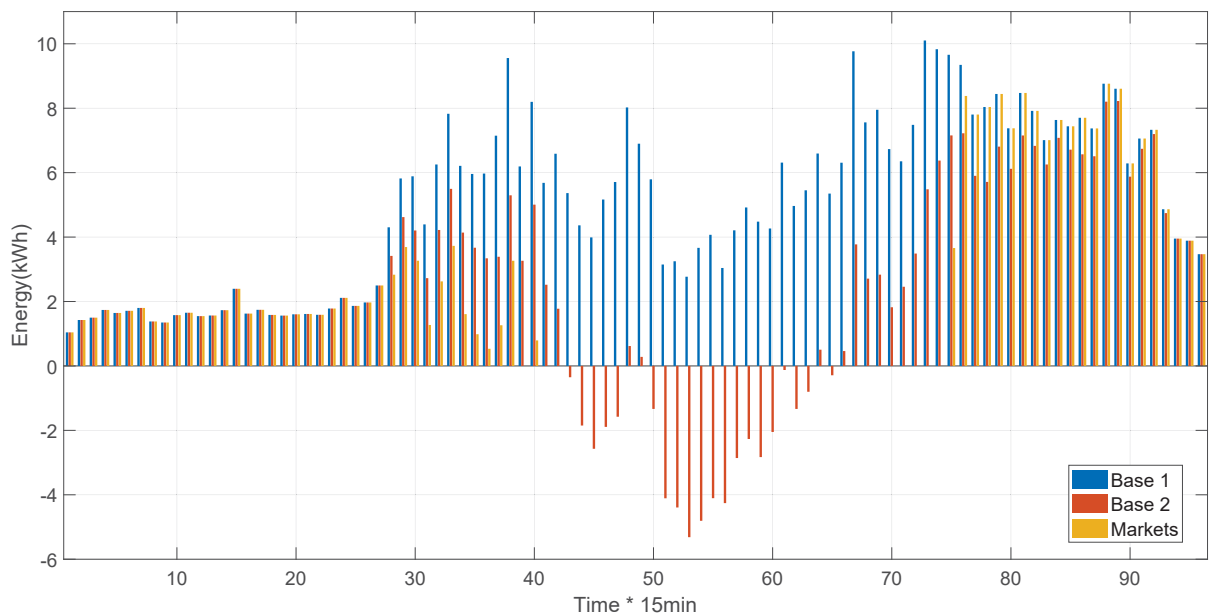


FIGURE 39 – Energy balance which will be required by the utility as a sum of all agents - loads, PVs, and storage systems at 60% PV Penetration

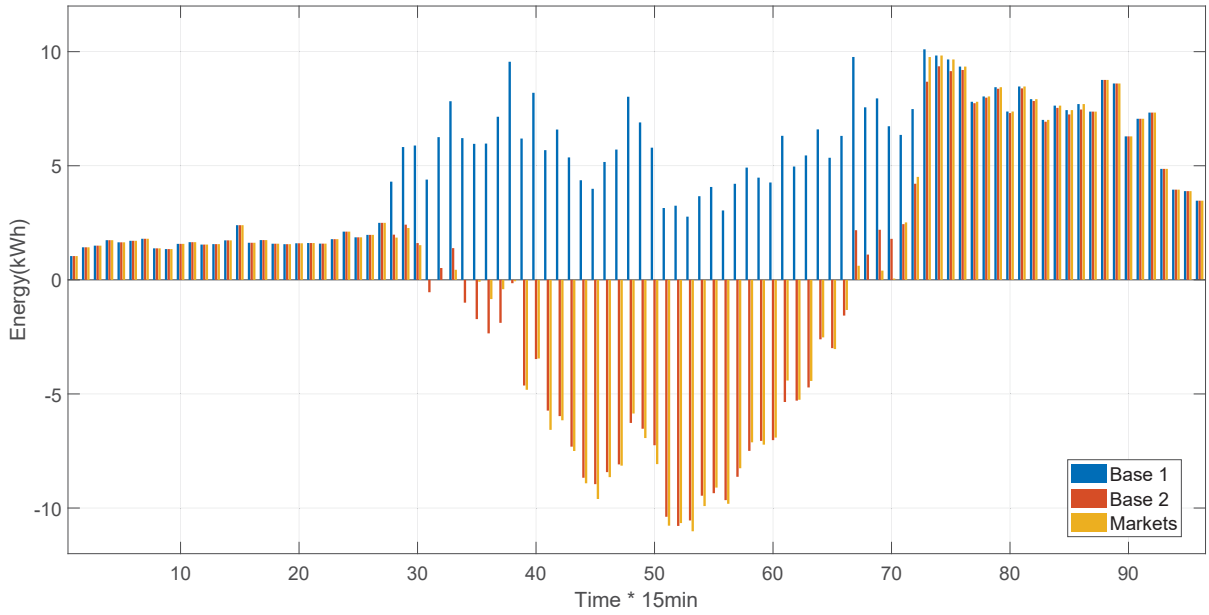


FIGURE 40 – Energy balance perceived by the utility at the point of common coupling at 10% Storage Penetration

4.6 LOCAL ENERGY MARKETS AS ONE OF THE APPROACHES TO LOCALLY COORDINATING DERS

Net-metering and local energy market approaches can be viewed as forms of local coordination of DERs, or in other words, how do these approaches compare in terms of independence on the main grid. To make such an evaluation, we compare here the amount of energy both frameworks require from the main grid for different amounts of DER penetration, as means of testing how impacted would the loads be in case of disconnection from the main grid. This has at least two consequences that are in itself related: one is the acceptance of the approach by the prosumers considering their security of supply, and the other is the impact on utility interruption indexes.

Traditionally, interruption indexes are measured in duration and frequency of interruption, in the legacy operation of the grid where no DERs are present. With DER deployment, a better measure to establish energy reliability is not the presence of the main grid, but the overall average energy lost during disconnection which was not able to be provided by the DERs.

Figures 41 and 42 show the average load loss for net-metering and local market scenarios for different PV and storage penetration, respectively, as a percent of the load loss in the case of no DER scenario (Eq. 4.8).

$$E_{loss}[\%] = 100 \frac{E_{loss}}{E_{loss,noDERs}} \quad (4.8)$$

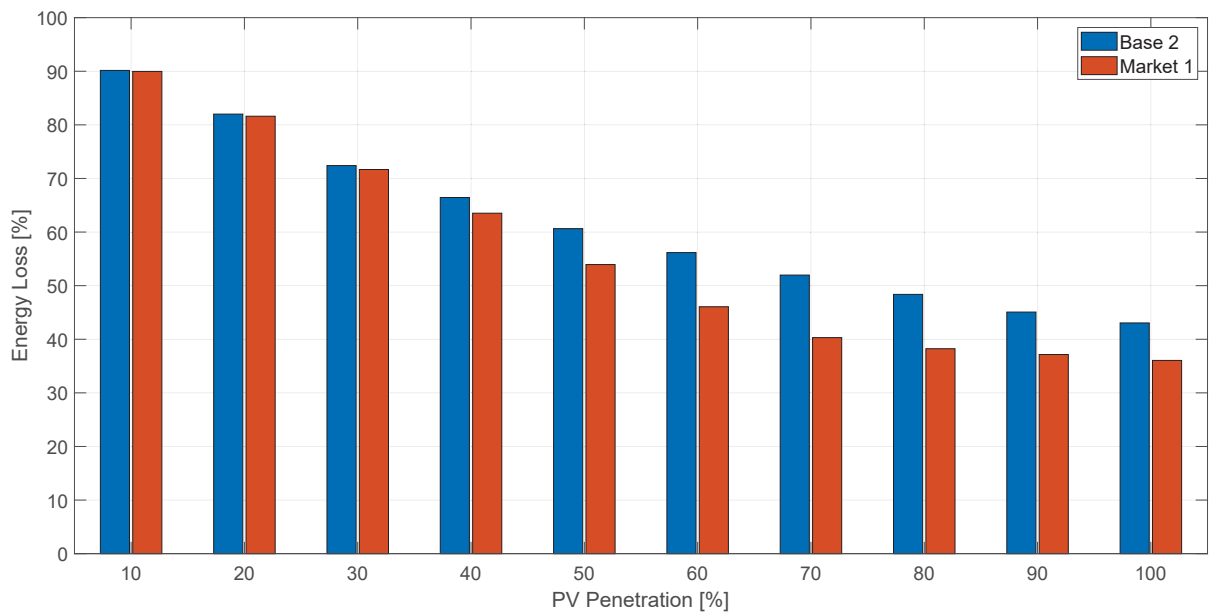


FIGURE 41 – Load loss as a percent from the no-DER deployment scenario for different PV penetrations)

