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Supervisor: Associate Professor Ivan Rajšl, PhD

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MODELIRANJE LOKALNOGA TRŽIŠTA ELEKTRIČNOM ENERGIJOM NA RAZINI DISTRIBUCIJSKIH MREŽA

DOKTORSKI RAD

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About the Supervisor

Ivan Rajšl (https://www.fer.unizg.hr/ivan.rajsl) was born in 1983 in Slavonski Brod, Croatia. He received his bachelor's and doctoral degrees from the Faculty of Electrical Engineering and Computing, University of Zagreb. At the same Faculty, he was elected as the assistant professor in 2016, and in 2022 as the associate professor. During his doctoral and postdoctoral studies, he spent several months in training at the Norwegian University of Science and Technology - NTNU in Trondheim, Norway.

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O mentoru

Ivan Rajšl (https://www.fer.unizg.hr/ivan.rajsl) rođen je 1983. godine u Slavonskom Brodu, Hrvatska. Diplomirao je i doktorirao na Fakultetu elektrotehnike i računarstva Sveučilišta u Zagrebu. Na istom Fakultetu izabran je u zvanje docenta 2016. godine, a 2022. godine u zvanje izvanrednog profesora. Tijekom doktorskog i postdoktorskog studija proveo je nekoliko mjeseci na usavršavanju na Norveškom sveučilištu znanosti i tehnologije – NTNU u Trondheimu, Norveška.

Područje njegovog interesa obuhvaća energetsku učinkovitost, obnovljive izvore energije s naglaskom na poboljšane geotermalne sustave, modeliranje i optimizaciju elektroenergetskih sustava, distribuirana tržišta energije, modeliranje i optimizaciju tržišta električne energije s naglaskom na uštedu emisija CO2 i ublažavanje klimatskih promjena.

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Abstract

Global efforts and citizens' advocacy to mitigate climate change, advances in the development of technologies that utilise renewable energy sources, and development of information and communication technologies are driving the energy transition. The energy transition is characterised by the increasing share of variable renewable energy sources, primarily solar and wind, and the expansion of electrification in heating, transport and industry sectors. Variable and stochastic nature of energy production from solar and wind power plants requires flexibility in the power system and is transforming passive users into active participants in low carbon energy systems. Unlocking the potential of final users and transforming them into distributed flexibility providers requires the integration of new technologies, business models, and systematic change in the regulatory framework. In this process, electrical distribution networks are being transformed from a concept where they passively provide one-way power flows, to active smart grids with distributed energy sources, charging stations for electric vehicles, battery energy storage systems and other flexibility options.

Local electricity markets (LEMs) provide a solution that allows active electricity trading between consumers, producers and/or prosumers located in distribution networks. The concept should provide added value to the participants and accelerate the power sector's democratisation, decarbonisation, and decentralisation. However, the effects of local energy trading (LET) on voltage levels in distribution grids are in the early stage of research, together with the possible means of control, market design, market-clearing approaches and integration of the local energy trading within the electricity markets. This thesis investigates whether LET can reduce unfavourable consumption/production patterns and contribute to the maintenance of voltages and currents within limits. Further, if LET can improve the economic position of local flexibility providers and improve social welfare, meaning it could serve as a mean to enhance the integration of RES in electrical distribution networks through price incentives for supply/demand balancing.

To research this questions, models for LEM over a distribution network are developed, based on different methods for determining dispatched quantities and prices for participants. The models also allow assessment of impacts of different regulatory frameworks for LET, considering network fees, taxes and other levies in the power system. Further, a method for determining the effects of LET on voltage profiles and power flows over electrical distribution networks is proposed and utilized for studying effects of different elasticities and prices of demand and supply offering curves, as well as for different flexibility options. Finally, the necessary components for implementation of the concept within the energy communities in the European Union (EU) are researched, with a focus on price-forming methods that can be integrated into a net-billing system and adopted for different regulatory set-ups. Here, a method for the assessment of impacts on market participants is provided. The approach is applied for the assessment of the opportunities for LET in the small energy community in city of Križevci, considering local generation, flexibility options, and real-life regulatory requirements, and for the assessment of possible role of energy vectors in decarbnoisation of larger energy islands based on energy trading in a cooperative manner.

It is shown that the local energy trading has the potential to incentivise active participation of prosumers, which can lead to better demand/supply balancing at the local level. Consequently, voltage fluctuations can be decreased. However, this effect is not guaranteed in the cases of unbalanced three-phase LV distribution grids, where the implementation of LET can even lead to an increase in voltage unbalances. In assessment of flexibility options for LEMs, the results point out at significant differences across set-ups as well as between the geographical locations, and some of the results that can be highlighted are: demand responsive electric heat pumps and use of battery energy storage systems provide stand-out energy potency and can ensure self-sufficiency with smallest capacity of electricity production from local renewable energy sources, but comes with a growing costs for the increase of storage capacity; drawbacks of natural gas are greenhouse gas emissions and imports; and for hydrogen energy vector, lower efficiency and costs are still the main barriers. The assessment of effects on market participants have showed that, under the supportive regulatory environment, all members can benefit from participating in the LET, even though the distribution of the benefits depends on the applied market clearing method. On the other hand, the trade-offs are reflected on the reduced revenues for market participants that generate income based on transmission fees, taxes, and/or levies, subject to the applicable regulatory setup. Here, development of LEMs within the energy communities is seen as a first step in wider implementation of the concept.

Keywords: Local Energy Market, Energy Community, Peer-to-Peer Energy Trading, Distribution Network, Renewable Energy Sources

Modeliranje lokalnoga tržišta električnom energijom na razini distribucijskih mreža

Globalni napori za ublažavanje klimatskih promjena, napredak u razvoju informacijskih i komunikacijskih tehnologija te tehnologija koje koriste obnovljive izvore energije pokreću energetsku tranziciju. Energetsku tranziciju karakterizira sve veći udio varijabilnih obnovljivih izvora energije, prvenstveno sunca i vjetra, te širenje elektrifikacije u sektorima grijanja, prometa i industrije. Promjenjiva i stohastička priroda proizvodnje energije iz sunčanih i vjetrenih elektrana zahtijeva povećanje fleksibilnosti u elektroenergetskom sustavu te transformaciju pasivnih korisnika u aktivne sudionike niskougljičnih energetskih sustava. Otključavanje potencijala krajnjih korisnika i njihova transformacija u distribuirane pružatelje usluga fleksibilnosti zahtijeva integraciju novih tehnologija i poslovnih modela te sustavnu prilagodbu regulatornog okvira. U ovom procesu, elektroenergetske distribucijske mreže transformiraju se iz koncepta u kojem pasivno osiguravaju jednosmjerne tokove snaga, u napredne mreže s distribuiranim izvorima energije, punionicama za električna vozila, sustavima za pohranu energije i drugim opcijama fleksibilnosti.

Trend ovakvog razvoja dovodi do novih obrazaca u potrošnji i proizvodnji energije u distribucijskim mrežama što utječe na tokove snaga te stabilnost napona i frekvencije, posebno uzevši u obzir da su u niskonaponskim mrežama mnogi potrošači i trošila spojeni jednofazno. S ovakvim promjenama dolazi do pogonskih izazova u zadržavanju napona, struja i kvalitete električne energije unutar granica. Istovremeno, cilj modernih elektroenergetskih sustava je osigurati sigurnu, pristupačnu i okolišno prihvatljivu opskrbu energijom. Uz poštivanje specifičnosti električne energije kao dobra, postizanje ovih ciljeva u Europskoj uniji nastoji se provesti na tržišnim principima.

Tržišta električnom energije mogu se podijeliti na dugoročna tržišta, terminska tržišta (bilateralna i centralizirana) i spot tržišta. Razvoj suvremenih tržišta električnom energije u Europskoj uniji karakterizira međudržavna integracija i razvoj okvira koji treba omogućiti dekarbonizaciju i maksimalno aktiviranje opcija fleksibilnosti. U tom kontekstu, lokalna tržišta električne energije daju rješenje koje omogućuje aktivno trgovanje električnom energijom između kupaca, proizvođača i/ili aktivnih kupaca koji se nalaze u distribucijskim mrežama.

Elementi lokalnih tržišta električnom energijom mogu se podijeliti u 4 sloja: sloj elektroenergetske mreže, informacijski i komunikacijski sloj, kontrolni sloj, te poslovni sloj. Sloj elektroenergetske mreže sastoji se od fizičkih elemenata elektroenergetskog sustava, koji uključuju mrežu, transformatore, trošila, distribuirane izvore, spremnike energije, itd. Ovi elementi čine fizičku osnovu na kojoj se može implementirati lokalno trgovanje energijom. Informacijski i komunikacijski sloj sastoji se od računala i druge elektroničke opreme i sustava za prikupljanje, pohranjivanje, korištenje i elektroničku razmjenu podataka. Brojila i senzori prikupljaju informacije iz sloja elektroenergetske mreže i omogućuju informacijskom i komunikacijskom sloju da ih koristi. Kontrolni sloj trebao bi osigurati upravljačke funkcije u distribucijskim mrežama ili mikromrežama. U ovom sloju treba definirati strategije upravljanja kako bi se očuvala i/ili povećala kvaliteta opskrbe električnom energijom, stabilnost sustava, pouzdanost napajanja i kontrola tokova snaga u mreži. Poslovni sloj određuje pravila, mehanizme i algoritme kako se električnom energijom trguje između sudionika i s trećim stranama. Različiti poslovni modeli mogu se dizajnirati u poslovnom sloju za poticanje lokalnog trgovanja električnom energijom. Karakteristika ovog sloja je da je usko povezan sa zakonodavstvom koje regulira energetska tržišta, sudionike na tržištu i njihove uloge. S obzirom na široki raspon mogućih elemenata u svakom sloju, koncepti organiziranja lokalnog trgovanja električnom energijom su raznovrsni. Razlike se između ostalog mogu odnositi na načine određivanja količina i cijena, uključene kontrolne funkcije, dostupne tehnologije, regulatorni okvir ili informacijske i komunikacijske tehnologije.

Lokalno trgovanje energijom može se organizirati na tri načina: (1) Uzajamno (engl. peer-to-peer) trgovanje energijom: ovaj način karakterizira da sudionici na tržištu međusobno trguju izravno, bez posrednika; (2) Trgovanje energijom putem posrednika: u ovom slučaju posrednik sudjeluje na tržištu u ime prodavača i kupaca i dodjeljuje energiju od prodavača do kupaca; (3) Kombinacija uzajamnog i trgovanja putem posrednika: u ovako organiziranom tržištu sudionici na tržištu mogu trgovati energijom izravno ili putem posrednika. Za bilo koji dizajn lokalnih tržišta električne energije potrebni su tržišni igrači. Općenito, kao sudionici mogu se identificirati prodavači, kupci i posrednici ili poduzeća koja se bave energijom. Posrednici ili poduzeća koje se bave energijom su svi drugi igrači na tržištu osim prodavača ili kupaca, npr. operatori distribucijskog sustava, agregatori, tržišni operateri, pružatelji energetskih usluga, trgovci energijom, aukcionari, lokalni operateri ili upravitelji zajednica. Kako bi ubrzala energetsku tranziciju i podržala razvoj novih poslovnih modela, EU je definirala uzajamno trgovanje energijom i energetske zajednice u regulatornom okviru koji sve države članice moraju transponirati. Lokalna trgovina ili dijeljenje energije unutar energetskih zajednica pokazuje se kao koncept koji se ubrzano razvija u praksi, a broj pilot i komercijalnih projekata raste. Regulatorne intervencije u mrežnim naknadama, porezima i drugim naknadama, kao i definicije ograničenja i tehničkih zahtjeva, imaju važnu ulogu u isplativosti lokalnog trgovanja unutar energetskih zajednica. Pritom, u nekim državama članicama, lokalno trgovanje električnom energijom je dopušteno samo iza istog niskonaponskog transformatora.

Općenito, koncept lokalnog trgovanja energijom bi trebao pružiti dodanu vrijednost sudionicima i ubrzati demokratizaciju, dekarbonizaciju i decentralizaciju energetskog sektora. Međutim, učinci lokalnog trgovanja električnom energijom na napone u distribucijskim mrežama su u ranoj fazi istraživanja, zajedno s mogućim sredstvima kontrole, dizajnom tržišta, pristupima određivanju količina i cijena na tržištu te integracijom lokalnog trgovanja energijom s ostalim tržištima električne energije. Metode određivanju količina i cijena na tržištu (čišćenje tržišta) obično se formuliraju kao optimizacijski problemi s ciljem povećanja društvenog blagostanja ili minimizacije ukupnih troškova, ali postoji mnogo metoda za određivanje dispečiranih količina i cijena. Metode se razlikuju s obzirom na način izračuna, potrebe za podacima, kontrolne funkcije, kao i s obzirom na informatičke i komunikacijske zahtjeve. Iz perspektive povezivanja terminskog trgovanja električnom energijom s funkcijama stabilnosti u elektroenergetskom sustavu, glavne prilike vezano za distribucijske mreže i povezane mikromreže uključuju doprinos stabilnosti napona i sprječavanje zagušenja s obzirom na ograničenja vodova.

Ovaj rad istražuje može li lokalno trgovanje električnom energijom smanjiti nepovoljne obrasce potrošnje/proizvodnje i pridonijeti održavanju napona i struja unutar granica. Nadalje, istražuje može li lokalno trgovanje poboljšati ekonomsku poziciju lokalnih pružatelja usluga fleksibilnosti i poboljšati društveno blagostanje, odnosno poslužiti kao sredstvo za poboljšanje integracije obnovljivih izvora energije u električne distribucijske mreže putem cjenovnih poticaja za uravnoteženje ponude i potražnje.

Modeli za određivanje cijena i količina na lokalnom tržištu električnom energijom na razini distribucijskih mreža razvijeni su na dva načina. Prvi pristup je na principu algoritma centralno agregirane dvostruke aukcije, koji je razvijen i korišten za simulaciju lokalnog trgovanja električnom energijom. U prvom koraku, sudionici u distribucijskoj mreži kreiraju ponude potražnje i prodaje na temelju svojih potreba, elastičnosti potražnje, kapaciteta i cijena. Nakon toga, sve ponude za prodaju i potražnju šalju se na tržište dvostruke aukcije, gdje se ponude agregiraju, te određuju ravnotežne količine i cijene. Konačno, informacije o određenim količinama s najnižim troškovima šalje se sudionicima. Vremenski horizont simuliranog tržišnog sloja je 24 h, s rezolucijom od 5 minuta. Razvijeni algoritam određuje ravnotežne cijene i količine s petominutnom rezolucijom. Rezultati se mogu zatim koristiti za proučavanje učinaka u distribucijskoj mreži u drugom dijelu doprinosa rada. Drugi pristup temelji se na mješovitom cjelobrojnom linearnom programiranju za određivanje količina i cijena, a podrazumijeva ulogu lokalnog koordinatora za razmjenu energije u optimizaciji rada opcija fleksibilnosti sudionika, npr. unutar energetske zajednice. Ovdje lokalni koordinatora za razmjenu energije optimira rad opcija fleksibilnosti, a cijene se određuju naknadno na temelju unaprijed definiranih formula. Metode su primjenjive za različite regulatorne postavke. Predložene metode određivanja cijena prikladne su i za okruženja u kojima potrošači mogu imati različite dobavljače energije, jer treće strane (poput operatora distribucijskog sustava ili operatora tržišta) mogu verificirati podatke te se određene naknade mogu uključiti u lokalno trgovanje - kao što je naknada za distribuciju energije, porezi ili slično.

Nadalje, predložena je metoda za određivanje učinaka lokalnog trgovanja električnom energijom na naponske profile i tokove snaga na razini distribucijskih mreža. Metoda je korištena za analizu učinaka različitih elastičnosti i cijena potražnje i ponude, kao i različitih opcija fleksibilnosti. Nastavno na model određivanja cijena i količina na lokalnom tržištu električnom energijom, određene količine za sudionike koriste se kao ulaz u model distribucijske mreže za analizu tokova snage i naponskih profila. Simulacija u distribucijskim mrežama provodi se s rezolucijom od jedne sekunde koristeći petominutne količine iz prethodnog koraka, što rezultira profilima napona u vremenskom horizontu od 24 sata i rezolucijom od jedne sekunde. Ovdje se ograničenja tokova snaga, koja bi interno mogla biti uključena u metodi određivanja cijena i količina zanemaruju, iz razloga što se proučavaju učinci na napone sabirnica koji proizlaze iz nekontroliranog ponašanja sudionika i različitih pristupa određivanju ponuda. Tokovi snaga i profili napona u distribucijskoj mreži se analiziraju bez provođenja dispečiranja s ograničenjima tokova snaga za promatrani vremenski horizont, odnosno svaki interval trgovanja.

Modeli također omogućuju procjenu utjecaja različitih regulatornih okvira za lokalno trgovanje energijom, s obzirom na mrežne naknade, poreze i druge naknade u elektroenergetskom sustavu. U tu svrhu istražuju se potrebne komponente za implementaciju koncepta unutar energetskih zajednica u EU, s naglaskom na metode oblikovanja cijena koje se mogu integrirati u sustav neto naplate i usvojiti za različite regulatorne okvire. Razvijena metoda za procjenu ekonomskih učinaka lokalnog tržišta električnom energijom na sudionike temelji se na izračunu prihoda za sudionike na tržištu i niveliranih troškova potrošene energije za članove. Zbog važnosti sezonskih učinaka na proizvodnju iz obnovljivih izvora energije, rad spremnika i višeenergijskih vektora, modelirano je dinamičko lokalno trgovanje električnom energijom sa satnom razlučivosti i s godišnjim horizontom. Pristup se primjenjuje za procjenu mogućnosti lokalnog trgovanja u maloj energetskoj zajednici u gradu Križevcima, a s obzirom na lokalnu proizvodnju, opcije fleksibilnosti i stvarne regulatorne zahtjeve, te za procjenu moguće uloge energetskih vektora u dekarbonizaciji energetskih otoka temeljenih na trgovanju energijom na kooperativan način.

Pokazalo se da lokalno trgovanje električnom energijom ima potencijal potaknuti aktivno sudjelovanje kupaca, što može dovesti do boljeg uravnoteženja potražnje i ponude na lokalnoj razini. Posljedično, fluktuacije napona se mogu smanjiti. Međutim, ovaj učinak nije zajamčen u slučajevima neuravnoteženih trofaznih niskonaponskih distribucijskih mreža, gdje implementacija lokalnog trgovanja energijom može čak dovesti do povećanja naponskih neravnoteža. U procjeni opcija fleksibilnosti za lokalne energetske sustave, rezultati ukazuju na značajne razlike među opcijama kao i među geografskim lokacijama, a neki od rezultata koji se mogu istaknuti su: električne dizalice topline i korištenje baterijskih spremnika energije mogu osigurati samodostatnost uz najmanji kapacitet proizvodnje električne energije iz lokalnih obnovljivih izvora energije, ali dolaze s rastućim troškovima za povećanje kapaciteta spremnika; nedostaci korištenja prirodnog plina su emisije stakleničkih plinova i uvoz energije; dok su za korištenje vodika kao energetskog vektora manja učinkovitost i troškovi još uvijek glavne prepreke. Procjena učinaka na sudionike na tržištu pokazala je da, pod poticajnim regulatornim okruženjem,

svi članovi mogu imati koristi od sudjelovanja u lokalnom trgovanju energijom, iako raspodjela koristi ovisi o primijenjenoj metodi određivanja cijena i količina. S druge strane, utjecaji se odražavaju na smanjene prihode za sudionike na tržištu koji ostvaruju prihod na temelju naknada za prijenos, poreza i/ili nameta, ovisno o primjenjivim regulatornim postavkama. Pritom se razvoj lokalnih tržišta električnom energijom unutar energetskih zajednica identificira kao prvi korak u široj provedbi koncepta.

Ključne riječi: Lokalno tržište električnom energijom, Energetska zajednica, Uzajamno trgovanje električnom energijom, Distribucijska mreža, Obnovljivi izvori energije

Contents

Chapter 1

Introduction

In the endeavours to mitigate climate change and increase energy security in a most cost-competitive way, member states (MSs) of the European Union (EU) have decided to set an ambitious aim for reducing greenhouse gas (GHG) emissions, improving energy efficiency, and increasing the share of renewable energy sources (RES). The aim is to reach carbon neutrality of the EU's economy by 2050. Significant improvements in power system planning and operation are required to achieve these objectives. Broad integration of RES requires a high level of flexibility due to their variable nature.

The research undertaken in this thesis focuses on establishing local electricity markets (LEMs) as a means of activating prosumers' flexibility, increasing social welfare, and improving power system stability to support integration of higher share of variable RES. The research objective is to look into various LEM models and their effects on the power system's distribution network and market participants.

1.1 Background and Motivation

Achieving the climate-neutral economy entails a transition from a fossil-fuel-based to a decarbonised energy sector. Decarbonisation of the energy sector requires strong global adoption of RESs and increased energy efficiency. On the demand side, a wider electrification in industry, buildings and transportation is expected, driving the increase in electricity consumption. The traditional power system was conceived on the premise of large, dislocated power plants, passive demand, and production that is adjusting to the demand and ensuring power system stability. Under that framework, electrical distribution networks were designed to passively distribute energy to final users.

Integration of variable and distributed RES (out of which mostly solar and wind power plants) in high share increases uncertainty and operational complexity in the power system. Due to the variable nature of energy production from RES, ensuring power system reliability and maintaining power system stability requires development of new flexibility options on both supply and demand sides. In this process, electrical distribution network is being transformed from passive element that is providing one-way power flows, into the active systems with distributed energy resources (DERs), battery energy storage systems (BESSs), charging stations for electric vehicles (EVs), demand response (DR) programs and other flexibility options. This requires new management and operational methods, and can only be achieved along with comprehensive equipping of the power system with information and communication technologies (ICT) under the smart grid paradigm. Further, the transformation requires systematic and multi-dimensional approach as policy and regulatory framework have to support new business models to enable competitive market-based integration of RES and development of flexibility services.

1.2 Objective of the Thesis

Local energy trading (LET) at LEMs is a concept that allows energy trading between different peers (decentralised generation, prosumers, consumers) in the local distribution grid. In that way, it can provide added value to the participants, accelerate the integration of RESs, improve the grid stability and potentially provide auxiliary services to the rest of the power system. However, many questions and challenges still have to be explored to accelerate the implementation of LET concept in practice and in wider scope. The impact of LET on voltage levels in distribution networks, control methods, market design, market pricing methods, and local market interaction with other electricity markets are areas where there is still ongoing research.

The aim of the PhD thesis is to research ways of implementing a near-real-time LET in electrical distribution networks, effects on local power flows, voltage levels, and contributions to social welfare. The aim is to research the following main hypothesis:

- LET can reduce unfavourable consumption/production patterns and contribute to the maintenance of voltages and currents within limits;
- LET can increase the competitiveness of local flexibility providers and improve social welfare;
- LET can enhance the integration of renewable energy sources in electrical distribution networks through price incentives for supply/demand balancing.

To research the questions, the methodology taken in this thesis are based on the development of the models of LEMs that allow modelling penetration of different flexibility options, such as BESSs, change of behaviour of prosumers or integration of multi-energy vectors. A method is provided to analyse the impacts on the distribution network, assessing the impacts on voltage profiles and power flows. Finally, the power system is characterised by many players and complex interactions. Therefore, interventions in the legal framework have to be well designed. A method for assessing of effects of LEMs on market participants is proposed to contribute to this area, and related results are analysed.

The scientific contribution of the thesis is divided into three parts:

- Short-term model for near real-time local electricity market over a distribution network;
- Method for determining the effects of local energy trading on voltage profiles and power flows over electrical distribution networks; and
- Method for assessing the impacts of the local electricity market on market participants.

1.3 Structure of the Thesis

The thesis is structured as follows:

- Chapter 2 describes electricity markets and provides overview of market structures with LEMs considering the design, market players and examples of pilot projects. Secondly, the overview of pricing and market clearing approaches are presented;
- Chapter 3 presents main stability and control functions as well as underlying information and communication technologies. As a second part in this Chapter, methods for addressing network constraints in LEMs are outlined together with the flexibility options in local energy systems that are utilized in the thesis;
- Chapter 4 highlights the main contributions of the thesis and links them to the related publications;
- Chapter 5 presents the list of all relevant publications;
- Chapter 6 summarizes the author's contribution to the publications;
- Chapter 7 concludes the thesis and highlights the main findings.

Chapter 2

Local Electricity Markets

Ongoing trends of decentralisation, digitalization, decarbonisation, and democratization in the energy sector enable new business models that imply active participation of citizens and development of LEMs. LET is a concept that allows active participation of market players and energy trading in local distribution network, and possibly in the rest of the power system. Small market participants, acting as peers, can be owners of DERs, distributed storage systems (DSS) as well as they can manage other flexibility options like multi-energy systems or change their behavior to provide DR. LEMs can be designed in a way that can, inter alia, provide value added to the participants, accelerate the integration of distributed energy resources and improve the power system stability and reliability. However, due to the novelty of the concept, solutions for cost-effective implementation on a commercial scale are still in an early stage of research, as well as the effects on a local distribution network.

The components for implementation of LET can be grouped into four layers: grid layer, ICT layer, control layer, and business layer [1]. In this Chapter, the introduction in electricity markets is provided, and an overview of state-of-the-art concepts, solutions and challenges under the business layer considering the emerging regulatory framework are presented. This Chapter also highlights how the contribution of the thesis fills the main gaps in this research area.

2.1 Introduction to Electricity Markets

Particularities of electricity, when observed as a tradable commodity, are that it is inextricably linked with a physical system, its delivery occurs continuously, and supply and demand have to be balanced constantly. In case the limitations of the power grid are exceeded, or the supply/demand balance is not maintained, the system can collapse with disastrous consequences. Further specificity is that the electricity from one producer cannot unambiguously be taken by some consumer, as it flows through the system in accordance with the physical laws, leading to the pooling of production and consumption. Moreover, due to the cycling patterns and uncertainty of consumption and production, variations in marginal cost over the course of a day and even hours usually appear [2].

To allow the trading of energy, power is integrated over a certain time interval. The advantage of shorter time intervals is that in that case state in the system is more accurately represented. However, large generating units or consumers seek certainty and prefer trading for quantities and prices that are fixed over a longer time. These diverse preferences and interests lead market designs of forward markets with longer time intervals, to markets with shorter periods. The time intervals for energy exchange at electricity markets are usually not lower than 15 minutes, while the near-real time trading is considered in cases when energy is dispatched every 5 minutes [3]. Complementary to forward markets, there is commonly a spot market as a last resort and is primarily used for balancing services.

Even though there are common principles across the electricity markets worldwide, substantial differences exist in the designs of wholesale electricity markets considering the responsibilities of transmission and market operators, options for market participation, ownership of exchanges, and shares of bilateral or auction market trades. A particular difference is also in the creation of bids for sellers. An overview of the differences can be found in [4, 5]. This thesis focuses on the EU electricity market and the ongoing development of LEMs under the EU framework.

A sequence in the EU electricity markets is shown in Figure 2.1, based on the [6]. It is evident that electricity trading can start months or even years ahead of delivery in forward markets - either for energy, transmission rights, or balancing capacity. The primary purpose of long-term markets is to provide a hedging opportunity for sellers and buyers. Long-term cross-zonal transmission rights are traded separately through auctions [6], and they provide an opportunity for hedging price differences between bidding zones. Long-term contracts are considered to happen until one day before delivery.

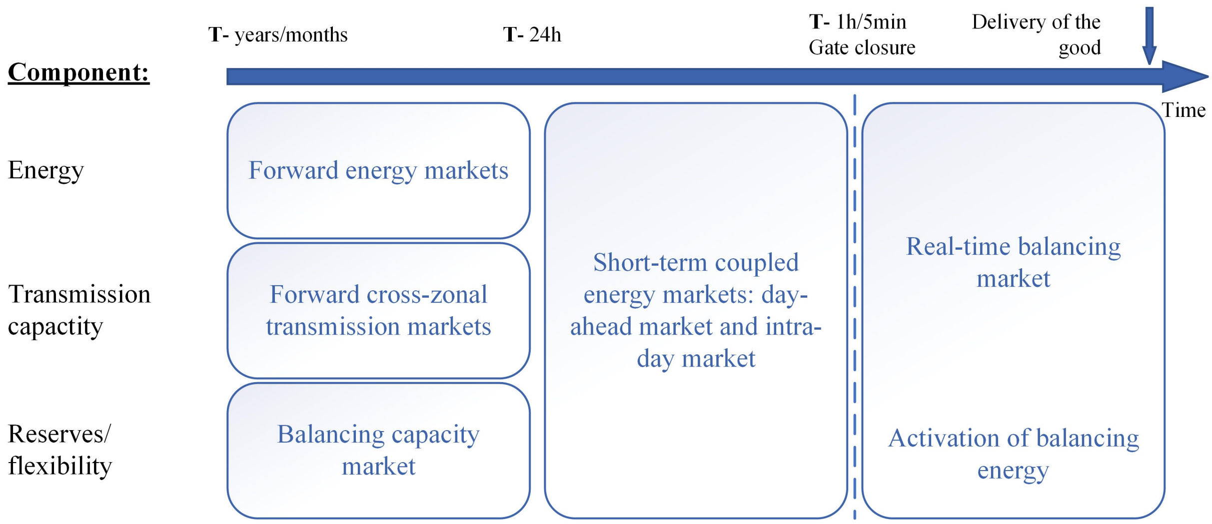

Figure 2.1: Sequence of electricity markets in the EU

When it comes up to one day before delivery, electricity markets are considered short-term markets. Generally, they are comprised of the forward day-ahead market, forward intraday markets, and the (near) real-time balancing (spot) market. For the day-ahead market, auctions are held the day before the delivery. In this process sellers and buyers submit their bids to the market operator (MO) on a centralised market. Then MO clears the auction and settles the trades. As a result of the auctions, a schedule for the next day is obtained and communicated with the participants. In the EU, cross-zonal transmission capacity is predominantly allocated jointly (implicitly) with energy in the day-ahead market in the process called market coupling [6].

2.2 Design of Forward Markets

Forward markets for electrical energy can be organized as decentralised (bilateral) or centralised [2]. In decentralised markets, offers to buy or sell lead to interactions between participants and finally to bilateral trades. In centralised markets, offers are aggregated and considered together to determine the market equilibrium in one step.

2.2.1 Decentralised Trading

The key feature of decentralised trading is that the price of each transaction is defined independently by the parties included - there is no one "official" price. However, in the case of over-the-counter (OTC) trading or in the case of the use of electronic platforms for matching, an anonymised data can be published to give market players a better reference on the state and development of the market. The approaches for decentralised trading are [2]:

- Customized long-term contracts: the purpose of these contracts is primarily on the sale of large amounts of power (hundreds to thousands of MW) over a long period of time (months to years). They are suitable in cases when a generating company wants to finance a certain project and is looking to have a long-term contract to ensure certainty on future revenues. In the other hand, a buyer also reduces uncertainty by having some amount of power secured over a long period for known prices.
- OTC trading: these trades take place outside of power exchanges without intermediaries or clearing houses - trading partners are in contact with each other directly or through brokers. Transactions can be conducted over online trading platforms or through brokerage companies. There are often standardised profiles on how much energy should be delivered over different periods of the day or week. This approach is usually used for smaller amounts of energy and shorter time periods than customised long-term contracts.
- Electronic trading: in this approach, participants use electronic trading platforms in the process of offering bids for buying and selling energy. Here, the software is used to match the bids and deals are struck automatically, and prices are displayed so that all participants can track the development of the market. The advantage of this approach is that it is cheap and fast. Similarly to OTC trading, it is commonly also used for standardized profiles, and participants often use it to fine-tune their positions ahead of the scheduled delivery periods.

In the EU, the intraday market is predominantly organized as a 'book of orders' where zones (i.e. books in each participating country) are coupled [6].

2.2.2 Centralised Trading

The main difference between centralised and decentralised trading is that a market provides a mechanism for reaching equilibrium under centralised approach, instead of relying on interactions between sellers and buyers.

Typically, an operation of centralised markets is organised as a double-side auction in the following steps: sellers and buyers submit their bids with quantities and prices offered for selling or buying energy. Based on those bids, cumulative supply and demand offer curves are formed. Demand is typically determined based on a forecast and is highly inelastic in electricity markets. The intersection of aggregated demand and supply curves represents a market equilibrium, and the found price is considered the market-clearing price. This means that all selling offers with submitted prices below the equilibrium price are accepted. Similarly, all buying offers submitted with a price above the equilibrium price are accepted. Based on the found market equilibrium, the sellers and buyers are informed of the price and amounts of energy they are obliged to sell or buy from the market. The market-clearing price represents the price of additional MWh and is called a system marginal price (SMP). All sellers are usually paid

SMP, and all buyers have to pay SMP. This way, global welfare is maximised, and an economic dispatch is performed. This approach is considered superior in cost minimisation to pay-as-bid schemes, as pay-as-bid schemes would lead to guessing the SMP instead of submitting marginal costs and consequently likely lead to an increase in prices [2, 6].

In the EU there are several centralised markets, such as Nordpool [7], MIBEL [8], EPEX [9], HUPX [10], or CROPEX [11], and day-ahead markets are organized as centralised double-side auctions. A review of day-ahead electricity market and important features of the world's major electric power exchanges can be found in [12].

2.3 Spot Markets

Electricity spot markets serve as a last resort to balance supply and demand as sellers and buyers cannot predict their production or consumption with perfect accuracy, especially with high penetration of variable RES. In the EU, spot markets are called balancing markets[6]. However, since there could be a risk of achieving an inadequate response at every moment in the system if balancing is left to market players, system operators are tasked to maintain system the stability and serve as a counter-party to all trades. Therefore, it is not a spot market in the full sense, but it is called a 'managed spot market'[2].

To keep with the market philosophy, any participant that is willing to adjust its supply or demand should be allowed to do so on a competitive basis. This approach should provide the system operator with the broadest possible balancing options and minimise balancing costs. In spot markets, producers can submit bids to increase or decrease their production, or the demand-side can offer balancing resources by increasing or decreasing their consumption. However, the system operator can be concerned about the quantity or price of balancing resources if all of them are submitted shortly before real-time. Therefore, it can purchase balancing options on a long-term basis. Under such contracts, the resource provider is paid a fixed price (option fee) to ensure the availability of balancing capacity. These contracts usually specify the fee to be paid when resources are used [2].