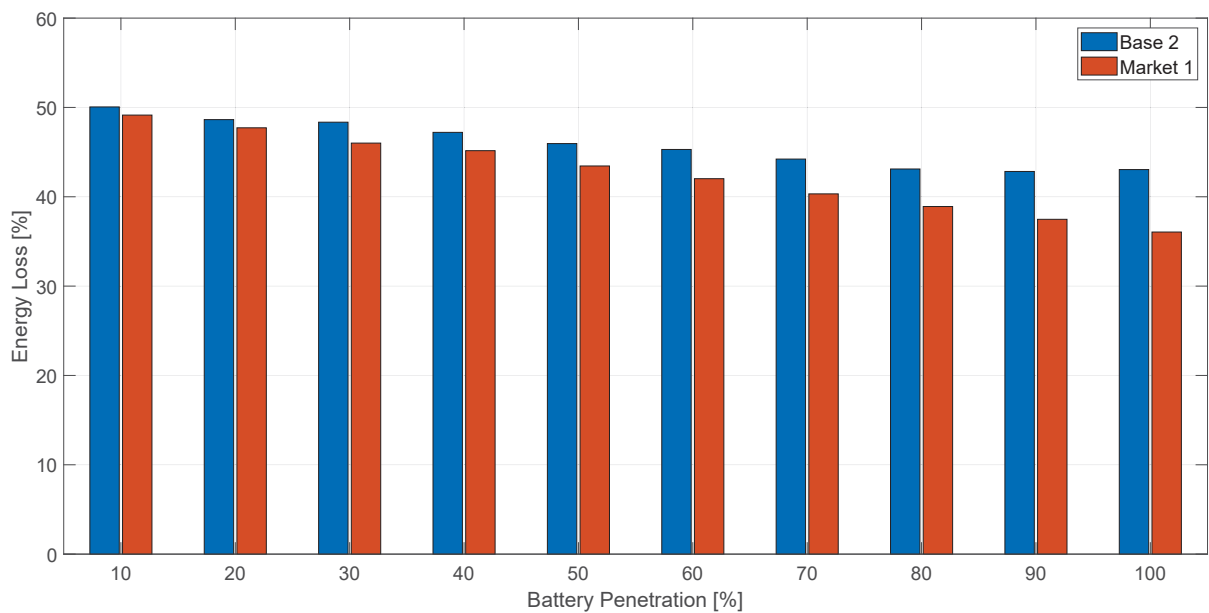


FIGURE 42 – Load loss as a percent from the no-DER deployment scenario for different Storage penetrations)

It is observed that the load loss is reduced at a greater rate for the local market scenario in comparison with net-metering with the increase of DER deployment. The local market framework has an advantage over net-metering in this aspect, given that the higher amount of flexibility of operation due to the effects of the collective consumption can better address load loss issues by grid disconnection.

Regarding the overall operation performance comparison, both utility and pro-

sumers can benefit more from the market operation due to its greater flexibility opportunities to improve network usage as long as a careful planning horizon with growing number of participants and varying DER penetrations is considered.

A possibility would be active allocation of DERs by the utility to strategically help grid operation. In such case, these allocated utility's assets would bid into the proposed energy markets as independent market participants according to a predefined cost-recovery curve. The adjustments or regulations that should be considered for the proposed energy trading scheme on account of this possible utility investment is also a topic for further research.

4.7 REDUCING COSTS FOR PROSUMERS

As already shown in Section 4.3, the local market scenarios bring advantages for the prosumers as opposed to net-metering in terms of reduction in energy bills, as long as the transaction fees are not too high.

When allowed to participate in the market, the prosumer will see a change in perceived prices for buying and selling energy. The mean value of the purchase and sell prices can be seen in Figures 43 and 44, respectively. The perceived prices for buying energy in the local market are greater than in net-metering scenario, because of the self-consumption phenomenon (prosumers self-consume PV energy at $0\$/kWh$ in the net-metering scenario, whereas they "buy" from their PV in the local market scenario). Meanwhile, they also perceive a greater price for the sale of energy offers, which results in a lower total energy bill in the end for each household.

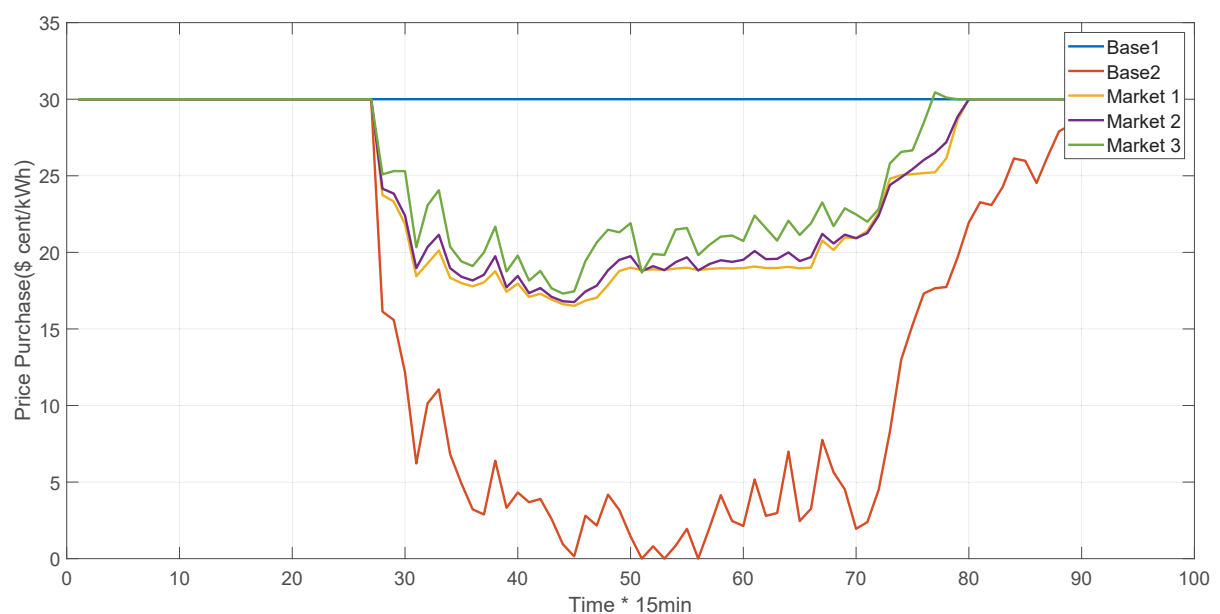


FIGURE 43 – Mean purchase prices perceived by the prosumers at each market slot

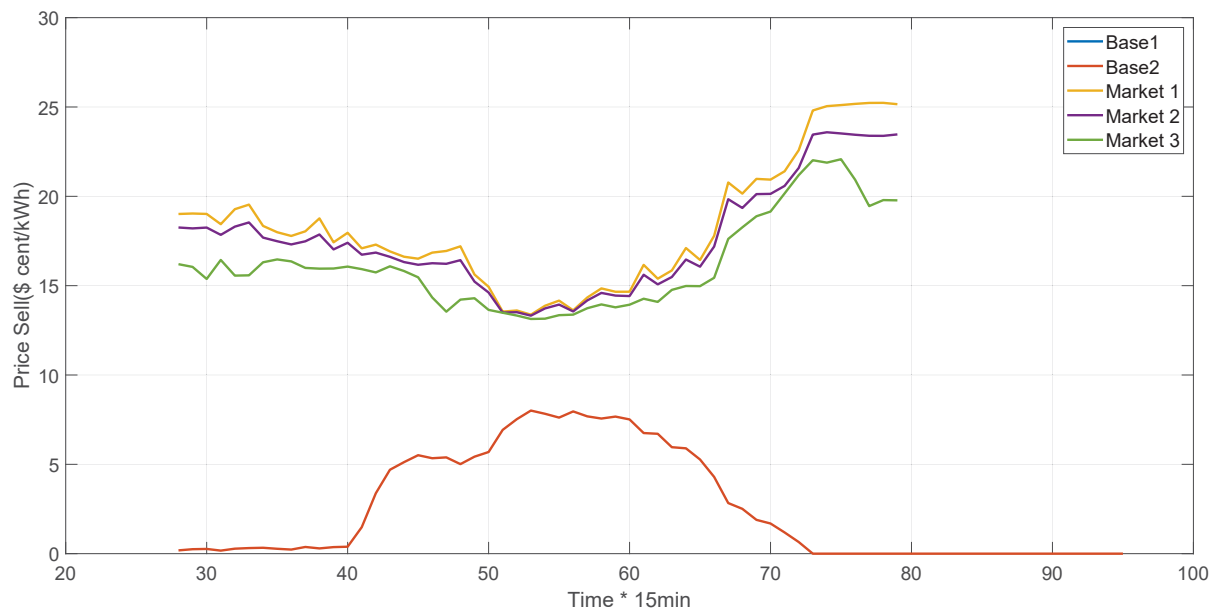


FIGURE 44 – Mean sell prices perceived by the prosumers at each market slot

This brings an indirect benefit for the prosumer to participate in the market, which the value there is to be found in the availability of production and flexibility of consumption. In other words, to maximize their profit, the prosumer could invest in greater generation and storage capacity or adjust their behaviors to consume less energy when the prices are higher. So, the better prices for energy sales present in the P2P local market scenario can be a motivation for more DER deployment and contribute to accelerating the transition to sustainable distributed generation.

4.8 DISCUSSION

The so far provided analyses modeled and quantified opportunities and challenges for all stakeholders in the adoption of local peer-to-peer energy markets. These analyses are summarized in Tables 15 and 16. With basis on the found results, the research questions posed in the Section 1.3 are discussed.

- How do P2P markets compare to net-metering/self-consumption in economic and technical performance?

In terms of revenue impact comparison, the analyses showed that market-driven systems are still a challenge to be tackled in order to provide both prosumers and utility with motivation enough to adopt and participate in the market. In none of the scenarios looking strictly to revenue were both stakeholders better off at the same time in comparison to the net-metering regulation.

The study presented in (HAIDER et al., 2021) also evaluates retail market performance for DERs under different stakeholder perspectives, and also reaches that the utility is not profiting as much from a retail market scenario as from net energy metering or traditional scenarios. It proposes then, that the utility turns its objective from making a large profit to an approach of social equity and profit socialization. Also (HERENCIC et al., 2021) sees how the economic benefits for prosumers affect the system operators negatively and speak for a "golden mean" where the profits are divided. However, both these studies look only at revenue comparison and do not quantify other possible advantages for the utility as a form of compensation for the revenue loss in a more comprehensive analysis. In (TUSHAR et al., 2021a), the perspective of the energy retailer is the focus as opposed to the prosumer, and the advantages for this retailer in terms of revenue compensation are also explored. This study brings out the importance of this theme but presents a quantification in a toy example in an exploratory manner.

At grid performance comparison, the simulated base case did not result in a positive impact for the utility in regard to the net-metering scenario. However, when varying PV and storage penetration, some setups can lead to an improvement on grid operation when in the market-driven scenario. The study in (DYNGE et al., 2021), which compares the grid performance for P2P and no-P2P scenarios, also finds that the voltages tend to fluctuate more in P2P trading. That study has found different results in system losses. The P2P trading scenario presents in that study significantly more losses than the no-P2P scenario. This difference is due to a difference in market design, since in (DYNGE et al., 2021) in the P2P trading scenario the batteries are allowed to engage in arbitrage, which provides a substantial difference in operation. In another study (BARANCSUK, 2021), a low voltage network is also analyzed, finding advantages in operating the grid in a P2P market scenario. That study however does not compare to the operation of the DERs in other regulation frameworks, it rather compares the local market to a base case with no DERs in a traditional utility operation.

By comparing net-metering and decentralized markets as a non-wire alternative to infrastructure investment, we found that the market operation has better potential to flexibility. Nonetheless, "proper" operation setups must be found to explore this flexibility in terms of PV/storage penetration sensitivity analysis. In previous works, most P2P analyses assume a given penetration of DER, which provides a static framework. This is limiting in that it does not allow for utilities to establish plans assuming different levels of DER in their networks, where real-world LEMs deployment is known to happen throughout a planning horizon with varying DER penetrations. An exception is (AZIM et al., 2020), which does perform an analysis on varying storage penetration. However, it focuses exclusively on losses quantification and does not include variations of other DERs.

The next advantage for the utility would be the functioning of the market-based scenario in comparison to net-metering as a better approach for local coordination of DERs. This is a clear advantage of the market operation since it taps onto the potential for collective consumption of the group. By analyzing a hypothetical islanding situation, the market operation was able to better coordinate the resources to tackle the load loss issue, which would directly impact the SAIDI and SAIFI indexes for the utility in a positive way.

Finally, the potential reduction of costs for the prosumers were compared as an advantage for the utility as well, in the sense of measuring its business success in terms of customer satisfaction. In this sense, the market framework has a clear advantage in comparison to the net-metering scenario before the implementation of network fees.

- What are the economic impacts of network fees as lost revenue adjustment mechanisms in peer-to-peer market schemes for utilities and prosumers?

Network fees in the form of grid and transaction fees are able to adjust revenue loss from market scenarios when compared to net-metering operation. One interesting finding is that the variation of number of agents, fee values, and DER deployment have a proportional impact on fee income, with certain thresholds where the utility revenue loss in regard to net-metering scenario can be reversed. Also, income impact between prosumers and utilities is strictly competitive in regards to net-metering - if the utility is profiting from the market operation in relation to net-metering, the prosumers are certainly losing from entering the market. This suggests to the utilities and policymakers, when designing the markets, that much care must be taken in order not to overdo fees in order not to scare prosumers out of the market, considering that a functioning market can only work with enough participants to ensure liquidity. A possible solution would be floating fees prices to variations in market participation and DER penetration. This way a compromise in revenue balance could be reached in order not to penalize either side.

- How do variations in DER penetration impact P2P markets in comparison to the net-metering/ self-consumption grid operation?

The different impacts in DER deployment sensitivity analysis highlight the need to do an integrative analysis of the said impacts. For example, when varying PV and storage penetration, the results show that for a penetration value of around 60%, the revenue for the utility is minimized in comparison to net-metering. However, for this penetration, the market shows the best possible outcome in terms of grid operation, being able to avoid reverse flows and minimizing grid utilization. In other words, the proportion of PV and storage that brings the least amount of revenue also provides the

least amount of cost for the utility. This is a key finding from this work that, to the best of the author's knowledge, hasn't been explored in other studies. Future research is needed due to its significance in the decision to adopt LEMs in distribution systems.

- And lastly, is it possible under the assumptions taken, that there is a scenario where both stakeholders - utility and prosumers - benefit more from peer-to-peer market schemes than from net-metering self-consumption regulatory framework?

This research has shown that a careful design of local market structures is needed for a decentralized energy market to be beneficial to all stakeholders, but such an equilibrium is achievable. The utility must be greatly involved in designing the market structure, possibly customizing solutions for different grid configurations. These customized solutions should take into account the grid particularities of each utility, but also under premises of a regulatory framework. Additional important aspects include the number of market participants, deployed DER generation profiles, generation-to-storage deployment ratios, the value of network fees, among others. The gains in operation flexibility on market-driven frameworks should also be acknowledged. This flexibility either the potential to be an asset and be quantified by itself, as it can bring operation cost reductions for the utility; or it can become a liability to operation if poorly coordinated. In summary, market operation offers opportunities but also challenges that must be thoroughly analyzed to ensure that its implementation will bring forth robustness, reliability, and effectiveness to the power system.

TABLE 15 – Results summary from performance comparison for each analyzes criterion

RoadBlocks	Analysis	Criteria	Results
Revenue Streams	Revenue Stream Performance Comparison	Revenues from the utility X Revenues from the Prosumers in all scenarios	From considering only revenues from energy sale, the P2P scenario is beneficial to the prosumer and disadvantageous for the utility. Once transaction fees are introduced, the situation is reverted.
		Proportion of prosumers who are better / worse off	The number of prosumers who are in advantage in comparison to net-metering decrease drastically with the introduction of transaction fees
		Sensitivity to number of agents	The utility benefits in revenue from increase of number of agents with regards to fee income.
		Sensitivity to network (grid and transaction) fees	By increasing the fees, there is a point where the P2P framework starts being more beneficial for the utility than the net-metering scenario. This comes, however, at a higher cost and the perceived disadvantage for the prosumer to participate in the market.
		Sensitivity to PV / Storage Penetration	Increase in PV and storage penetration result in more revenue from network fees due to higher market liquidity.
Unwanted Effects in Grid Operation	Grid Performance comparison: Net Metering x P2P	Voltage Profile	In neither of the frameworks the voltage is crossing its limits. However, for the base setup the market operation showed a higher voltage volatility.
		Transformer Load Factor	Transformer load factor deteriorates for market scenario due to bigger periods of higher collective autonomy and smaller imports from the grid.
		Circuit Losses	Circuit losses are not impacted from the different operations for the analyzed case study.
		Sensitivity to PV / Storage Penetration	There is a certain PV/storage penetration ratio that enables the local circuit to maximize self-consumption, avoiding reverse fluxes of power in P2P market scenarios, a feature that does not happen in net-metering scenario.

TABLE 16 – Results summary of analysis from local energy markets advantages

Advantages of LEM for the utility	Analysis	Criteria	Results
LEM as a non-wire alternative	Qualitative analysis of investment deferral - comparison between net-metering x P2P	Sensitivity to load increase and PV and storage penetration	The P2P scenario provides no perceived advantage for the utility in the case of exclusive load increase. However, the PV/storage ratio can be used within the market scenario to avoid reverse power flows to the main grid.
LEM as one of the approaches to locally coordinating DERs	Qualitative analysis of alleviating curtailment	Operation of microgrid in islanded mode - comparison of shedded load net metering x P2P	P2P operation resulted in reduced load loss in comparison to net-metering operation
Reducing costs for prosumers	Revenue Stream Performance Comparison	Revenues from the utility X Revenues from the Prosumers in all scenarios	Regarding exclusively costs from energy purchases and sales, prosumers always take advantage from the market in comparison to net-metering. When fees are introduced, prosumers can be worse off in market participation.
		Transaction Prices	Prosumers profit from better transaction prices in market participation.
		Sensitivity to number of agents	More market participants benefit the prosumers by increasing market liquidity and as a consequence its efficiency. However, the number of transactions per agent increases and so does the expenses in transaction fees.
		Sensitivity to network fees	The increase in fee prices will eat up the profits from the prosumers. If not balanced, they are likely to dismotivate the prosumer to join the market.

4.9 OUTLOOK

This performed study has brought light on some issues regarding local energy markets' impacts on distribution systems from a multiple stakeholder approach. As such, it also opened a set of new questions for future research and deepened the understanding of market approaches for distribution system operation. Some examples are detailed below.

To start, a deeper economic feasibility analysis of PV rooftop and storage implementation within a peer-to-peer market regulation framework is envisioned. The idea is to better understand cost recovery of distributed generation under market-driven operation by modeling costs of implementation and operation and maintenance. The levelized cost of energy (LCOE) and net present value could be calculated to see if a cost recovery under different market settings is possible, and how it compares to the cost recovery under net-metering.