Due to the different operational needs in the power systems, spot markets are designed to be able to provide adequate balancing services. In the EU, the balancing is divided to three processes. First is frequency containment, where the reserve category is Frequency Containment Reserves (FCR). The second process is frequency restoration, where reserve categories are Automatic Frequency Restoration Reserves (aFRR) and Manual Frequency Restoration Reserves (mFRR). The third process is reserve replacement, where Replacement Reserves (RR) is a reserve category [6]. These reserves mainly differ in response time and the maximum duration of delivery. Listed balancing services are commonly referred to as ancillary services for frequency control. From the time the frequency drops or spikes, FCR is activated almost at the moment to stabilise the frequency. For the FCR, the fastest types of reserves are activated and operated using a collaborative process involving all transmission system operators (TSOs) of the synchronous area. Within a few minutes, the frequency restoration process begins. The Frequency Restoration Proces (FRP) is operated per Load-Frequency Control (LFC) Area, which is mainly equal to the TSO's control area [13]. Firstly aFRR and subsequently mFRR are activated to take over from FCR. Here, aFRR is activated automatically by a controller operated by the TSO, mFRR is activated at the specific manual request of the TSO. FRR aim to restore the frequency to its nominal value. As a final process, after approximately 15 minutes or more, RR, the slowest type of reserves, can be activated if needed to support or replace FRR. Not all LFCs have RR, as this process is not mandatory [6]. Spot markets can be defined just for energy, or for capacity and energy. They are just partly harmonised but are in the process of stronger integration in the EU [14]. Where implemented, RR is usually remunerated for reserved power capacities and subsequently paid for energy activated [15]. Additional examples of ancillary services for non-frequency control are voltage support or congestion management, which are considered grid services due to their more localised nature. More information on balancing markets can be found in [16, 17]

2.4 Market Structures with Local Electricity Markets

The introduction to electricity markets presented above gave information on general concepts. Traditionally, electricity trading has been conducted between generators connected on transmission network as sellers, and retailers as buyers. Current trends and studies [18] suggest that by 2050, about 50% of EU residents could be generating their own renewable energy. This renewable energy is largely being connected to distribution network, together with EVs, BESSs, and demand response providers.

Through active participation, consumers/prosumers can improve their economic position but also contribute to the power system stability. Consumers are becoming providers of flexibility and the positive effect of their active participation can lead to the balancing of the local grid and rest of the power system, as well as on increasing the potential for integrating RESs [19]. Those benefits can be achieved through a LET concept that allows active consumers (acting as peers) to trade electricity in distribution networks [20, 21]. This section provides an overview of market designs and market players of LEMs.

2.4.1 Market Design and Market Players

LET typically refers to transferring energy from a grid element with an energy surplus to one with an energy deficit [22] in smart distribution grids. To facilitate a LET between different parties, a LEM is needed. LET can be classified based on the interaction of market players in three types [23], as shown in Figure 2.2.

Different interactions between market players are possible under the wholesale market, considering the complexity of electricity markets, as described in Section 2.1. In addition to that, LEMs are being developed. The types and features of LEM trading concepts are:

(i) Peer-to-peer (P2P) electricity trading: market participants interact with each other directly, without intermediary entities;

(ii) Electricity trading through a mediator: A mediator participates in the market on behalf of sellers and buyers and allocates energy from sellers to buyers;

(iii) Combination of P2P and trading through a mediator: Market participants can either trade energy directly or through a mediator.

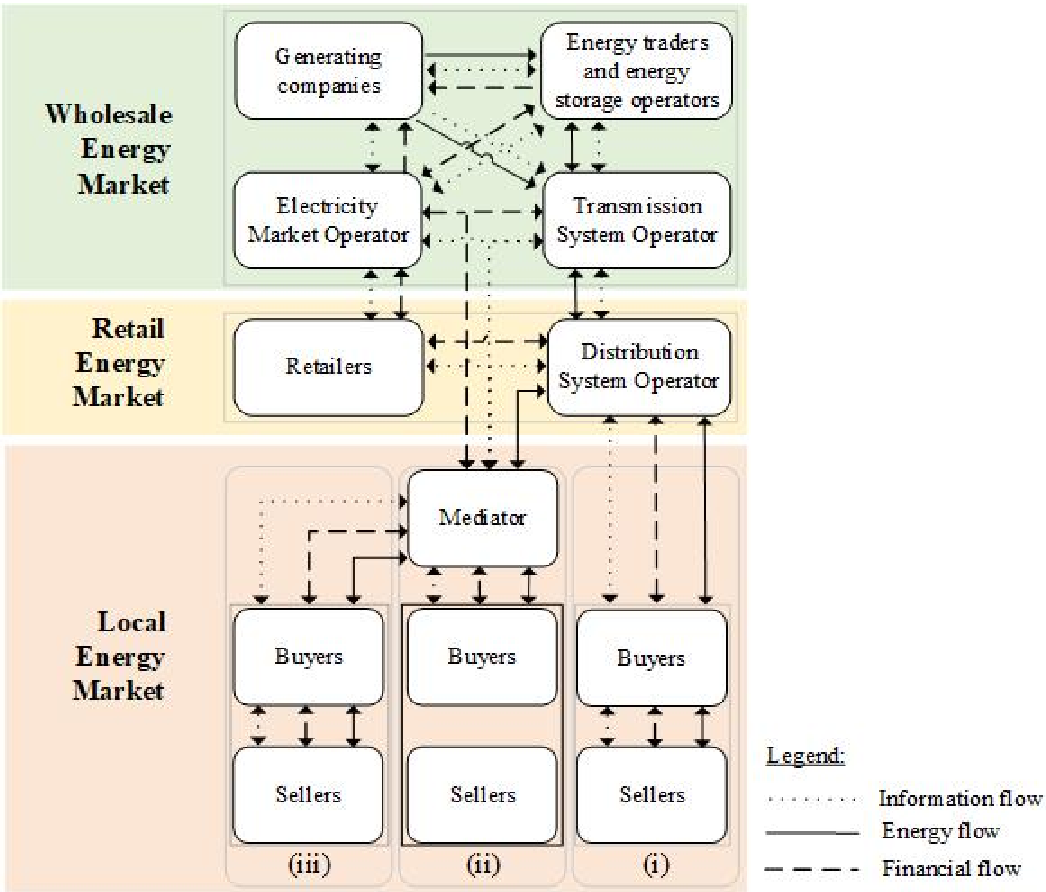

Figure 2.2: Market structures with local energy trading

For any design of the LEMs, market players are needed. In general, as participants in the LEMs, sellers, buyers, and mediators or energy dealing businesses can be identified [23]:

- Sellers are market participants with the ability of generating or storing energy, e.g. power generators, DERs, DSSs, EVs, utility companies, prosumers, smart homes, microgrids;
- Buyers are market participants that demand energy from the market, e.g. housing, industrial plants, businesses, consumers, prosumers;

- Mediators or energy dealing businesses are any other players on the market besides sellers or buyers, e.g. distribution system operators (DSOs), aggregators [24], market operators, smart energy service providers (SESPs) [25], energy traders, auctioneers [26], local operators [27], or community managers [28].

Under this classification, a mediator can also be a facilitator of the P2P electricity trading [29]. Moreover, a P2P trading platform can facilitate the trading, which would demand administration and maintenance from a third party as a minimum. Most of the pilot projects and reviewed papers examine LET over LET platforms [1, 30, 31]. For the purpose of inclusiveness, in this thesis, it is considered that LET and P2P can also be facilitated over a third party or a trading platform. That is in line with the definition set by the EU [24], where P2P trading of renewable energy means: “the sale of renewable energy between market participants by means of a contract with pre-determined conditions governing the automated execution and settlement of the transaction, either directly between market participants or indirectly through a certified third-party market participant, such as an aggregator”. According to [20], different types of platforms support P2P energy trading: 1) retail supplier platforms; 2) vendor platforms; 3) microgrid and community platforms and 4) public blockchain platforms, and not all of them imply P2P trading in local distribution networks. Architecture for LET platform applicable for microgrids was proposed in [1] as a four-layer system architecture. The listed layers are the power grid layer; the ICT layer; the control layer; and the business layer. When assessing the design of ‘microgrid energy markets’, authors of [31] identified seven key components as: microgrid setup; grid connection; information system; market mechanism; pricing mechanism; energy management trading system; and related regulation.

A debate on the evolution of the EU’s legal framework to speed-up decarbonisation in the energy sector is ever-present. However, processes take time, as changes in the energy sector’s legal framework can have far-reaching consequences, involve many participants, and often encounter opposite viewpoints. Some countries experiment with regulatory sandboxes to test innovative solutions and explore the impacts of regulatory changes under controlled conditions [32]. Further, the introduction of ‘citizen energy communities’ [24] and ‘renewable energy communities’ [29] as new legal terms in the EU’s regulatory framework is important, as those provisions can allow special local regulatory set-ups that can be integrated in the general energy sector regulatory landscape. As of the middle of 2021, most of the EU’s member states (MSs) were in the phase of drafting adequate laws and bylaws to transpose mandatory provisions set in the EU directives. EU directives set the general framework, so different national approaches are appearing [33]. Term collective self-consumption (CSC) is used for “jointly acting renewables self-consumers” [29], i.e., situations where at least two prosumers cooperate, either in the same building or multi-apartment block or within broader premises if allowed. This concept can also allow a group of households to partially cover their own energy needs by installing PV systems and sharing or trading energy between them [34].

The focus of CSCs is on the specific activity, and the focus of energy communities (ECs) is on a certain organizational format [32], where renewable energy communities (RECs) and citizen energy communities (CECs) are further defined separately [33]. LET or local energy sharing (LES), in principle, can be conducted within ECs, or ECs could be trading peers in a wider-range trading scheme. Here, LES is commonly referred to in cases where total costs are minimized for the group of prosumers and sharing price is determined based on the predefined formula [28]. ECs, under specific rules, can further take part in production, consumption, aggregation, energy storage, energy efficiency, or charging services for electric vehicles (EVs) or provide other energy services to its members or shareholders. The overview of key similarities and differences between CECs and RECs can be found in [33]. Throughout the transposition process, MSs have to decide, inter alia, on spatial limitations, allowed capacities, local grid tariffs, or conditions for using the public grid. Introducing local grid tariffs or reducing grid fees and other surcharges can significantly improve the economic feasibility of LET [35].

2.4.2 Pilot Projects

The first implementation of a LET in a microgrid was applied in 2016 in the Brooklyn Microgrid project [31]. The implementation was achieved through a P2P trading platform using distributed ledger technology (DLT) as an information system for processing and recording transactions. However, identified aspects that could be improved include local balancing, market mechanism, pricing mechanisms, scalability and legal environment [31]. To date, many new pilot projects have been initiated and research is ongoing, where overviews are listed in [1, 31, 36, 37, 38, 39]. The introduction of ECs in the EU regulatory framework further accelerated the development of new projects, as the regulatory framework was seen as a major challenge in most of the early developing projects [31, 36, 40]. The following projects can be listed as examples of advances in the implementation of the LET concept:

- Brooklyn Microgrid project [31]: a microgrid energy market was established in Brooklyn, New York. The participants were members of a virtual community energy market platform and connected via an electrical microgrid built in addition to the existing distribution grid. Members are equipped with solar PV systems. Also, additional energy meters were installed and used under the transactive energy paradigm and on top of existing analog meters. The system was run on a private blockchain protocol. In its development, integration with the energy market was seen as a major challenge preventing more significant benefits for the members.
- Energy village Lu če [41]: an energy community was created in remote village Luče, Slovenia, consisting of members equipped with solar PV systems, home BESSs, community BESS, and EV charging point, all under the same LV feeder. DSO's smart meters

and third-party SCADA and microgrid management systems are used as an ICT system. It was developed as a regulatory exception with reduced grid fees CSC scheme over the distribution network, where LES is planned to be implemented. As main challenges, a restriction to one LV feeder and undefined responsibilities and procedures between the DSO and microgrid operator were recognised.

•Monash Microgrid [42]: transactive energy management (TEM) solution has been proposed with a framework for designing, implementing, and deploying energy management in microgrids. The applicability is discussed with the presentation of complete hardware and software base for a platform to deploy a TEM in Monash University microgrid, Australia. In example scenarios, the design choices for achieving desired objectives are presented.

•Energy community Rafina [43]: the energy sharing community is being implemented by participating the municipality and citizens in Rafina, Greece. Used technologies are solar PVs, and energy is shared over the public distribution grid. For data collection, DSO's smart meters are used. Optimisation or integration of additional flexibility options is not implemented or planned under the virtual net metering scheme. Under the virtual net metering scheme, the grid can be used as BESS. The scheme removes grid charges, and the EC can define sharing rules. As the main challenges, the following are recognized: all members have to have the same retailer, and delays in grid connections.

•Neighborhood in village Heeten [44, 45]: used technologies are solar PVs, EV chargers, and EV batteries, but LET is restricted to public LV feeder in Heeten, The Netherlands. Users are provided with smart meters and a consumer app to support demand response, a BESS management system, and energy flow control at the connection point of the neighbourhood are developed. Households are organised in an EC under the 'Energy Act Experiments Regulation' for LEM . Volumetric grid charges for LES are omitted, and only the capacity part is charged. Replication potential depends on regulatory development.

2.5 Pricing and Market Clearing Approaches

A general goal of electricity markets is to drive the costs down and increase the global welfare, while preserving a required system stability and security [2]. This section gives an overview of optimisation objectives and market clearing methods for LEMs.

2.5.1 Optimisation Objective

In most cases, social welfare maximisation is considered the objective of market-clearing [23]. It is defined as the sum of consumers' surplus and producers' surplus that contribute to more user comfort with lower utility company costs. If the profit of each participant is maximised, social welfare maximisation can maximise the total welfare of the market. It can be modelled by summation of the utility of all buyers minus the cost of all sellers as presented in (2.1):

$$\max\left(\sum_{j=1}^{N_B} U_j(d_j) - \sum_{i=1}^{N_S} C_j(s_i)\right) \tag{2.1}$$

where $N_S = \{1, ..., N_S\}$ is set of sellers and $N_B = \{1, ..., N_B\}$ the set of buyers in the market. The cost of providing s_i energy offered by seller i to the market can be approximated by different functions, e.g. a quadratic convex function as given in equation (2.2) [46]:

$$C_i(s_i) = \alpha_i {s_i}^2 + \beta_i s_i + \gamma_i \tag{2.2}$$

where α_i, β_i, and γ_i are predefined positive constraints which are used to model the amount of energy that a seller is willing to sell at different prices. These parameters are specific for each seller and depend on the type of generation.

A utility function can be used for modelling of the satisfaction level of the buyers that depends on their demand from the market. The utility function for each buyer j and demand d_j has to satisfy three conditions: it should be non-decreasing, the marginal benefit of costumers should be a non-increasing function, and no energy consumption should bring no benefits [23, 46].

Different types of utility functions can be used under these conditions, but the quadratic utility function is common in the literature because it yields a linear marginal profit (a derivative of the utility function) which is favourable in solving optimisation problems. For example, the quadratic utility function for buyer j can be modelled with (2.3) as proposed in [47] and [48]:

$$U_j(d_j) = \begin{cases} \omega_j d_j - \delta_j d_j^2 & d_j < \frac{\omega_j}{2\delta_j} \\ \frac{\omega_j^2}{2\delta_j} & d_j \geq \frac{\omega_j}{2\delta_j} \end{cases} \tag{2.3}$$

where ω_j and δ_j are predefined positive constants that define how a buyer reacts to different prices. These parameters can vary between buyers and reflect the impacts of different times of day or climate conditions.

After market clearing, the total energy demand should be equal to the total energy supplied as shown in (2.4) which is the constraint of the objective function (2.1):

$$\sum_{i=1}^{N_S} s_i = \sum_{j=1}^{N_B} d_j. \tag{2.4}$$

The energy cost minimization is also being used as the objective function in market clearing, in cases when the goal is to minimise the cost of energy and system operational costs [23]. In this case, a cost function can be defined for each player and the objective is to minimise the total cost as indicated in (2.5), subject to energy balance constraint as in (2.6):

$$\min \sum_{k=1}^{N_T} C_k(p_k) \tag{2.5}$$

subject to:

$$\sum_{k=1}^{N_T} p_k = 0 \tag{2.6}$$

where N_T is the number of total players in the market, k the index of market players, and $C_k(p_k)$ the cost function of each player p_k. Here, instead of defining a utility function for buyers as in (2.3), a quadratic cost function like (2.2) can be defined for each player, where $p_k > 0$ indicates that player$k$ is a seller and $p_k < 0$ shows that energy is consumed or drawn from the system and player k is a buyer in that time interval.

2.5.2 Market Clearing

The 'equilibrium price' (also known as 'market clearing price') should be found in the market clearing. The methodology used for the market clearing can vary due to assumptions, market structure, market players' behaviour, and particular market rules. Therefore, different methods can be applied for market clearing or objective function optimisation depending on the system modelling. Moreover, to make system modelling more accurate, a combination of methods can be implemented [23]. Also, it is useful to notice that most of the existing pilot projects implemented static pricing with the ex-ante defined price as a first step towards the more advanced methods for LET [31], and some authors proposed energy-sharing models [49] where the community costs are minimized and LES price can be determined ex-post by a predefined formula. According to [23], market clearing approaches can be classified to non-distributed, distributed methods, and hybrid and other, as shown on the 3.1.

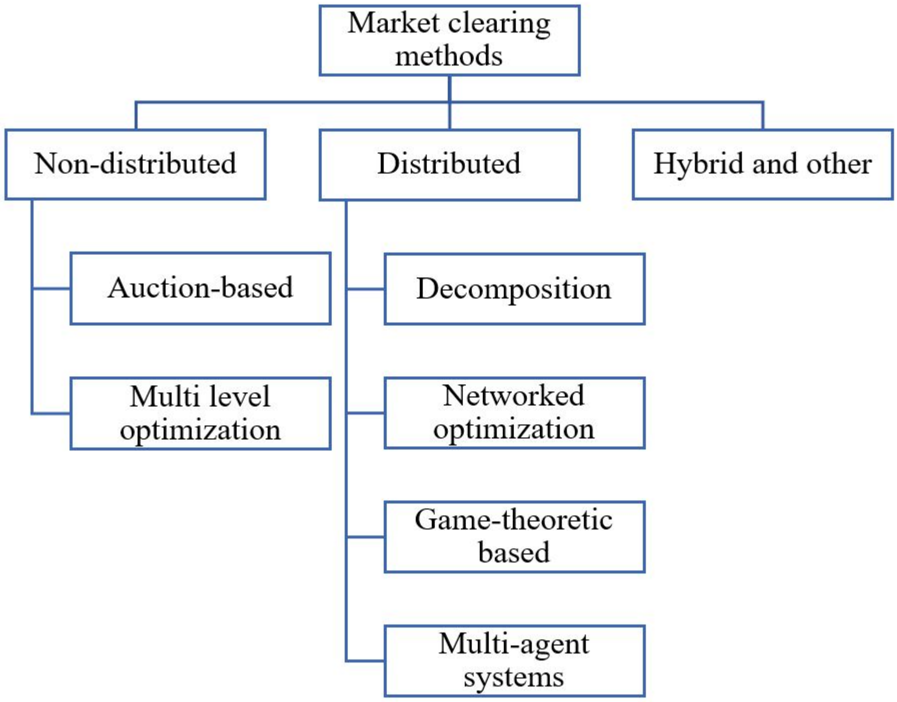

Figure 2.3: Classification of market clearing methods

A key characteristic of non-distributed approaches are that calculations are conducted centrally by a mediator, for example by a market operator or a community manager [28]. Auction-based methods and multi-level optimisation are common methods for centralised market clearing.

•Auction-based methods: most of the wholesale energy markets operate based on auction principles. In general, an auction is a negotiation mechanism where the negotiation is facilitated by an intermediary, and is usually based on an automated set of rules [50]. In the electricity markets auctions can be divided to one-sided, or two-sided, depending whether only buyers or sellers participate or both at the same time. Number of authors proposed auction-based solutions for LET [51, 52, 53, 54].

•Multi-level optimisation: under this approach, an optimisation problem is divided into sections, and each section is linked with a level of optimisation. Thereby, optimisation in upper levels depends on the results of lower levels, and the upper level variables define the context of the lower level. Several authors proposed multi-level optimisation frameworks for electricity markets - day-ahead, intraday, and ancillary services markets [55, 56], where as additional level distribution-level flexibility markets can be added [57, 58].

A key feature of distributed optimisation methods is that the calculations can be distributed between participants [59]. Distributed methods can further be classified into four main groups - decomposition, networked optimisation, game theoretic, and agent-based methods:

•Decomposition methods: a large-scale problem is decomposed into several subproblems based on the objective function structure and constraints [60]. After decomposition, each subproblem can be solved separately, but a coordinator is required to ensure the convergence of local decisions to the global optimum [61]. Decomposition methods can be used for large scale problems and can distribute computation requirements among the participants.

- Networked optimisation: it is used for problems that can be decomposed considering the structure of the original problem. It is a particular type of decomposition method without applying a central coordinator [23]. The decomposition structure is usually based and aligned to the communication structure [62]. The networked optimisation is associated with graph theory, where a graph models the distribution network with vertices as market players. In the graph representation of the network, players' ability for information exchange is indicated by an edge between their vertices. This method is appropriate for cases when participants can exchange information only with their immediate neighbours [59].
- Game theory-based methods: game theory studies the decision-making process of several players with possible cooperative and conflicting objectives. It can be divided into cooperative games and non-cooperative games. Defined "as the formal study of the mathematical model of several decision-making players with possible cooperation and conflicting objectives" [23]. Under LET, where participants operate their flexibility options to maximise their profits, game theory method can be a suitable approach. Moreover, similarly to the networked optimisation, game theory can be used in cases of limited available information where agents tend to optimise local objective [62].
- Agent-based methods: these can be used for large-scale systems with various types of interacting agents. It is suitable and common for modelling complex dynamics of the electricity markets [63, 64, 65, 66, 67]. Under this approach, subjects can be modelled as agents that cab be a single variables within a computer program to complex intelligent objects with wide range of actions and decisions.

For the implementation of energy trading, approaches can be combined - for example, agent-based or game theory-based methods can be used for positioning of individual market players and bidding, while their offers are cleared centrally on a auction based market. Further, among other methods proposed for LET, a bilateral contract network was implemented in [68], min–max optimisation strategy and fair sharing to find the best algorithm to form a virtual association of prosumers in [69], or search theory in [70]. Moreover, a genetic optimisation and rolling-horizon technique are applied in [71] for the day-ahead scheduling of the electrical appliances, while the artificial bee colony algorithm to solve the non-linear optimisation problem was used in [72]. Further reviews on the application of artificial intelligence (AI) and machine learning (ML) in energy markets can be found in [73, 74, 75].

When physical constraints are included in optimisation of energy system operation, those problems are known under term optimal power flow (OPF) [76]. The application of listed market clearing methods for LET is a form of optimisation of power system, so if the physical constraints are included in the market clearing methods, they become special cases of OPF problems. The methods for addressing network constraints and integration of control in LET are closely considered in Chapter 3.

2.6 Connection to the Contributions

The first part of the dissertation's contribution provides a short-term model for near real-time local electricity market over a distribution network. That way, the research on modelling and implementation of double-sided auction market clearing for LET in electrical distribution networks (described in Section 2.5) is expanded.

The second part of the dissertation's contribution is related to the method for determining the effects of LET on voltage profiles and power flows over electrical distribution networks. This analysis implementation of different market clearing methods (as described in Section 2.5) and LEM setups on voltage profiles and power flows as part of the stability issues for distribution networks and microgrids as further elaborated in Section 3.2.

The third part of the dissertation's contribution provides a method for assessing the impacts of the local electricity market on market participants. This is particularly important in context of integration of LEMs in electricity markets as described in Sections 2.1 and 2.4.

Chapter 3

Control and Network Constraints in Local Energy Trading

As listed in Chapter 2 the components for implementation of LET can be grouped into four layers: grid, ICT, control, and business [1]. The overview of the state-of-the-art developments under the business layer was presented in Chapter 2. In this Chapter, an overview of physical preconditions for grid and ICT components are presented, as well as advances in control and addressing of network constraints based on market principles.

3.1 Stability and Control in Distribution Network and Microgrids

It is important to provide an introduction to principal stability and control challenges in distribution networks to allow the integration of LEMs with control functions. Further, as some LEMs or ECs can be organized as microgrids, an overview of microgrid stability challenges is also provided in this Section.

3.1.1 Stability Classification

In modern power systems with a lot of converter-driven RES, the stability can be classified into five categories: frequency stability, voltage stability, rotor angle stability, converter-driven stability, and resonance stability [77]. In traditional power systems, the dynamic behaviour of synchronous generators played a dominant role in the analysis of power system stability problems, and only the first three categories were recognised in the previous classification [78].

DERs are often the main power supply in microgrids and modern distribution networks. DERs can be classified into two categories compared to the interface modes: (1) inverter interfaced DERs; (2) DERs connecting to microgrid directly [79]. PV panels, small direct-drive wind turbines, micro gas turbines, batteries, flywheel energy storage, and supercapacitors are connected to the grid by inverters. On the contrary, double-fed induction generators, diesel generators, and small hydro units are connected to grids without inverters. RESs are usually applied as much as possible in designing local energy systems, so inverter-interfaced DERs are used widely in microgrids and modern distribution networks, making the operating characteristics quite different from the traditional grid [79, 80]. The classification of microgrid stability, proposed in [79] classifies the stability according to the microgrid operation mode. The timeframe and physical characteristics of the instability process are also considered. There, long term is a timeframe in a range of minutes to hour; short term is a timeframe ranging from milliseconds to seconds, and the ultra-short term is a timeframe lower than milliseconds (usually microseconds). The microgrid stability issues are classified into grid-connected microgrid stability problems and islanded microgrid stability problems:

- In grid-connected mode, the frequency in the local distribution networks and microgrids is in principle maintained by the utility grid due to the usually relatively small size of microgrids compared to the utility grid. Thereby, the frequency and the rotor angle stability are usually not the focus in the analysis of the grid-connected microgrids [79]. In the case of small disturbance stability, the analysis is mainly focused on the role of droop gains and load fluctuation on the voltage stability. The switching process of interfaced inverters is usually not considered, so it is considered a short-term issue [79]. In the case of transient stability (significant disturbances, such as short-circuit fault), the dynamic response of different DERs, fault current contribution of DERs with different control strategies, and the power flow characteristics of a microgrid are usually discussed. As the short fault issues are happening within the milliseconds, the transient stability issues are considered ultra-short-term and short-term phenomena.
- In islanded mode, the microgrid has to maintain the balance of power supply and load variation, so the frequency stability is an important issue. Since inverter-based DERs and DSSs are normal main constituents in microgrids and their dynamic process is not similar to the machinery rotating process of synchronous generators, the rotor angle problems are usually out of the focus and islanded microgrid stability is classified into the voltage stability and frequency stability [79]. Similar to the grid-connected microgrid stability analysis, in the case of small disturbance stability, the analysis is mainly focused on the influence of droop gains, load fluctuations and effects of changes in the production of DERs on the voltage and frequency. The timeframe of these issues is from hours to seconds, so those issues are categorised as both long term and short term phenomena [79]. In case of transient stability issues, such as short circuit fault, open circuit fault, loss of DERs and load, etc., the analysis is focused on the ability of the microgrid to maintain the operating conditions of the microgrid. The timeframe of these issues is from several

hours to milliseconds, so those issues are categorised as long-term, short-term, and ultra-short-term phenomena. Also, the islanding or grid connecting processes are part of the transient stability issues [80].

By the definition, microgrids have to be able to operate in island mode for some amount of time [81]. There is not a consensus opinion on how long microgrids should be able to operate in island mode. However, most of the authors do not consider it necessary for the microgrid to have yearly adequacy of island operation except if microgrids are not connected to the utility grid [82]. Ensuring system adequacy is an additional challenge for energy islands, ECs or microgrids [83, 84].

3.1.2 Control Functions

Control in distribution network and microgrids can be ensured by the energy management systems (EMSs) [85], whose function is to ensure "both supply and demand side management, while satisfying system constraints, to realize an economical, sustainable, and reliable operation" [82]. EMSs can provide many benefits, such as generation dispatch, energy savings, reactive power support, frequency regulation, reliability to loss of load, cost-reduction, energy balance, GHG emission reduction, and enhance customer participation and customer privacy [85]. Authors of [31] introduced the term 'energy management trading system' (EMTS) for the microgrid energy markets, which is, basically, an EMS whose functionality is based on trading strategies. As a main management system of the LET in microgrids, EMTS needs access to the (near real-time) demand and supply data of its market participant and constant integration with the pricing mechanism to secure the reliable operation of the microgrid. EMTS should allow communication with the utility grid and the rest of the market to maximize the benefits for the peers [20].

According to [85], control functions can be divided in three levels: (1) Upstream network interface: decision for island/interconnected mode, market participation, upstream coordination; (2) Microgrid control: voltage/frequency control, active/reactive power control, load consumption/shedding, black start; and (3) Local control and protection: protection, primary voltage/frequency control, primary active/reactive power control, battery management.

Also, similarly to the communication architectures, the operation can be organized in a centralised or decentralised manner [82, 85]. In centralised control, the main function lies with the central controller that optimises the operation of DERs, DSSs and controllable loads by sending control signals. Operation strategy can take account of market prices of electricity and fuel costs, grid security, ancillary services requests by the DSO etc. In case of centralised control, control is usually organized hierarchically [86, 87], due to the different stability issues and corresponding timeframes. The list, hierarchy, and corresponding timeframes of the microgrid control operations are shown in Fig. 3.1 [87].

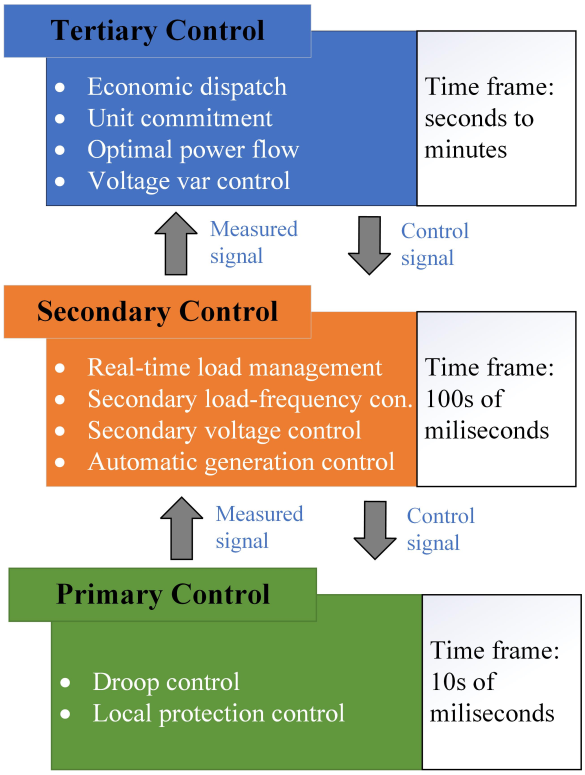

Figure 3.1: List, hierarchy, and timeframes of microgrid control operations

In decentralised approaches, the main responsibility lies with controllers that compete or collaborate in accordance with the defined control strategies [82]. This approach can be suitable in cases when there is no single ownership of DERs, i.e. where several decisions should be taken locally and possibly with competing interests. In both approaches to control, some basic data or functions can be centrally available, such as local production and demand forecasting and security monitoring. The implementation of decentralised control is discussed also in [88, 89].

Based on [82], key attributes that affect the performance of the control algorithms are: (1) number of nodes; (2) number of message exchanges; (3) size and structure of the system model; (4) desired level accuracy and optimality. The choice between the centralised and decentralised approach for microgrid control depends on the main objectives and the special characteristics of the controlled microgrid. Detail list of characteristic is available at [82], and the general conclusion is that the centralised approach is suitable for a system with one specific goal and a decentralised for a system with several goals. It also comes with a simpler design and could allow easier installation of new equipment. Authors of [89] concluded that decentralised control of microgrids improves reliability because the single point of failure is eliminated. However, the challenges are in the synchronisation of controllers, where a certain level of intelligence is needed to optimise performance and protection. For that, communication links are essential so that cybersecurity issues can arise.

3.1.3 Underlying Information and Communication Technologies

ICT infrastructure consists of meters, sensors, computers, and other electronic equipment and systems that collect, store, use, and send data electronically [1]. ICT infrastructure is recognized as a layer for LET platforms [1] and as a component of the microgrid energy markets [31]. The use of modern ICT infrastructure is heavily linked to the 'smart grid' concept which is in [90] defined as "a modern electric power grid infrastructure for improved efficiency, reliability and safety, with smooth integration of renewable and alternative energy sources, through automated control and modern communications technologies." In [91, 92, 93, 94] the communication technologies and network requirements for different smart grid applications were assessed. In [95, 96] linked challenges and opportunities were analysed. Authors of [97, 98] focused on the review of ICT infrastructure applicable for microgrids. Moreover, authors of [99, 100, 101] proposed different simulation methods for evaluating the performance of ICT infrastructures and the impact on the electric power grid.

Communication interfaces in smart grids should allow bi-directional communication to different controllers [98]. The communication nodes are commonly created by adding ICT capabilities to the underlying DERs or components, and upgrading them to intelligent electronic devices (IEDs) [91], so that they can exchange data and/or control commands. Communication protocols are used to ensure accurate data exchange between communication nodes. A protocol suite consists of layers with an assigned set of functions using one or more protocols. Thereby, data communication networks usually use multiple levels of protocols based on the ISO-OSI (International Standards Organization/ Open Systems Interconnect reference) model [98].

The usual past and present control systems use centralised architectures where a central controller communicates with all resources and make decisions. The control is usually implemented by the Supervisory Control and Data Acquisition (SCADA) systems [98] that use the Enhanced Performance Architecture (EPA) model [91]. EPA has three layers instead of the seven layers defined in the OSI model. Traditionally, SCADA systems use direct communication links (i.e. not over internet) to exchange commands and data in line with various protocols. Usual protocols in the power sector are MODBUS, PROFIBUS, CANBus or DNP3. They all have in common that they are generally based around Client-Server (Master-Slave) architectures with bus network (centralised) topologies [98].

The visible current trend is using new communication technologies based on the internet or on Common Information Model (CIM). The Internet architecture is based on TCP/IP protocol (Transmission Control Protocol and Internet Protocol). TCP/IP is an effective solution to the problem of achieving end-to-end communications and TCP/IP protocol suite is used by the Internet [98]. This fact leads to the evolution of the above-listed protocols towards the Modbus/TCP, DNP3 over TCP and Profinet which allows them to be integrated on the traditional SCADAs. These protocols use the benefits of TCP/IP and upgrade their capabilities. For example, Modbus or Profibus over TCP/IP communication systems can report undesirable events as incorrect address, packet failure, illegal function code received, etc [98]. Moreover, DNP3 over TCP/IP supports timestamps and data quality information that can be included in the messages. However, despite these improvements, the centralised control based in client-server communication architectures can cause inadequate services, bottlenecks, or under-utilization of the network resources in the communication system, provoked by several causes, e.g.: a failure in the centralised control point could lead to several faults or even shut down the entire system; the nodes (slaves) are not able to start a communication themselves with the master; and there are difficulties to manage data in real time of a wide range of devices [98].

The proposed classification of control schemes based on their communication network is given in [102]. Listed architectures are centralised, decentralised hierarchical, and distributed with the examples in SCADA, multi-agent systems (MASs), and P2P overlays respectively. Main advantage of emerging distributed architecture is in avoidance of single point of failure and ability to reach high security and scalability standards with lover costs. More detailed descriptions and characteristics of listed architectures as well as protocols are available in [98].

Use of the distributed ledger technology (DLT) and blockchain technology in the energy sector and microgrids got under significant attention lately, and an overviews of the state-of-art and potential for the use of blockchain technology in the energy sector was done in [31, 37, 103, 104], while the possible application for the P2P trading was analysed in [105]. The findings are that there are possible benefits for the use of DLT and blockchain technology in the energy sector but also significant challenges remain. The main drivers are data management without third-party supervision, transparent and secure transaction log, use of 'smart contracts' for enabling transactions and settlement, and incentivizing end-consumer participation. On the other hand challenges with scalability, limited transaction loads and transaction speed, potential high energy consumption and costs as well as regulatory restrictions and lack of standardization remain to be solved for wider implementation.

Communication technologies are used for data transfer between the communication nodes (which are organized under the particular communication architecture), while the data is structured and exchanged in line with the communication protocols. There are many communication technologies with corresponding pros and cons [106], and they can generally be classified into wired and wireless [91].

Historically, wired communication technologies have been used in the electrical grid due to their better performance than wireless technologies regarding robustness, reliability, security, and bandwidth properties [98]. However, an important drawback of wired technologies is the higher deployment cost, which is getting more important due to the ever-growing need for data exchange. Wired technologies which are usually used in microgrids are serial communication RS-232/422/485 for SCADA systems, Ethernet (IEEE 802.3 technology), bus-based technologies (e.g. ModBus, ProfiBus) and Power-Line Communication (PLC). However, those technologies, except of Ethernet, are not capable to provide reliable decentralised communications [98].

As an alternative, wireless technologies are characterized by (in general) lower performance in terms of robustness, but they are increasing their security capabilities and could be an important solution for distributed microgrid communication links considering also their lower installation costs [96, 98, 102]. Mostly used solutions for wireless internet access in microgrids are Family standards IEEE 802.15 (Wireless Personal Area Network, WPANs), or IEEE 802.11, Wi-Fi (WLANs). Those networks transmit small amounts of information over relatively small distances and could be used to implement links either between DERs and/or between DERs and central controllers. On the other hand, cellular networks (4G/3G/HSPA, LTE (Long-Term Evolution), LTE-A (Long-Term Evolution Advanced), and Evolution–Data Optimised) could be used for communication between network operators and/or between more microgrids [98]. The listed wireless technologies facilitate communication between nodes in a single hop (i.e. from one node to another node). Mobile Ad-hoc Networks (MANETs) or Wireless Mesh Network (WMNs) are wireless multi-hop networks, which means that they facilitate coverage over multiple wireless hops. In these networks, nodes operate as both host and routers which extends the area range. Wireless Sensor Networks (WSNs) are also similar and they have been created to resolve limitations and improve the performance of WPANs, WLANs, WMNs, and MANETs. The lists with the key wired and wireless technologies are listed in [98, 102, 106]. The technologies are classified also based on the following categories where they are used to: wide area network (WAN); neighbourhood area network (NAN); consumer premises area network (CPAN) which include home area networks (HAN), building area networks (BAN), and industrial area network (IAN).

3.2 Addressing Control and Network Constraints in Local Electricity Markets

As elaborated above, key locally affected stability challenges in grid-connected distribution feeders refer to voltage stability [79] and congestion management since the line power flow constraints must be respected [107]. When power system control functions are observed from the market design perspective, attention has to be paid to the timeframes of certain activities, as stability issues vary from milliseconds to minutes/hours. In contrast, the time intervals for electricity trading on forward markets are commonly not lower than 15 minutes. In some cases, near-continuous trading is conducted, where energy is dispatched every 5 minutes [3, 87]. Therefore, only some control functions have the same timeframe as the forward electricity trading (unit commitment, economic dispatch, optimal power flow, and Volt/VAr control). In contrast, the other control functions can be further regulated by grid codes [108], market for the auxiliary services (spot market) [109], added control loops [86], and/or by the deployment of energy management systems [85].

The existing literature investigating impacts of LET on distribution grid proposed various means of supervision and/or control:

- Zhang et al. [1] foresaw the external role of DSOs to accept or reject orders in the period between the gate closure and the energy exchange. The approach mirrored the organisation of the wholesale markets. However, due to the complexity of the distribution systems, it could be a difficult task for the DSOs to monitor and control transactions in many LEMs simultaneously, especially considering the ongoing trend of decreasing trading intervals and increasing diversity of DERs.
- Tushar et al. [110] proposed a P2P energy trading scheme that could help reduce peak electricity demand. The method is based on the cooperative Stackelberg game where the centralised power system acts as the leader that has to determine the price at the peak demand period to stimulate prosumers to lower their demand. However, the paper didn't analyse the effects on local voltage stability and didn't integrate network constraints with the market mechanism.
- Morstyn et al. [111] proposed a P2P electricity trading platform based on the multiclass energy management concept to facilitate trading between prosumers with different preferences (beyond merely financial ones). The proposed energy management system has a goal to maximize power flows between prosumers and satisfy the distribution network power balance. Similarly to the previously described researches, the voltage stability or constraints of power lines were out of the scope of the proposed energy management system.
- Long et al. [112] analysed the P2P energy sharing based on a two-stage aggregated BESS control in a community microgrid. The work showed the potential of centrally managed operation of BESSs to reduce energy bills and increase the annual self-consumption and self-efficiency of the energy community. Moreover, with the integration of fair compensation prices, each participant can benefit financially compared to conventional power-to-grid (P2G) energy trading. The insights were valuable, but the voltage stability was also out of the scope of the analysis.
- Guerrero et al. [67] went further and proposed a methodology based on the network sensitivity analysis to ensure that P2P energy trading in a low-voltage (LV) distribution grid remains under network constraints. The used market mechanism was based on the continuous double auction (CDA). The technical constraints were integrated into it to provide a possibility to block transactions with a high risk of causing voltage problems or allocate extra costs to participants in those transactions. The assessment of the sensitivity of the

network to transactions was based on the estimation of the voltage sensitivity coefficients (VSCs), the power transfer distribution factors (PTDFs), and the loss sensitivity factors (LSFs). The method was tested on a typical U.K. LV network. This method is compatible with the CDA market mechanism, where each transaction has a buyer and a seller. However, it is not suitable for the LEM organised as a local electricity exchange where all supply and demand curves are centrally aggregated to find market clearing prices and quantities, which is also considered in the paper.

Further, a comprehensive review of impacts of LEMs integration in power systems [113] highlighted that voltage variations and phase imbalances, system peak levels, and congestion are the most common issues, while the integration of network constraints is possible through power flow equations, network tariffs signals or power losses signals. Also, the same review pinpointed the importance of the inclusion of DSO in a decision-making process and market mechanism since it has access to crucial grid information.

Implementation of LET directly impacts the stability in local distribution networks or microgrids. In forward LET, the tertiary control functions (as defined in [87]) could be integrated with market clearing, while for primary and secondary control additional methods are used or can be merged with LEM spot market as listed above. Among additional market clearing methods for LET that have incorporated network constraints are: [30, 57, 61, 64, 65, 67].

3.2.1 Flexibility Options in Local Energy Systems

Flexibility options are required to achieve maximum LET benefits in terms of increased local self-sufficiency, decreased costs, increased social welfare, or decreased voltage fluctuations. There are different possibilities for the provision of flexibility in local energy systems, such as demand response, solar PV systems, advanced inverters, BESSs, and combinations of multi-energy systems (MESs).

Several authors researched the optimal operation of flexibility options and integration of MESs. Wang et al. made a review and analysed a prospect of integrated DR with MESs [114]. It is argued that in the power system DR is limited due to the high costs of discomfort and a lot of must-run loads, so the integrated DR with MES could expand the potential of DR without affecting consumers' comfort. Geidi et al. [115] presented an approach for combined optimisation of coupled power flows of MESs including electricity, gas and district heating systems. With the developed model, combined economic dispatch and optimal power flow problems are stated for transmission and conversion of energy. Proposals for operation of power-to-X facilities in multi-energy systems are also emerging [116], such as power-to-hydrogen [117], power-to-hydrogen-and-heat [118] etc. For example, Pötzinger et al. [119] analysed the influence of hydrogen-based storage systems on self-consumption and self-sufficiency of residential photovoltaic systems. The results showed that battery storage systems are preferable for short-time storing, while hydrogen-based storage systems are favored for seasonal storage, but not economical at a present time due to the high investment costs. Mathiesen et al. [120] presented the concept of development and design of energy systems that integrate electricity, heating and transport sectors, including various storage options, to provide the necessary flexibility to integrate large penetrations of variable RESs and achieve 100% renewable energy systems. It is advocated that inter-sectoral and multi-vectoral integration of energy systems leads to the cost-optimal energy systems with high share (towards 100%) of RES. Martinez Ceseña et al. [121] developed a unified operation and planning optimisation, subject to long-term uncertainties and based on a stochastic MILP. There, the electricity, natural gas and ambient heat were modelled as energy sources and electricity and heating as energy consumption. Energy transformations and storage options included a gas boiler, EHP, CHP, and heat storage.

It is evident that researches use different indicators to assess and optimise the planning and/or operation of local energy systems and usually, the optimisation objective is the minimization of investment or operational costs.

3.3 Modelling of the Network and Flexibility Options in the Thesis

Traditional power systems were based on a premise where supply is adjusting to the passive demand and networks are planned based on a conservative approach to be able to facilitate the peak demands. Especially in distribution networks, near real-time data measurement and analysis were relatively scarce. More precisely, the level of distribution networks is the research area where changes are rapid due to a steep rise in installations of DERs, heat pumps, EV chargers, BESSs and multi-energy systems, as described in Subsection 3.3. New management and business models, such as LET, are therefore emerging here and are being integrated with control functions, as described in Section 3.2. These innovations would not be possible without underlying ICT solutions as listed in Subsection 3.1.3.

The short-term model for near real-time LEM over a distribution network developed in first part of the thesis' contribution allows modelling of activation of demand response (as one of the flexibility options described in Subsection 3.3) in distribution network based on market principles. It allows modelling of different supply and demand offering curves of market participants, contributing to the methodological approaches for modelling of LEMs, and the subsequent impact of LEMs. Second approach under this contribution provides a model for optimal scheduling of community flexibility options by a coordinator. Here, the modelling of prosumers different flexibility options and multi-energy systems is provided.

Second thesis' contribution is focused on impacts of LET on voltage levels and power flows in distribution network. The developed model allows modelling of impacts on power flows and voltage levels for different elasticities and prices of prosumers, as well as for different spatial distribution of producers and flexibility options. This provides insight into questions of the expected effects of anarchy behavior of peers under LEMs on distribution networks and if contributions to stability and control functions (Section 3.1) can be achieved that way.

A method for assessing the economic impacts on market participants proposed under the third part of the thesis' contribution takes into account the roles of market players such as DSO, TSO, suppliers, as well as impacts on taxes and levies in case a LEM is established within an EC. Regulatory changes in grid tariffs can be an essential intervention to maximise the activation of flexibility options (as elaborated in Subsection) and reap positive effects on local stability and power flows (as presented in Section 3.1). However, in addition to the benefits for the participating prosumers, these interventions must not lead to unfair effects on other electricity market participants.

Chapter 4

Main Scientific Contributions

This thesis is built on the contribution divided into three parts. The first one provides a short-term model for a near real-time LEM over a distribution network. Here, two approaches have been developed: a centrally aggregated double-auction market mechanism, and a MILP LES market clearing model that is applicable for different regulatory setups, with novel methods for determining energy sharing compensation price. The second part of the contribution provides a method for determining the effects of LET on voltage profiles and power flows over electrical distribution networks. This part contributes to the research of the question of effects of the near-real-time LET in a distribution network, with a focus on the effects of supply and demand offering curves on power flows and voltage levels in a LV distribution grid. The third part of the contribution provides a method for assessing the impacts of the LEM on market participants. The method is suited for different regulatory frameworks and can serve in assessing active consumers with multi-energy systems. The method is applied in the case studies of LET within different energy communities and energy vectors to capture the effects also of diverse energy vectors under the LET concept.

4.1 Short-term Model for Near Real-time Local Electricity Market over a Distribution Network

A development of ICT technologies and decreasing costs of RES, supported by the evolving regulatory framework are opening opportunities for new business models, such as LET in electrical distribution networks. For this contribution, two approaches for modelling a near real-time LEM over a distribution network have been developed.

Firstly, a centrally aggregated double auction LET algorithm has been developed and used to simulated LET. In the first step, demand and supply offers are created by the peers in the distribution grid, based on their demand needs, demand elasticity, supply capacity, and supply offering prices. Afterward, all supply and demand offers are sent to the double-auction market, where offers are aggregated, and equilibrium volumes and prices are determined. Finally, the least-cost dispatch is sent to the peers. The time horizon of the simulated market layer is 24 h, with 5 min resolution. From the developed algorithm, equilibrium prices and volumes (unit commitment of the peers) with a five-minute resolution are obtained and can be subsequently used for studying effects in the distribution grid in second part of the thesis's contribution. The method has been presented in [P_1], and further elaborated and case studies expanded in [P_7 and [P_8].

The second approach is based on a MILP LES market clearing model that implies the role of a local energy sharing coordinator (LESC) that is optimising the operation of flexibility options of the peers participating in LET, e.g. within an energy community. Here, LESC dispatches flexibility options and prices is determined ex-post based on predefined formulas. The method is applicable for different regulatory setups, with novel methods for determining energy sharing compensation price. Proposed price-forming methods are suitable for environments where prosumers can have different energy suppliers, third parties (like DSOs or market operators) could control the sharing price ex-post, and where certain charges can be included in LES - such as distribution fee, taxes, or similar. This method is presented in [P_2] and [P_{10}], while the application for multi-energy communities is presented in [P_3].

4.2 Method for Determining the Effects of Local Energy Trading on Voltage Profiles and Power Flows over Electrical Distribution Networks

In order to investigate the issue of voltage stability in the case of different LET strategies and offering curves, a method for determining the effects on voltage profiles and power flows over electrical distribution networks has been developed. Following the model of LET presented in the first part of the thesis's contribution, the dispatch of the committed peers is used as an input to the model of the distribution network feeder to analyse the power flows and voltage levels. The least-cost dispatch is sent to the peers, where the effects of LET on power flows and voltage levels are studied for different elasticities and prices of the peers, as well as for different setups of the peers considering the installed capacities of solar PV systems in LET zone. The simulations in the test feeder are conducted with a one-second resolution using a five-minute dispatch from the previous step, resulting in the voltage profiles over 24 h time-horizon and in a resolution of one second. Here, the security-constrained unit commitment (SCUC), which could internally include line limits as well as voltage and phase angle constraints as constraints in the auction method, is not implemented. The reason for this is due to the fact that effects on bus voltages resulting from the anarchy behavior of different bidding approaches of the peers are studied. This is done by analysing power flows and voltage levels in a distribution grid in a case when time-demanding SCUC and security-constrained economic dispatch (SCED) calculations are not performed for observed time horizon and each trading period, respectively. The method is presented in [P_1], and further elaborated and case studies expanded in [P_7 and [P_8].

4.3 Method for Assessing the Impacts of the Local Electricity Market on Market Participants

The last part of the contribution focuses on assessing the impacts of the LEM on market participants. For this purpose, a method has been created that can be applied to different regulatory frameworks and different setups of LET zone. Given the recent development of the regulatory framework in the EU that introduced the definitions of energy communities, they are seen as a favourable environment for the application of LET within them. It is due to the special provisions that intervene in taxes, grid fees and other levies, making energy trading or sharing increasingly feasible for the members of the communities. Regulatory limitations for energy trading zones are mostly linked with distribution network topology or geographical distance, subject to countries' decisions [P_2]. A developed method for assessing the economic impacts of a LEM on market participants is based on a calculation of revenues for market participants and levelized costs of energy consumed for members of LET zone. Due to the importance of seasonal effects on RES production and operation of BESSs and multi-energy vectors, the dynamically operation of LET with hourly resolution and with a yearly horizon is used for this purpose. As revenues for market participants greatly depend on a regulatory framework, the method is adaptable for application on different regulatory setups. Further, due to the fact that synergies of multi-energy vectors can accelarate decarbnoisation of energy communities and energy islands, a method is also extended and applied for analysis of multi-energy systems. The method is presented in [P_2] and [P_{10}], while the application for multi-energy communities is presented in [P_3].

Chapter 5

List of Publications

The publications relevant for this thesis and considered as the main contributions are divided into two sections: journal papers and conference papers. These papers are chosen due to their close connections with LET in electrical distribution networks. All three journal papers [P_1-P_3] are attached as listed in Chapter Publications. However, only four out of seven conference papers are attached in Chapter Publications due to the brevity of the thesis [P_5, P_7, P_8, P_{10}].

Further, several additional author's papers are omitted from the list below, however, they can also be presented as an extended part of the thesis. Those papers cover market strategies of coordinated bidding of RES, and scheduling of multi-energy microgrids under uncertainty, which are extended aspects of the integration of RES in low-carbon energy systems. The interested reader can find them under Chapter Biography.

5.1 Journal Papers

Published

[P_1]L. Heren čić, P. Ilak, and I. Rajšl, "Effects of Local Electricity Trading on Power Flows and Voltage Levels for Different Elasticities and Prices, " *Energies*, 12(24), 4708, 2019, ISSN: 1996-1073, DOI: 10.3390/en12244708

[P_2]L. Heren čić, M. Kirac, H. Keko, I. Kuzle, and I. Rajšl, "Automated energy sharing in MV and LV distribution grids within an energy community: A case for Croatian city of Križevci with a hybrid renewable system," *Renewable Energy*, 191, 176-194, 2022, ISSN : 0960-1481, DOI: 10.1016/j.renene.2022.04.044

[P_3]L. Heren čić, M. Melnjak, T. Capuder, I. Andročec, and I. Rajšl, "Techno-economic and environmental assessment of energy vectors in decarbonization of energy islands," *Energy Conversion and Management*, 236, 114064, 2021, ISSN: 0196-8904, DOI: 10.1016/j.enconman.2021.114064

5.2 Conference Papers

Published and Presented

[P_4]P. Ilak, I. Rajšl, L. Heren čić, Z. Zmijarević, and S. Krajcar, "Decentralized Electricity Trading in the Microgrid: Implementation of Decentralized Peer-to-Peer Concept for Electricity Trading (P2PCET)," in *Mediterranean Conference on Power Generation, Transmission, Distribution and Energy Conversion (MEDPOWER 2018)*, 2018, Dubrovnik, Croatia 10.1049/cp.2018.1868

[P_5]L. Heren čić, P. Ilak, I. Rajšl, Z. Zmijarević, M. Cvitanović, M. Delimar, and B. Pećanac, "Overview of the main challenges and threats for implementation of the advanced concept for decentralized trading in microgrids," in *IEEE EUROCON 2019 -18th International Conference on Smart Technologies*, 2019, Novi Sad, Serbia 10.1109/EUROCON.2019.8861906

[P_6]M. Kelava, L. Heren čić, Z. Zmijarević, and I. Rajšl, "Uzajamno (peer-to-peer) trgovanje energijom iz obnovljivih izvora u kontekstu paketa propisa Čista energija za sve Europljane," in *14. simpozij o sustavu vođenja EES-a (Cigre 2020)*, 2020, Hrvatska

[P_7]L. Heren čić, P. Ilak, and I. Rajšl, "Peer-to-Peer Electricity Trading in Distribution Grid: Effects of Prosumer's Elasticities on Voltage Levels," in *2020 6th IEEE International Energy Conference (ENERGYCon)* 2020, Gammarth, Tunisia, 10.1109/ENERGYCon48941 .2020.9236564

[P_8]L. Heren čić, P. Ilak, and I. Rajšl, "Impact of Producer's Offering Prices in Peer-to-Peer Electricity Trading on Power Flows in Distribution Grid," in *2020 6th IEEE International Energy Conference (ENERGYCon)* 2020, Gammarth, Tunisia, 10.1109/ENERGYCon48941.2020.9236607

[P_9]P. Ilak, L. Heren čić, H. Benković, and I. Rajšl, "Concept for Automated Energy Trading in MV and LV Electrical Distribution Grids Based on Approximated Supply Function Equilibrium," in *IEEE EUROCON 2021 - 19th International Conference on Smart Technologies* 2021, Lviv, Ukraine, 10.1109/EUROCON52738.2021.9535567

[P_{10}]L. Heren čić, P. Ilak, I. Rajšl, and M. Kelava, "Local Energy Trading Under Emerging Regulatory Frameworks: Impacts on Market Participants and Power Balance in Distribution Grids," in *IEEE EUROCON 2021 - 19th International Conference on Smart Technologies* 2021, Lviv, Ukraine, 10.1109/EUROCON52738.2021.9535547

Upcoming conference

[P_{11}]E. Svetec, L. Heren čić, and A. Hrga, "Options for Application of Distributed Ledger Technologies in Development and Operation of Energy Communities," in *SpliTech 2022: 7th International Conference on Smart and Sustainable Technologies* 2022, Split and Bol, Croatia

[P_{12}]M. Beus, L. Herenčić, H. Pandžić, and I. Rajšl, "Laboratory Setup for Stability and Optimization Studies of Hybrid Microgrids," in *SpliTech 2022: 7th International Conference on Smart and Sustainable Technologies* 2022, Split and Bol, Croatia

Chapter 6

Author's Contribution to the Publications

The contributions of this thesis are achieved during the period of 2018-2022 at the University of Zagreb, Faculty of Electrical Engineering and Computing, Unska 3, HR-10000 Zagreb, Croatia. The research was conducted under projects listed below:

- Project Implementation of Peer-to-Peer Advanced Concept for Electricity Trading (IMPACT) – supported in part by Croatian Science Foundation under grant No. UIP-2017-05-4068.
- Project Active Neighborhoods Energy Markets Participation (ANIMATION) – supported in part by Croatian Science Foundation under grant No. IP-2019-04-09164.
- Project Improved energy planning through the Integration of Smart Grid concepts in the Danube Region (STRIDE), funded by the European Union funds (ERDF, IPA) through Interreg Danube Transnational Programme.

The author's main contribution in each paper is listed below:

[P_1]In the journal paper *"Effects of Local Electricity Trading on Power Flows and Voltage Levels for Different Elasticities and Prices"*: literature review; conceptualization and development of the methodology for assessment of effects of local energy trading in distribution network based on a near-continuous, centrally aggregated double-auction market mechanism in Matlab environment; input data collection; and paper writing and elaboration of the results.

[P_2]In the journal paper *"Automated energy sharing in MV and LV distribution grids within an energy community: A case for Croatian city of Križevci with a hybrid renewable system"*: literature review; overview and comparison of the progress in development of energy communities with LES in the EU; a MILP LES market clearing model that is applicable for different regulatory setups, with novel methods for determining energy sharing compensation price; a method for assessing the economic impacts of the LEM on market participants considering the applicable regulatory framework; input data collection; and paper writing and elaboration of the results.

[P_3]In the journal paper *"Techno-economic and environmental assessment of energy vectors in decarbonisation of energy islands"*: literature review, proposal of unified mixed-integer linear programming, multi-vector unit-commitment model for analyzing multi-energy vectors over multiple sets and combinations; definition of novel indicators for techno-economic and environmental assessment of different multi-energy vectors in decarbonisation of energy islands; input data collection; visualization and graphics; and paper writing and elaboration of the results.

[P_4]In the conference paper *"Decentralized Electricity Trading in the Microgrid: Implementation of Decentralized Peer-to-Peer Concept for Electricity Trading (P2PCET)"*: literature review; paper writing; and live presentation.

[P_5]In the conference paper *"Overview of the main challenges and threats for implementation of the advanced concept for decentralized trading in microgrids"*: literature review; research and systematization of challenges and threats; paper writing; and live presentation.

[P_6]In the conference paper *"Uzajamno (peer-to-peer) trgovanje energijom iz obnovljivih izvora u kontekstu paketa propisa Čista energija za sve Europljane"*: literature review; and part in paper writing.

[P_7]In the conference paper *Peer-to-Peer Electricity Trading in Distribution Grid: Effects of Prosumer’s Elasticities on Voltage Levels"*: literature review; proposal of methodology for local energy trading and assessment of effects in distribution networks; model simulation in Matlab environment; definition of case study; paper writing; and live presentation.

[P_8]In the conference paper *"Impact of Producer’s Offering Prices in Peer-to-Peer Electricity Trading on Power Flows in Distribution Grid"*: literature review; proposal of methodology for local energy trading and assessment of effects in distribution networks; model simulation in Matlab environment; definition of case study; paper writing; and live presentation.

[P_9]In the conference paper *"Concept for Automated Energy Trading in MV and LV Electrical Distribution Grids Based on Approximated Supply Function Equilibrium"*: literature review; part in paper writing; and live presentation.

[P_{10}]In the conference paper *"Local Energy Trading Under Emerging Regulatory Frameworks: Impacts on Market Participants and Power Balance in Distribution Grids"*: literature review; LET market clearing model; method for the assessment of the different regulatory set-ups on the economic feasibility of LET; optimization of community trading formulated as MILP model and solved in Matlab environment; paper writing; and live presentation.

[P_{11}]In the conference paper *"Options for Application of Distributed Ledger Technologies in Development and Operation of Energy Communities"*: overview of the current non-DLT solutions in the pilot site; identification and evaluation of potential DLT solutions; paper writing in part; and live presentation.

[P_{12}]In the conference paper *"Laboratory Setup for Stability and Optimization Studies of Hybrid Microgrids"*: overview of the existing laboratory setups; conducting laboratory testing; and paper writing in part.

Chapter 7

Conclusions and Future Work

The thesis's primary focus is the modelling of LEMs as one of the levers in the activation of flexibility options in distribution networks and supporting the transition towards a low-carbon power system. Section 7.1 outlines the main conclusions, while Section 7.2 gives an overview of the author's possible future research directions.

7.1 The Main Conclusions of the Thesis

On a road to climate neutral-economies, power systems have to reach almost total decarbonisation. Deep integration of variable RES requires a thorough evolution and transformation of energy systems, which is a multi-disciplinary and multi-dimensional process including regulatory, technical, social, environmental, and economic changes. The introduction and development of LEMs is a mean for activation of local flexibility options, engagement of citizens, increasing global welfare, and acceleration of energy transition.

The thesis proposes a short-term model for near real-time local electricity trading over a distribution network. The model is developed as a aggregated double-auction trading mechanisms and applied in the IEEE European LV Distribution Grid Test Feeder. Further, a model that incorporates a LESC for operation of flexibility options is demonstrated. The thesis assessed the implications of implementing LEMs in distribution network with a significant RES capacity and active participation of prosumers through demand response. Also, it is investigated if LEMs can be operated without time-consuming SCUC calculations for observed time horizons and without SCED calculations for each trading period. The analysis included implications on the power flows and voltage stability on the local distribution grid. The results point out at several valuable insights:

- LET can significantly contribute to the local supply-demand balancing and thus decrease the imports from the upstream grid and increase the potential for integration of RES, but the main preconditions are implementation of LEM and availability of flexibility options;

- In a LEM organized in an auction-based manner, the participants' strategies for demand and supply offering curves have a significant impact on market-clearing prices and quantities, i.e., local electricity consumption and production, and thus affect the initiated power flows and voltage levels. At the same time, LEM market-clearing prices and quantities significantly depend on the organization of the LEM and integration with the rest of the electricity market, particularly on the prices and quantities of electricity that can be sold to, or bought from the upstream grid.
- The scenario analysis has shown that, within the boundary conditions, LET can be operated without SCUC and SCED calculations for each trading period. The analysis of the effects of supply and demand offering strategies showed that the low supply offering prices contribute to the rise in the local electricity consumption and production, rise in the volumes of locally traded electricity and as well potentially higher exports to the upstream grid, consequently increasing the voltage levels. On the contrary, high supply offering prices have opposite impacts. The effects of demand elasticity changes depend on the shape of the demand curves and their relation with the supply curves, so the effects are not unambiguous. Namely, the increase in demand elasticity can lead, but not necessarily, to effects similar to those caused by the low supply offering prices.
- The effects on average voltage profiles in considered scenarios primarily depended on the power flows from/to the upstream grid, as the improvement of local electricity supply-demand balancing (behind the substation) led to the minimization of voltage drops and to the increase in voltage levels. Moreover, that way voltage deviations were also decreased. However, in cases of an unbalanced LV distribution grid, there is no guarantee, and the implementation of LET can even lead to an increase in voltage unbalances.
- Economic feasibility and achievement of benefits in terms of increased social welfare through LET or LES greatly depend on the regulatory framework. It is shown that advanced provisions, like adjustment of tariffs, levies, and taxes for LES, can lead to the increased economic attractiveness of LES for the members. At the same time, reduced revenues for market participants on the basis of transmission fees, taxes, and levies can happen, subject to specifics of the regulatory framework. However, well-designed regulatory provisions can have positive impacts on the energy balances and optimisation of the operation of the distribution system, and consequently, possibly decrease the need for investment in the transmission grid. The analysis of different LES price-forming methods showed that even though all members benefit from participating in the EC, effects on the distribution of benefits across the members are significantly different, subject to the price-forming method.
- There are significant differences across different LEM set-ups considering the included flexibility options and geographical locations, and some of the results that can be high-

lighted are: demand-responsive electric heat pumps and use of BESSs provide stand-out energy potency and can ensure self-sufficiency with the smallest capacity of electricity production from local RES, but come with growing costs for the increase of storage capacity; use of imported natural gas as a transition fuel could be an affordable solution but comes with cost risk and does not lead to the fulfilment of self-sufficiency or environmental goals; hydrogen energy vector has significant potential, especially in cases where seasonal energy storage is needed, but the low efficiency and the costs are still the main barriers.

Those insights have important implications for designing the LEMs and associated market and control mechanisms. Also, insights could have impacts on the operation of distribution systems where LEMs are implemented, as DSOs could adjust their operational role. Further, the DSO establishing its data offers in a more robust fashion for relevant market participants could become one of the key enablers for agile and cost-effective local communities in the coming years.

7.2 Future Work

The LEM models have been developed and impacts assessed in this dissertation. Future research will focus on innovative models for operation of the DSOs and integration of DSO-TSO coordination signals in LEMs. This way, the integration of voltage and power flow constraints with LEM clearing mechanism can be integrated. Moreover, the implementation of game-theory in automated bidding strategies of the peers participating in LEM is foreseen. On top of development of additional methods and simulations, a real-life implementation of pilot project is planned, where concepts will be tested and new evidences collected.

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Abbreviations

aFRRAutomatic Frequency Restoration Reserve

AIArtificial Intelligence

ASAncillary Service

BANBuilding Area Network

BESSBattery Energy Storage System

CDAContinuous Double Auction

CECCitizen Energy Community

CIMCommon Information Model

CMCommunity Manager

CPANConsumer Premises Area Network

DADay-Ahead

DERDistributed Energy Resources

DGDistributed Generation

DRDemand Response

DSODistribution System Operator

DSSDistributed Storage Systems

DLTDistributed Ledger Technologies

ECEnergy Community

EMSEnergy Management System

EMSEnergy Management Trading System

EPAEnhanced Performance Architecture

EVElectric Vehicle

EUEuropean Union

FCRFrequency Containment Reserve

FRPFrequency Restoration Proces

HENHome Area Network

IANIndustrial Area Network

ICTInformation and Communications Technology

IEDIntelligent Electronic Devices

ISOInternational Standards Organization

LEMLocal Electricity Market

LESLocal Energy Sharing

LETLocal Energy Trading

KKTKarush-Kuhn-Tucker

LFCLoad-Frequeny Control

LTELong-Term Evolution

LSFLoss Sensitivity Factor

LVLow-Voltage

LPLinear Programming

MANETMobile Ad-hoc Network

MASMulti-Agent Systems

mFRRManual Frequency Restoration Reserve

MESMulti-Energy System

MSMember States

MILPMixed Integer Linear Programming

MMRNMid-Market Rate Net

NMNNeighbourhood Area Network

OTCOver-the-Counter

OPFOptimal Power Flow

MOMarket Operator

OSIOpen Systems Interconnect

P2GPower-to-Grid

P2PPeer-to-Peer

PCSPrimary control Reserve

PVPhotovoltaic

PTDFPower Transfer Distribution Factor

RECRenewable Energy Community

RESRenewable Energy Sources

SCADASupervisory Control and Data Acquisition

SCEDSecurity-Constrained Economic Dispatch

SCUCSecurity-Constrained Unit Commitment

SESPSmart Energy Service Providers

TSOTransmission System Operator

TEMTransactive Energy Management

V2GVehicle-to-grid

VPPVirtual Power Plant

VSCVoltage Sensitivity Coefficients

WMNWide Area Network

WMNWireless Mesh Network

WPANWireless Personal Area Network

WSNWireless Sensor Network

Publications

There are in total 3 journal papers [P_1-P_3] and 7 conference papers [P_4-P_{10}] under this thesis. All journal papers are attached bellow. However, only 4 papers presented in the international conferences are attached due to the brevity of the thesis [P_5, P_7, P_8, P_{10}].

Published Journal Papers

[P_1]L. Heren čić, P. Ilak, and I. Rajšl, "Effects of Local Electricity Trading on Power Flows and Voltage Levels for Different Elasticities and Prices, " *Energies*, 12(24), 4708, 2019, ISSN: 1996-1073, DOI: 10.3390/en12244708

[P_2]L. Heren čić, M. Kirac, H. Keko, I. Kuzle, and I. Rajšl, "Automated energy sharing in MV and LV distribution grids within an energy community: A case for Croatian city of Križevci with a hybrid renewable system," *Renewable Energy*, 191, 176-194, 2022, ISSN : 0960-1481, DOI: 10.1016/j.renene.2022.04.044

[P_3]L. Heren čić, M. Melnjak, T. Capuder, I. Andročec, and I. Rajšl, "Techno-economic and environmental assessment of energy vectors in decarbonization of energy islands," *Energy Conversion and Management*, 236, 114064, 2021, ISSN: 0196-8904, DOI: 10.1016/ j.enconman.2021.114064

Published and Presented Conference Papers

[P_4]P. Ilak, I. Rajšl, L. Heren čić, Z. Zmijarević, and S. Krajcar, "Decentralized Electricity Trading in the Microgrid: Implementation of Decentralized Peer-to-Peer Concept for Electricity Trading (P2PCET)," in *Mediterranean Conference on Power Generation, Transmission, Distribution and Energy Conversion (MEDPOWER 2018)*, 2018, Dubrovnik, Croatia 10.1049/cp.2018.1868

[P_5]L. Heren čić, P. Ilak, I. Rajšl, Z. Zmijarević, M. Cvitanović, M. Delimar, and B. Pećanac, "Overview of the main challenges and threats for implementation of the advanced concept for decentralized trading in microgrids," in *IEEE EUROCON 2019 -18th International Conference on Smart Technologies*, 2019, Novi Sad, Serbia 10.1109/EUROCON.2019.8861906

[P_6]M. Kelava, L. Heren čić, Z. Zmijarević, and I. Rajšl, "Uzajamno (peer-to-peer) trgovanje energijom iz obnovljivih izvora u kontekstu paketa propisa Čista energija za sve Europljane," in *14. simpozij o sustavu vođenja EES-a (Cigre 2020)*, 2020, Hrvatska

[P_7]L. Herenčić, P. Ilak, and I. Rajšl, "Peer-to-Peer Electricity Trading in Distribution Grid: Effects of Prosumer's Elasticities on Voltage Levels," in *2020 6th IEEE International Energy Conference (ENERGYCon)* 2020, Gammarth, Tunisia, 10.1109/ENERGYCon48941.2020.9236564

[P_8]L. Herenčić, P. Ilak, and I. Rajšl, "Impact of Producer's Offering Prices in Peer-to-Peer Electricity Trading on Power Flows in Distribution Grid," in *2020 6th IEEE International Energy Conference (ENERGYCon)* 2020, Gammarth, Tunisia, 10.1109/ENERGYCon48941.2020.9236607

[P_9]P. Ilak, L. Herenčić, H. Benković, and I. Rajšl, "Concept for Automated Energy Trading in MV and LV Electrical Distribution Grids Based on Approximated Supply Function Equilibrium," in *IEEE EUROCON 2021 - 19th International Conference on Smart Technologies* 2021, Lviv, Ukraine, 10.1109/EUROCON52738.2021.9535567

[P_{10}]L. Herenčić, P. Ilak, I. Rajšl, and M. Kelava, "Local Energy Trading Under Emerging Regulatory Frameworks: Impacts on Market Participants and Power Balance in Distribution Grids," in *IEEE EUROCON 2021 - 19th International Conference on Smart Technologies* 2021, Lviv, Ukraine, 10.1109/EUROCON52738.2021.9535547

Upcoming Conference

[P_{11}]E. Svetec, L. Herenčić, and A. Hrga, "Options for Application of Distributed Ledger Technologies in Development and Operation of Energy Communities," in *SpliTech 2022: 7th International Conference on Smart and Sustainable Technologies* 2022, Split and Bol, Croatia

[P_{12}]M. Beus, L. Herenčić, H. Pandžić, and I. Rajšl, "Laboratory Setup for Stability and Optimization Studies of Hybrid Microgrids," in *SpliTech 2022: 7th International Conference on Smart and Sustainable Technologies* 2022, Split and Bol, Croatia

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Effects of Local Electricity Trading on Power Flows and Voltage Levels for Different Elasticities and Prices

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Abstract: Local electricity trading is a concept that allows active electricity trading between consumers, producers and/or prosumers located in a local low voltage distribution grid. The concept should provide added value to the participants and accelerate the democratization, decarbonization and decentralization of the power sector. The effects of local electricity trading on voltage levels in distribution grids are just in the early stage of research, together with the possible means of control, market design, market-clearing approaches and integration of the local electricity trading within the electricity markets. The aim of this work is to contribute to the research by examining if near real-time local electricity trading can be implemented in a distribution grid without time-consuming security-constrained unit commitment calculations for the observed time horizon and without security-constrained economic dispatch calculations for each trading period. Moreover, this work investigates if the implementation of local electricity trading can contribute to the avoidance of unpredictable and unfavorable consumption/production patterns, which can appear in the distribution grid due to the random behavior of a large number of participants. It is analyzed if a contribution to the maintenance of the voltages and currents within limits can be achieved that way. The method for simulation of a local electricity market and analysis of power flows and voltage levels is presented. The auction-based local electricity trading is simulated and applied on the modified IEEE European Low Voltage Test Feeder where the effects of local electricity trading on power flows and voltage levels are studied for boundary elasticities and prices of demand and supply offering curves. It is shown that the local electricity trading has potential to incentivize active participation of prosumers, which can lead to better demand/supply balancing at the local level and to a decrease of voltage fluctuations.