Another envisioned possibility for future work would be to explore the impact of network fees on consumer behavior. In the present study, the customer behavior was not modified by price, meaning they didn't enter demand response mode by modifying their consumption patterns. In a more complex model, this could be taken into consideration. In this way, the impacts on revenues and grid operation would take a more dynamic reaction when fees are modified.

This study explored some of the effects of storage and PV penetration on utility. A deeper evaluation could be envisioned, where PV and storage penetration amounts are optimized for best market and grid operation outcomes. Even though the expansion of distributed generation is prosumer-defined and not controlled by the utility, the utility could use this information for the installation of utility-owned distributed generation allocated strategically at different nodes in the distribution system.

This list is not extensive and other research possibilities for the continuation of this investigation are possible. Other variations of market structures and network fees among others can be studied to keep improving the understanding of market-based operation impacts on the distribution systems.

5 CONCLUSION AND FUTURE WORK

The present study aimed to develop and carry out a systematic evaluation and quantification of P2P local energy markets' impacts on power distribution utilities in an integrated manner. It aimed at contributing on how P2P market-based operation of the distribution grid impacts the utilities as opposed to self-consumption/net-metering operation paradigms in a context of mass penetration of distributed energy resources (DERs).

Decentralized energy markets offer a promising solution for the integration of DERs. However, although the benefits for the prosumers are already well understood, little is known about its impacts on the utilities. So far, no regulatory framework in any country allows for the widespread adoption of decentralized energy markets due to this incertitude.

To target this knowledge gap, this study developed a comprehensive approach for the impact analysis of decentralized energy markets on utilities. First, literature research to review the concept of peer-to-peer and decentralized energy markets is conducted. Also, the up-to-date literature on the impacts of decentralized energy markets is carried out to assemble a better overview of these markets' feasibility for both primary stakeholders, prosumers, and utility alike. It showed that, after a period of trending research of market designs and mainly benefits for the prosumers, studies are recently turning the focus on the investigation of possible benefits for utilities.

This work created an evaluation framework with criteria to analyze the main roadblocks and opportunities for the utility to the adoption of P2P local energy markets. This evaluation framework made an effort to encompass both technical and economical aspects, summarized mainly in revenue performance analysis and grid operation performance analysis.

To execute this evaluation, a co-simulation platform was developed, connecting a market model to a power flow model. The market model consisted of a continuous pay-as-bid double auction running in 15-minute market slots. During a market slot, the agents make their bids and offers and once there is a match, a bilateral trade occurs. The utility also bids and offers and therefore participates in the market. Grid and transaction fees are also implemented. The whole setup is run for 24 hours, which is also used for the time-series steady-state grid calculations on the power flow model.

A case study based on a 55-users low voltage test feeder is constructed, each one possessing load, PV rooftop, and storage system. The results are analyzed in different scenarios comprising net-metering regulation, P2P market operation, and the

introduction of network fees.

The revenue performance comparison showed that the implementation of the market is decreasing revenue for the utility in comparison with a net-metering regulation. Nonetheless, by the implementation of grid and transaction fees the utility is capable of reversing the revenue loss. The analysis from the prosumers' point of view is the opposite: the market is benefiting the prosumer in comparison to net-metering, but network fees can erase this relative gain for the prosumer. This shows that a compromise in revenue balance will be needed when designing market structures and network fees in order not to penalize a single side of the stakeholders.

The grid operation performance comparison showed that the market operation for the base case study does not bring significant unwanted effects on grid operation. Even if it does not cause under- or overvoltages surpassing the operational limits, the market operation causes more voltage volatility. Transformer load factors are also worsened in market operation, not due to higher peaks, but due to longer periods of idle operation. This idle operation is a result of a more autonomic functioning of the system in regards to load demand from the main grid in reference to net-metering scenario, due to the collective self-consumption effect created in the market scenario.

The collective self-consumption effect created from the market scenario shows itself to be a great asset for grid operation. When varying PV penetration, the market scenario shows more flexibility in operation than the net-metering scenario. It was also discovered that there is an optimal point of a certain PV and storage combination penetration that maximizes the internal self-consumption inside the feeder and avoids reverse power flows upward the power network, thus minimizing dependence on the main grid. This feature could benefit the utility in the form of minimizing interruption indexes and operational cost reduction due to less utilization of the grid, even though the revenues for this operation are minimized in regard to net-metering.

Finally, for a decentralized energy market to be beneficial to all stakeholders, care must be taken when designing the market structures. The utility must be greatly involved in these designs. The regulators must pay attention to parameters such as the number of agents participating the markets, amount of DER deployment, generation-to-storage deployment ratios, the value of network fees, among others. The gains in the flexibility of operation in market-driven framework should be acknowledged. Depending on market structure and conditions, this flexibility has the potential to be an asset and be valued itself, as it can bring operation cost reduction for the utility; or it can turn into a liability to operation if poorly coordinated. In summary, the market operation offers opportunities but also dangers that must be thoroughly analyzed to ensure that its implementation is bringing reliability, sustainability, and effectiveness to the power system.

The main continuation for future research regards making the non-financial metrics tangible into economical quantification, or in other words, decoding the decentralized markets' cost reduction potential for the utility in economic terms. With that analysis, it would be then possible to deepen the financial and economic analysis of P2P markets implementation in terms of cost recovery and return of investment for the stakeholders.

Other possibilities of research opened by this study are to analyse the impact of P2P markets and the implementation of fees on consumer behaviour. When the consumer is exposed to different prices at various times of the day, considering the prosumers active role on a decentralized market, would that change their consumer behaviour? If yes, how would this change in behaviour impact the grid operation? This could be a major point of market design: to explore shaping of consumption behaviour to, besides serving the consumers individual interests, also service grids interests.

Finally, among other recommendations for future work, a study to deepen the analysis of how variation in DER penetration can be used for maximizing the market outcomes and efficient grid operation is suggested. It became clear during the current study that this is an important gap in decentralized energy market design analysis, considering the great variation the PV-to-storage deployment ratios have produced in market scenario outcomes.

In summary, this study has contributed as first steps toward comprehending how could the utilities embrace the approach of peer-to-peer energy markets as a feasible and profitable solution for its grid coordination challenges, all the while keeping prosumers' benefits and sovereignty. These first steps can already give initial directions to the policymakers, but they also open a set of new questions which must be taken upon by further research.

REFERENCES

ADAMS, S.; BROWN, D.; CÁRDENAS ÁLVAREZ, J. P.; CHITCHYAN, R.; FELL, M. J.; HAHNEL, U. J.; HOJCKOVA, K.; JOHNSON, C.; KLEIN, L.; MONTAKHABI, M.; SAY, K.; SINGH, A.; WATSON, N. Social and economic value in emerging decentralized energy business models: A critical review. **Energies**, v. 14, n. 23, p. 1–29, 2021. ISSN 19961073. DOI: [10.3390/en14237864](https://doi.org/10.3390/en14237864). Citado 1 vez na página 15.

AKTER, M. N.; MAHMUD, M. A.; OO, A. M. An optimal distributed transactive energy sharing approach for residential microgrids. **IEEE Power and Energy Society General Meeting**, 2018-Janua, p. 1–5, 2018. ISSN 19449933. DOI: [10.1109/PESGM.2017.8273879](https://doi.org/10.1109/PESGM.2017.8273879). Citado 0 vez na página 31.

AL, D. H. E.; OLYMPIC PENINSULA PROJECT, N. T. I. S. **Pacific Northwest GridWise™ Testbed Demonstration Projects, Part I**. [S.l.], 2007. P. 157. DOI: [10.2172/926122](https://doi.org/10.2172/926122). Disponível em: http://www.gridwise.pnl.gov/docs/op_project_final_report_pnnl17167.pdf. Citado 1 vez na página 26.

ALBADI, M.; EL-SAADANY, E. Overview of wind power intermittency impacts on power systems. **Electric Power Systems Research**, v. 80, n. 6, p. 627–632, 2010. ISSN 0378-7796. DOI: <https://doi.org/10.1016/j.epsr.2009.10.035>. Disponível em: <https://www.sciencedirect.com/science/article/pii/S0378779609002764>. Citado 1 vez na página 21.

ALVES, F. C. L.; PEREIRA, A. O.; SÁNCHEZ, J. C. M. Analysis of regulatory process for the implementation of smart metering in Brazil. **Decision Analytics Journal**, v. 3, p. 100053, 2022. ISSN 2772-6622. Citado 1 vez na página 28.

ANDONI, M.; ROBU, V.; FLYNN, D.; ABRAM, S.; GEACH, D.; JENKINS, D.; MCCALLUM, P.; PEACOCK, A. Blockchain technology in the energy sector: A systematic review of challenges and opportunities. **Renewable and Sustainable Energy Reviews**, Elsevier Ltd, v. 100, November 2018, p. 143–174, 2019. ISSN 18790690. DOI: [10.1016/j.rser.2018.10.014](https://doi.org/10.1016/j.rser.2018.10.014). Disponível em: <https://doi.org/10.1016/j.rser.2018.10.014>. Citado 1 vez na página 24.

ASKELAND, M.; BACKE, S.; BJARGHOV, S.; KORPÅS, M. Helping end-users help each other: Coordinating development and operation of distributed resources through

local power markets and grid tariffs. **Energy Economics**, v. 94, 2021. ISSN 01409883. DOI: [10.1016/j.eneco.2020.105065](https://doi.org/10.1016/j.eneco.2020.105065). Citado 3 vezes nas páginas 24, 40, 41.