Keywords: electricity; trading; voltage stability; distribution grid; renewable energy sources

1. Introduction

The declining costs of installation of distributed renewable energy sources (RESs) [1] and distributed storage systems (DSS) [2], development of information and communication technology (ICT) [3], and rise of the citizens' desire to actively participate in decision making and decarbonization of the energy system [4] have enabled the development of innovative business models and energy management systems in the power sector. Local electricity trading (LET) at local energy markets (LEM) is a concept that should allow electricity trading between different peers (decentralized generation, prosumers, consumers) [5] in local distribution grid [6] and that way provide value-added to the participants, accelerate the integration of RESs, improve the grid stability and potentially provide auxiliary services to the rest of the power system [7,8]. In doing so, LEMs can be organized as peer-to-peer (P2P) electricity trading, electricity trading through a mediator, or combination of P2P electricity trading and trading through a mediator [5].

However, many questions and challenges still have to be explored to accelerate the implementation of LET concept in practice and in wider scope [9–11]. LEMs can be organized just as a business layer or can include network constraints in trading mechanisms [5]. Further, the inclusion of advanced ICT and control mechanisms can transform distribution grids to smart microgrids [7]. Part of the power system is considered a microgrid if three conditions are met [12]: (1) the resources and loads within that microgrid are operated in harmonization with each other; (2) it is possible to locate the internally interconnected part of the power system around which clear electrical boundaries can be drawn and (3) microgrid can connect and disconnect from the main grid. Management and control of LET to remain under network constraints and to further contribute to the stability in distribution grid and grid-connected microgrids is an area where additional research is needed [5,9,11,13].

In modern distribution grids and grid-connected microgrids, the installed capacity of distributed energy resources (DERs) usually refers to inverter-based photovoltaic (PV) systems and battery energy storage systems (BESSs) [14]. Frequency is mainly maintained by the utility grid so, when assessing stability issues in distribution networks and grid-connected microgrids, the frequency and the rotor angle stability are usually not considered [14].Those issues are prominent when analyzing the operation of the power system at a larger scale [15] or islanded microgrids [14]. Most important stability issues in grid-connected microgrids are related to voltage stability [14]. At the same time, current flow constraints of the power lines have to be respected [16]. Voltage stability issues can further be classified into small disturbance stability and transient stability. Researches of small disturbances mainly focus on influences of droop gains and load fluctuation, and researches of transient stability focus on influences of large disturbances, such as short-circuit fault, dynamic response of DERs, contribution of DERs to fault current, and the power flow issues of microgrids [14]. The timeframes of stability and control issues in microgrids are various (from milliseconds to minutes/hours), while the time units for energy exchange at electricity markets are usually not lower than 15 min, and the near-continuous trading is considered in cases when energy is dispatch every 5 min [17]. Therefore, energy trading timeframes correspond to the timeframe of tertiary control in microgrids [18]. Thus, when microgrid control functions are observed from the market design perspective, electricity trading can contribute to economic dispatch, unit commitment, optimal power flow and Volt/VAr control, while the other control functions can be additionally regulated by the grid codes [19] that define obligations for primary and secondary control in microgrids, by the auxiliary services markets [20], additional control loops [21] and/or by the energy management systems [22].

The overview of existing research that investigates the effects of LET on distribution grid, and means of supervision and management of LET under network constraints, is provided below. Zhang et al. [10] foresaw the external role of DSOs to accept or reject orders in the period between the gate closure and the energy exchange. The approach mirrored the organization of the wholesale markets. However, due to the complexity of the distribution systems, it would be a difficult task for the DSOs to monitor and control transactions in many microgrids simultaneously, especially considering the ongoing trend of decreasing trading intervals and increasing diversity of microgrids. Tushar et al. [23] proposed a P2P energy trading scheme that could help reduce peak electricity demand. The method is based on the cooperative Stackelberg game where the centralized power system acts as the leader that has to determine the price at the peak demand period to stimulate prosumers to lower their demand. However, the paper didn't analyze the effects on local voltage stability and didn't integrate network constraints with the market mechanism. Morstyn et al. [13] proposed a P2P electricity trading platform based on the multiclass energy management concept to facilitate trading between prosumers with different preferences (beyond merely financial ones). The proposed energy management system has a goal to maximize power flows between prosumers and satisfy the distribution network power balance. Similarly to the previously described researches, the voltage stability or constraints of power lines were out of the scope of the proposed energy management system. Long et al. [24] analyzed the P2P energy sharing based on a two-stage aggregated BESS control in a community microgrid. The work showed the potential of centrally managed operation of BESSs to reduce energy bills, increase annual self-consumption and self-efficiency of the energy community. Moreover, with the integration of proper compensation prices, each participant can benefit financially in comparison with conventional power-to-grid (P2G) energy trading. The insights were valuable, but the voltage stability was also out of the scope of the analysis. Guerrero et al. [25] went further and proposed a methodology based on the network sensitivity analysis that should ensure that P2P energy trading in low-voltage (LV) distribution grid remains under network constraints. The used market mechanism was based on the continuous double auction (CDA), and the technical constraints were integrated into it to provide a possibility to block transactions with high risk of causing the voltage problems or allocate extra costs to participants in those transactions. the assessment of sensitivity of network to transactions was based on the estimation of the voltage sensitivity coefficients (VSCs), the power transfer distribution factors (PTDFs) and the loss sensitivity factors (LSFs). The method was tested on a typical U.K. LV network. This method is compatible with the CDA market mechanism where each transaction has a buyer and a seller. However, it is not suitable for the LEM organized as a local electricity-exchange where all supply and demand curves are centrally aggregated with the goal of finding market clearing price and quantities, which is the case researched in this paper. Ilak et al. [26–28] analyzed the strategies and aspects of coordinated operation of variable RES (for example wind power plants) and controllable DSS (for example reversible hydropower plants) on the wholesale energy markets. The scope of this research is important in the context of LEM assessed in this paper, because the similar principles can be implemented on the operation of variable RES (usually solar PV systems) and DSSs (usually BESSs) owned by the prosumers in the distribution grid.

This paper contributes to the research of the question if the near-real-time local electricity trading can be implemented in a distribution grid without time-consuming security-constrained unit commitment (SCUC) calculations for the observed time horizon (i.e., one day) and without security-constrained economic dispatch (SCED) calculations for each trading period (i.e., every five minutes). Secondly, this paper contributes to the investigation of the effects of supply and demand offering curves on power flows and voltage levels in a LV distribution grid. The implemented LEM is based on a near-continuous, centrally aggregated double-auction market mechanism. The research is conducted by testing if the implementation of the LET can contribute to the avoidance of unpredictable and unfavorable consumption/production patterns, which can appear in the distribution grid due to the random behavior of a large number of participants. It is studied if a contribution to the maintenance of the voltages and currents within the limits can be realized that way.

To perform the research, the scenario analysis of the impacts of different offering curves of participants is conducted in the case of the IEEE European LV Test Feeder [29]. Near-continuous LET (5 min trading period) is assumed based on the EUPHEMIA [30] algorithm approach for estimation of equilibrium prices and volumes. Comparative analysis of simulation results is provided between these hypothetical scenarios and reference results obtained from the simulation on the IEEE European LV Test Feeder.

The applied method is described in Section2. The method is divided into stage one and stage two. In stage one, the auction-based method for LET is described, while in stage two, the method for simulation of effects of LET on LV distribution grid power flows and voltage levels is presented. The case study is presented in Section3, based on which the discussion is drawn in Section4.

2. Method for Local Electricity Trading and Estimation of Its Impacts on the Grid

In order to investigate the issue of the voltage stability in the case of different LET strategies and offering curves, the centrally aggregated double auction LET algorithm was developed based on the EUPHEMIA [30] algorithm approach. The time horizon of the simulated market layer is 24 h, with 5 min resolution. From the developed algorithm, equilibrium prices and volumes (unit commitment of the peers) with a five-minute resolution is obtained. The dispatch of the committed peers is used as an input to the IEEE European LV Test Feeder [29] to analyze the power flows and voltage levels. The flowchart of the applied method is presented in the FigureA1in the AppendixA. It is shown that in the first step, demand and supply offers are created by the peers in the distribution grid, based on their demand needs, demand elasticity, supply capacity, and supply offering prices. Afterward, all supply and demand offers are sent to the double-auction market, where offers are aggregated, and equilibrium volumes and prices are determined. Finally, the least-cost dispatch is sent to the IEEE European LV Test Feeder grid, where the effects of LET on power flows and voltage levels are studied.

The simulation of the IEEE European LV Test Feeder is conducted with one-second resolution using a five-minute dispatch from the previous step, resulting in the voltage profiles over 24 h time-horizon and in a resolution of one second. Scenario analysis is conducted for four cases of (supply and demand) offering curves of peers which simulate events from high to low electricity prices and high to low demand elasticity in the microgrid market. Also, the comparative analysis of the LET simulation results and the reference scenario simulation results on the IEEE European LV Test Feeder is provided. In the following subsections, the methods for the LET utilizing prosumer demand flexibility and different supply offering curves, as well as network model, are briefly explained.

2.1. Auction-Based Method for LET

The goal of the first stage of the simulation is to find a selection of offered supply and demand blocks that satisfy the energy balance requirement and maximize the global welfare defined as in Equation (1):

$$\max\left\{\sum_{t=1}^{T}\sum_{b=1}^{B}\sum_{i=1}^{I}\left(-ACCEPT_{s,t,b,i}\cdot q_{s,t,b,i}\cdot p_{s,t,b,i}+ACCEPT_{d,t,b,i}\cdot q_{d,t,b,i}\cdot p_{d,t,b,i}\right)\right\} \tag{1}$$

The supply offers in Equation (1) have a negative sign. In this way, producer costs are minimized (which is equivalent to maximizing producer profit or surplus), and gross consumer surplus is maximized. Since demand is price-sensitive (elasticity > 0) in the assumed market, the goal function needs to include demand offers (called double–auction market). Otherwise, if demand is assumed to be completely insensitive to prices, the benefit received by the consumer is constant and does not need to be taken into consideration in the goal function. Under these conditions, the goal function would be represented by minimizing the total cost of producing energy. The goal function for global welfare maximization is subject to market and technical constraints that include:

- energy balance constraints for each time period t, in time horizon made of T periods, as listed in Equation (2):

$$\sum_{b=1}^{B}\sum_{i=1}^{I}ACCEPT_{s,t,b,i}\cdot q_{s,t,b,i}\geq\sum_{b=1}^{B}\sum_{i=1}^{I}ACCEPT_{d,t,b,i}\cdot q_{d,t,b,i} \tag{2}$$

- technical constraints of maximal supply and demand capacities for each peer i in period t ($q_{MAX_{s,t,i}}$ and $q_{MAX_{d,t,i}}$ respectively) have to be integrated into demand and supply offers, while individually can be written as in Equations (3) and (4):

$$0\leq\sum_{b=1}^{B}q_{s,t,b,i}\leq q_{MAX_{s,t,i}} \tag{3}$$

$$0\leq\sum_{b=1}^{B}q_{d,t,b,i}\leq q_{MAX_{d,t,i}} \tag{4}$$

In Equations (1)–(4) $\{s,\ d\}$ is the index set of the offer types, and s means supply, d means demand. The t is discrete time step over simulated time horizon $t\in\{1,2,\ldots,\ T\}$. The b is offer block, $b\in\{1,2,\ldots,\ B\}$. The i is the index of the peer, $i\in\{1,2,\ldots,\ I\}$. $ACCEPT_{s,t,b,i}$ is the binary acceptance variable for supply offer of the peer i, in block b and period t, $ACCEPT_{s,t,b,i}\in\{0,1\}$. $ACCEPT_{d,t,b,i}$ is the acceptance variable for demand offer of the peer i, in block b and period t, $ACCEPT_{d,t,b,i} \in \{0, 1\}$. The $q_{s,t,b,i}$ is the offered supply volume of the peer i, in block b and in period t. The $q_{d,t,b,i}$ is offered demand volume of the peer i, in block b and in period t. The $p_{s,t,b,i}$ is the offered supply price of the peer i, in block b and in period t. The $p_{d,t,b,i}$ is the offered demand price of the peer i, in block b and in period t.

The final solution of the goal function (Equation (1)) finds the equilibrium volumes, but in some cases, there could be a mismatch between committed generation and demand (Equation (2)) due to the possible generation constraints and constraints in consumer consumption. The aim is to equalize as much as possible the generation and production, which means equilibrium price is approximated as a midpoint of marginal producer and marginal consumer prices (the MATLAB code that solves this issue is provided in the Supplementary Materials).

In order to simulate behavior of LET in the distribution network feeder, the centralized double auction mechanism such as EUPHEMIA is suitable. Here, the SCUC, which would internally include line limits as well as voltage and phase angle constraints as constraints in the auction method [31], is not implemented. The reason for this is due to the fact that we analyze bus voltages resulting from the anarchy behavior of different bidding approaches of the peers. This is done by analyzing power flows and voltage levels in a distribution grid in a case when SCUC and SCED calculations are not performed for observed time horizon and each trading period, respectively. Additional technical details on the EUPHEMIA algorithm is available in [30].

2.2. Method for Simulation of Effects of LET on LV Distribution Grid Power Flows and Voltage Levels

The dispatched supply and demand quantities of the peers from the first stage of the simulation framework are used in the second stage to simulate the effects on the voltage stability in the LV distribution network. As a reference network model for the simulation, the IEEE European LV Test Feeder [29,32] was selected. The IEEE European LV Test Feeder is a radial distribution feeder at the voltage level of 416 V (phase-to-phase) and a base frequency of 50 Hz, which is typical for the European low voltage distribution systems [32]. The application of the test feeder is suitable for the distribution research and planning, as it enables analysis of time-series rather than static power flow solutions. This is becoming increasingly important for analyzing dynamic behavior of different products and concepts on the distribution network, such as integration of DERs, Volt/VAr control, operation of BESS, etc. [32], as well as for application of simulations in various timeframes. Moreover, the feeder fits well with the topology of the island Krk distribution grid, where the LET will be implemented under the IMPACT project [8,33]. Therefore, the IEEE European LV Test Feeder is recognized as the most suitable for simulation and analysis of the effects of LET on voltage levels and power flows. The network topology of the test feeder is shown in Figure1[32,34,35].

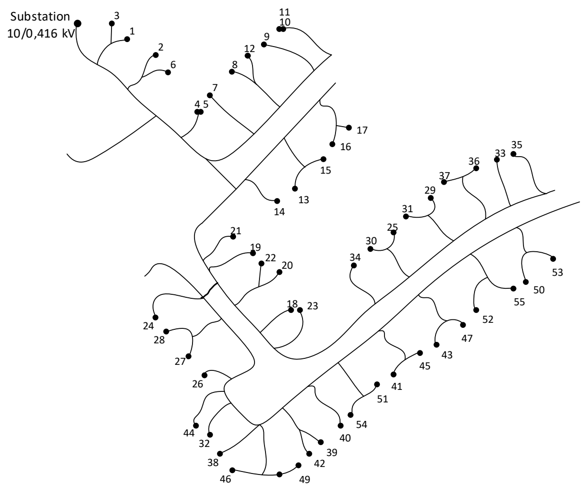


Figure 1. Topology of the IEEE European LV Test Feeder where the simulation of the LET was implemented.

3. Case Study

The case study assesses the impacts of different supply and demand offering strategies. Supply offer curves strategies reflect moments of high electricity prices and scarcity of supply in some scenarios and low electricity prices and oversupply in other scenarios. The demand offering curves reflect different flexibility and demand response abilities of the peers, as the demand curve elasticity is varied between the scenarios.

3.1. Scenarios and Input Data

The behavior of the production peers is analyzed for the two extreme behaviors: (1) when they practice higher markup, i.e., they aim to achieve additional revenue on top of actual cost and are ready to restrain from production and (2) when they bid with the lower offering prices, i.e., close to the short-run marginal costs (SRMC) and are expecting higher volumes of energy sold. The behavior of demand peers is varied based on the demand elasticity in two cases: (1) higher elasticity, where the application of demand response is assumed possible to a greater extent, and (2) lower elasticity, where the application of demand response is assumed possible to the lower extent. The demand in this microgrid is generally assumed inelastic in the area where local demand and supply curves intersect (absolute value of elasticity < 1), which is common in the electricity market [36,37] and this elasticity is increased and decreased to obtain the two demand elasticity scenarios on which price scenarios are tested.

Based on the variations of the behavior of the peers, the four scenarios are created (scenarios S1-S4). Moreover, the reference scenario (SREF) is assessed where the production is assumed maximal. It is a hypothetical case simulating the existence of feed-in tariffs for electricity production from renewable energy sources. Also, in this scenario demand is inelastic, as it represents the passive behavior of the peers as in traditional electricity LV distribution systems. The key differences of the analyzed scenarios and the used input data for individual peers are shown in Table1.

Table 1. Key differences of the analyzed scenarios and input data for individual peers, where "High" supply price is set at 0.075 EUR/kWh and "Low" supply price at 0.025 EUR/kWh.

Scenario	S1	S2	S3	S4	SREF
Maximal supply offering price	High	High	Low	Low	NA (feed-in-tariff)
Price elasticity of demand	Increased	Decreased	Increased	Decreased	Perfectly inelastic (passive demand)

In all cases, the nominal consumption patterns are taken from the IEEE European LV Test Feeder [29] and it is assumed that every fourth peer is equipped with the PV systems of the nominal capacity of 4 kW. The time-pattern of possible maximal production from the PV systems for the analyzed day was taken from [38] for 1 June. The minimum bidding blocks are assumed as 0.5 kW quantity. The creation of offering blocks for the peers is conducted in accordance with the Equations (5) and (6) for supply and demand, respectively, and is depicted in Figure2.

$$p_{s,t,b,i} = \frac{p_{N_{s,t,i}}}{q_{MAX_{s,t,i}}} q_{s,t,b,i}, \; where: \; 0 \leq q_{s,t,b,i} \leq q_{MAX_{s,t,i}} \tag{5}$$

$$p_{d,t,b,i} = -\frac{2 \cdot p_{N_{d,t,i}}}{1+k} q_{d,t,b,i} + \frac{p_{N_{d,t,i}} \cdot 2 \cdot q_{MAX_{d,t,i}}}{1+k}, \; where: \; 0 \leq q_{d,t,b,i} \leq q_{MAX_{d,t,i}} \tag{6}$$

where $p_{N_{s,t,i}}$ is the nominal supply price (final price in the supply curve) of the peer i in period t, $p_{N_{d,t,i}}$ is the nominal demand price of the peer i in period t. It is assumed the same as the supply price from the utility grid, i.e., 0.100 EUR/kWh. Reference consumption $q_{N_{d,t,i}}$ of the peer i in period t (reference values are taken from the IEEE European LV Test Feeder) can be increased by the k blocks where each block equals 0.5 kW, i.e., $q_{MAX_{d,t,i}} = q_{d,N_{t,i}} + \frac{1+k}{2}$ (kW).

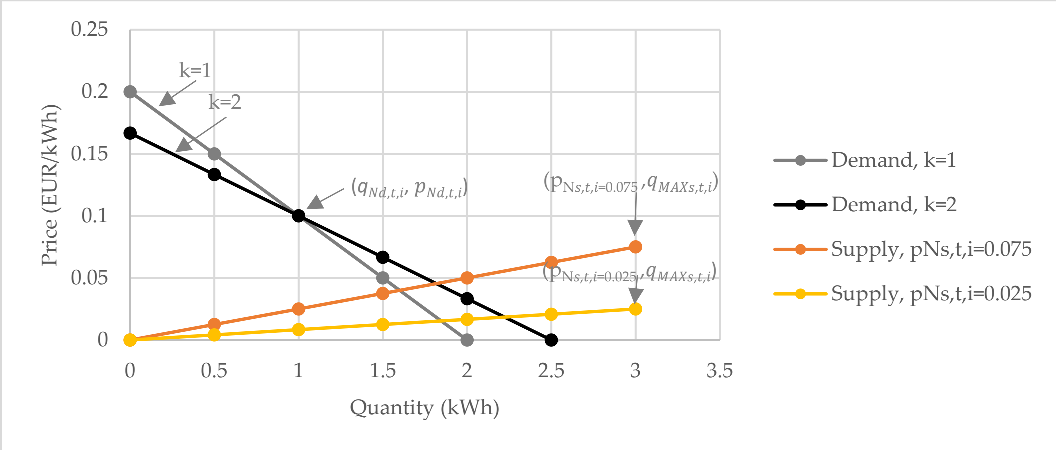


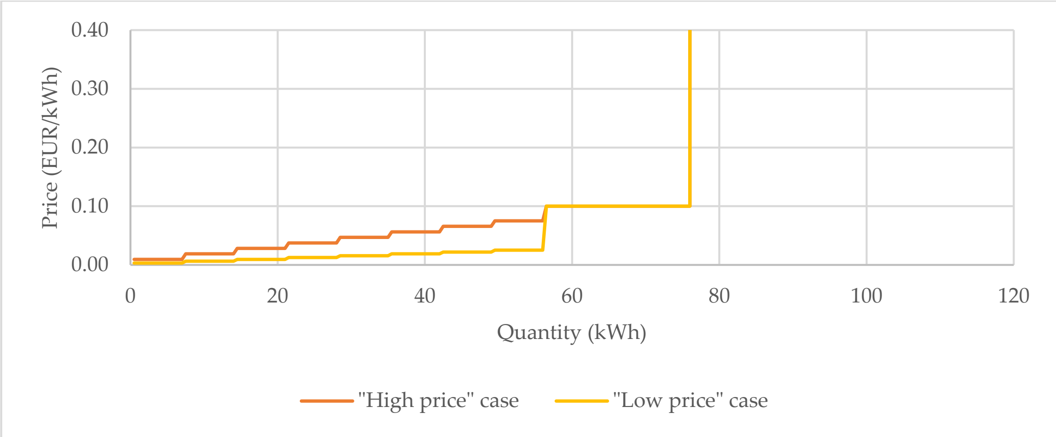
Figure 2. Illustration of the demand and supply offering curves of the peers for the cases: (1) for the demand curves $p_{N_{d,t,i}}$ = 0.100 EUR/kWh, $qD_{N_{t,i}}$ = 1 kWh and the differences relate to the slope of the curves which is defined by the factor k; (2) for the supply curves $q_{MAX_{s,t,i}}$ = 3 kWh and the differences relate to the nominal supply price are defined by the $p_{N_{s,t,i}}$.

The applied approach for creating supply and demand offers allows transparent and tractable analysis using the nominal (final) supply prices $p_{N_{s,t,i}}$ and slopes of the demand curves around the nominal price $p_{N_{d,t,i}}$ (see Figure2). The e ffects of varying nominal prices of the supply curve and slope around the nominal price of the demand curves are shown in Figure2.

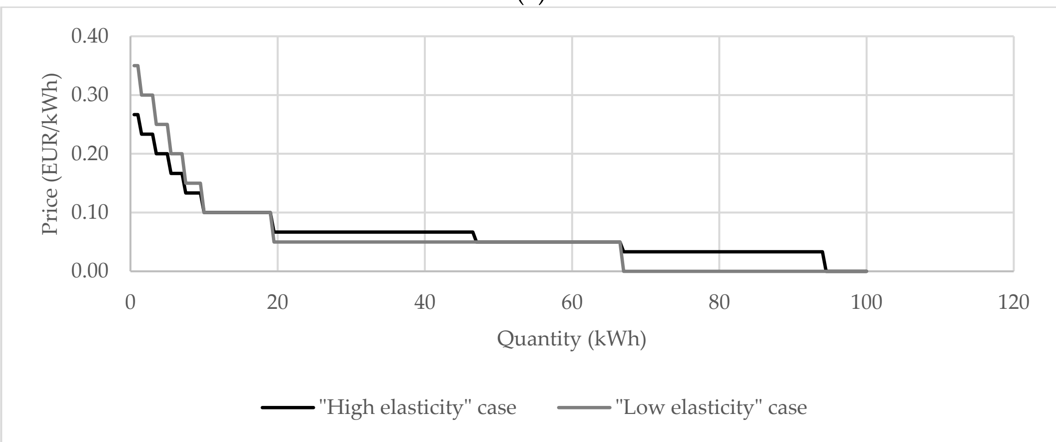
Moreover, in all scenarios, it is assumed that the supply price from the utility grid is fixed at 0.100 EUR/kWh, and the price of selling to the utility grid is fixed at 0.050 EUR/kWh. Also, for the sake of clarity in the presentation of the results and decreasing the simulation time, the time horizon of 120 min is analyzed in the case study. The analyzed timeframe is from 8 a.m. to 10 a.m. The chosen timeframe is the one when demand is available and production capacity from the installed PV systems of the peers is also available. The resolution of trading periods is 5 min, and the calculation of the voltages is presented in a one-minute resolution to ease the display of results of voltage level forms. Analysis of the longer timeframes is possible using the MATLAB code available in the Supplementary Materials.

Based on the input data listed above, the aggregated supply and demand curves are shown in Figure3for the time interval 9:35–9:40 a.m. In Figure3a, the aggregated supply curves are shown for the "high price" and "low price" supply offers. In Figure3b, the aggregated demand curves are shown for the "high elasticity" and "low elasticity" demand curves.

The aggregated merit order supply and demand offers are used to find the equilibrium prices and quantities in line with the methods presented in Section2.1. In Figure4, the found equilibrium prices and volumes are shown for the scenarios S1–S4, for the same time interval 9:35–9:40 a.m. The effects of different maximal supply offering prices and elasticities of demand are visible in the illustrative scenarios shown in Figure4. In the S1 scenario, with "high prices" and "increased elasticity", the found equilibrium price is the highest due to the impact of offers with high prices. In the S2 scenario, the effect of lower elasticity of the demand led to lower volumes and prices, meaning peers sold less energy. The S3 and S4 scenarios demonstrated the market-clearing under the assumption of "low prices", and "increased elasticity" and "decreased elasticity", respectively. Those assumptions led to the lower market-clearing prices and higher traded volumes.



(a)



(b)

Figure 3. Merit order supply and demand curves: (**a**) Aggregated (merit order) supply offers for the "high price" and "low price" cases in the time interval 9:35–9:40 a.m. (**b**) Aggregated demand offers for the "high elasticity" and "low elasticity" cases in the time interval 9:35–9:40 a.m.

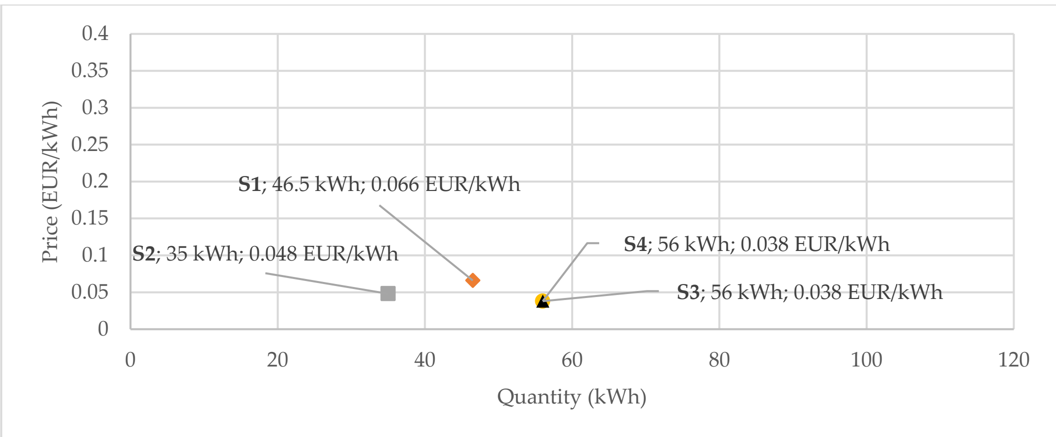


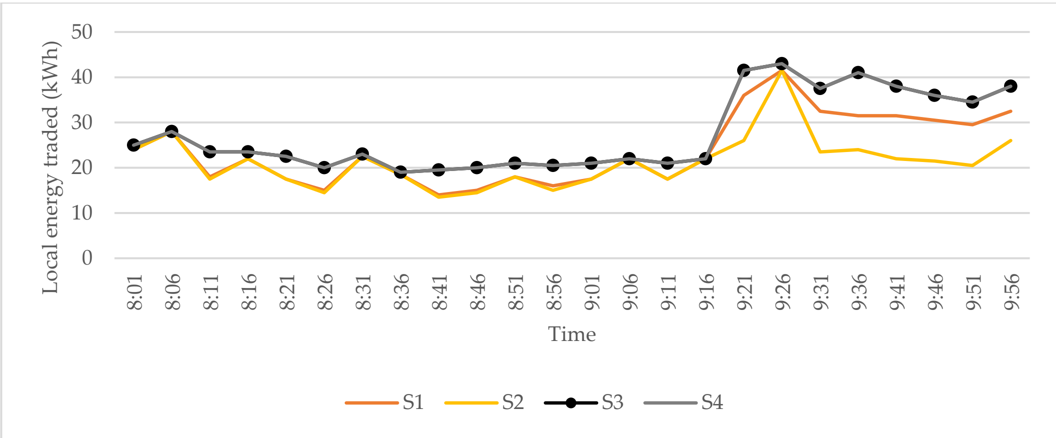
Figure 4. Equilibrium prices and volumes (points of intersections of supply and demand curves) for the scenarios S1–S4 of the one 5-min time interval (9:35–9:40 a.m.) of market trading. The labels of the points mark scenario names, quantities, and prices, respectively.

Interestingly, due to the composition of the offering curves, the intersection point is the same in S3 and S4 scenarios. Also, it is evident that the effects of "low prices" in supply offers had a bigger impact compared to the changes in elasticity, which is due to the fact that changes in elasticity of electricity demand are relatively less intense compared to the changes in supply offer prices.

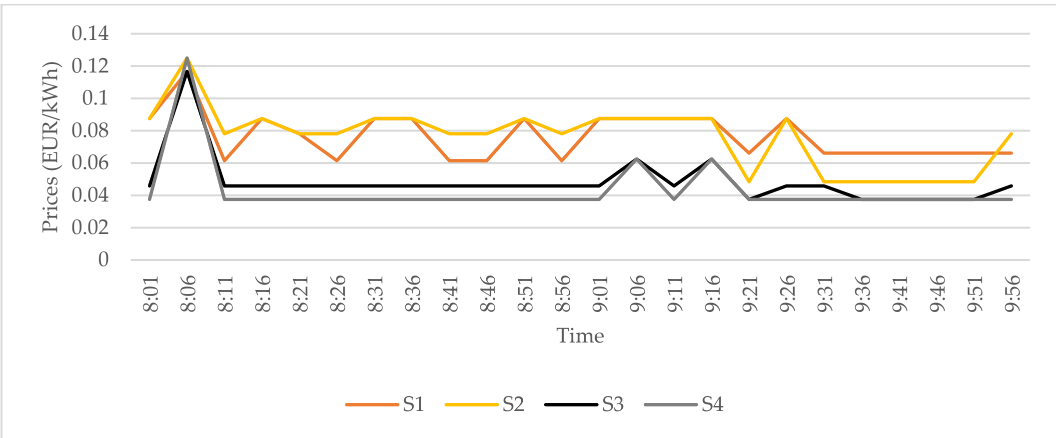
On those price and demand scenarios, the voltage stability is assessed in the second stage of the simulation for all the periods in the assessed time horizon. The simulation was conducted in MATLAB software environment [35].

3.2. Outputs of the First Stage of the Simulation: Equilibrium Quantities and Prices

As elaborated in the previous section, the outputs of the first stage of the LET are the equilibrium prices, volumes, and least-cost dispatch calculation. The calculated dispatch is input for the second stage, i.e., analysis of the effects on voltage levels in the IEEE European LV Test Feeder. Due to the number of 55 peers, only the aggregated values are displayed in Figure5. In Figure5a, the equilibrium volumes are shown. In Figure5b, the equilibrium prices are shown in the analyzed scenarios. Similarly to the analyzed one period in the previous subsection, the effects of different maximal supply offering prices and demand elasticities are here visible in a longer time horizon.



(**a**)



(**b**)

Figure 5. The auction-based LET: (**a**) The equilibrium prices in analyzed time horizon, (**b**) The volume of LET energy traded in analyzed time horizon.

In the S2 scenario (Figure5a), with "high prices" and "decreased elasticity", the found equilibrium volumes are the lowest due to the fact that in the analyzed scenarios decrease of elasticity increases the slope of the demand curve, and since the aggregated nominal demand offer prices are higher than the aggregated supply offer prices for the aggregated nominal demand quantity, the decrease of the slope of demand offer curve decreases the equilibrium quantities. The effects on equilibrium prices (Figure5b) for the analyzed scenarios are not always consistent (comparison of equilibrium prices for the scenarios S1 and S2 in the time period 8:00–9:15 a.m.), which is due to the fact the equilibrium prices are approximated as a midpoint of marginal producer and marginal consumer prices, in each period. That midpoint can be misleading n a case of a relatively small number of peers, and the equilibrium price can be determined more precisely with additional sub-problem, such as in EUPHEMIA algorithm [30]. However, for this research, it is out of the scope, as the equilibrium volumes are essential for analyzing the power flow and voltages. The scenarios S3 and S4 demonstrated the market-clearing under the assumption of "low prices", and "increased elasticity" and "decreased elasticity", respectively. Those assumptions led to the lower market-clearing prices and higher traded volumes. In the S4 scenario, the traded volumes correspond to the ones in scenario S3, but due to the lower elasticity of the demand curve, the equilibrium prices are lower on average.

3.3. Results: Power Flows

The effects of trading and dispatched demand and supply quantities on microgrid energy balance for the observed period from 8:00 a.m. until 10:00 a.m. across the modelled scenarios are numerically shown in Table2and graphically in Figure6. The energy balance is divided on the: (1) Peers self-consumption, which is the energy produced by the PV systems owned by the prosumers and consumed immediately at their locations, (2) Local energy trading in the observed distribution grid, which is the energy produced by the PV systems owned by the prosumers and not consumed by themselves but traded with the other peers in the local distribution grid, (3) Export to the upstream grid, which is the surplus energy exported out of the observed distribution grid, and (4) Import from upstream grid, which is the energy imported to the observed distribution grid in periods when local demand is higher than local supply.

Table 2. Energy balance (kWh) in the microgrid for the analyzed scenarios in the observed time horizon (from 8:00 a.m. until 10:00 a.m.).

Item	SREF	S1	S2	S3	S4
Total microgrid consumption	1321	783.5	687	883	883
Total microgrid production	896	778.5	682	896	896
Peers self-consumption	282	205.5	172.5	235	235
Local electricity trading	583	573	509.5	643	643
Import from upstream grid	456	5	5	5	5
Export to upstream grid	−31	0	0	−18	−18

It can be observed that in the scenario SREF (Figure6a), the total consumption in the microgrid is at the nominal values and highest. Electricity production is also maximal, but with given demand and supply capacity ratio, the demand is higher for most of the time. Consequently, a significant share of energy consumed (34.5%) is imported from the upstream network in the SREF scenario (Table2). In comparison, in the scenarios with implemented LET, where demand elasticity is defined by offer curves, a decrease of energy consumption and avoidance of extreme market prices is possible as elasticity enables consumers to buy less when the prices are higher (Figures3and4). In the S1 scenario, the LET with high offer prices and increased demand elasticity led to the decrease in total energy consumption by 40.7% and decrease in the energy production by 13.1% compared to the SREF scenario. Those effects combined led to the decrease in the imports from the upstream network from 34.5% to 0.6%. Also, the export to the upstream grid does not occur. In the S2 scenario, the decreased demand elasticity led to the decrease in energy consumption and decrease in locally traded electricity. Decrease of supply offering prices in scenarios S3 and S4 led to the increase of energy consumption and locally traded eletricity in the local distribution grid.

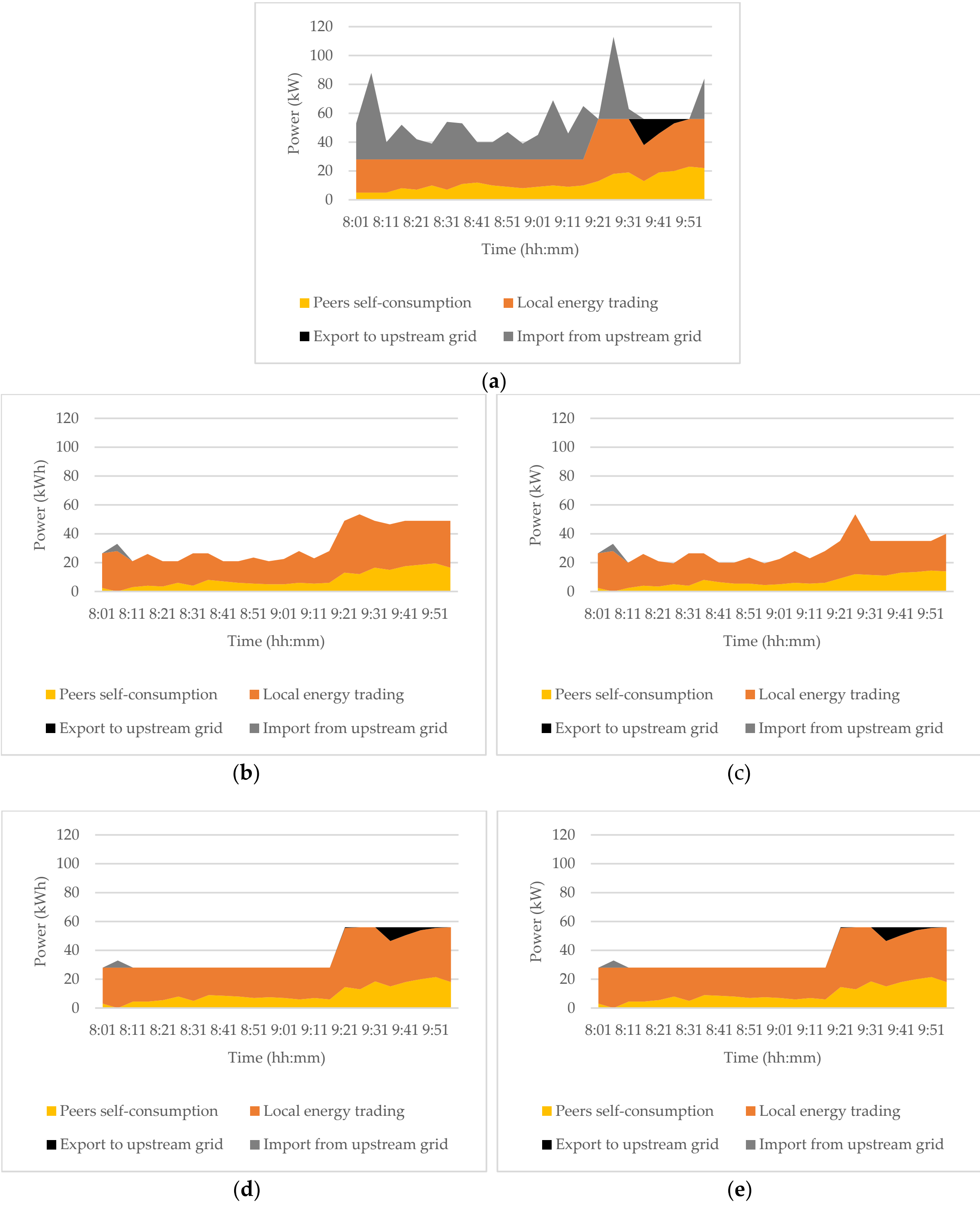


Figure 6. Energy balance in the microgrid: (**a**) Energy balance in reference scenario SREF; (**b**) Energy balance in the S1 scenario; (**c**) Energy balance in the S2 scenario; (**d**) Energy balance in the S3 scenario; (**e**) Energy balance in the S4 scenario.

Due to the modeled demand elasticity, the social welfare maximization was found in conditions when the local production is maximal, and demand is adjusted to the supply levels. Moreover, the exports to the grid proved justified in those scenarios. The scenarios S3 and S4 are equal in terms of energy balance as the decrease of demand elasticity in the S2 scenario didn't change the equilibrium quantities for the given input parameters.

3.4. Results: Voltage Levels

Based on the outputs of the first stage of the simulation and calculated least-cost dispatch, the impacts of the dispatch on the voltage levels in the IEEE European LV test feeder are studied. In Figure7, voltage (U) and voltage di fferences (dU) over time (minutes) for different busses are shown. Due to a large amount of data (voltages for 906 buses × 7.200 s × 3 phases × 5 scenarios), the chosen data is shown in 3D graphs and the voltages are displayed in a one-minute resolution. For a further overview of the results, the reader is advised to use the electronically available data and MATLAB files available in the Supplementary Materials, where detailed voltage results are available in an interactive form. In Figure7a, voltage levels for 906 buses over 120 min for the reference scenario (SREF) are shown. The results presented in Figure7b–e show the voltage di fferences between S1 and SREF; S1 and S2; S1 and S3; and S2 and S3 scenarios respectively.

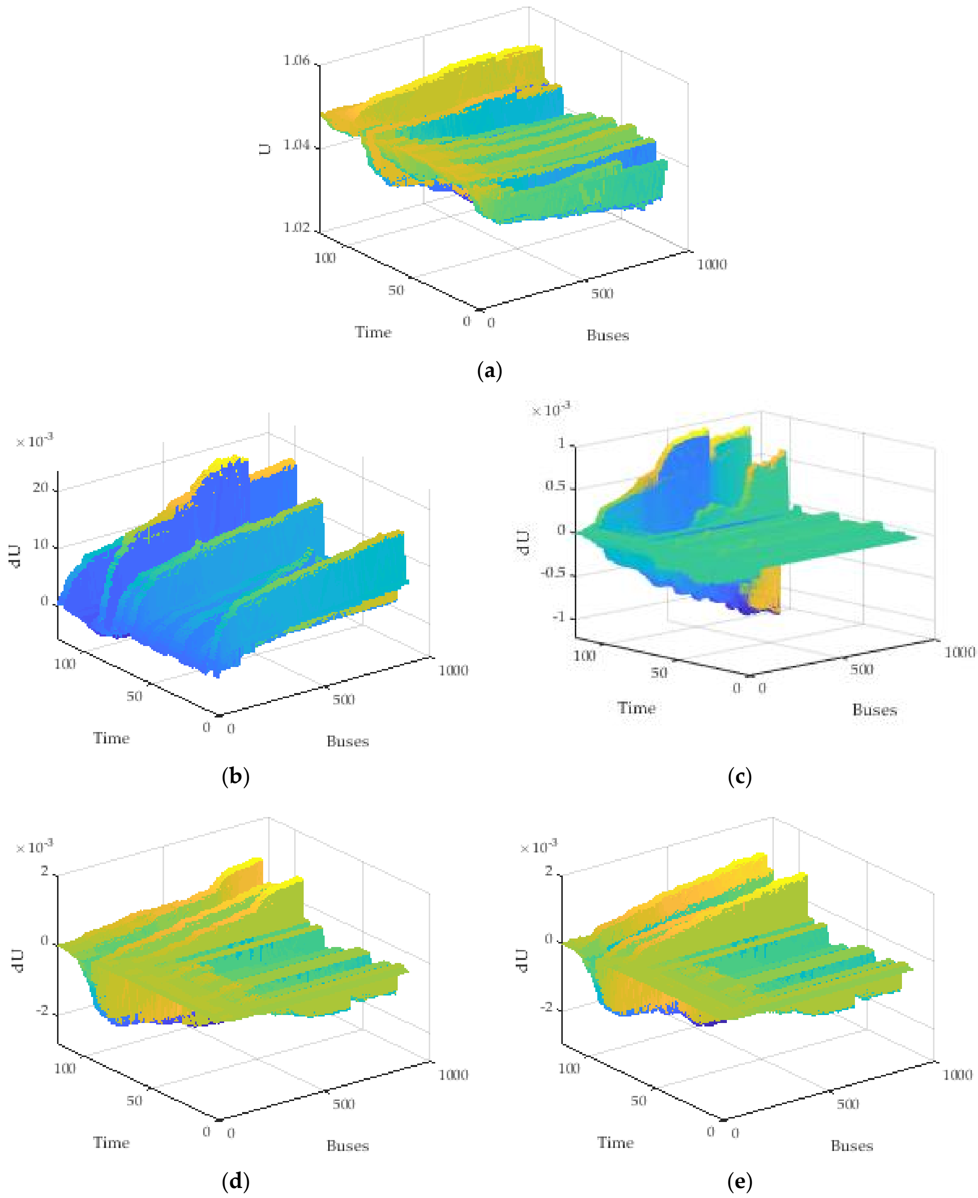


Figure 7. Voltage, U (p.u.) and voltage differences, dU (p.u.) over time (minutes) for different busses: (**a**) Voltage in reference scenario SREF; (**b**) Voltage difference between scenario S1 and SREF; (**c**) Voltage difference between scenario S1 and S2; (**d**) Voltage difference between scenario S1 and S3; (**e**) Voltage difference between scenario S2 and S3.

Moreover, the average voltage levels and differences from the nominal voltage across the analyzed scenarios are summarized in Table 3 and shown in Figure 8. As visible in Figure 7, due to the fact that the tap changer ratio is set to 1.05 at the secondary side of the transformer, the voltage level at the bus 1 is 1.05 p.u. in all scenarios. In the SREF scenario (Figure 7a), it can be observed that the voltage levels are within the boundaries prescribed by the norms for the LV distribution grid (±10% from nominal voltage) [39]. Also, the voltage drop towards the end of the feeder can be observed, particularly at the buses where no distributed generation is present, which is a usual phenomenon in the distribution grid [40]. On average, the voltages are 0.486% below the nominal voltage (Table 3 and Figure 8). The comparison of the voltages in scenarios S1 and S2 (Figure 7a) shows that, on average, voltages in the S1 scenario are higher by 0.46% (Table 3) compared to the SREF scenario. This can be explained by the decrease of energy consumption and minimization of the imports from the upstream grid (Table 2 and Figure 6b) due to the active participation of peers in the LET and application of demand response, due to the high equilibrium prices. The consequent reduction of power flows from the transformer substation to the ends of the distribution grid leads to a decrease of currents from the upstream grid to the users in the microgrid and decreases the voltage drop, i.e., raises the voltage levels [40,41]. In the S2 scenario (Figure 7c, Table 3, and Figure 8), it can be observed that, on average, voltage levels are further slightly increased compared to the S1 scenario. That can be explained due to the fact that the decrease of demand elasticity in this scenario leads to the decrease of equilibrium volumes, decrease of energy consumption and decrease of locally traded electricity (Table 2 and Figure 6c), which in turn causes lower power flows from the upstream grid and decreases voltages drops, i.e., increases voltage levels. In the S3 scenario (Figure 7d), on average, voltages are higher compared to the S1 scenario (Figure 7c, Table 3, and Figure 8). This is due to the fact that in the S3 scenario equilibrium volumes of locally traded electricity are increased due to the lower offer prices. That leads to an increase of exports to the upstream network and to an increase of local power flows, due to increased distributed generation and demand balanced locally in the distribution grid (Table 2 and Figure 6d). Those power flows resulted in lower voltage drops [40], i.e., additionally increased voltage levels in the S3 scenario compared to the S2 scenario. The comparison of the scenarios S2 and S3 (Figure 7e), shows similar results as the comparison of the scenarios S1 and S3, i.e., the voltages in the S3 scenario are increased (Table 3 and Figure 8). It is due to the fact that the low offering prices increase energy consumption, production and the locally traded electricity (Table 2 and Figure 6d). In this case, those impacts are more significant than the impacts of the increased elasticity, which is causing the opposite effects (Table 2 and Figure 6e). From the Table 3 and Figure 8, it is also visible that the average voltage levels in the scenarios with the implemented LET are closer to the nominal voltage (0.006% below nominal, on average), compared to the SREF scenario (0.486% below nominal), meaning implementation of LET in distribution grid can contribute to decreasing voltage drops and stabilizing voltage levels.

Table 3. Average voltage levels and difference of the average voltage level from the nominal in all scenarios.

Scenario	SREF	S1	S2	S3	S4
Average voltage level	1.04490	1.04977	1.04983	1.05008	1.05008
Average voltage level difference from the nominal	−0.486%	−0.022%	−0.016%	0.007%	0.007%

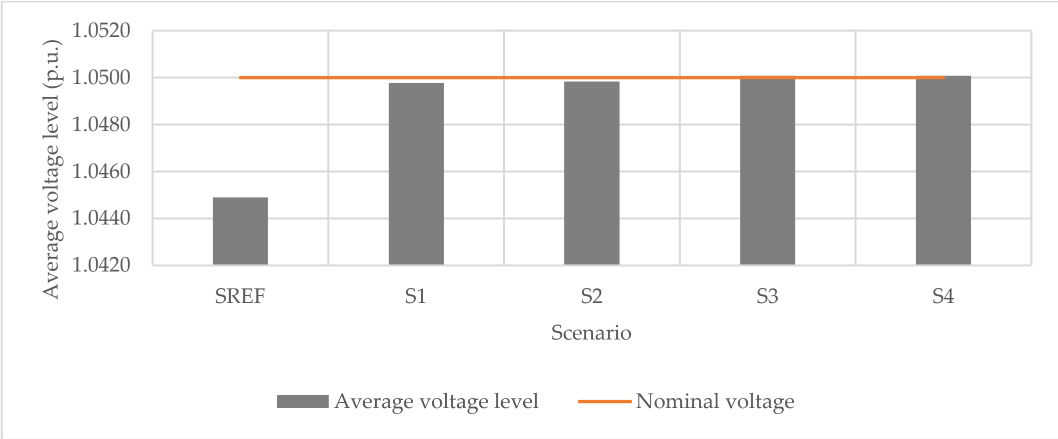


Figure 8. Average voltage levels in the analyzed scenarios.

Moreover, differences between voltage deviations in all scenarios compared to the nominal voltage are quantified using the mean absolute error (MAE). That way, additional comparisons can be made and provide interesting insights into the effects of offer prices and demand elasticity on voltage levels and voltage deviations. In Table 4 and Figure 9, deviations from the nominal voltage are quantified using MAE for all voltage deviations (dU), positive voltage deviations (dU^+) and negative voltage deviations (dU^-).

Table 4. MAE between grid voltage and nominal voltage (for all deviations, positive deviations, and negative deviations) over all periods, busses, and phases. For the clarity of the results, MAE is divided by the nominal voltage and expressed as a percentage.

Scenario	SREF	S1	S2	S3	S4
MAE (all voltage deviations) (%)	1.300%	0.700%	0.650%	0.730%	0.730%
MAE (positive voltage deviations) (%)	1.072%	0.707%	0.676%	0.751%	0.751%
MAE (negative voltage deviations) (%)	1.432%	0.697%	0.626%	0.718%	0.718%

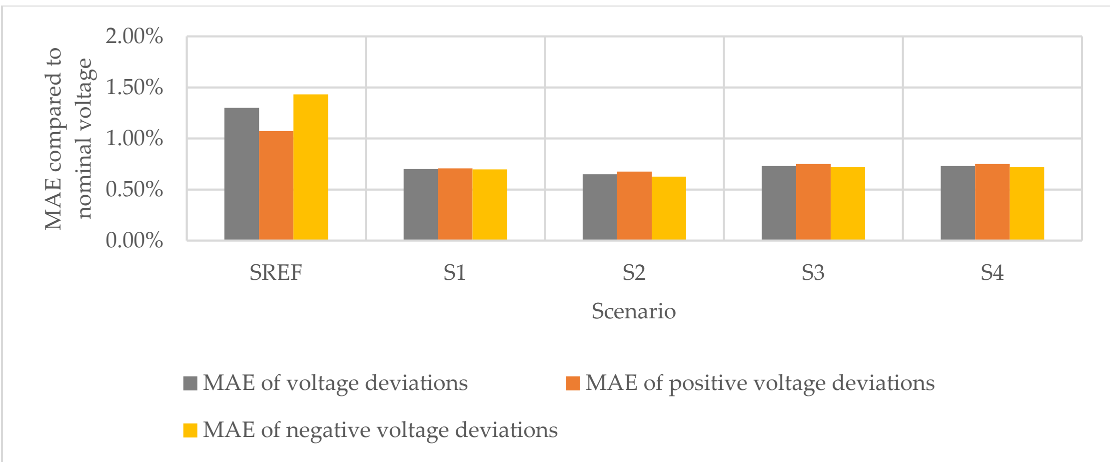


Figure 9. MAE of the voltage deviations (for all deviations, positive deviations, and negative deviations) from the nominal voltage over all periods, busses, and phases. For the clarity of the results, MAE is divided by the nominal voltage and expressed as a percentage.

From Table4and Figure9, it can be observed that in the SREF scenario, MEA for all voltage deviations equals to 1.30% of the nominal voltage, and the dominant are negative voltage deviations (1.43% for the negative compared to the 1.07% for the positive deviations). The sum of the deviations led to the decrease of the voltage levels from the nominal by −0.486%, as seen in Table3and Figure8. In all scenarios that include simulation of the active LET (scenarios S1–S4), MAE is nearly halved for all voltage deviations (ranges from 0.65% to 0.73%). In the S1 scenario (high supply prices, increased demand elasticity) the MAE of all voltage deviations equals 0.70%, with the domination higher impact of positive voltage deviations (0.71%) compared to the MAE of negative voltage deviations (0.70%). However, even though the MAE of positive voltage deviations is higher, the average voltage level dropped by 0.022% compared to the nominal, which means that there is a larger number of the negative voltage deviations. The effects of the decreased demand elasticity in the S2 scenario led to a decrease in total energy consumption and decrease in volumes of locally traded electricity (Figure6and Table2). That, in turn, led to the decrease of voltage deviations (all, positive, and negative) (Table4, Figure9) and to a slight rise of the average voltage level (Table3, Figure8), in comparison with the S1 scenario. The decrease of supply offering prices in scenarios S3 and S4 led to an increase in the total energy consumption, production, and increase in volumes of locally traded electricity (Figure6and Table2). Moreover, it led to the exports to the upstream grid, which in turn led to the upstream power flows, increase of average voltage level (Table3, Figure8), and to the increase of voltage deviations, especially positive voltage deviations (Table4, Figure9), in comparison with the scenarios S1 and S2. Finally, it can be seen that the MAE of voltage deviations in the scenarios with the active LET are, on average, 54% lower than in the SREF scenario.

4. Discussion

The paper proposes the method for simulation and analysis of the effects of different elasticities and prices in offering curves of the peers participating in the LET, on power flows and voltage levels in the distribution grid. The proposed LET is based on a centrally aggregated double-auction trading mechanism and applied in the IEEE European LV Distribution Grid Test Feeder. The paper contributes with the assessment and exploration of implications of implementing LEMs in distribution grid with a significant RES capacity and active participation of prosumers through demand response. Also, it is investigated if LEMs can be operated without time-consuming SCUC calculations for observed time horizons and without SCED calculations for each trading period. The analysis includes implications on the power flows and voltage stability on the local distribution grid.

The results point out at several valuable insights. LET can significantly contribute to the local supply-demand balancing and thus decrease the imports from the upstream grid. In a LEM organized in an auction-based manner, the participants' strategies for demand and supply offering curves have significant impact on market-clearing prices and quantities, i.e., local electricity consumption and production, and thus affect the initiated power flows and voltage levels. At the same time, LEM market-clearing prices and quantities significantly depend on the organization of the LEM and integration with the rest of the electricity market, particulary on the prices and quantities of electricity that can be sold to, or bought from the upstream grid. Also, the scenario analysis has shown that, within the given boundary conditions, LET can be operated without SCUC and SCED calculations for each trading period. The analysis of the effects of supply and demand offering strategies showed that the low supply offering prices contribute to the rise in the local electricity consumption and production, rise in the volumes of locally traded electricity and as well potentially higher exports to the upstream grid, consequently increasing the voltage levels. On the contrary, high supply offering prices have opposite impacts. The effects of demand elasticity changes depend on the shape of the demand curves and relation with the supply curves, so the effects are not unambiguous, as the increase of demand elasticity can lead to the effects similar to the ones caused by the low supply offering prices but not necessarily. In the observed scenarios, the decrease of demand elasticity led to the decrease of equilibrium prices and volumes, while the decrease of supply offering prices led to the increase of local energy consumption and volumes traded. The effects on average voltage levels in considered scenarios primarily depended on the power flows from/to the upstream grid, as the improvement of local electricity supply-demand balancing (behind the substation) led to the minimization of voltage drops and to the increase in voltage levels. Moreover, that way voltage deviations were also decreased.

Those effects can have important implications for designing the LEMs and associated market and control mechanisms. Also, insights could have impacts on the operation of distribution systems where LEMs are implemented, as DSOs could reduce LV levels at the secondary side of distribution transformers in order to address the effects of LETs on voltage levels.

Future work and research include the exploration of the voltage and frequency response in the cases when LET is implemented in microgrids that can operate in the island mode. Further, in the IMPACT project [33], a laboratory setup for testing LET concepts in small-scale microgrids, and real-life testing in a community microgrid is foreseen. Moreover, since the used model for LET is based on the EUPHEMIA algorithm [30], it means that electricity trading between microgrids can be organized in an analogy to the market coupling between the zones of the wholesale markets, where microgrids would serve as zones in the wholesale markets. Thereby, the cross-border lines of the wholesale markets can be represented by substations between neighboring microgrids, and substation rated power would serve as a total transfer capacity (TTC). For the calculation of the net transfer capacity (NTC), TTC has to be reduced by the transmission reliability margin (TRM) to cover for the forecast uncertainties and probabilistic real-time events [42]. Further, available transfer capacity (ATC) could be calculated as NTC reduced by the notified transmission flows (NTF), which covers for the already reserved contract sizes (for example, day-ahead or hour-ahead contracts between microgrid participants). Consequently, the idea is that the final ATC would serve as a transfer capacity that remains available for further commercial LET activity and is used in the market coupling algorithm [30,42]. That way, implicit cross-microgrid capacity allocation mechanism and trading could be implemented in the code in the future.

Supplementary Materials: The following are available online athttp: //www.mdpi.com/1996-1073/12/24/4708/s1, MATLAB code and Voltages results.

Author Contributions: L.H. and P.I. have contributed to conceptualization and developed the methodology. L.H. developed the software and simulation framework, conducted formal analysis and writing—original draft preparation, and created the visualizations. L.H., P.I. and I.R. have contributed to validation and writing—review and editing. I.R. contributed to supervision and project administration. P.I. and I.R. contributed to the acquisition of project funding.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

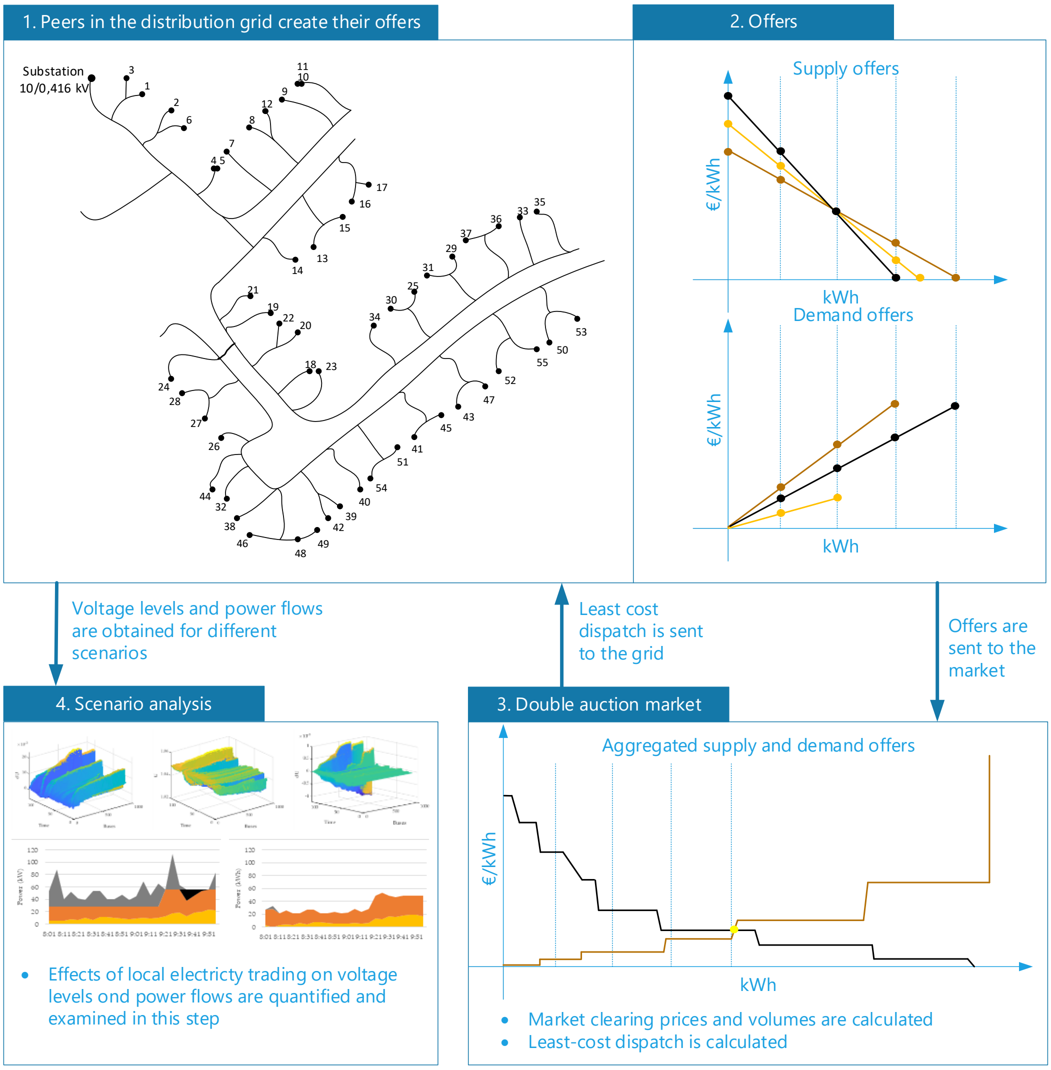

Figure A1. Flowchart of the used method.

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Automated energy sharing in MV and LV distribution grids within an energy community: A case for Croatian city of Križevci with a hybrid renewable system

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A B S T R A C T

Local energy sharing (LES) is a concept that enables sharing between distribution system participants such as consumers, producers, and prosumers at the local level in a transparent and cooperative manner. It can improve local supply-demand balancing, reduce voltage deviations, and improve social welfare. However, the feasibility of such an approach is highly dependent on the regulatory framework and implementation requires investment in an adequate information and communication infrastructure. This paper examines components for the implementation of LES within energy communities in the EU, with a focus on price-forming methods that can be integrated into a net-billing system and adopted for different regulatory set-ups. Further, a method for the assessment of impacts on market participants is provided. The approach is applied for the assessment of the opportunities for LES in the city of Križevci, considering local generation, flexibility options, and real-life regulatory requirements. It is shown that LES under appropriate regulatory provisions can be an effective market-based mechanism for stimulating local generation and flexibility activation, and that way support decarbonization and local self-sufficiency. All members can benefit from participating in the energy community, but the distribution of the benefits notably depends on the applied LES price-forming method. On the other hand, subject to regulatory setup, the trade-offs are reflected on reduced revenues for market participants that generate income based on transmission fees, taxes, and/or surcharges.

1. Introduction

Increased installations of distributed energy resources (DERs) lead to the need for smart power system operation in distribution grids [1], both at low voltage (LV) and medium voltage (MV) levels. Steep modern development of information and communication technologies (ICT) is a key enabling factor for smart grids and the development of innovative management and business models [2]. Local energy trading (LET) is a concept that allows peer-to-peer (P2P) and centralized energy trading between prosumers, consumers, and producers (regarded here as trading peers) in LV and MV distribution grid [3]. Local energy sharing (LES) is usually referred to in LET cases where total costs are minimized for the group of prosumers and sharing price is determined based on the predefined formula [4]. Application of these market-based mechanisms can lead to improved local demand-supply balancing, decreased voltage deviations from their nominal values, and improved social welfare [5–8]. Researchers have proposed various approaches to LET, including centralized auction-based trading [9], bilateral contract networks [10], or centrally coordinated trading or sharing [11]. The assessments of techno-economic potential of cooperation between prosumers with hybrid renewable systems have showed that energy sharing can promote self-sufficiency, reduce net costs and contribute to bill savings [12,13]. Also, it was pointed out that it could promote development of energy systems in rural areas [13]. Operation of energy storages can further be conducted in a way that increases benefits for the prosumers but also helps network operator in resolving network issues [14]. In the other hand, some battery-sharing strategies can lead to higher

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number of charging cycles and consequently shorten the battery service life [12]. The assessments of challenges and barriers for the implementation and economic viability of LET identified regulatory framework as a possible stumbling block and an important prerequisite for the achievement of the benefits of the concept [15,16]. There, due to the complex influence of regulatory provisions in the power system, a regulatory set-up should be carefully designed, and impacts assessed.

A debate on the evolution of the EU's legal framework to adequately facilitate rapid changes in the power sector is ever-present, but that process takes time. It is down to the fact that changes in power sector's legal framework can have far-reaching consequences, must involve a large number of participants throughout the electricity supply chain, and often encounter opposite viewpoints [17]. To test innovative solutions and explore the impacts of regulatory changes under controlled conditions, some countries experiment with regulatory sandboxes [18]. Further, the introduction of 'citizen energy communities' and 'renewable energy communities' [19] as new legal terms in the EU's regulatory framework is significant [20], as those could allow special local regulatory provisions, without changing the general regulatory landscape. As of the middle of 2021, most of the EU's member states (MSs) were in the phase of drafting of the new laws and bylaws to transpose mandatory provisions set in the EU directives into the national regulatory frameworks [20,21]. EU directives set the general framework, so different national approaches can be seen. Term collective self-consumption (CSC) is used for "jointly acting renewables self-consumers" [19], i.e., situations where at least two prosumers cooperate, either in the same building or multi-apartment block or within wider premises if allowed. This concept could also be utilized to allow a group of households to partially cover their own energy needs by installing PV systems and sharing or trading energy between them [22,23]. While the focus of CSCs is on the specific activity, the focus of energy communities (ECs) is on a certain organizational format [20], where renewable energy communities (RECs) and citizen energy communities (CECs) are further defined separately [16]. LET or LES, in principle, can be conducted within ECs, or ECs could be trading peers in a wider-range trading scheme. In practice, throughout the transposition process, MSs have to decide, inter alia, on spatial limitations, allowed capacities, local grid tariffs, or conditions for use of public grid [20]. Here, an introduction of local grid tariffs or reduction of other surcharges has the potential to vastly improve the cost-viability of LET [24]. A study conducted for the case of Austria [25], showed that ECs have potential to accelerate solar PV adoption and therefore contribute to achievement of climate and energy policy goals until 2030.

The overview of the existing literature and advances in development of LES projects in the EU (Section 2) shows that most of the papers focus on singular components needed for the implementation of energy sharing within ECs, while approaches to real-life implementation are varied and have to effectively connect multiple layers. Due to the novel and diverse legislative framework across the EU MSs, different state of smart metering infrastructure and market prices, same approach cannot be applied across all of the MSs, and economic attractiveness varies. Also, importance of social aspect should not be underestimated in the implementation phase, as concept has to be presented as simple as possible to EC's members to allow comprehensibility and social support for the projects [26]. Therefore, robust and tailor-made quantitative and qualitative analysis of potentials for application of LES considering the multiple layers and real-life regulatory environments requires further research and dissemination. The goal of this work is to provide a framework for evaluation of the feasibility of LES under different regulatory set-ups that arise from the transposition of the EU's Renewable Energy Directive [19] and Internal Electricity Market Directive [27], with a case study focusing on new provisions in Croatia. In doing so, we provide a method for assessment of the implications on different market participants, such as transmission system operator (TSO), DSO, prosumers participating in LES, and impacts on taxes and levies affected by the LES. Further, to perform the research, LES is simulated as a market with a local energy sharing coordinator (LESC), where volumes are determined based on the optimal unit commitment dispatch model of the flexibility options, and the energy sharing prices are determined ex-post based on the three methods: a) mid-market rate (MMR), b) excess-missing ratio in a trading interval (EMRu), and c) excess-missing ratio in a trading period (EMRm).