AZIM, M. I.; POURMOUSAVI, S. A.; TUSHAR, W.; SAHA, T. K. Feasibility Study of Financial P2P Energy Trading in a Grid-tied Power Network. **IEEE Power and Energy Society General Meeting**, 2019-Augus, p. 1–4, 2019. ISSN 19449933. DOI: [10.1109/PESGM40551.2019.8973809](https://doi.org/10.1109/PESGM40551.2019.8973809). arXiv: [1909.04763](https://arxiv.org/abs/1909.04763). Citado 2 vezes nas páginas 36, 37.

AZIM, M. I.; TUSHAR, W.; SAHA, T. K. Investigating the impact of P2P trading on power losses in grid-connected networks with prosumers. **Applied Energy**, Elsevier, v. 263, February, p. 114687, 2020. ISSN 03062619. DOI: [10.1016/j.apenergy.2020.114687](https://doi.org/10.1016/j.apenergy.2020.114687). Disponível em: <https://doi.org/10.1016/j.apenergy.2020.114687>. Citado 2 vezes nas páginas 36, 38, 77.

BARANCSUK, L. Feasibility study of a local peer-to-peer energy market : Implications on a real-life LV distribution grid. n. 824330, 2021. Citado 1 vez na página 77.

BAROCHE, T.; MORET, F.; PINSON, P. Prosumer markets: A unified formulation. **2019 IEEE Milan PowerTech, PowerTech 2019**, IEEE, 2019. DOI: [10.1109/PTC.2019.8810474](https://doi.org/10.1109/PTC.2019.8810474). Citado 3 vezes nas páginas 28, 37, 38.

BOTELHO, D. F.; DIAS, B. H.; OLIVEIRA, L. W. de; SOARES, T. A.; REZENDE, I.; SOUSA, T. Innovative business models as drivers for prosumers integration - Enablers and barriers. **Renewable and Sustainable Energy Reviews**, Elsevier Ltd, v. 144, March, p. 111057, 2021. ISSN 18790690. DOI: [10.1016/j.rser.2021.111057](https://doi.org/10.1016/j.rser.2021.111057). Disponível em: <https://doi.org/10.1016/j.rser.2021.111057>. Citado 3 vezes nas páginas 15, 39.

CHASSIN, D. P. Multi-scale Transactive Control In Interconnected Bulk Power Systems Under High Renewable Energy Supply and High Demand Response Scenarios, nov. 2017. arXiv: [1711.09704](https://arxiv.org/abs/1711.09704). Disponível em: <http://arxiv.org/abs/1711.09704>. Citado 1 vez na página 23.

CHEN, Y.; HU, M. A swarm intelligence based distributed decision approach for transactive operation of networked building clusters. **Energy and Buildings**, Elsevier, v. 169, p. 172–184, 2018. ISSN 03787788. DOI: [10.1016/j.enbuild.2018.03.047](https://doi.org/10.1016/j.enbuild.2018.03.047). Disponível em: <https://www.sciencedirect.com/science/article/pii/S0378778817337763>. Citado 0 vez na página 31.

CIOCIA, A.; AMATO, A.; DI LEO, P.; FICHERA, S.; MALGAROLI, G.; SPERTINO, F.; TZANOVA, S. Self-Consumption and Self-Sufficiency in Photovoltaic Systems: Effect of Grid Limitation and Storage Installation. **Energies**, v. 14, n. 6, 2021. ISSN 1996-1073. DOI: [10.3390/en14061591](https://doi.org/10.3390/en14061591). Disponível em:

<https://www.mdpi.com/1996-1073/14/6/1591>. Citado 1 vez na página 36.

COLLINS, L. D.; MIDDLETON, R. H. Distributed Demand Peak Reduction with Non-Cooperative Players and Minimal Communication. **IEEE Transactions on Smart Grid**, ieeexplore.ieee.org, v. 10, n. 1, p. 153–162, 2019. ISSN 19493053. DOI: [10.1109/TSG.2017.2734113](https://doi.org/10.1109/TSG.2017.2734113). Disponível em:

<http://ieeexplore.ieee.org/abstract/document/7999238/>. Citado 1 vez na página 30.

DIVSHALI, P. H.; CHOI, B. J.; LIANG, H.; SÖDER, L. Transactive demand side management programs in smart grids with high penetration of EVs. **Energies**, v. 10, n. 10, p. 1–18, 2017. ISSN 19961073. DOI: [10.3390/en10101640](https://doi.org/10.3390/en10101640). Citado 0 vez na página 31.

DUDJAK, V.; NEVES, D.; ALSKAIF, T.; KHADEM, S.; PENA-BELLO, A.; SAGGESE, P.; BOWLER, B.; ANDONI, M.; BERTOLINI, M.; ZHOU, Y.; LORMETEAU, B.; MUSTAFA, M. A.; WANG, Y.; FRANCIS, C.; ZOBIRI, F.; PARRA, D.; PAPAEMMANOUIL, A. Impact of local energy markets integration in power systems layer: A comprehensive review. **Applied Energy**, Elsevier Ltd, v. 301, August, p. 117434, 2021. ISSN 03062619. DOI: [10.1016/j.apenergy.2021.117434](https://doi.org/10.1016/j.apenergy.2021.117434). Disponível em: <https://doi.org/10.1016/j.apenergy.2021.117434>. Citado 3 vezes nas páginas 15, 40.

DYNGE, M. F.; CRESPO DEL GRANADO, P.; HASHEMIPOUR, N.; KORPÅS, M. Impact of local electricity markets and peer-to-peer trading on low-voltage grid operations. **Applied Energy**, Elsevier Ltd, v. 301, July, p. 117404, 2021. ISSN 03062619. DOI: [10.1016/j.apenergy.2021.117404](https://doi.org/10.1016/j.apenergy.2021.117404). Disponível em: <https://doi.org/10.1016/j.apenergy.2021.117404>. Citado 5 vezes nas páginas 40, 66, 68, 77.

EPRI. **OpenDSS**. [S.l.: s.n.], 2021. Disponível em:

<https://sourceforge.net/projects/electricdss/>. Citado 1 vez na página 45.

ESFAHANI, M. M.; HARIRI, A.; MOHAMMED, O. A. A Multiagent-Based Game-Theoretic and Optimization Approach for Market Operation of Multimicrogrid Systems. **IEEE Transactions on Industrial Informatics**, ieeexplore.ieee.org, v. 15,

n. 1, p. 280–292, 2019. ISSN 15513203. DOI: [10.1109/TII.2018.2808183](https://doi.org/10.1109/TII.2018.2808183). Disponível em: <https://ieeexplore.ieee.org/abstract/document/8295249/>. Citado 1 vez na página 32.

EURELECTRIC. **Prosumers – an integral part of the power system and the market**. [S.l.], jun. 2015. Citado 1 vez na página 21.

FAQIRY, M. N.; DAS, S. Double Auction with Hidden User Information: Application to Energy Transaction in Microgrid. **IEEE Transactions on Systems, Man, and Cybernetics: Systems**, v. 49, n. 11, p. 2326–2339, 2019. ISSN 21682232. DOI: [10.1109/TSMC.2018.2800006](https://doi.org/10.1109/TSMC.2018.2800006). Citado 1 vezes nas páginas 24, 31.

FULLER, J. C.; SCHNEIDER, K. P.; CHASSIN, D. Analysis of residential demand response and double-auction markets. In: IEEE Power and Energy Society General Meeting. [S.l.]: ieeexplore.ieee.org, 2011. P. 1–7. ISBN 9781457710018. DOI: [10.1109/PES.2011.6039827](https://doi.org/10.1109/PES.2011.6039827). Disponível em: <http://ieeexplore.ieee.org/abstract/document/6039827/>. Citado 1 vezes nas páginas 31, 32.

GRID SINGULARITY. **Grid Singularity Exchange**. [S.l.: s.n.], 2021. Disponível em: <https://d3a.io>. Citado 2 vezes nas páginas 45, 49.

GUERRERO, J.; CHAPMAN, A. C.; VERBIC, G. Decentralized P2P Energy Trading under Network Constraints in a Low-Voltage Network. **IEEE Transactions on Smart Grid**, IEEE, v. 10, n. 5, p. 5163–5173, 2018. ISSN 19493053. DOI: [10.1109/TSG.2018.2878445](https://doi.org/10.1109/TSG.2018.2878445). arXiv: [1809.06976](https://arxiv.org/abs/1809.06976). Citado 1 vez na página 31.

GUERRERO, J.; GEBBRAN, D.; MHANNA, S.; CHAPMAN, A. C.; VERBIČ, G. Towards a transactive energy system for integration of distributed energy resources: Home energy management, distributed optimal power flow, and peer-to-peer energy trading. **Renewable and Sustainable Energy Reviews**, v. 132, June, 2020. ISSN 18790690. DOI: [10.1016/j.rser.2020.110000](https://doi.org/10.1016/j.rser.2020.110000). Citado 2 vezes nas páginas 36, 37.

GWAC. **GridWise Transactive Energy Framework Draft Version**. [S.l.]: [osti.gov](https://www.osti.gov), 2013. v. 1, p. 1–23. Disponível em: <https://www.osti.gov/scitech/biblio/1123244>. Citado 2 vezes nas páginas 14, 20.

HAIDER, R.; D'ACHIARDI, D.; VENKATARAMANAN, V.; SRIVASTAVA, A.; BOSE, A.; ANNASWAMY, A. M. Reinventing the Utility for DERs: A Proposal for a DSO-Centric Retail Electricity

Market, 2021. DOI: [10.1016/j.adapen.2021.100026](https://doi.org/10.1016/j.adapen.2021.100026). arXiv: [2102.01269](https://arxiv.org/abs/2102.01269). Disponível em: <http://arxiv.org/abs/2102.01269%5C%0Ahttp://dx.doi.org/10.1016/j.adapen.2021.100026>. Citado 2 vezes nas páginas 63, 77.

HAO, H.; CORBIN, C. D.; KALSI, K.; PRATT, R. G. Transactive Control of Commercial Buildings for Demand Response. **IEEE Transactions on Power Systems**, ieeexplore.ieee.org, v. 32, n. 1, p. 774–783, 2017. ISSN 08858950. DOI: [10.1109/TPWRS.2016.2559485](https://doi.org/10.1109/TPWRS.2016.2559485). Disponível em: <http://ieeexplore.ieee.org/abstract/document/7460977/>. Citado 1 vez na página 32.

HAYES, B. P.; THAKUR, S.; BRESLIN, J. G. Co-simulation of electricity distribution networks and peer to peer energy trading platforms. **International Journal of Electrical Power and Energy Systems**, Elsevier, v. 115, January 2019, p. 105419, 2020. ISSN 01420615. DOI: [10.1016/j.ijepes.2019.105419](https://doi.org/10.1016/j.ijepes.2019.105419). Disponível em: <https://doi.org/10.1016/j.ijepes.2019.105419>. Citado 3 vezes nas páginas 36, 37, 45.

HEO, K.; KONG, J.; OH, S.; JUNG, J. Development of operator-oriented peer-to-peer energy trading model for integration into the existing distribution system. **International Journal of Electrical Power and Energy Systems**, Elsevier, v. 125, August 2020, p. 106488, 2021. ISSN 01420615. DOI: [10.1016/j.ijepes.2020.106488](https://doi.org/10.1016/j.ijepes.2020.106488). Disponível em: <https://doi.org/10.1016/j.ijepes.2020.106488>. Citado 1 vez na página 41.

HERENCIC, L.; ILAK, P.; RAJSL, I.; KELAVA, M. Local energy trading under emerging regulatory frameworks: Impacts on market participants and power balance in distribution grids. **EUROCON 2021 - 19th IEEE International Conference on Smart Technologies, Proceedings**, IEEE, p. 449–454, 2021. DOI: [10.1109/EUROCON52738.2021.9535547](https://doi.org/10.1109/EUROCON52738.2021.9535547). Citado 2 vezes nas páginas 63, 77.

HU, J.; YANG, G.; KOK, K.; XUE, Y.; BINDNER, H. W. Transactive control: a framework for operating power systems characterized by high penetration of distributed energy resources. **Journal of Modern Power Systems and Clean Energy**, Springer Berlin Heidelberg, v. 5, n. 3, p. 451–464, 2017. ISSN 21965420. DOI: [10.1007/s40565-016-0228-1](https://doi.org/10.1007/s40565-016-0228-1). Citado 0 vez na página 31.

IEA. Security of Clean Energy Transitions. **Security of Clean Energy Transitions**, 2021. DOI: [10.1787/cc14cdd2-en](https://doi.org/10.1787/cc14cdd2-en). Citado 1 vez na página 20.

IEA. World Energy Outlook 2019. **World Energy Outlook Series**, 2019. Disponível em: <https://www.iea.org/reports/world-energy-outlook-2019>. Citado 1 vez na página 21.

IEEE. **IEEE PES Test Feeder Cases**. [S.l.: s.n.], fev. 2016.

<https://cmte.ieee.org/pes-testfeeders/resources/>. Citado 1 vez na página 52.

IPCC. Climate Change 2021. **The Physical Science Basis. Contribution of Working Group 1 to Sixth Assessment Report of the Intergovernmental Panel on Climate Change**, in press, 2021. Disponível em: <https://www.ipcc.ch/report/ar6/wg1/>. Citado 1 vez na página 20.

ISMAEL, S. M.; ABDEL ALEEM, S. H.; ABDELAZIZ, A. Y.; ZOBAA, A. F.

State-of-the-art of hosting capacity in modern power systems with distributed generation. **Renewable Energy**, v. 130, p. 1002–1020, 2019. ISSN 0960-1481. DOI: <https://doi.org/10.1016/j.renene.2018.07.008>. Disponível em:

<https://www.sciencedirect.com/science/article/pii/S0960148118307936>. Citado 1 vez na página 21.

JENKINS, M.; KOCKAR, I. Impact of P2P trading on distributed generation curtailment in constrained distribution networks. **Electric Power Systems Research**, Elsevier, v. 189, April, p. 106666, 2020. ISSN 03787796. DOI: [10.1016/j.epsr.2020.106666](https://doi.org/10.1016/j.epsr.2020.106666). Disponível em: <https://doi.org/10.1016/j.epsr.2020.106666>. Citado 1 vezes nas páginas 36, 38.

JOGUNOLA, O.; IKPEHAI, A.; ANOH, K.; ADEBISI, B.; HAMMOUDEH, M.; SON, S. Y.; HARRIS, G. State-of-the-art and prospects for peer-to-peer transaction-based energy system. **Energies**, mdpi.com, v. 10, n. 12, 2017. ISSN 19961073. DOI: [10.3390/en10122106](https://doi.org/10.3390/en10122106). Disponível em: <http://www.mdpi.com/1996-1073/10/12/2106>. Citado 3 vezes nas páginas 14, 25, 31.

JOINT RESEARCH CENTER. **Distribution System Operators Observatory 2018**. [S.l.: s.n.], 2019. ISBN 9789279987380. DOI: [10.2760/2690](https://doi.org/10.2760/2690). Citado 1 vez na página 27.

KIM, B.; BAE, S.; KIM, H. **Optimal energy scheduling and transaction mechanism for multiple microgrids**. v. 10. [S.l.]: mdpi.com, 2017. DOI: [10.3390/en10040566](https://doi.org/10.3390/en10040566). Disponível em: <http://www.mdpi.com/1996-1073/10/4/566/htm>. Citado 0 vez na página 31.

KIRSCHEN, D.; STRBAC, G. **Fundamentals of Power System Economics**. United Kingdom: John Wiley & Sons Ltd, 2004. ISBN 0-470-84572-4. Citado 3 vezes nas páginas 19, 21, 28.

KOK, K. The PowerMAcher: Smart Coordination for the Smart Electricity Grid. **PhD Thesis**, dare.ubvu.vu.nl, November, p. 293, 2013. ISSN 1098-6596. arXiv: [arXiv:1011.1669v3](https://arxiv.org/abs/1011.1669v3). Disponível em: <http://medcontent.metapress.com/index/A65RM03P4874243N.pdf>. Citado 5 vezes nas páginas 20, 22, 23, 25, 26, 33.

KOK, K.; ROOSSIEN, B.; MACDOUGALL, P.; VAN PRUISSSEN, O.; VENEKAMP, G.; KAMPHUIS, R.; LAARAKKERS, J.; WARMER, C. Dynamic pricing by scalable energy management systems Field experiences and simulation results using PowerMatcher. **IEEE Power and Energy Society General Meeting**, ieeexplore.ieee.org, 2012. ISSN 19449925. DOI: [10.1109/PESGM.2012.6345058](https://doi.org/10.1109/PESGM.2012.6345058). Disponível em: <http://ieeexplore.ieee.org/abstract/document/6345058/>. Citado 1 vez na página 24.

KOK, K.; WIDERGREN, S. A Society of Devices: Integrating Intelligent Distributed Resources with Transactive Energy. **IEEE Power and Energy Magazine**, ieeexplore.ieee.org, v. 14, n. 3, p. 34–45, 2016. ISSN 15407977. DOI: [10.1109/MPE.2016.2524962](https://doi.org/10.1109/MPE.2016.2524962). Disponível em: <http://ieeexplore.ieee.org/abstract/document/7452756/>. Citado 4 vezes nas páginas 14, 24, 26, 27.

KÜSTER, K. K.; AOKI, A. R.; LAMBERT-TORRES, G. Transaction-based operation of electric distribution systems: A review. **International Transactions on Electrical Energy Systems**, May, p. 1–17, 2019. ISSN 20507038. DOI: [10.1002/2050-7038.12194](https://doi.org/10.1002/2050-7038.12194). Citado 4 vezes nas páginas 14, 19, 35–37.

LIU, Y.; ZUO, K.; LIU, X. (; LIU, J.; KENNEDY, J. M. Dynamic pricing for decentralized energy trading in micro-grids. **Applied Energy**, Elsevier, v. 228, May, p. 689–699, 2018. ISSN 03062619. DOI: [10.1016/j.apenergy.2018.06.124](https://doi.org/10.1016/j.apenergy.2018.06.124). Disponível em: <https://doi.org/10.1016/j.apenergy.2018.06.124>. Citado 1 vez na página 33.

LIU, Z.; WU, Q.; MA, K.; SHAHIDEHPOUR, M.; XUE, Y.; HUANG, S. Two-Stage Optimal Scheduling of Electric Vehicle Charging Based on Transactive Control. **IEEE Transactions on Smart Grid**, v. 10, n. 3, p. 2948–2958, 2019. ISSN 19493053. DOI: [10.1109/TSG.2018.2815593](https://doi.org/10.1109/TSG.2018.2815593). Citado 1 vez na página 23.