In particular, this paper contributes with the following:

- Overview and a comparison of the progress in development of ECs with LES in the EU, with respect to the used technologies, ICT infrastructure, control functions, business models and challenges under the emerging regulatory frameworks.
- A mixed-integer linear programming (MILP) LES market-clearing model that is applicable for different regulatory set-ups, with novel methods for determining energy sharing compensation price. Proposed price-forming methods are suitable for the environments where prosumers can have different energy suppliers, third parties (like DSOs or market operators) could control the sharing price ex-post, and where certain charges can be included in LES - such as distribution fee, taxes, or similar.
- Method for assessing the economic impacts of the local electricity market on market participants considering the applicable regulatory framework. The approach has been applied on a case-study analysis taking into account the real-life data and practical implementation challenges for the Croatian city of Križevci, where local energy sharing is being implemented within a citizen energy community as defined in the Croatian regulatory framework.

The rest of the paper is organized as follows: Section 2 provides a literature review on the advances in developing LES projects within ECs in the EU, Section 3 contains the description of the method, Section 4 presents the input data and scenarios of the case study of the city of Križevci in Croatia, in section 5 the results are presented, and in section 6 main conclusions are listed and discussed.

2. Advances in developing LES projects within ECs in the EU

The overview in this section is organized into two subsections where the first subsection reviews literature and real-life provisions taken by the EU MSs for adjusting regulatory framework to facilitate LES and ECs. The second subsection reviews the literature and projects considering the operational aspects of ECs – included technologies, ICT infrastructure, control functions, business models, and main challenges.

2.1. Emerging legislative frameworks for energy communities

Clean Energy for all Europeans Package (CEEP) [28] in 2019 introduced definitions of CSCs, RECs, and CECs at the EU level. Those concepts can be observed interchangeably and support the implementation of LES. The overview of the ongoing transposition processes in MSs is summarized in Table 1. There is a wide range of nuances that differentiate the approaches taken by the MSs in the transposition of the general definitions into the national legislative frameworks [16,29]. The focus of the overview is on provisions that

Table 1
Overview of the approaches in transposition of CEEP provisions in the chosen MSs.

MS	Allocation of energy and responsibilities	System boundaries and limits	Grid tariffs and taxes for LES	Ref.
Austria	DSO allocates the energy based on the distribution key for each 15-min period under the CSC scheme. Different legal forms are possible for ECs.	LV or MV RECs are differentiated, which affects the grid fee reductions differently. The use of a public grid is possible also for CSC.	Reduced volumetric part, percentages depend on whether LV or MV REC. Capacity part reduced based on imports from the grid. Removal of RES surcharges and electricity tax for LES.	[16,29]
Croatia	Under the CEC scheme, DSO allocates the energy based on the distribution key, billing periods to be defined.	CECs are limited to LV feeders, production up to 80% consumption of capacity, and members have to be in the same municipality.	Distribution network fee remains, bylaws must define effects on other price components (transmission fee, surcharges, taxes).	[16] [34]
Greece	Virtual net metering scheme – netting between the generated and consumed energy, excess energy not reimbursed.	Production capacity can be up to 100% of consumption capacity or 3 MW. Production has to be located within the geographical region or system related, depending on location. Members of the EC must have the same supplier.	Grid tariffs are removed for LES within the virtual net metering scheme, but excess energy is not reimbursed.	[16] [35]
Portugal	Control by the DSO and DGEG. An additional entity needed to communicate with them under the CSC scheme.	Evaluated individually by the DGEG.	The volumetric part of the grid fees is removed for higher network levels. Under the CSC scheme, LES pays a fee. For consumers with a capacity of below 41.4 kVA only consumption-based fees, for larger consumers also a capacity-based component.	[16] [36]
Slovenia	No need for a legal entity for CSC. Connection points should not take part in other support schemes, CECs have to be cooperatives.	ECs limited to the same LV feeders.	Grid tariffs are removed for LES within the CSC scheme.	[16] [37]
Spain	A sharing key has to be defined by the CSC. DSO and suppliers clear balances based on it.	ECs limited to either: internal network, same LV feeders, production and consumption connection points must be within a geographical range of 500 m, or their cadastral reference must be under the same sector.	Grid tariffs are removed for LES within the CSC scheme - both capacity and consumption-based fees	[16,32] [38]

enable implementation and the economic attractiveness of LES.

The overview of the responsibilities and principles for allocation of energy (Table 1) shows that some countries allow LES under the umbrellas of different legal forms - CSCs, RECs, or CECs. A common approach is that members have to determine the allocation key, while DSO allocates the energy based on the smart meter data and communicates it with suppliers, and other market participants (e.g., Austria, Croatia, Slovenia, Spain) [16]. Contrary, Portugal requires control by the DSO and Directorate-General for Energy and Geology (DGEG). Further, an additional entity is needed to communicate with them under the CSC scheme. The approach to system boundaries and limits for CSC and ECs is also diverse – from linking the scope with power system topology such as limiting ECs to LV feeders (e.g., Croatia, Slovenia, CSC in Spain), locational proximity (e.g. CSC scheme in France [30], ECs in Spain), or case-by-case assessment (Portugal), while Austria differentiated LV and MV RECs [16,29]. Most of the MSs allowed the use of public grid only for ECs, while CSC is a reserved scheme for multi-apartment buildings (exceptions are examples of Austria, France, Portugal, Spain where public grid use is allowed also under the CSC scheme [16]). Further limits can include the need that EC members have the same supplier (Greece) or affiliation to the same municipality (e.g., CEC in Croatia [31]) or sector (e.g., CSC in Spain). Also, limits to installed capacities (up to 3 MW in Greece), number of members can appear (e.g., up to 1000 members in Poland), or legal form of ECs (e.g., energy cooperative in Slovenia). Approaches to grid tariffs and taxes have a key role in creating the economic attractiveness of LES within CSCs or ECs. A common approach is the adjustment or removal of some of the grid charges, levies, and/or taxes for local energy shared (e.g., Austria, Croatia, Greece, Portugal, Slovenia, Spain) [16,32]. Here, some countries affected the volumetric (consumption)-based fees, while some focused-on power (capacity)-based fees. A different approach, resulting in a similar effect, is in retention of the standard fees, but on top of them introducing subsequent reimbursements for local energy shared (e.g., Italy) [33].

Between the challenges for the implementation of a near real-time LES, several issues commonly appear across the MSs. On the technical side, the real-time smart meter data access is still recognized as a challenge in many MSs (e.g., Austria, Croatia, Portugal), while on the organizational side, operative procedures and/or bylaws are lacking in several MSs (e.g., Croatia, Portugal, Slovenia) [16,20].

2.2. Ongoing implementation of energy sharing within energy communities

The overview of examples in implementation of real-life energy communities and LES within them in the EU is provided in this subsection. The overview is structured based on the layers as proposed by Zhang et al. [39]: power grid, ICT, control, and business layer. The summary of the overview with references is shown in Table 2.

From the perspective of the energy production technologies, all 6 reviewed projects use solar PVs, and 3 of them (Germany, Netherlands, Slovenia) expand the systems with the use of battery energy storage systems (BESSs), and 4 with EV chargers (Germany, Netherlands, Portugal, Slovenia). That approach can be explained due to the simplicity and decreasing costs of solar PV systems, while the motivation for installations of BESSs varies from research purposes to commercial applications. All projects foresee the use of public distribution grid. However, project sites in Slovenia and Netherlands are restricted to LV feeder, project site in Portugal focuses on the group of multi-apartment buildings. In the Crevillent municipality in Spain, the distribution grid is operated by the cooperative, but several subordinated ECs are planned also due to the LV feeder restriction. Further, ECs can even be organized as microgrids, which would imply they should be able to operate in island mode [40]. Out of the reviewed projects, only the pilot site in Slovenia is designed and can be operated that way [37,41]. Contrary to other projects, sonnenCommunity in Germany is not locally-oriented, but aggregates users of vendor's BESSs from different locations (Table 2) – therefore not an EC as considered in CEEP's definitions.

Table 2
Overview of the components and implementation methods for emerging local energy sharing projects in the EU.

Type of a community project, Country	Energy technologies	ICT infrastructure	Control functions	Market and legal model	Main challenges	Ref.
Community of BESS owners sonnenCommunity, Germany	Solar PVs, BESSs, EV chargers, public grid.	BESSs vendor's metering and communication system.	BESS management system provided by the vendor.	Energy sharing pool of the vendor, licensed as a retailer, no locational limit, vendor optimizes BESS operation.	No additional benefits for members located close to each other.	[7,61] [39]
Energy community of the municipality and citizens in Rafina, Greece	Solar PVs, public distribution grid.	DSO's smart meters.	Not implemented nor planned under the virtual net metering scheme.	Virtual net metering within the EC, reduced grid charges, sharing rules defined by the EC, netting done by the retailer.	All members have to have the same retailer, lack of crowdfunding legislative framework, grid connection delays.	[41] [35]
Group of multi-apartment buildings Alta de Lisboa, Portugal	Solar PVs, EV chargers, public distribution grid.	DSO's smart meters, could be expanded with smart management tools in the future when PV capacity will be increased.	Not implemented at present, energy management system planned for the future.	Operated as a CSC, reduced network tariffs, planned to be transformed to EC by the Copernico cooperative.	Lack of smart meters, unclear procedures for registration of the EC and application of LES.	[41] [62]
Remote village Luče, Slovenia	Solar PVs, community BESS, home BESSs, EV charging point, restricted to public LV feeder.	DSO's smart meters, third-party SCADA and microgrid management system.	Supply-demand management system, EC organized and run as a microgrid, the operation can be overruled by the DSO.	Regulatory exception - reduced grid fees, CSC scheme over the distribution network, LES planned to be implemented.	Restricted to LV feeder, no formal responsibilities and procedures between DSO and microgrid operator.	[41] [37]
Neighborhood in Village Heeten, The Netherlands	Solar PVs, EV chargers, EV batteries, restricted to public LV feeder.	Smart meters and a consumer app to support demand response.	BESS management system, energy flow control at the connection point of the neighborhood, demand response.	Households organized in EC, under 'Energy Act Experiments Regulation', local energy market, no volumetric grid charges for LES, just capacity.	Replication potential depends on regulatory development.	[63] [64] [65]
Cooperative-operated grid in municipality Crevillent, Spain	Municipal and household solar PVs, public distribution grid.	Installation of smart meters in progress.	Not implemented in the present, flexibility and demand response measures planned.	Municipal generation owned by the cooperative, reduced electricity fee for EC members, static percentage of production for energy sharing.	Limit of LV feeder and 500 m for the members means several EC should be established, lack of smart meters.	[41] [66] [67] [38]

ICT infrastructure consists of meters, sensors, computers and other electronic equipment and systems that collect, store, use, and send data electronically [39]. In Refs. [42–45] the communication technologies and network requirements for different smart grid applications were assessed. In Refs. [46,47] linked challenges and opportunities were analyzed. In the reviewed projects, in cases where energy sharing is intended to be conducted ex-post and integrated into the billing system (Greece), data from the DSO's meters are sufficient and not necessarily with near real-time availability. The approaches towards the ICT infrastructure are closely related to the implementation of control functions. In projects where advanced energy management systems are deployed or planned to be deployed (Germany, Portugal, Slovenia), additional metering infrastructure is foreseen, meaning third parties that operate ECs don't rely on the DSO's smart meters. Lack of DSO's smart meters, or issues with accessibility of data in real-time are among the reasons for this trend. The pilot site in Spain is a specific case as the public grid is also owned by the cooperative looking to implement LES. The usual past and present communication architectures are based on a central controller that communicates with all EC resources and makes decisions. The control is usually implemented by the Supervisory Control and Data Acquisition (SCADA) systems [48]. However, the evolution from the centralized to distributed architectures of communication systems is linked to the evolution of control for the microgrids and ECs and can be expected to continue with the rising complexity in the future [49]. Also, use of the distributed ledger technology (DLT) and blockchain technology in the energy sector and microgrids got under significant attention lately. Overview of the state-of-art and potential for the use of blockchain technology in the energy sector was done in Refs. [50–52], while the possible application for the P2P trading was analyzed in Ref. [53], and firstly implemented in Brooklyn Microgrid project in New York in 2016 [54].

Several pieces of research [3,55] reviewed proposed market frameworks for LET and community—based markets considering the potential designs and market clearing approaches. Based on the existing proposals, any market players besides sellers or buyers can be a local energy sharing coordinator (LESC), e.g. distribution system operators (DSOs), aggregators, market operators, smart energy service providers [56], energy traders, auctioneers [57], local operators [55,58]. Further, LES can be conducted through a trading platform, which at least requires administration and maintenance from a third party [59]. A comprehensive review of impacts of LEMs integration in power systems [60] showed that the integration of network constraints can be done through power flow equations, network tariffs signals, or power losses signals. Also, it was highlighted that it is important to include DSOs in a decision-making process and market mechanism, since it has access to crucial grid information. From the perspective of business models, all reviewed projects (Table 2) are designed as ECs with LES between their members, except the sonnenCommunity in Germany, which was conceived before the provisions defined in CEEP and primarily aims at energy pooling and participation in different energy markets and is not restricted to a certain local area. In other cases, special provisions that allow EC members to use the public distribution grid for LES with the decreased network charges laid the foundation for business cases even without considering the active bidding of ECs in energy markets. Local active energy management within ECs contribute to the feasibility of LES in cases where billing is done based on metering in each interval (Netherlands, Portugal, Slovenia, Spain), while in the case of virtual net-metering (Greece) ECs are not stimulated for near real-time optimization of flexibility options as metering is netted in longer time horizon. The reviewed pilot LES projects opted for LES based on the static formulas for setting energy sharing prices and quantities. Considerations on different existing proposals for price determination mechanisms for ECs are analyzed in Ref. [4], where dynamic pricing and uncertainty are considered. However, due to the novelty of regulatory provisions and the required learning period for market participants, starting as simple as possible is a logical way forward and a visible approach in the reviewed projects (Table 2).

The effects of new provisions on the feasibility of community energy projects are country-specific and not yet adequately explored in general, due to the novelty of the provisions. Cielo et al. analyzed the possible business model under the 2020 Italian regulation [33] and found out that the provision leads to both positive economic and environmental performance for the EC. However, the effects on wider system participants were not observed. Further, based on the review of the literature and developing projects, it is evident that real-life implementation has to integrate all technical layers with the social dynamic and regulatory aspects [26]. As a consequence, implementation takes time and has to overcome challenges on the road. As the main recognized challenges and barriers among the reviewed projects, the following can be highlighted: the incomplete or unclear regulatory framework (Greece, Portugal, Slovenia, The Netherlands), lack of DSOs smart meters (Portugal, Spain). Further, some provisions restrict the potential development of ECs, such as the requirement for the same supplier of the members (Greece), or limitations for LES to be located in LV network feeder (Slovenia, Spain, The Netherlands). On contrary, in virtual EC sonnenCommunity there are no additional benefits for the members if they are located in proximity to each other, as the business model was conceived before the CEEP provisions on ECs. However, presented business models and frameworks have to be considered as developing, meaning future changes and adaptations are always possible.

3. Method

The method consists of three parts: (1) the LES mechanism including LESC responsible for optimal scheduling of flexibility options and energy vectors in the energy community, that could be applied under different regulatory frameworks; (2) three methods for forming of price for energy shared, one based on the mid-market rate and two based on the supply-demand ratio (SDR) [68] - modified in a way that reduces data collection needs and allows a third party (such as DSO) to monitor and administers energy sharing, and called excess-missing ratio (EMR). That is particularly important in cases where the EC is organized over the public distribution network and could include different suppliers for prosumers; and (3) method for estimation of effects on the market participants, namely DSO, TSO, suppliers, taxes, levies, and members of the EC, based on the levelized cost of energy consumed. This methodology allows analysis of the economic effects on different market participants, while the energy sharing model allows analysis of local power balance and energy indicators.

3.1. Local energy sharing - unit commitment

To simulate LES, a centrally coordinated LES mechanism is implemented with a goal to minimize the operating cost of the EC. It is assumed that LESC operates the available flexibility options of the prosumers. In the model, the availability of BESS is modeled as it is available on the site, while the model can be expanded to include also other options, like heat storage, electric vehicles, or hydrogen production [69]. A schematic diagram of the concept is shown in Fig. 1. Here, the locations of power transformers and measurement points are not explicitly depicted as members of the EC can be located at the point of common coupling and operated similarly to a microgrid or can be dispersed at the distribution grid and act as a virtual power plant – subject to the requirements of the legislative framework and topology of the local distribution grid. Also, LESC can use DSO's smart meters or install additional metering and ICT infrastructure. The application of the model on the real-life example is described later detailly in Section 3. Further, EC, in principle, can include different types of members – household and/or commercial sector prosumers, as well as pure producers or passive consumers.

The optimization objective is defined in Equation (1).

$$\min\left\{\sum_{t=1}^{T}\sum_{p=1}^{P}\left(E_{t,p}^{g,b}\cdot\pi_{t,p}^{g,b}+E_{t,p}^{l,b}\cdot C_{t}^{l,b}+C_{p}(P_{t,p})-E_{t,p}^{g,s}\cdot\pi_{t,p}^{g,s}\right)\right\} \tag{1}$$

Where $\pi_{t,p}^{g,s}$ is the price of electricity (depending on the regulatory set-up, can be defined to cover system fees, taxes or levies) which is sold (exponent s) at the amount of $E_{t,p}^{g,s}$ by a peer p to the upstream grid (exponent g) in interval t; $\pi_{t,p}^{g,b}$ is the price of electricity (usually includes system fees, taxes or levies) bought (exponent b) at the amount of $E_{t,p}^{g,b}$ by a peer p from the grid (exponent g) in interval t; and $C_{t}^{l,b}$ is the cost added to the local electricity traded (e.g. DSO fee, VAT, or other fees and levies) which is bought (exponent b) at the amount $E_{t,p}^{l,b}$ by a peer p from the LEM (exponent l) in interval t. $C_p(P_{t,p})$ is the operating cost of peer p (typically quadratic) and is a function of its real output power $P_{t,p}$ in interval t. Index sets are $p\in\{1,2,\ldots,P\}$ and $t\in\{1,2,\ldots,T\}$ where P is a total number of peers and T is the number of time intervals in the time horizon.

The optimization objective is subject to constraints defined in Equations (2) – (11). There, in Equation (3) is energy balance constraint, in Equation (2) is LES constraint, in Equation (4) is solar PV production constraint, Equations (5) – (6) define active power capacity constraints of prosumers' connection to the grid, and Equations (7) – (11) constraints of BESSs. The inequalities and equations in (3) – (11) are defined for every t and every p ($\forall t\in\{1,2,\ldots,T\}$, $\forall p\in\{1,2,\ldots,P\}$) while (2) is defined for every t:

$$\sum_{p=1}^{P}E_{t,p}^{l,s}=\sum_{p=1}^{P}E_{t,p}^{l,b} \tag{2}$$

$$\mathrm{D}_{t,p}-P_{t,p}=-E_{t,p}^{g,s}+E_{t,p}^{g,b}-E_{t,p}^{l,s}+E_{t,p}^{l,b}-E_{t,p}^{ch}+E_{t,p}^{dis} \tag{3}$$

$$0\leq P_{t,p}\leq P_{t,p}^{max} \tag{4}$$

$$0\leq E_{t,p}^{g,s}\leq P_{p}^{g,s,Max} \tag{5}$$

$$0\leq E_{t,p}^{g,b}\leq P_{p}^{g,b,\ Max} \tag{6}$$

$$SoC_{t,p}=SoC_{t-1,p}+E_{t,p}^{ch}\cdot\eta_{ch}-\frac{E_{t,p}^{dis}}{\eta_{dis}} \tag{7}$$

$$0\leq E_{t,p}^{ch}\leq E_{t,p}^{ch,\ max}\cdot N_{t,p}^{ch,bin} \tag{8}$$

$$0\leq E_{t,p}^{dis}\leq E_{t,p}^{dis,\ max}\cdot N_{t,p}^{dis,bin} \tag{9}$$

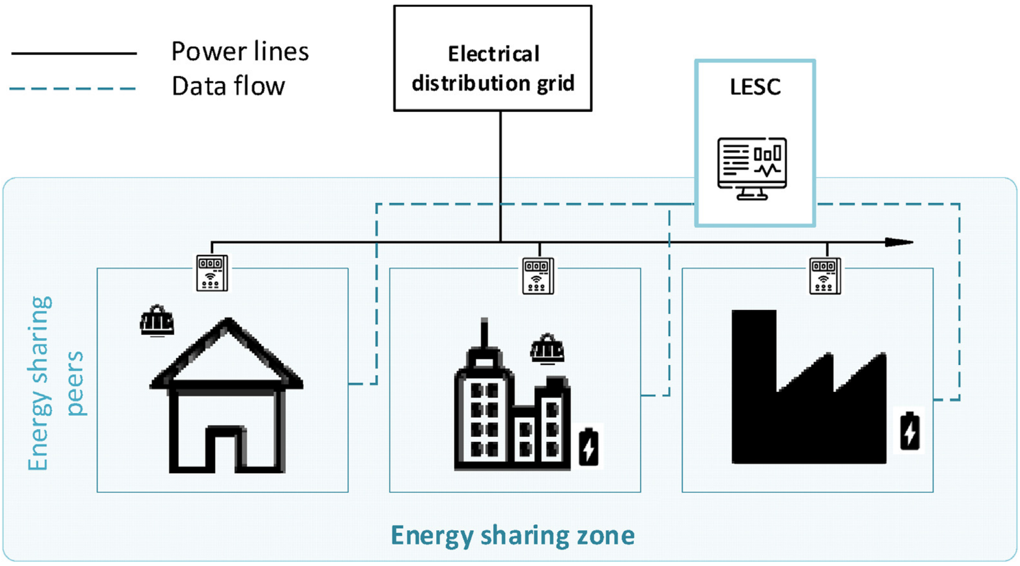


Fig. 1. Concept for local energy sharing with a local energy sharing coordinator.

$$N_{t,p}^{ch,bin} + N_{t,p}^{dis,bin} \leq 1 \tag{10}$$

$$SoC_p^{min} \leq SoC_{t,p} \leq SoC_p^{max} \tag{11}$$

Where $D_{t,p}$ is demand, $P_{t,p}$ is electricity production, $E_{t,p}^{ch}$ is electricity charged to BESSs, and $E_{t,p}^{dis}$ is electricity discharged by the BESSs. $P_p^{g,s,Max}$ and $P_p^{g,b,Max}$ are available power capacities of prosumers constraint the sold and bought energy to the grid for $t \in \{1, 2, \ldots, T\}$. $SoC_{t,p}$ is the state of charge of BESSs, SoC_p^{max} and SoC_p^{min} are maximum and minimum state of charge of BESSs, $E_{t,p}^{ch,\ max}$ and $E_{t,p}^{dis,\ max}$ are maximal charging and discharging power of BESSs, $N_{t,p}^{ch,bin}$ and $N_{t,p}^{dis,bin}$ are binary variables for charging and discharging respectively.

As elaborated in the Introduction, the regulatory landscape in the EU is increasingly changing to facilitate the energy transition [20]. However, there are fine nuances across the MSs, and no single solution fits all locations. This approach allows modeling of different regulatory provisions, tariffs and allocations of regulated electricity price components (REPCs) [24], such as distribution fees, transmission fees, surcharges, and taxes [34].

3.2. *Local energy sharing - price formation and integration with a net-billing scheme*

The analysis of different existing proposals for price determination mechanisms for ECs can be found in Ref. [4]. With our work, we upgrade them and integrate with the energy sharing model with a third-party administrator, requiring only one measuring point for each peer. Moreover, we adapt them in a way that can transparently include distribution network or other fees, LES could be subject to under different regulatory setups. The analysis [4] has shown that in a Bill sharing net method (BSNM) passive peers are always better off, as they get a free ride on the expense of the active prosumers. For these reasons we do not consider BSNM in our paper. We present three methods for LES price determination: Mid-market ratio (MMR); Excess-missing ratio in a billing interval (EMRu); and Excess-missing ratio in a billing period (EMRm). The feature of the analyzed methods is that they require just smart meters' energy exchange data – therefore not 'behind the meter' data and can be applied transparently ex-post by a third party, such as DSO or electricity market operator. That is particularly important in cases where prosumers have different suppliers.

This is in line with the energy sharing definition in Croatia; it allows/recognizes energy sharing over the distribution grid only considering the data known and available to the DSO [31]. Members of the EC have to define and submit the billing key according to which the electricity is shared. Unlike in some other countries, the smart meters in Croatia are installed just at the connection point of the prosumer with the grid, and not additionally on the connection of PV panels.

3.2.1. *Mid-market ratio*

Under the Mid-market ratio (MMR) scheme, the LES price is determined as a midpoint between the weighted average selling price in case without LES, increased by LES fees, and weighted average buying price in case without LES in each interval t, as shown in Equations 12–14 and illustrated in Fig. 2.

$$\pi_t^l = \frac{\left(\overline{\pi}_t^{g,b} + \overline{\pi}_t^{g,s} + C_t^{l,b}\right)}{2} \tag{12}$$

$$\overline{\pi}_t^{g,b} = \frac{\sum_{p=1}^{P}\left(M_{t,p} \cdot \pi_{t,p}^{g,b}\right)}{\sum_{p=1}^{P} E_{t,p}^{g,b}} \tag{13}$$

$$\overline{\pi}_t^{g,s} = \frac{\sum_{p=1}^{P}\left(X_{t,p} \cdot \pi_{t,p}^{g,s}\right)}{\sum_{p=1}^{P} E_{t,p}^{g,s}} \tag{14}$$

Where π_t^l is the LES price in each interval t, $\forall t \in \{1, 2, \ldots, T\}$. $\overline{\pi}_t^{g,b}$ and $\overline{\pi}_t^{g,s}$ are the weighted average cost of electricity bought and sold to the upstream grid of the peers in case without LES. $X_{t,p}$ is the sum of excess and $M_{t,p}$ is the sum of missing energy of individual peers. Those are the sums of energy exported and imported from an upstream grid or from the other peers in the energy community (if LES is implemented), in time interval t, $\forall t \in \{1, 2, \ldots, T\}$, and $\forall p \in \{1, 2,$

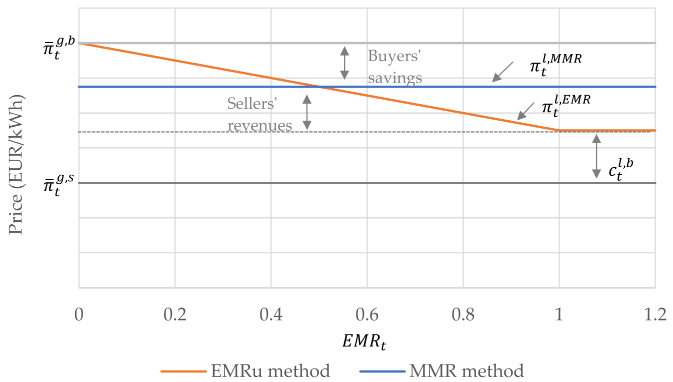


Fig. 2. Principle for determining the local energy sharing price under MMR and EMRu methods.

$\dots,P\}$. $X_{t,p}$ equals $E_{t,p}^{g,s}+E_{t,p}^{l,s}$, and $M_{t,p}$ equals $E_{t,p}^{g,b}+E_{t,p}^{l,b}$. $C_t^{l,b}$ are the costs that have to be paid to third parties when energy is shared within the community, in each interval t, $\forall t\in\{1,2,\dots,T\}$. Typically, those would relate to distribution fees, taxes or other fees if prescribed by the legislative framework or set by the LESC. The effects on the bills of individual peers are calculated by Equations 15–17.

$$EMRu_t=\frac{\sum_{p=1}^{P}(X_{t,p})}{\sum_{p=1}^{P}(M_{t,p})}=\frac{\sum_{p=1}^{P}\left(E_{t,p}^{g,s}+E_{t,p}^{l,s}\right)}{\sum_{p=1}^{P}\left(E_{t,p}^{g,b}+E_{t,p}^{l,b}\right)} \tag{15}$$

$$S_{t,p}^{l,s}=\begin{cases}\left(\pi_t^{l}-\pi_{t,p}^{g,s}-C_t^{l,b}\right)\cdot\dfrac{1}{EMRu_t}\cdot X_{t,p},\ EMRu_t\ge 1\\ \left(\pi_t^{l}-\pi_{t,p}^{g,s}-C_t^{l,b}\right)\cdot X_{t,p},\ 0<EMRu_t<1\\ 0,\ EMRu_t=0\end{cases} \tag{16}$$

$$S_{t,p}^{l,b}=\begin{cases}\left(\pi_{t,p}^{g,b}-\pi_t^{l}\right)\cdot M_{t,p},\ EMRu_t\ge 1\\ \left(\pi_{t,p}^{g,b}-\pi_t^{l}\right)\cdot EMRu_t\cdot M_{t,p},\ 0\le EMRu_t\le 1\\ 0,\ EMRu_t=0\end{cases} \tag{17}$$

Here, $EMRu_t$ is the excess-missing ratio defined as the ratio of the sum of excess ($X_{t,p}$) and missing ($M_{t,p}$) energy of individual peers. Further, $S_{t,p}^{l,s}$ are revenues of the seller peers p (producer surplus), while $S_{t,p}^{l,b}$ are savings of seller peers p (consumer surplus) due to the local energy sharing in time interval t, $\forall t\in\{1,2,\dots,Tm\}$, and $\forall p\in\{1,2,\ \dots,\ P\}$. The advantage of the application of this method is that data from only one smart meter per peer is needed and therefore energy sharing can be monitored by a third party (such as DSO or market operator), and results of energy sharing (revenues and savings) integrated with the net-billing scheme and in suppliers' bills, e.g., bills can be reduced at the end of the billing period (e.g., one month) for the prosumers even with different energy suppliers. This allows formal energy and bill sharing with a minimal administrative burden for the stakeholders – both in cases if additional advanced local energy management is applied, or if energy sharing is conducted based just on the different supply and demand patterns of EC members.

3.2.2. Excess-missing ratio in billing interval

The second method, Excess-missing ratio in billing interval ($EMRu_t$) for sharing price determination is based on the supply-demand ratio (SDR) as proposed in Ref. [68], but modified to include LES fees and linear slope of the price curve, as listed in Equation (18) and illustrated in Fig. 2.

$$\pi_t^{l}=\begin{cases}\pi_t^{g,b},\ EMRu_t=0\\ \pi_t^{g,b}-EMRu_t\cdot\left(\pi_t^{g,b}-C_t^{l,b}-\pi_t^{g,s}\right),\ 0<EMRu_t<1\\ \pi_t^{g,s}+C_t^{l,b},\ 1\le EMRu_t\end{cases} \tag{18}$$

The illustration of local energy sharing price is depicted in Fig. 2 for MMR and EMRu. The costs that have to be paid to third parties for local energy shared ($C_t^{l,b}$) remain in buyers' bills but impact the sellers' revenues and buyers' savings (when compared with the situation without LES). After the fee has been taken into account, under the MMR the LES price is determined as a midpoint between the price of energy bought from the grid ($\pi_t^{g,b}$) and price of energy sold to the grid ($\pi_t^{g,s}$) in each interval, while under the EMRu, the LES price is determined linearly depending on the EMR, inversely proportional to EMR, and between the price of energy bought from the grid ($\pi_t^{g,b}$) and price of energy sold to the grid ($\pi_t^{g,s}$) in each time interval t. That way, the members of the EC get better-off when participating in LES in both cases.

The sellers' revenues and buyers' savings can be calculated in each interval t based on the local energy sharing price π_t^{l}, and proportional allocation of quantities of energy shared between the prosumers. The calculation of revenue of each seller, in comparison with the case without LES, is defined in Equation (19), while the calculation of cost-savings of individual buying peers is defined in Equation (20).

$$S_{t,p}^{l,s}=\begin{cases}0,\ EMRu_t\ge 1\\ \left(\pi_t^{l}-\pi_t^{g,s}\right)\cdot X_{t,p},\ 0<EMRu_t<1\\ 0,\ EMRu_t=0\end{cases} \tag{19}$$

$$S_{t,p}^{l,b}=\begin{cases}\left(\pi_t^{g,b}-\pi_t^{l}\right)\cdot M_{t,p},\ EMRu_t\ge 1\\ \left(\pi_t^{g,b}-\pi_t^{l}\right)\cdot EMRu_t\cdot M_{t,p},\ 0\le EMRu_t\le 1\\ 0,\ EMRu_t=0\end{cases} \tag{20}$$

The difference in comparison with the MMR method is that here savings of the seller peers are zero when $EMRu_t\ge 1$, but, in the other hand LES price depends on $EMRu_t$, and thus is changing across the billing intervals, so in some intervals seller peers can receive price than in MMR method.

3.2.3. Excess-missing ratio in a billing period

The Excess-missing ratio in a billing period (EMRm) method is similar to EMRu, but the ratio is calculated over the billing period, e.g., one month. The EMRm ratio is defined in Equation (21), and the LES price is defined in Equation (22).

$$EMRm_t=\frac{\sum_{t=1}^{Tm}\sum_{p=1}^{P}(X_{t,p})}{\sum_{t=1}^{Tm}\sum_{p=1}^{P}(M_{t,p})}=\frac{\sum_{t=1}^{Tm}\sum_{p=1}^{P}\left(E_{t,p}^{g,s}+E_{t,p}^{l,s}\right)}{\sum_{t=1}^{Tm}\sum_{p=1}^{P}\left(E_{t,p}^{g,b}+E_{t,p}^{l,b}\right)} \tag{21}$$

$$\pi_t^{l}=\begin{cases}\pi_t^{g,b},\ EMRm_t=0\\ \pi_t^{g,b}-EMRm_t\cdot\left(\pi_t^{g,b}-C_t^{l,b}-\pi_t^{g,s}\right),\ 0<EMRm_t<1\\ \pi_t^{g,s}+C_t^{l,b},\ 1\le EMRm_t\end{cases} \tag{22}$$

Where $EMRm_t$ is the excess-missing ratio defined as the ratio of the sum of energy exported ($X_{t,p}$) from and imported ($M_{t,p}$) to individual peers, in a certain billing period, $\forall t \in \{1,2,\ldots,Tm\}$, and $\forall p \in \{1,2,\ldots,P\}$, where Tm is a number of billing intervals in a billing period.