MENGELKAMP, E.; GÄRTTNER, J.; ROCK, K.; KESSLER, S.; ORSINI, L.; WEINHARDT, C. Designing microgrid energy markets: A case study: The Brooklyn Microgrid. **Applied Energy**, Elsevier Ltd, v. 210, p. 870–880, 2018. ISSN 03062619.

DOI: [10.1016/j.apenergy.2017.06.054](https://doi.org/10.1016/j.apenergy.2017.06.054). Disponível em:
<https://doi.org/10.1016/j.apenergy.2017.06.054>. Citado 1 vez na página 26.

MORET, F.; BAROCHE, T.; SORIN, E.; PINSON, P. Negotiation algorithms for peer-to-peer electricity markets: Computational properties. In: 20TH Power Systems Computation Conference, PSCC 2018. [S.l.: s.n.], 2018. P. 1–7. ISBN 9781910963104. DOI: [10.23919/PSCC.2018.8442914](https://doi.org/10.23919/PSCC.2018.8442914). Citado 1 vez na página 23.

MORET, F.; PINSON, P. Energy Collectives: A Community and Fairness Based Approach to Future Electricity Markets. **IEEE Transactions on Power Systems**, ieeexplore.ieee.org, v. 34, n. 5, p. 3994–4004, 2019. ISSN 15580679. DOI: [10.1109/TPWRS.2018.2808961](https://doi.org/10.1109/TPWRS.2018.2808961). Disponível em:
<https://ieeexplore.ieee.org/abstract/document/8301552/>. Citado 1 vez na página 24.

MORET, F.; TOSATTO, A.; BAROCHE, T.; PINSON, P. Loss allocation in joint transmission and distribution Peer-to-peer markets. **IEEE Transactions on Power Systems**, v. 36, n. 3, p. 1833–1842, 2021. ISSN 15580679. DOI: [10.1109/TPWRS.2020.3025391](https://doi.org/10.1109/TPWRS.2020.3025391). arXiv: [2001.05396](https://arxiv.org/abs/2001.05396). Disponível em:
<http://arxiv.org/abs/2001.05396>. Citado 2 vezes nas páginas 36, 38.

MORSTYN, T.; COLLETT, K. A.; VIJAY, A.; DEAKIN, M.; WHEELER, S.; BHAGAVATHY, S. M.; FELE, F.; MCCULLOCH, M. D. OPEN: An open-source platform for developing smart local energy system applications. **Applied Energy**, v. 275, p. 115397, 2020. ISSN 0306-2619. DOI: <https://doi.org/10.1016/j.apenergy.2020.115397>. Disponível em:
<https://www.sciencedirect.com/science/article/pii/S0306261920309090>. Citado 1 vez na página 14.

MORSTYN, T.; TEYTELBOYM, A.; HEPBURN, C.; MCCULLOCH, M. D. Integrating P2P Energy Trading with Probabilistic Distribution Locational Marginal Pricing. **IEEE Transactions on Smart Grid**, IEEE, v. 11, n. 4, p. 3095–3106, 2020. ISSN 19493061. DOI: [10.1109/TSG.2019.2963238](https://doi.org/10.1109/TSG.2019.2963238). Citado 1 vezes nas páginas 36, 39.

NIKOLAIDIS, A. I.; CHARALAMBOUS, C. A.; MANCARELLA, P. A Graph-Based Loss Allocation Framework for Transactive Energy Markets in Unbalanced Radial Distribution Networks. **IEEE Transactions on Power Systems**, IEEE, v. 34, n. 5, p. 4109–4118, 2019. ISSN 15580679. DOI: [10.1109/TPWRS.2018.2832164](https://doi.org/10.1109/TPWRS.2018.2832164). Citado 2 vezes nas páginas 36–38.

NUNNA, H. S.; SRINIVASAN, D. Multiagent-Based Transactive Energy Framework for Distribution Systems with Smart Microgrids. **IEEE Transactions on Industrial Informatics**, ieeexplore.ieee.org, v. 13, n. 5, p. 2241–2250, 2017. ISSN 15513203. DOI: [10.1109/TII.2017.2679808](https://doi.org/10.1109/TII.2017.2679808). Disponível em:

<http://ieeexplore.ieee.org/abstract/document/7874097/>. Citado 0 vez na página 31.

PARAG, Y.; SOVACOO, B. K. Electricity market design for the prosumer era. **Nature Energy**, v. 1, n. 4, p. 16032, 2016. ISSN 2058-7546. DOI: [10.1038/nenergy.2016.32](https://doi.org/10.1038/nenergy.2016.32). Disponível em: <http://www.nature.com/articles/nenergy201632>. Citado 2 vez na página 14.

PASSEY, R.; SPOONER, T.; MACGILL, I.; WATT, M.; SYNGELLAKIS, K. The potential impacts of grid-connected distributed generation and how to address them: A review of technical and non-technical factors. **Energy Policy**, v. 39, n. 10, p. 6280–6290, 2011. Sustainability of biofuels. ISSN 0301-4215. DOI:

<https://doi.org/10.1016/j.enpol.2011.07.027>. Disponível em:

<https://www.sciencedirect.com/science/article/pii/S0301421511005519>. Citado 1 vez na página 36.

PAUDEL, A.; SAMPATH, L. P.; YANG, J.; GOOI, H. B. Peer-to-Peer Energy Trading in Smart Grid Considering Power Losses and Network Fees. **IEEE Transactions on Smart Grid**, v. 11, n. 6, p. 4727–4737, 2020. ISSN 19493061. DOI: [10.1109/TSG.2020.2997956](https://doi.org/10.1109/TSG.2020.2997956). Citado 1 vezes nas páginas 36, 38.

PENA-BELLO, A.; PARRA, D.; HERBERZ, M.; TIEFENBECK, V.; PATEL, M. K.; HAHNEL, U. J. J. Integration of prosumer peer-to-peer trading decisions into energy community modelling. **Nature Energy**, v. 7, n. 1, p. 74–82, 2022. ISSN 2058-7546. DOI: [10.1038/s41560-021-00950-2](https://doi.org/10.1038/s41560-021-00950-2). Disponível em:

<https://doi.org/10.1038/s41560-021-00950-2>. Citado 1 vez na página 39.

PINSON, P. **Renewables in Electricity Markets: Module 2 - From bilateral contracts to the electricity pool**. [S.l.: s.n.], 2019.

<http://pierrepinson.com/index.php/teaching/module-2-electricity-spot-markets-e-g-day-ahead/>, Last accessed on 2022-03-07. Citado 0 vez na página 29.

PINSON, P.; BAROCHE, T.; MORET, F.; SOUSA, T.; SORIN, E.; YOU, S. **The Emergence of Consumer-centric Electricity Markets**. [S.l.: s.n.], 2017. P. 1–5. ISBN 2016112530. Disponível em:

<http://pierrepinson.com/docs/pinsonetal17consumercentric.pdf>. Citado 0 vez na página 22.

PRESSMAIR, G.; KAPASSA, E.; CASADO-MANSILLA, D.; BORGES, C. E.; THEMISTOCLEOUS, M. Overcoming barriers for the adoption of Local Energy and Flexibility Markets: A user-centric and hybrid model. **Journal of Cleaner Production**, Elsevier Ltd, v. 317, July, p. 128323, 2021. ISSN 09596526. DOI:

[10.1016/j.jclepro.2021.128323](https://doi.org/10.1016/j.jclepro.2021.128323). Disponível em:

<https://doi.org/10.1016/j.jclepro.2021.128323>. Citado 2 vezes nas páginas 39, 41.

RENANI, Y. K.; EHSAN, M.; SHAHIDEHPOUR, M. Optimal transactive market operations with distribution system operators. **IEEE Transactions on Smart Grid**, ieeexplore.ieee.org, v. 9, n. 6, p. 6692–6701, 2018. ISSN 19493053. DOI:

[10.1109/TSG.2017.2718546](https://doi.org/10.1109/TSG.2017.2718546). Disponível em:

<http://ieeexplore.ieee.org/abstract/document/7955039/>. Citado 1 vezes nas páginas 31, 32.

RÖVEKAMP, P.; SCHÖPF, M.; WAGON, F.; WEIBELZAHN, M.; FRIDGEN, G. Renewable electricity business models in a post feed-in tariff era. **Energy**, v. 216, 2021. ISSN 03605442. DOI: [10.1016/j.energy.2020.119228](https://doi.org/10.1016/j.energy.2020.119228). Citado 2 vezes nas páginas 39, 41.

SCHNEIDER, D.; KÜSTER, K. K.; SIEFERT, M.; SPECKMANN, M. Available active power estimation for the provision of control reserve by wind turbines. In: EUROPEAN Wind Energy Conference and Exhibition, EWEC 2013. [S.l.: s.n.], 2013. v. 1, p. 530–535. ISBN 9781632663146. Citado 2 vezes nas páginas 20, 23.

SIEMENS. **Distributed Energy Systems: Pooling Resources**. [S.l.: s.n.], 2016.

<https://www.siemens.com/customer-magazine/en/home/cities/distributed-energy-systems-pooling-resources.html>, Last accessed on 2019-04-05. Citado 0 vez na página 25.