The sellers' revenues and buyers' savings can be calculated in each interval t based on the local energy sharing price π_t^l, and proportional allocation of quantities of energy shared between the prosumers. The calculation of revenue of each seller, in comparison with the case without LES, is defined in Equation (23), while the calculation of cost-savings of individual buying peers is defined in Equation (24).

$$S_{t,p}^{l,s} = \begin{cases} 0, \ EMRm_t \geq 1 \\ \left(\pi_t^l - \pi_t^{g,s}\right) \cdot X_{t,p}, \ 0 < EMRu_t < 1 \\ 0, \ EMRm_t = 0 \end{cases} \tag{23}$$

$$S_{t,p}^{l,b} = \begin{cases} \left(\pi_t^{g,b} - \pi_t^l\right) \cdot M_{t,p}, \ EMRm_t \geq 1 \\ \left(\pi_t^{g,b} - \pi_t^l\right) \cdot EMRm_t \cdot M_{t,p}, \ 0 \leq EMRm_t \leq 1 \\ 0, \ EMRm_t = 0 \end{cases} \tag{24}$$

3.3. Assessment of effects on market participants

To assess the effects of LES on the market participants, their revenues and/or costs are calculated and compared for different scenarios. The importance of dynamic simulation compared to static allocation of produced energy in ECs was analyzed by Fina et al. [70]. It was shown that dynamic simulation more precisely determines the share of local energy consumption of an EC with PVs, and therefore economic attractiveness of an EC. With the inclusion of BESS, the importance of dynamic simulation over the yearly horizon further increases. Therefore, we simulate the operation dynamically and with yearly horizon. In Equations 25–29 the revenues for TSO, DSO, RES levies, taxes, and suppliers are defined, respectively. In Equation (30) the costs for energy trading for each prosumer are defined, and in Equation (31) the levelized costs of energy consumed are defined for each prosumer. Revenues for market participants greatly depend on a regulatory framework, and the equations are defined taking into account the existing billing principles in Croatia.

$$R_T^{TSO} = \sum_{t=1}^{T} \sum_{p=1}^{P} \left(\lambda_t^{trans} \cdot E_{t,p}^{g,b}\right) \tag{25}$$

$$R_T^{DSO} = \sum_{t=1}^{T} \sum_{p=1}^{P} \left(\lambda_t^{dist} \cdot \left(E_{t,p}^{g,b} + E_{t,p}^{l,b}\right)\right) \tag{26}$$

$$R_T^{RES} = \sum_{t=1}^{T} \sum_{p=1}^{P} \left(\lambda_t^{RES} \cdot E_{t,p}^{g,b}\right) \tag{27}$$

$$R_T^{SUP} = \sum_{t=1}^{T} \sum_{p=1}^{P} \left(E_{t,p}^{g,b} \cdot \pi_t^{g,b} - E_{t,p}^{g,s} \cdot \pi_t^{g,s}\right) \tag{28}$$

$$R_T^{TAX} = \left(1 + \lambda_t^{TAX}\right) \cdot \left(R_T^{TSO} + R_T^{DSO} + R_T^{RES} + R_T^{SUP}\right) \tag{29}$$

$$CT_T^p = \sum_{t=1}^{T} \left(E_{t,p}^{g,b} \cdot \pi_t^{g,b} + E_{t,p}^{l,b} \cdot \pi_t^{l,b} - E_{t,p}^{g,s} \cdot \pi_t^{g,s} - E_{t,p}^{l,s} \cdot \pi_t^{l,s}\right) \tag{30}$$

$$LCOE_T^p = \frac{\sum_{a=1}^{A}\left(CI_p^{a,T} \cdot CRF^{a,T} + CF_p^{a,T} + COM_p^{a,T}\right)}{\sum_{t=1}^{T} \mathrm{D}_{t,p}} + \frac{\sum_{t=1}^{T}\left(E_{t,p}^{g,b} \cdot \pi_t^{g,b} + E_{t,p}^{l,b} \cdot \pi_t^{l} - E_{t,p}^{g,s} \cdot \pi_t^{g,s} - E_{t,p}^{l,s} \cdot \pi_t^{l}\right)}{\sum_{t=1}^{T} \mathrm{D}_{t,p}} \tag{31}$$

Where R_T^{TSO} are the revenues of the transmission system operator over the observed time horizon, and for the case where the unit fee for transmission equals λ_t^{trans}. R_T^{DSO} are the revenues of the distribution system operator over the observed time horizon, and for the case where unit fee equals λ_t^{dist}. R_T^{RES} are the revenues collected based on the RES levy over the observed time horizon, and for the case where unit fee equals λ_t^{RES}. R_T^{SUP} are the revenues of the suppliers over the observed time horizon. R_T^{TAX} are the revenues collected based on the tax over the observed time horizon, and for the case where unit percentage equals λ_t^{TAX}. CT_T^p are the energy trading costs of the individual peer p over the observed time horizon. $LCOE_T^p$ is the levelized costs of the energy consumed for each individual peer p in time horizon. For the listed items, $\forall t \in \{1,2,\ldots,T\}$. $CI_p^{a,T}$ are investment costs in each technology a $\forall a \in \{1,2,\ldots,A\}$, and $CRF^{a,T}$ is a capital recovery factor that equals $\frac{(1+k)^{T^a} \cdot k}{(1+k)^{T^a}-1}$, used for annualizing the investment costs in the lifetime of the investment (T^a) considering the weighted average cost of capital (k). $CF_p^{a,T}$ is the fuel cost over the observed time horizon that equals $\sum_{t=1}^{T} CF_p^{a,t}$ and $CF_p^{a,t}$ is the fuel cost in time interval t, $\forall t \in \{1,2,\ldots,T\}$, $COM_p^{a,T}$ is the operation and maintenance cost in time interval t, $\forall t \in \{1,2,\ldots,T\}$, $\mathrm{D}_{t,p}$ is the energy demand over the observed time horizon and for $\forall t \in \{1,2,\ldots,T\}$. Here, due to the seasonal nature of supply and demand and impacts on indicators, the observed period T should represent the number of intervals in one year.

4. Case study

The case study is conducted on the example of the city of Križevci in Croatia. It consists of public buildings in an urban area in the city of Križevci, it is also a pilot site under COMPILE project [71]. The goal at the site is to create new value through the co-optimization of existing and new technologies. Artificial intelligence (AI) and advanced forecasting tools plan to be tested to improve technical performance leading to increased economic benefit and profitability of the business model, which will be the first of a kind application. That way, by connecting different technologies, it will be possible to apply innovative sharing economy concepts among the site's location. For the case study, three scenarios with different regulatory setups are analyzed and impacts on different market participants assessed.

4.1. Energy infrastructure at the site's locations

The pilot site is focused on public buildings – a technology park (hereinafter Tech Park), a public library (hereinafter Library), and a kindergarten (hereinafter Kindergarten). The electricity demand patterns at the site's locations are shown in Fig. 3. Tech Park is hosting around 30 firms ranging from IT start-ups to chemical companies, which are housed in office buildings and halls (Fig. 4). The demand shown in Fig. 3 is from the energy meter of the office building. The consumption measured at the Tech Park is characterized by the spikes in energy demand mostly due to the HVAC systems that use heat pumps. The energy demand mostly goes up to 50 kWh/h, while some peaks reach up to about 70 kWh/h. On low-consumption (non-working) days the demand reaches just up to 10 kWh/h. Energy consumption in Kindergarten and Library have mutually similar patterns that are characterized by the weakly schedule where demand is significantly lower during Saturday and Sunday since objects do not work on those days. The hourly energy demand at both objects typically reaches up to about 15–20 kWh/h on workdays, while during weekends or night the consumption is typically below 5 kWh/h. At present, the subjects have the same energy supplier, but application of the methodology allows possibility of change of suppliers in the future.

The locations of Tech Park and Library have been equipped with solar PV systems of 30 kW each, with an expected yearly production of up to about 39 MWh each [72]. The PV system at the Tech Park office building was the first Croatian citizen crowd funded PV plant, built in 2018 through a crowdfunding platform [73]. A PV system on Library rooftop was installed in 2019. Moreover, a BESS of installed capacity of 19.2 kWh, and an EV charger were installed at the location of Tech Park in 2020. The BESS is installed 'behind the meter' of the office building in Tech Park.

Based on the real-life and literature [69,74] costs, the case-study prices for technologies are set as follows: specific investment costs for solar PV systems are set at 1.100 EUR/kW, specific annual operative costs at 22 EUR/kW, and lifetime at 25 years. The specific investment cost of BESS is set at 550 EUR/kWh and 200 EUR/kW, specific annual operative costs at 8.74 EUR/kWh, and a lifetime of 10 years. In practice, the costs have shown a good correlation with literature assessment for solar PV systems, especially for the system installed in 2019 on Library, while the system on Tech Park was slightly more expensive due to the higher costs and earlier stage in the market development in 2018. On the other hand, the costs of the BESS were somewhat at the high end compared to the literature examples. This is due to the fact that the market for building-integrated BESSs is in a very early stage of development in Croatia, unlike the already established and growing solar PV market.

4.2. Distribution grid

All objects are connected to the utility distribution grid and are located in a diameter of 500 m. A birds-eye view of the locations and network topology is shown in Fig. 4, while the additional network and communication scheme is shown in Fig. 5. The MV voltage grid is supplied from the three-winding 110/35/10 kV transformer, and this part of the city is supplied with the 10 kV lines. The LV distribution feeders are radial at the voltage level of 0.4 kV (phase-to-phase) and a base frequency of 50 Hz, which is typical for the European low voltage distribution systems. It has to be noticed that Tech Park is connected to a separate TS 10/0.4 kV transformer, while the Library and the Kindergarten are connected to the same TS 10/0.4 kV transformer. This is important due to the fact that regulatory provisions for ECs and LET or LES in some countries can recognize them only in cases where prosumers (sharing nodes) are supplied from the same MV/LV substation (in that case a similarity with microgrids with standard connection to the upstream grid via point of common coupling can be observed), while in other countries they are recognized depending on the proximity or other conditions [20].

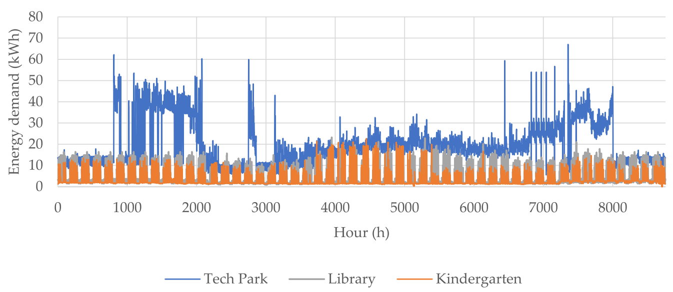


Fig. 3. Electricity demand at the site's locations.

4.3. Metering and communication infrastructure at the site's locations

In Croatia, the DSO is tasked with metering infrastructure and provides metering services to all energy suppliers. In the process of planning and installation of ICT equipment for monitoring and control of the battery, initial idea was to utilize the relevant data from the DSO's smart meters to monitor the energy exchange with the grid. To reach the DSO data, there are two options – capturing the data directly from the meter, or accessing it from the centralized DSO database after it has been read by the DSO. However, only some of the meters support the use of a serial user-facing port at the meter itself. The DSO also does not currently make available the readout of the device language message specification (DLMS) interface to the end-users. Furthermore, the meter itself is owned by the DSO and even for a meter that has the serial user port, the option must be enabled in the meter and no power is available for additional equipment in the measuring cabinet. Also, the cabinet is often located at the edge of the land, so an additional communication cable connection (or wireless system) to the user's premises is needed in order to process the serial port data. Finally, the data from the DSO's central database is usually refreshed once daily after the meter register readout is performed, so it is not suitable for near real-time management of the community.

For these reasons, it was decided that a separate metering infrastructure is required. The additional meters at users' premises have been installed and they were connected to an instance of a SCADA system. For one of the meters, its initial location required notifying the DSO to reach the meter, and for that location, a robust but comparatively more expensive approach has been selected for reading of the optical impulse readout from the meter - an industrial-class remote terminal unit (RTU) device that relays the data to the SCADA computer. The finally implemented metering and communication system consists of meters connected to an instance of a SCADA system. The SCADA reads out the data from the meters, the RTU, and the data from inverters, which makes the necessary data available in near real-time and can be used for forecasting and optimization of operation of BESS. The scheme of the power lines and communication infrastructure is depicted in Fig. 5. Therefore, the following data is being collected:

- Tech Park: energy production and other measurements at the solar system inverter, charging, discharging and other measurements at the BESS's inverter, power load at the location's main switchboard.
- Kindergarten: power load at the location's main switchboard.
- Library: energy production and other measurements at the solar system inverter, power load at the location's main switchboard.

Fig. 4. Location with a principal scheme of the network topology.

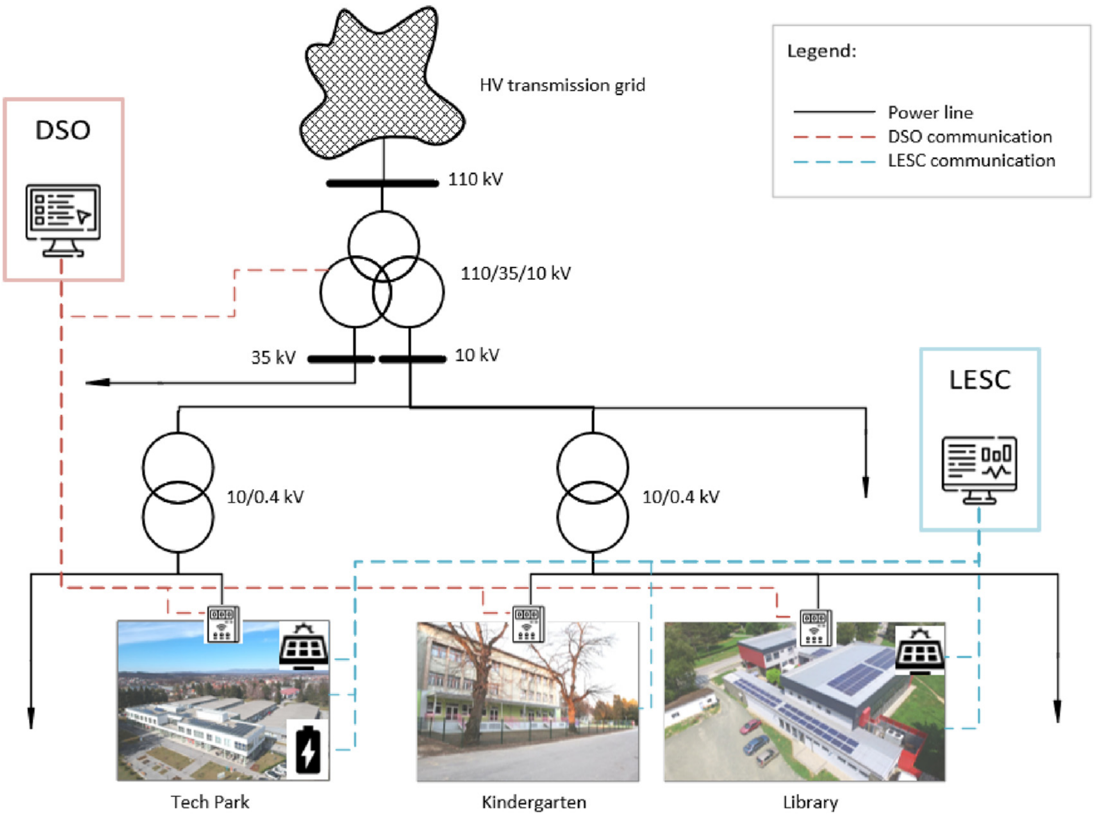


Fig. 5. Model of the network feeder.

4.4. Applicable legislative framework

In Croatia, the Law on Renewable Energy Sources and High-efficiency Cogeneration [75] defines type of individual net-metering scheme for prosumers in households' sector, and a net-billing scheme for business sector. An additional correction factors are applied based on the ratio of energy exported and imported. In this case study, we analyze application of LES for the business sector and therefore the scheme is defined in Equation (32).

$$\pi_t^{g,s} = \begin{cases} \overline{c}_m^g \cdot 0.9, & \sum_{t=1}^{Tm} E_{t,p}^{g,b} \geq \sum_{t=1}^{Tm} E_{t,p}^{g,s} \\ \overline{c}_m^g \cdot 0.9 \cdot \frac{\sum_{t=1}^{Tm} E_{t,p}^{g,b}}{\sum_{t=1}^{Tm} E_{t,p}^{g,s}}, & \sum_{t=1}^{Tm} E_{t,p}^{g,b} < \sum_{t=1}^{Tm} E_{t,p}^{g,s} \end{cases} \quad (32)$$

Where $\overline{c}_t^g$ is the average electricity price that a user pays to his supplier, without any contributions and taxes for that category, in the accounting period of one month. $E_t^{g,b}$ is the energy bought from the grid in hour t, $E_t^{g,b}$ is the energy sold to the grid t, $\forall t \in \{1, 2, \ldots, Tm\}$, and Tm is the number of hours in a month. In the case of oversizing solar PV, which would lead to more exports than imports from the grid, the price for exporting decreases due to the applied factor that is the ratio of energy imported and exported to the grid in the accounting period of one month. In the above-mentioned law, local energy sharing, or trading is not foreseen. However, the Law on Electricity Market [31] defines and foresees additional provisions for citizen energy communities in Croatia, allowing local energy sharing, under which network charges to DSO still have to be paid. Members of the community can define the energy and cost-sharing formula between the members and deliver it to the DSO, who is then responsible for the integration of it in electricity bills. The idea behind this provision is to encourage local energy sharing but without depriving system operators of their fair fees for grid operation. Further, it is specified that members have to be on the same LV feeder, i.e., behind the same 10(20)/0.4 kV transformer. By-laws are yet to be adopted on operational aspects.

Some countries opted for an approach where energy sharing is not limited behind the one 10(20)/0.4 kV transformer but can be conducted over a distribution network either in the proximity of 500 m or without similar limitation [16]. Out of those two approaches, both have pros and cons. The advantages of allowing energy sharing within EC just behind the same 10(20)/0.4 kV substation (similar to the case of the microgrid) are in easier control of power flows and voltages on the same radial LV distribution feeder. Also, the implementation of control and energy management mechanisms is more straightforward. On the other hand, the drawbacks are in the facts that local energy sharing within the same 10(20)/0.4 kV substation can provide limited scope as usually not many bigger consumers are located on the same 10(20)/0.4 kV substation, and electrical lines don't follow administrative/living areas or neighborhoods. The advantages of allowing energy sharing also on the MV distribution grid in a certain (similar to the case of the virtual power plants) are in the fact that more subjects can be incentivized to invest in local generation and energy management systems. However, from the system perspective, that could lead to significant challenges as the MV distribution network could have different supply directions, and improvement of local supply-demand balancing without considering the local grid infrastructure could even lead to increased voltage fluctuations and power/energy disbalances.

4.5. Modelling scenarios and cases

The analyzed scenarios are listed in Table 3. The scenarios are differentiated considering the legislative concept of how the subjects appear on the market. In scenario S0, the existing situation is represented, where each peer appears individually under the existing net-billing scheme in Croatia. In scenario S1, it is assumed that the Library and Kindergarten form an EC – it is a scenario in line with the proposed legislative concept in Croatia, under which energy community members have to be behind the same 10(20)/0.4 kV transformer. Scenario S2 goes further and assumes that energy sharing is allowed also over the MV grid, meaning all three subjects could take part in EC and share energy locally, which is an approach some EU countries have taken already [16]. Scenarios S1 and S2 are further differentiated by cases, considering different LES price forming methods.

A general formulation of the optimization problem was defined in Equation (1), while the specific costs are shown in Table 4, where c_t^g is the cost of energy imported from the grid (supplier) in time interval t for peer p, λ^{dist} is a distribution fee, λ^{trans} is a transmission fee, λ^{sur} is the unit cost of surcharges (e.g., RES surcharge), λ^{tax} is the tax on electricity (e.g. value-added tax) in percentage points. Application of those costs in Equation (1) allows modeling of different regulatory setups (scenarios) as listed in Table 1. Network charges are volumetric-based in Croatia. Here it is foreseen that distribution system charges and related VAT will have to be paid for local energy shared, but no RES levies or TSO charges.

The input data on prices and fees are taken from a real-life example in Croatia for a two-tariff model as shown in Table 5. Used conversion rate is 7.53 HRK/EUR.

Table 3
Analyzed scenarios.

Scenario	Case	Legislative concept	Market appearance of the peers			Sharing price forming method
			Tech Park	Library	Kinder-garten	
S0		Individual net billing	Solo	Solo	Solo	/
S1	_MMR	Sharing allowed for peers behind the same MV/LV substation	Solo	EC	EC	MMR
	_EMRu					EMRu
	_EMRm					EMRm
S2	_MMR	Sharing allowed over local distribution network (e.g., in a radius of 500 m)	EC	EC	EC	MMR
	_EMRu					EMRu
	_EMRm					EMRm

Table 4
Application of regulatory framework to modelling aspects.

Case	$\pi_t^{g,s}$	$\pi_t^{g,b}$	$C_t^{l,b}$
Individual net billing	$c_{t,p}^g \cdot 0.9$	$(c_{t,p}^g + \lambda^{dist} + \lambda^{trans} + \lambda^{sur}) \cdot (1 + \lambda^{tax})$	N/A
Individual net billing and LET tariff within EnC	$c_{t,p}^g \cdot 0.9$	$(c_{t,p}^g + \lambda^{dist} + \lambda^{trans} + \lambda^{sur}) \cdot (1 + \lambda^{tax})$	$\lambda^{dist} \cdot (1 + \lambda^{tax})$

Table 5
Application of regulatory framework to modelling aspects.

Item	High (day) tariff	Low (night) tariff	Ref.
$c^{g}_{t,p}$ (EUR/kWh)	0.062	0.030	[76]
$\lambda^{dist,b}$ (EUR/kWh)	0.032	0.016	[77]
$\lambda^{trans,b}$ (EUR/kWh)	0.015	0.007	[77]
$\lambda^{sur,b}$ (EUR/kWh)	0.013	0.013	[78]
$\lambda^{tax,b}$ (%)	13%	13%	[76]

5. Results and discussion

The time horizon of the case study is one year, and the interval of the LES is assumed as 1 h. The results are divided on effects on dispatch and power balance, and effects on economic indicators for participating parties.

5.1. Effects on economic dispatch and power balance

In Fig. 6 the summary power balance for the subjects is shown over the last week in May (22nd week in a year). It is evident that in scenarios S0 and S1 (Fig. 6a and b, respectively) there are hours when imports from and exports to the upstream grid appear at the same time. It is due to the fact that not all prosumers are members of the EC, meaning no LES is allowed, despite the fact that physical power flows can be closed locally over the distribution grid. In scenario S2 (Fig. 6c) this phenomenon is eliminated and LES maximized in order to minimize the costs for the prosumers. Further, it can be observed that the operation of the BESS is modified in each scenario, as optimal cooperative scheduling under the LES scheme leads to differences in the timing of the charging and discharging patterns to minimize the EC's operating costs. For further understanding, the detailed power balance of individual prosumers for the same week is shown in Figure A1 in Appendix A.

In Table 6 and Fig. 7, the cumulative energy balance over the observed time horizon of one year is shown for each prosumer and in total, in absolute and relative terms, respectively. Tech Park is the largest consumer with about 175,000 kWh/year, which is more than Kindergarten (31,538 kWh/year) and Library (41,953 kWh/year) combined. Kindergarten has no production, while solar PV systems at Tech Park and Library are expected to produce approximately the same energy of about 39,000 kWh/year. In relative terms, due to the relatively small capacity in comparison to demand, the energy produced in Tech Park is almost exclusively consumed on-site, which is further increased using the BESS. In scenarios S0 and S1, the demand at Tech Park is 22% met from local production and 78% from upstream energy imports, while only 1% energy (compared to demand) is exported to the upstream grid.

In scenario S2 (where Tech Park is also a member of the EC), the upstream energy imports decrease by 3% points in favor of local energy exchange, while 1% of the energy is again exported upstream. Kindergarten site has no production and therefore in scenario S0, it imports 100% of energy from the upstream grid, while in S1 and S2 scenarios that percentage drop to 76% and 79% respectively in favor of local imports. The share in scenario S2 decrease in comparison with the S1 scenario due to the fact that in scenario S2 surpluses from the Library are shared among the Tech Park also, not just with the Kindergarten. PV power system on Library is sized in a way that satisfies about 51% of on-site consumption, while the rest is exported to the upstream grid (scenario S0), or locally and upstream grid (scenarios S1 and S2). In total, community self-sufficiency reaches the maximum of 29% in scenario S2 (Fig. 7), where self-consumption and local energy shared are summarized.

It should be noted that economic dispatch is conducted in the first stage based on the value of external prices and fees, and does not depend on the LES price-forming method, which is done ex-post in the second stage.

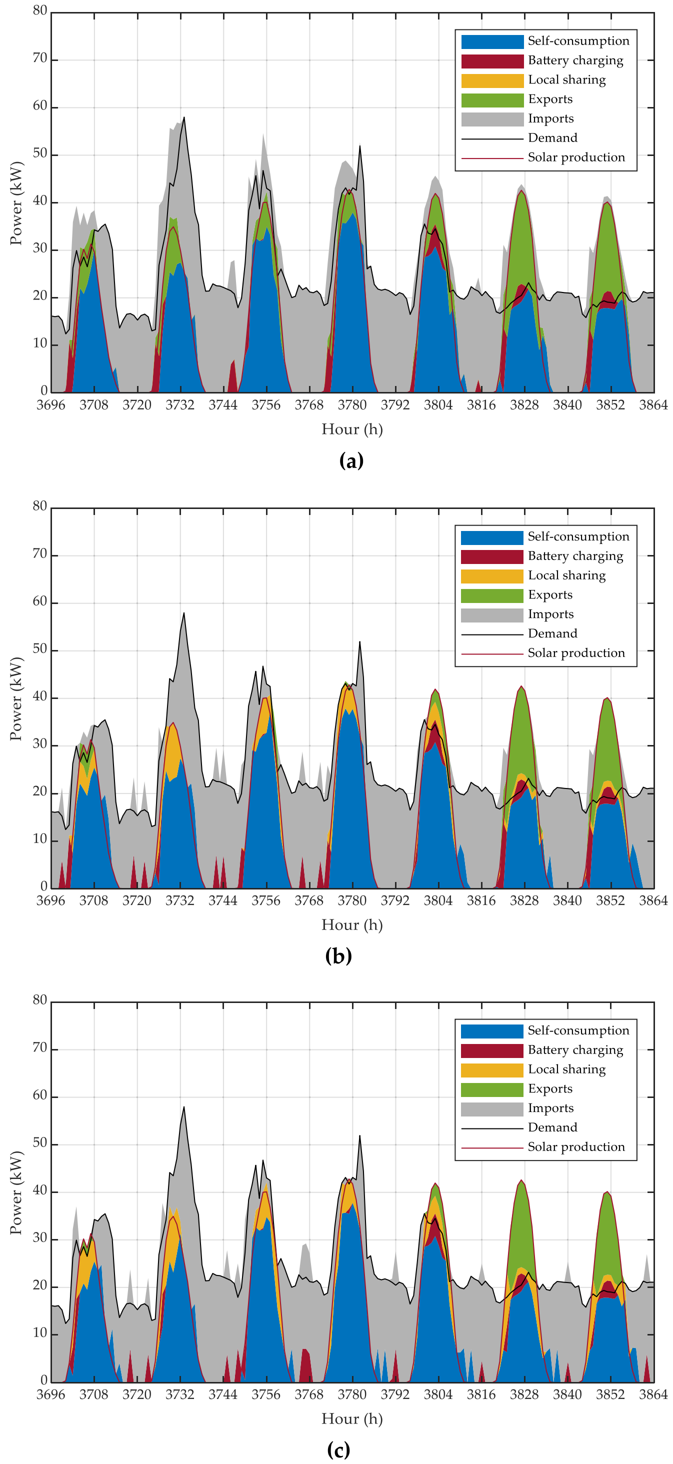


Fig. 6. Summary power balance for the subjects on last week in May (22nd week in a year) in the following scenarios: (a) scenario S0; (b) scenario S1; (c) scenario S2.

5.2. Effects on economic indicators for the parties

The LES prices, calculated in accordance with the presented MMR, EMRu, and EMRm methods, are shown in Fig. 8 over the last

Table 6
Cumulative energy balance over one year in scenarios and participants.

Item	Scenario	Tech Park	Kindergarten	Library	Total
Energy demand (kWh)	All	174,360	31,538	41,953	247,852
Production (kWh)	All	39,076	0	38,640	77,716
Self-consumption (kWh)	S0	37,667	0	21,589	59,256
	S1	37,667	0	21,589	59,256
	S2	37,270	0	21,589	58,860
Community energy imports (kWh)	S0	0	0	0	0
	S1	0	7467	0	7467
	S2	5650	6656	18	12,324
Community energy exports (kWh)	S0	0	0	0	0
	S1	0	0	7467	7467
	S2	538	0	11,787	12,324
Upstream energy imports (kWh)	S0	136,694	31,538	20,364	188,596
	S1	136,694	24,070	20,364	181,128
	S2	131,483	24,882	20,346	176,710
Upstream energy exports (kWh)	S0	1409	0	17,050	18,459
	S1	1409	0	9583	10,992
	S2	1268	0	5264	6531

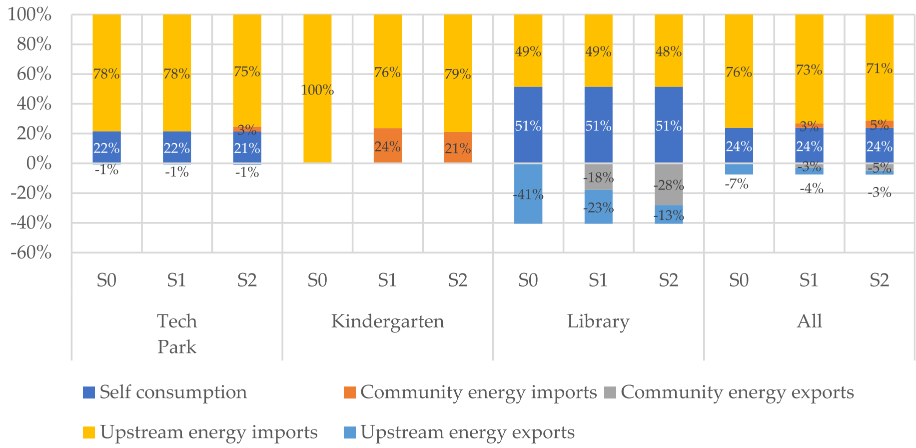
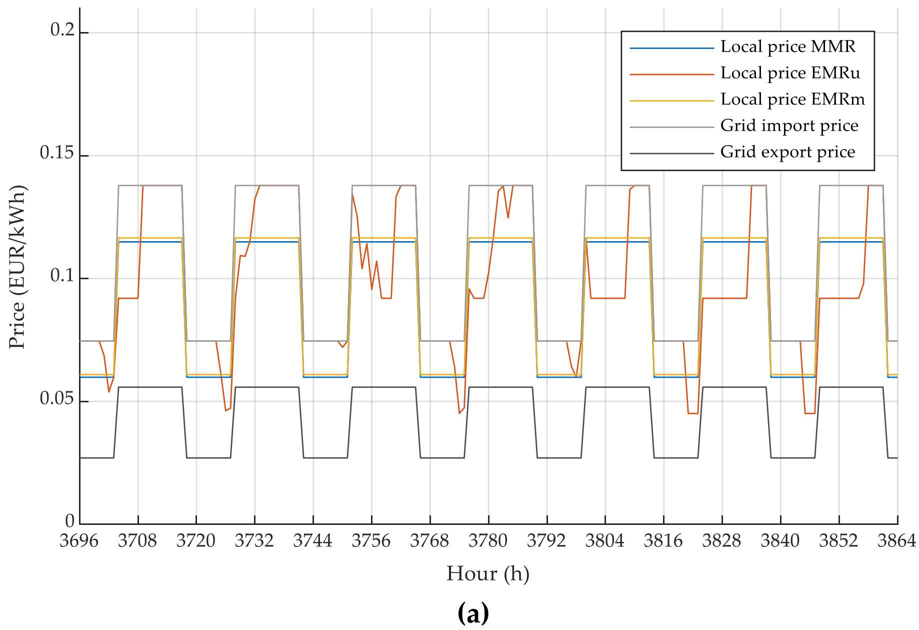


Fig. 7. Cumulative energy balance over one year for scenarios and participants, shown as a percentage of individual demand.

week in May (22nd week in a year), for scenarios S1 and S2. Further, in Fig. 9, average monthly prices are shown for the observed scenarios and cases. In scenario S0 there is no LES and therefore no local price is formed. The formation of the local price is a consequence of the number of peers in the EC, dispatch of flexibility options, and relation of excess and missing energy. In cases EMRu and EMRm, the LES prices range between the upstream import and export prices, and are inversely proportional to EMR, either on billing interval (EMRu), or billing period (EMRm). In MMR case, LES prices are midpoint between $\pi^{g,b}_{t,p}$ and $\pi^{g,s}_{t,p}$ increased by $C^{l,b}_{t}$. The inclusion of additional subjects with supply-demand patterns that lead to better local supply-demand balancing within the EC consequently leads to sharing of the benefits. Here, the inclusion of the Tech Park in the EC in scenario S2 leads to higher demand and higher LES price, which goes in favor of Library, as it receives higher income for the surpluses in cases where the price is formed based on EMRu and EMRm. In contrast, Kindergarten in S2 cannot receive all available surpluses when needed (Fig. 6c), and, on average, pays a higher price for the local energy imports in S2 scenario than in S1 scenario (Fig. 8b). The results in Fig. 9 show that LES price-forming based on MMR leads to the smallest oscillations across the months, however, even here the price is not fixed as there are two tariffs under which energy can be exchanged. This could further vary with the more advanced pricing in the future, such as dynamic tariffs.

The effects on net revenues or costs of the participating parties are shown in Table 7, and the unit revenues per energy transmitted/distributed are shown in Fig. 10. On the revenue side, the biggest impacts of the regulatory provisions are seen for the TSO, surcharges and taxes. The inclusion of all subjects in EC (scenario S2) reduces TSO's revenue and unit revenue per energy transmitted by 8.2% when compared with the individual net billing scheme (scenario S0). However, it should be noted that reduction comes as the consequence of the fact that energy shared locally doesn't have to be transmitted, as power flows can be met locally in the distribution network. As a result, the technical losses in the network are reduced too. Therefore, the LES provision encourages local self-sufficiency. At the same time, the mechanism should not be equated with the schemes such as net-metering, which raise significant concerns over the ‘utility death spiral’ [34,79]. The LES within an EC encourages local supply-demand balancing which is not the case with the net-metering scheme. Further, under the LES scheme within an EC, there are no changes in unit revenues per energy distributed for the DSO (Fig. 10), as the scheme defines that DSO fee has to be paid when distribution grid is used, and total revenue can even increase when LES is maximized (Table 7). The effects on the surcharges and tax revenues depend on whether those fees are charged for energy shared locally. In this case, it is modeled that taxes will be charged on distribution fees and no surcharges will be applied on energy shared locally within the EC. Therefore, those revenues decrease.