SORRELL, S.; SPEIRS, J.; BENTLEY, R.; MILLER, R.; THOMPSON, E. Shaping the global oil peak: A review of the evidence on field sizes, reserve growth, decline rates and depletion rates. **Energy**, v. 37, n. 1, p. 709–724, 2012. 7th Biennial International Workshop “Advances in Energy Studies”. ISSN 0360-5442. DOI:

<https://doi.org/10.1016/j.energy.2011.10.010>. Disponível em:

<https://www.sciencedirect.com/science/article/pii/S0360544211006694>. Citado 1 vez na página 20.

TONGSOPIT, S.; ZINAMAN, O. R.; DARGHOUTH, N. R. **Understanding the Impact of Distributed Photovoltaic Adoption on Utility Revenues and Retail Electricity Tariffs in Thailand**. [S.l.], nov. 2017. Citado 1 vez na página 15.

TUSHAR, W.; SAHA, T. K.; YUEN, C.; LIDDELL, P.; BEAN, R.; POOR, H. V. Peer-to-Peer Energy Trading With Sustainable User Participation: A Game Theoretic Approach. **IEEE Access**, IEEE, v. 6, p. 62932–62943, 2018. ISSN 21693536. DOI: [10.1109/ACCESS.2018.2875405](https://doi.org/10.1109/ACCESS.2018.2875405). arXiv: [1809.11034](https://arxiv.org/abs/1809.11034). Citado 1 vez na página 30.

TUSHAR, W.; SAHA, T. K.; YUEN, C.; SMITH, D.; POOR, H. V. Peer-to-Peer Trading in Electricity Networks: An Overview. **IEEE Transactions on Smart Grid**, IEEE, v. 11, n. 4, p. 3185–3200, 2020. ISSN 19493061. DOI: [10.1109/TSG.2020.2969657](https://doi.org/10.1109/TSG.2020.2969657). arXiv: [2001.06882](https://arxiv.org/abs/2001.06882). Citado 5 vezes nas páginas 30, 34–37.

TUSHAR, W.; YUEN, C.; SAHA, T.; CHATTOPADHYAY, D.; NIZAMI, S.; HANIF, S.; ALAM, J. E.; POOR, H. V. Roles of retailers in the peer-to-peer electricity market: A single retailer perspective. **iScience**, Elsevier Inc., v. 24, n. 11, p. 103278, 2021. ISSN 25890042. DOI: [10.1016/j.isci.2021.103278](https://doi.org/10.1016/j.isci.2021.103278). Citado 3 vezes nas páginas 40, 41, 77.

TUSHAR, W.; YUEN, C.; SAHA, T. K.; MORSTYN, T.; CHAPMAN, A. C.; ALAM, M. J. E.; HANIF, S.; POOR, H. V. Peer-to-peer energy systems for connected communities: A review of recent advances and emerging challenges. **Applied Energy**, Elsevier Ltd, v. 282, PA, p. 116131, 2021. ISSN 03062619. DOI: [10.1016/j.apenergy.2020.116131](https://doi.org/10.1016/j.apenergy.2020.116131). arXiv: [2011.11118](https://arxiv.org/abs/2011.11118). Disponível em: <https://doi.org/10.1016/j.apenergy.2020.116131>. Citado 1 vez na página 15.

VAKILI, R.; AFSHARNIA, S.; GOLSHANNAVAZ, S. Interconnected microgrids: Optimal energy scheduling based on a game-theoretic approach. **International Transactions on Electrical Energy Systems**, v. 28, n. 10, p. 1–21, 2018. ISSN 20507038. DOI: [10.1002/etep.2603](https://doi.org/10.1002/etep.2603). Citado 1 vez na página 30.

VILLIERS, A. D.; CUFFE, P. a Peer-to-Peer Electricity Marketplace, p. 1–6, 2020. Citado 1 vezes nas páginas 36, 38.

VYTELINGUM, P.; RAMCHURN, S. D.; VOICE, T. D.; ROGERS, A.; JENNINGS, N. R. Trading agents for the smart electricity grid. **Proceedings of the International Joint Conference on Autonomous Agents and Multiagent Systems, AAMAS**, v. 2, p. 897–904, 2010. ISSN 15582914. Disponível em: <http://eprints.soton.ac.uk/268361/>. Citado 1 vez na página 32.

WECKESSER, T.; DOMINKOVIĆ, D. F.; BLOMGREN, E. M.; SCHLEDORN, A.; MADSEN, H. Renewable Energy Communities: Optimal sizing and distribution grid impact of photo-voltaics and battery storage. **Applied Energy**, v. 301, p. 117408, 2021. ISSN 0306-2619. DOI: <https://doi.org/10.1016/j.apenergy.2021.117408>. Disponível em: <https://www.sciencedirect.com/science/article/pii/S0306261921008059>. Citado 1 vez na página 36.

WITTMAYER, J. M.; AVELINO, F.; PEL, B.; CAMPOS, I. Contributing to sustainable and just energy systems? The mainstreaming of renewable energy prosumerism within and across institutional logics. **Energy Policy**, v. 149, September 2020, 2021. ISSN 03014215. DOI: [10.1016/j.enpol.2020.112053](https://doi.org/10.1016/j.enpol.2020.112053). Citado 1 vez na página 15.

WU, F. F.; VARAIYA, P. Coordinated multilateral trades for electric power networks: theory and implementation. **International Journal of Electrical Power & Energy Systems**, v. 21, n. 2, p. 75–102, 1999. ISSN 0142-0615. DOI: [https://doi.org/10.1016/S0142-0615\(98\)00031-3](https://doi.org/10.1016/S0142-0615(98)00031-3). Disponível em: <https://www.sciencedirect.com/science/article/pii/S0142061598000313>. Citado 1 vez na página 19.

ZINAMAN, O. DISTRIBUTED SOLAR UTILITY TARIFF AND REVENUE IMPACT ANALYSIS A Guidebook for International Practitioners. November, 2020. Disponível em: <https://www.nrel.gov/docs/fy21osti/78058.pdf>. Citado 3 vezes nas páginas 15, 40, 54.

APPENDIX 1 - SCIENTIFIC CONTRIBUTIONS

Main publications originated in this doctorate:

- Published journal paper: KÜSTER, K. K.; AOKI, A. R.; LAMBERT-TORRES, G. Transaction based operation of electric distribution systems: A review. *International Transactions on Electrical Energy Systems*, n. May, p. 1–17, 2019. ISSN 20507038.
- Submitted manuscript for a journal paper: KÜSTER, K. K.; GEBBRAN, D.; AOKI, A. R.; LAMBERT-TORRES, G.; GEVERS, D. N. Adoption of Local Peer-to-Peer Energy Markets: Technical and Economical Perspectives for Utilities. *IEEE Transactions on Smart Grids*, IEEE. date of submission: 26-04-2022.

Other scientific productions carried out during this doctorate:

- Poster submitted for presentation: KÜSTER, K. K.; GEBBRAN, D.; AOKI, A. R.; LAMBERT-TORRES, G.; GEVERS, D. N. Local Peer-to-Peer Energy Markets: perspectives for adoption by Utilities. DTU Summer School - Advanced Optimization, Learning, and Game-Theoretic Models in Energy Systems. Lyngby, Denmark. Date to be presented: June 2022.
- Published research paper: MACHADO, M.; SILVA, V. A.; BLASI, T. M.; KÜSTER, K. K.; AOKI, A. R.; FERNANDES, T. S. P.; LAMBERT-TORRES, G. Recent research and development of microgrids in Parana. *Brazilian Archives of Biology and Technology*, FapUNIFESP (SCIELO), v. 64, n. spe, 2021.
- Research stay: [2020,2021] Institut für neue Energie-Systeme (InES) at the Technische Hochschule Ingolstadt, Germany. *enGlobe - engineers go global Scholarship Program*.
- ANEEL R&D project: [2016,Atual] - PD-2866-0444-2016, Algoritmo multicritério espacial para aplicação de baterias para qualidade do fornecimento. Executing Entity: LACTEC. Contracting Company: COPEL. Coordinator: Patrício Rodolfo Impinnisi, Dr.
- Co-advisor of undergraduate: Victor Soares Sismotto. Desenvolvimento de blockchain para armazenamento de energia em baterias em redes ativas de distribuição. 2019. Trabalho de Conclusão de Curso. (Graduação em Engenharia Elétrica) - Universidade Federal do Paraná.

- Co-advisor of undergraduate: Paulo Ricardo Dolberth Menezes. Análise dos impactos de veículos elétricos em redes de distribuição via sistema blockchain. 2019. Trabalho de Conclusão de Curso. (Graduação em Engenharia Elétrica) - Universidade Federal do Paraná.
- Co-advisor of undergraduate: Lucas Berbeka Cleto. Operação de fontes de energia renovável no mercado varejista baseada em tecnologia blockchain. 2019. Trabalho de Conclusão de Curso. (Graduação em Engenharia Elétrica) - Universidade Federal do Paraná.
- Examination committee member: Wendy Correa Santo. Definição de um procedimento para a classificação de instalações do sistema de distribuição de alta tensão no contexto da confiabilidade. 2018. Trabalho de Conclusão de Curso. (Graduação em Engenharia Elétrica) - Universidade Federal do Paraná.
- Examination committee member: Eduardo Godoy Fernandes. Estudo comparativo entre diferentes algoritmos de decomposição modal para aplicações envolvendo geração distribuída. 2018. Trabalho de Conclusão de Curso. (Graduação em Engenharia Elétrica) - Universidade Federal do Paraná.