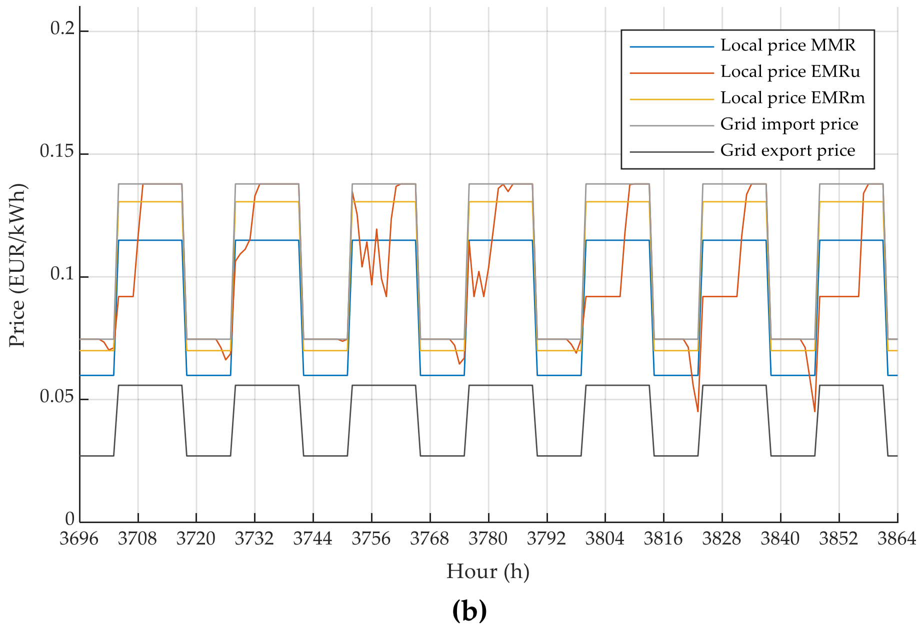


Fig. 8. Hourly local energy sharing prices on last week in May (22nd week in a year) for different price-forming methods and in the following scenarios: (a) scenario S1; (b) scenario S2.

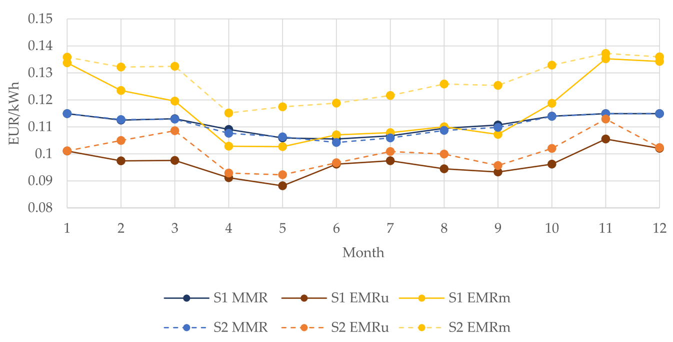


Fig. 9. Average monthly local energy sharing prices over the year for different price-forming methods and in the modeled scenarios.

From the perspective of the net costs for the prosumers, the implementation of EC proves to be favorable for all members (Table 7). However, the effects on the net costs vary across the scenarios and cases, which is evident in Table 7 and Fig. 11, where differences of net costs are shown in Scenario S0. Here several insights can be highlighted: individually, Kindergarten has the lower costs in scenario S1 (in the range from 145 to 273 EUR/year) than in scenario S2 (in the range from 44 to 224 EUR/year), when the same cases are compared. It is due to the fact that in scenario S1 all available surpluses from the Library can be used in Kindergarten, while in scenario S2 they are shared also with the Tech Park, which led to increased LES prices (Fig. 9) and distribution of benefits across more subjects (Figure A1). Next, there are no savings for Tech Park in scenario S1, as it does not participate in the EC, and the

Table 7
Cumulative net costs and revenues for the market participants over the observed period of one year.

Scenario	Case	Net revenues (EUR)						Net costs (EUR)			
		Supplier	TSO	DSO	Surcharges	Tax	Total	Tech Park	Kindergarten	Library	Total
S0		7791	2102	4582	2452	2330	19,256	14,124	3765	1367	19,256
S1	_MMR	7747	1996	4582	2355	2246	18,925	14,124	3599	1201	18,925
	_EMRu							14,124	3492	1309	
	_EMRm							14,124	3620	1181	
S2	_MMR	7711	1930	4590	2297	2196	18,724	14,003	3616	1106	18,724
	_EMRu							13,968	3541	1216	
	_EMRm							14,087	3721	917	

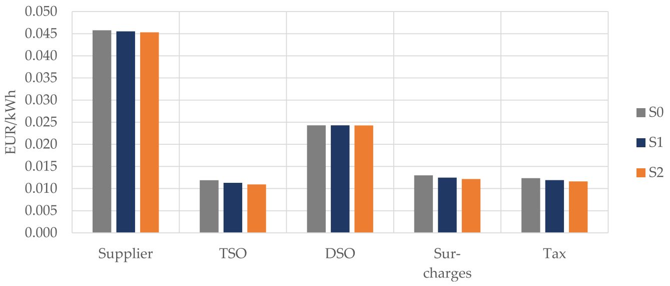


Fig. 10. Unit revenues for market participants.

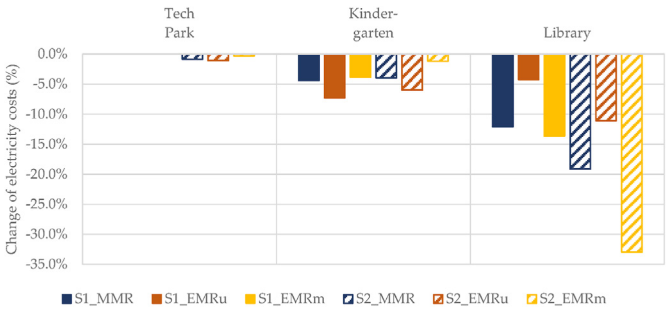


Fig. 11. Change of yearly net costs for the subjects in comparison with S0 scenario.

Table 8
Levelized cost of energy consumed for the prosumers in EUR/kWh.

Scenario	Case	Tech Park	Kinder-garten	Library	Total
S0		0.1063	0.1194	0.0987	0.1067
S1	_MMR	0.1063	0.1141	0.0947	0.1054
	_EMRu	0.1063	0.1107	0.0973	
	_EMRm	0.1063	0.1148	0.0942	
S2	_MMR	0.1056	0.1147	0.0924	0.1045
	_EMRu	0.1054	0.1123	0.0951	
	_EMRm	0.1061	0.1180	0.0879	

effects on Tech Park are the smallest both in relative terms (due to the highest consumption) and absolute terms (in range of 38–157 EUR/year) because own production often appearing in same intervals as surpluses from Library). BESS increases the self-consumption rate for the Tech Park and the optimal operation of the BESS changes with the inclusion of Tech Park in the EC (Figure A1) with an aim to decrease the costs in the objective function (Equation (1)). Library can achieve costs-savings from 58 to 186 EUR/year in S1 scenario and from 151 to 450 EUR/year in S2 scenario, depending on the cost-forming method (Table 7). Considering the different LES price-forming cases, EMRu favors the net buyers (primarily Kindergarten), while EMRm favors sellers, (primarily Library). MMR method reflects the central approach and could be the most simple and transparent approach to start with.

To evaluate the effects on prosumers considering the costs of investment and maintenance of equipment, the levelized cost of energy consumed $LCOE_T^p$ is calculated for each subject based on Equation (31) and shown in Table 8 and Fig. 12. In total, the prosumers benefit from the new regulatory provision and participation in EC as the total costs decrease from 0.1067 EUR/kWh in scenario S0 to 0.1045 EUR/kWh in scenario S2, or by 2.0%. On the individual level in S0 scenario, it is evident that Kindergarten has the highest $LCOE_T^p$, due to the fact that it has no solar PV installed, while solar PV systems decrease costs in Library and Tech Park. The combination of increased investment costs in BESS and a smaller share of energy from the solar PV in demand led to higher $LCOE_T^p$ in Tech Park then Library by 7.8%. In scenario S1, $LCOE_T^p$ for Kindergarten decreased by 3.8%–7.3% in comparison with S0 scenario, depending on the price-forming method, which is less than in S2 scenario it decreased by 1.6–6.0%. This trend is due to the fact that in S1 scenario Kindergarten can use all surpluses from Library, while in S2 scenario surpluses are shared also with the Tech Park. Tech Park records middle $LCOE_T^p$, and the changes between the scenarios are the smallest due to the fact that it uses almost all PV on-site and only in scenario S2 it is a member of the EC. The $LCOE_T^p$ of Library is the smallest as it gets most of the energy from the on-site solar PVs, and the costs further decrease as the subject is allowed to share energy locally for the price that is above the upstream buy-out price. Application of EMRm method in S2 scenario led to decrease of $LCOE_T^p$ for Library by 10.9%. When the MMR method is applied, the decrease of $LCOE_T^p$ equals 4.0% in S1 scenario and 6.3% in S2 scenario in comparison with S0 scenario (Table 8).

In scenario S1 the sharing could be conducted between Library and Kindergarten just based on the complementary supply-demand patterns of the members and no additional ICT infrastructure is needed besides the smart meters for billing. However, if the optimal operation of flexibility options is included, such as in S2 scenario, where the optimal operation of BESS is modeled for EC - forecasting of supply and demand is required. These further increases if additional flexibility and smart home options are included. This requires additional investments in ICT infrastructure. In this particular case, the equipment was partly financed through the research project [71] and the costs cannot be considered as a

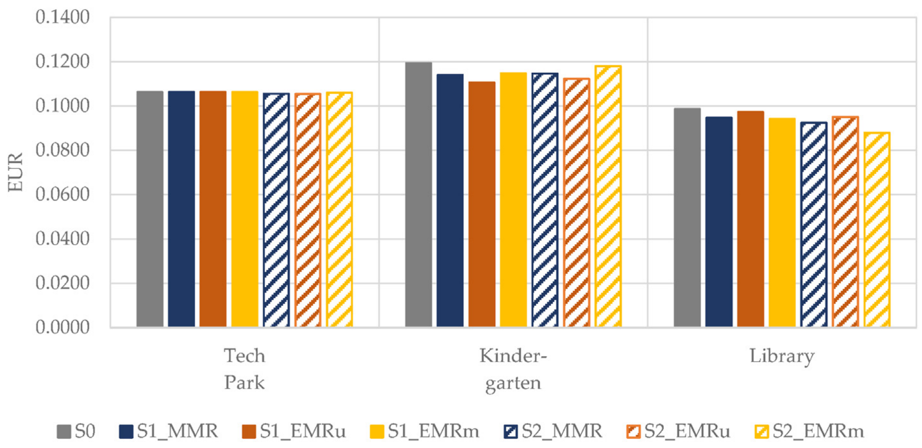


Fig. 12. Levelized cost of energy consumed for the subjects.

future commercial standard. Also, the peers were not charged for the cost. The market for smart home appliances and a "software-as-a-service" solutions for BESSs and ECs is emerging [80], and costs of that equipment will be subject to future development. From the perspective of business models, different options are possible [81], in case of community investment in ICT infrastructure, community members could invest or contract the service with a party LESC, whose costs can be included in investment costs and/or reimbursed through sharing fees. Due to the importance and challenges in forecasting production and consumption for small prosumers, continuation of research and policy incentives could be valuable in this area.

6. Conclusions

In the paper, it is shown that economic feasibility and achievement of possible benefits of local energy trading or sharing greatly depend on the regulatory framework. It is shown that advanced provisions, like adjustment of tariffs, levies, and taxes for LES, can lead to the increased economic attractiveness of LES for the members. At the same time, reduced revenues for market participants based on transmission fees, taxes, and surcharges can happen, subject to specifics of the regulatory framework. However, well-designed regulatory provisions can have positive impacts on the energy balances and optimization of the operation of the distribution system, and consequently, possibly decrease the need for investment in the transmission grid. Therefore, adjustment of network tariffs for LES could be a fair approach from the system's point of view. Future regulatory landscape could consist of different solutions with a view to ensure adequate expansion and maintenance of the network assets as well as to incentivize flexibility and local optimization together with the system flexibility markets. This idea goes well with emerging research proposing coexistence of flat-rate tariffs and advanced methods, such as time-of-use tariffs, LES tariffs, or marginal nodal pricing [82].

The case study analyzed a real-life definition of citizen EC and scenario that allows LES within a citizen EC, but just behind the same 10(20)/0.4 kV substation (scenario S1), such as in Croatia. Further, the scenario where local energy sharing is allowed in a distribution grid within an area of at least 500 m is analyzed (scenario S2), based on the set-ups in some other EU countries [16]. The approaches are compared with the initial scenario (scenario S0), where each subject appears individually on the market. All things considered, regulatory provisions that allow local energy sharing in energy communities behind the same 10(20)/0.4 kV substation appear like a sound first step towards the more legislatively and technically advanced models that would support local energy trading also over MV distribution grid in the future. In this process, possible operational changes of distribution grid topology should be considered when regulating LES.

For the implementation of optimal cooperative scheduling of the flexibility options within an energy community, investments in further ICT and smart home infrastructure and forecasting should be foreseen and implemented. However, it is not a prerequisite for the establishment of an EC and LES, especially where no flexibility options and smart home appliances are included, and third party (such as DSO) can administer LES. One of the indirect findings is that establishing a suitable metering and effective information-exchange infrastructure is quite challenging. The DSO establishing its data offers in a more robust fashion for relevant market participants could become one of the key enablers for agile and cost-effective local communities in the coming years.

The analysis of different LES price-forming methods showed that even though all members benefit from participating in the EC, effects on the distribution of benefits across the members are significantly different, subject to price-forming method. In the cases where the excess-missing method was applied in each interval (EMRu) most of the benefits were accounted to the net buyers (primarily Kindergarten). On the other hand, in the cases where the excess-missing ratio was applied over the billing period (EMRm), sellers reaped most of the benefits (primarily Library). Mid-market rate (MMR) proved to be a middle-of-the-road approach and could be the easiest and most transparent approach to start with in emerging ECs.

For future work, the inclusion of additional public buildings, flexibility options, and multi-energy vectors could be studied [69]. Further, implementation of local energy trading based on a game theory [83], as well as control of voltages and system dynamics with local energy trading is foreseen both in laboratory small-scale microgrid and in real-life community microgrid in the scope of IMPACT [5] and COMPILE [71] projects. Moreover, an application of the presented model for a broader analysis of cost effectiveness of

LES across different countries considering nuances in their regulatory setups and differences in factors such as cost of energy, solar irradiations, cost of capital or cost of technologies could be valuable action for identification of policy recommendation.

Author contributions

Conceptualization and methodology, L.H., M.K.; software, L.H.; validation, L.H., M.K.; formal analysis, L.H., M.K., H.K.; investigation and resources, L.H., M.K. and H.K.; data curation, L.H. and M.K.; writing—original draft preparation, L.H. and H.K.; writing—review and editing, all authors; visualization, L.H..; supervision, I.K. and I.R.; project administration, L.H., M.K. and I.R..; funding acquisition, I.K. and I.R. All authors have read and agreed to the published version of the manuscript.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A

In Figure A1, the Power balance of individual subjects on last week in May (22 nd week in a year) is shown across the scenarios.

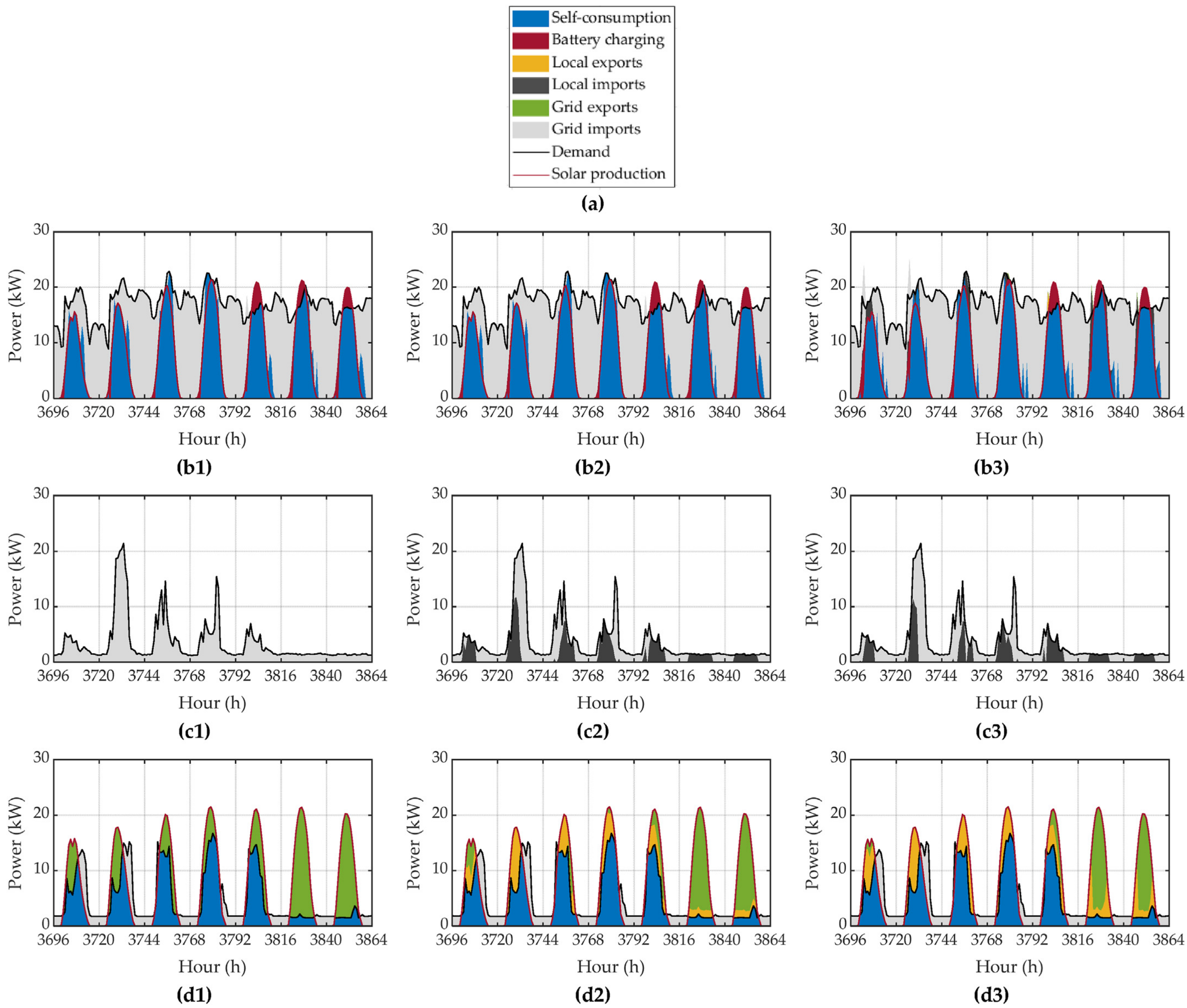

Fig. A1. Power balance of individual subjects on last week in May (22nd week in a year): (a) legend; (b1) Tech Park, scenario S0; (b2) Tech Park, scenario S1; (b3) Tech Park, scenario S2; (c1) Kindergarten, scenario S0; (c2) Kindergarten, scenario S1; (c3) Kindergarten, scenario S2; (d1) Library, scenario S0; (d2) Library, scenario S1; (d3) Library, scenario S2.

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Techno-economic and environmental assessment of energy vectors in decarbonization of energy islands

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ABSTRACT

Decarbonization and transformation of the power system go beyond integrating large shares of variable distributed energy sources; it implies understanding the increasing flexibility needs of the power system and breaking barriers in the process of transforming passive users to active participants in future low carbon energy systems. Unlocking the potential of final users and transforming them into distributed flexibility providers requires harmonization of operation through new models such as the association in energy communities. Multi-vector energy communities (MEC) can provide further flexibility options, enable integration of local energy generation and empower energy islands to increase self-sufficiency and resilience to external impacts. In line with this, the paper develops a unified mixed-integer linear programming (MILP) model of a MEC and rigorously assesses techno-economic performances of different combinations of energy sources, vectors and consumers. That way, the potential of different MECs for providing flexibility and increasing the utilization of electricity production from local renewable energy sources is assessed. Based on the results of the MILP models, the paper further proposes novel indicators for estimation of the techno-economic and environmental potential of different multi-energy vectors in decarbonization of energy islands. Case study analysis comprises of eight scenarios with different MEC's setups with realistic data from island Ærø in Denmark and island Vis in Croatia, capturing also geographical specificities. The results show significant differences across different MEC set-ups as well as between the geographical locations, and some of the results that can be highlighted are: demand responsive electric heat pumps and use of battery energy storage systems provide stand-out energy potency and can ensure self-sufficiency with smallest capacity of electricity production from local renewable energy sources, but comes with a growing costs for the increase of storage capacity; use of imported natural gas as a transition fuel could be affordable solution but does not lead to fulfilment of self-sufficiency or environmental goals; hydrogen energy vector has significant potential, especially in cases where seasonal energy storage is needed but the costs are still a main barrier; correlation of production and consumption patterns in island Ærø in Denmark favor wind energy, while the increased capacity and production from solar plants is more favorable in island Vis in Croatia.

1. Introduction

The pursuit for decarbonization of power system and integration of a high share of variable renewable distributed energy resources (DERs) in low-voltage (LV) distribution grid require coordination of different flexibility options at local level [1]. Flexibility options can include demand response (DR) [2], battery energy storage systems (BESSs) [3], electric vehicles (EVs) [4], as well as different multi-energy transformations [5], such as power-to-heat (P2H) [6], power-to-hydrogen (P2H2) [7], micro combined heat and power (CHP) plants or electric heat pumps (EHPs) with or without heat storage. For the meaningful operation and use of flexibility options, the appropriate energy planning and management have to be deployed [1]. Local energy management can be based on different concepts - from centralized energy management systems (EMSs) [8], energy hubs [9], and virtual power plants (VPPs) [10] to decentralized peer-to-peer (P2P) energy trading [11] or local energy trading (LET) [12]. Utilization of multi-energy vectors [13] in a pursuit for decarbonization of local energy systems is particularly

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important for energy islands, i.e. "isolated villages, small cities, urban districts, rural areas with weak or non-existing grid connections"[14], including physical islands [15]. Multi-vector energy communities (MECs) can contribute to decarbonization of energy islands and increase self-sufficiency and resilience to external impacts. However, due to the multi-dimensional impacts of energy systems, the challenge for MECs that are planning and operating energy islands is in designing, sizing, and operating different energy vectors for their needs [16].

In the existing literature (further reviewed in Section 2), most studies are focused either on methodologies for planning of microgrid/island energy systems using chosen energy vectors [17], or on modeling and optimization of operation of individual multi-energy systems (MESs), consisted of various energy vectors [18]. However, the comparative analysis of different MESs, considering their techno-economic and environmental performances as well as geographical locations of MECs deserves further research and dissemination. In this paper we utilize some of the known models of particular energy vectors and integrate them in a unified modelling and evaluation framework (further described in Section 3), based on which we can systematically evaluate and compare different multi-energy vectors (analyzed in Section 4). The purpose of this paper is to provide a comprehensive comparative techno-economic and environmental analysis of different multi-energy vectors for decarbonization of energy islands. To do that, the model of unified different multi-energy vectors is developed, and their performances are evaluated over a set of proposed technical, economic and environmental indicators. This research will allow planners and decision-makers a comprehensive overview and initial evaluation of options for energy communities and energy islands, considering geographical location and available technologies. Particularly, this paper contributes with the following:

- Unified mixed-integer linear programming (MILP), multi-vector unit-commitment model is proposed for analyzing multi-energy vectors over multiple sets and combinations. Modelling technique itself is not a contribution, rather the extensiveness of energy vectors included in modelled and assessed MECs. The value of the model is demonstrated over an extensive case-study of different energy vectors and evaluated based on the proposed methodology. The studies capture different technologies and their controllability (solar PV power plants, wind turbines, BESSs, gas boilers, gas micro CHPs, hydrogen electrolysis, hydrogen storage tanks, hydrogen micro CHPs, electricity consumption, and responsive temperature regulation with heat storage) as well as geographical and weather conditions across defined scenarios (scenarios applied on island Ærø in Denmark and island Vis in Croatia, assessing the implications and pathways for islands in north and south of Europe).
- Definition of novel indicators for techno-economic and environmental assessment of different multi-energy vectors in decarbonization of energy islands, based on the results of a unified MILP model for MEC. These indicators define energy potency, self-sufficiency, economic feasibility, and CO_2 intensity of multi-energy vectors for energy islands and that way serve to MECs' planers.

The rest of the paper is organized as follows. In Section 2 of this paper, the overview of the current state of the research regarding planning and sizing of low-carbon multi-energy islands, optimal operation of low-carbon multi-energy islands, as well as on used indicators for the evaluation of the performance of analyzed systems is given. The developed method and models of the energy islands for different energy vectors are described in Section 3 of this paper. The case study and the results are presented and discussed in Sections 4. Finally, the conclusions are drawn up in Section 5.

2. Literature review

The literature review is divided to two subsections out of which the first part reviews literature that focuses on planning and sizing of multi-energy systems, while the second subsection reviews literature that focuses on operation of multi-energy systems.

2.1. Planning and sizing of multi-energy systems

Duić et al. proposed a methodology for sustainable energy and resource planning for islands [19], which can help in choosing energy and resource flows integration based on the island needs, resources and applicable technologies. The case studies showed that the integration of different energy vectors and storage has a potential to increase the penetration of variable RESs. In this paper we continue the work with definition of novel indicators for techno-economic and environmental assessment and systematic quantitative comparison of MECs. Mathiesen et al. [5] presented the concept of development and design of energy systems that integrate electricity, heating and transport sectors, including various storage options, to provide necessary flexibility to integrate large penetrations of variable RESs and achieve 100% renewable energy systems. It is advocated that inter-sectoral and multi-vectoral integration of energy systems leads to the cost-optimal energy systems with high share (towards 100%) of RES. We agree that likewise development should be targeted for broad energy system, but we focused our analysis on comparable solutions with limited number of energy vectors as energy islands can usually focus on locally available resources and in their transition predominantly use certain energy vectors, as simultaneous development of many solutions with similar functions in one bounded location can be challenging and unjustified. Chua et al. [20] also showed that the tri-generation multi-energy system can lead to primary energy savings and CO_2 emissions savings. There, authors analyzed 20% and 40% RES penetration, while we expand the simulations with BESSs and analyze potential for 100% self-sufficiency, among others. Martinez Ceseña et al. [16] developed a unified operation and planning optimization, subject to long-term uncertainties and based on a stochastic MILP. There, the electricity, natural gas and ambient heat were modelled as energy sources and electricity and heating as energy consumption. Energy transformations and storage options included a gas boiler, EHP, CHP, and heat storage. On top of that, we further include BESSs and systematically compare different multi-energy vectors. Sachs et al. [21] studied sizing of the elements of electric layout, but considering only electricity demand, without multi-energy transformations. Huang et al. [22] developed an approach for modeling MESs as a directed acyclic graph with multiple layers with a goal to optimize set of equipment that should be invested in, and optimizing the related connections. However, no BESSs were included. Dorotić et al. [23] conducted a simulation using the EnergyPlan tool, with a goal to use vehicle-to-grid (V2G) to balance the island's electricity imports and exports and find the least-cost and most self-sufficient installed power for wind turbine (WT) and solar power plant (SPP). We further analyze and compare the options with use of hydrogen and natural gas as energy vectors. In Table 1, an overview of the highlighted literature focused on planning and sizing of multi-energy systems is given.

It also has to be noticed that for the development and operation of energy islands, the human role must not be underestimated, as the active participation of citizens is an important factor for implementation and acceleration of the energy transition [24]. Therefore, citizens can participate independently in the power market or through different kinds of associations. The importance of citizens' associations are already legally recognized as terms 'citizen energy community' [25] and 'renewable energy community' [26] are defined for specific legal entities in the European Union's (EUs) legislative framework. It is expected that energy communities will lead to a faster increase in the installed capacity of renewable energy sources (RES) and to a decrease in greenhouse gas (GHG) emissions [27].

Table 1
Summary of the highlighted literature focused on planning and sizing of multi-energy systems.

Reference	Energy sources	Energy transform. and storage	Useful energy use	Method	Main indicators
Chua et al. [20]	Solar Biomass Natural gas	CHP Solar Stirling dish Hydrogen CHP Biomass CHP Absorption cooling Auxiliary boiler Hydrogen storage	Electricity Heating Cooling	Three different operational schemes of varying renewable energy penetration were considered – peak shaving, 20% and 40% renewable energy penetration.	CO_2 emissions Investment cost Operational cost
Mathiesen et al. [5]	RES Liquid fuel Natural gas	CHP EHP Fuel synthesis BESS Heat storage Synthetic fuel/ Hydrogen storage	Electricity Heat Fuel for transport	The goal is to integrate smart electricity, thermal, and gas grids to enable 100% RES systems (including transport) simulation is conducted by using the EnergyPlan tool [5].	Primary energy supply Investment cost Operational cost
Martinez Ceseña et al. [16]	Electricity grid Natural gas Ambient heat	Gas boiler EHP CHP Heat storage	Electricity Heat	A unified operation and planning optimization subject to long-term uncertainties, based on a stochastic MILP.	Investment cost Operational cost
Sachs et al. [21]	Solar Oil	Solar Diesel generator BESSs	Electricity	Multi-objective optimization for the sizing of all components and determination of the electronic layout, divided into three problems to optimize economic and environmental objectives.	CO_2 emissions Investment cost Operational cost
Huang et al. [22]	Electricity grid Natural gas RES	Solar power plant CHP Heat storage Cooling storage	Electricity Heat Cooling	The approach models an MES as a directed acyclic graph with multiple layers and includes two stages: optimizing set of equipment that should be invested in, and the related connections.	Investment cost Operational cost
Dorotić et al. [23]	Variable RES Electricity grid	Solar power plant Wind power Electricity storage (V2G) Demand response	Electricity Heating Cooling Transport	Simulation using EnergyPlan tool [23], including V2G and balancing the island's electricity imports and exports to find the least-cost and most self-sufficient installed power for WT and SPP.	Investment cost Operational cost

2.2. Operation of multi-energy systems

Besides planning and sizing of MECs, a number of authors researched optimal operation of MESs and integration of different flexibility options. Wang et al. made a review and analyzed a prospect of integrated DR in multi-energy systems (MESs) [28]. It is argued that in the power system DR is limited due to the high costs of discomfort and a lot of must-run loads, so the integrated DR with MES could expand the potential of DR without affecting consumers' comfort. There are different approaches towards integration of DR with multi-energy systems [29], and to include it in the analysis, we integrate the responsive heating model based on the work from Zugno et al. [30] as an important flexibility option in the analyzed scenarios. Geidi et al. [31] presented an approach for combined optimization of coupled power flows of MESs including electricity, gas and district heating systems. With the developed model, combined economic dispatch and optimal power flow problems are stated for transmission and conversion of energy. The model made a valuable contribution to optimization of operation of MESs with gas electricity and district heating, but did not consider DR, BESS or hydrogen systems and did not analyze the adequacy issues of MESs. Parisio et al. [32] proposed a robust optimization problem of energy hub operations in order to satisfy energy needs while minimizing a cost function. There, the focus was on operational optimization, while we take into account also investment costs and provide comparison of different multi-energy vectors. Bracco et al. [33] presented a MILP model that optimizes design and operation of an energy system in urban areas where buildings are equipped with small-size CHP plants and connected by the heat distribution network. In it, the capital and operating costs, as well as CO_2 emissions are taken into account. The model compared the results with the case of separate electricity and heat production, but combinations or comparison with other energy vectors are not considered. Also, schemes for operation of power-to-X facilities in multi-energy systems are looming [34], such as power-to-hydrogen [35,36], power-to-hydrogen-and-heat [37] etc. For example, Huang et al. [38] developed a model that optimizes the operation of power-to-gas technology, by using the surplus wind power generation on the market to produce hydrogen and synthetic natural gas (SNG) and distribute it through the pipelines. The proposed system is compared with separate production systems and the simulation results showed the opportunities for energy and costs savings, and the investment feasibility. In our work, we actively analyze power-to-hydrogen as a most mature technology, while other options can be studied in the future. Dancker et al. [39] analyzed the implications on the self-sufficiency of microgrid with variable RES production for integrated and non-integrated approaches, where BESS is implemented in the non-integrated approach and an electrolyzer, a hydrogen storage tank and a fuel cell are implemented in the integrated approach. The economic evaluation has shown that a non-integrated approach is suitable for small degrees of self-sufficiency, and the integrated approach is preferable at higher degrees of self-sufficiency, i.e. the higher installed capacity of RES. It is a useful analysis for the assessment of the economic performance of these two particular cases, even though demand response was not included in the model. Pötzinger et al. [40] analyzed the influence of hydrogen-based storage systems on self-consumption and self-sufficiency of residential photovoltaic systems. The results showed that battery storage systems are preferable for short-time storing, while hydrogen-based storage systems are favored for seasonal storage, but not economical at a present time due to the high investment costs. The potential for production of heat energy was not evaluated in the paper. Capuder et al. [1] conducted techno-economic and environmental modeling based on MILP optimization and minimization of operational cost for MESs. Different techno-economic indicators, energy sources and energy transformations were observed, but as a storage option only heat storage was included. Bao et al. [41,42] optimized day-ahead and real-time scheduling of MESs with a goal of minimization of operational costs, but no environmental assessment was conducted, neither hydrogen energy vector was used. Mancarella et al. [43] researched the participation of MESs on the auxiliary services market, but did not consider investment costs, neither included hydrogen as an flexibility option. Pepiciello et al. [44] and Gong et al. [45] studied the scheduling of the MESs under uncertainty, which is valuable point of view, but only operations costs were considered in the evaluation.

An overview of the highlighted literature focused on the optimal operation of MESs is given in Table 2.

As evident, researches use different indicators to assess and optimize the planning and/or operation of MESs. Usually, the optimization objective is the minimization of investment or operational costs. An interdisciplinary evaluation and comparison of MECs could be based on approaches by Kumar et al. [46] and Santos et al. [47], who proposed frameworks for the design of microgrids using social, economic and technical analysis. The methodologies are suitable for rural microgrids and can be applied for island microgrids. However, their work considers electricity vector only, without multi-energy transformations, which limits flexibility options and can potentially result in suboptimal planning setups and higher operational costs. Further, Pramangioulis et al. [48] proposed a methodology for the determination and definition of key performance indicators (KPIs) for smart grids development in island energy systems. The final list includes 45 KPIs that can be used in evaluation of the projects. The listed KPIs are divided into technical, environmental, economic, social and legal KPIs and the suitability of their application depends on the goals of a particular project. Due to large number and different types of indicators listed in [48], the aim of this paper is to provide less indicators but ensure vivid insight and demonstrate the results on a realistic case study. Groppi et al. [49] did a valuable work on assessing the economic and environmental implications of the use of hydrogen energy vector and BESSs for increasing the energy independence of small islands, with a case study on a small island in Italy. By using the HOMER software, they have concluded that use of both energy vectors can increase energy independency, while the reached RES fraction was up to 11.3%. On this track, Meschede et al. [50] assessed the possible 100% RES energy system configurations for a small Canary island in 2030 using the EnergyPlan software. In our work, with the modelling framework that allows systematic comparison of wide range of energy vectors, broad case study analysis on islands in both northern and southern Europe, and comprehensive techno-economic and environmental indicators, we aim to further assess the foreseeable implications on the different energy vectors on a road towards a deep decarbonization of energy islands.

An important challenge linked with planning of isolated (off grid) energy islands based on the variable RES is to ensure generation adequacy [51], as the available generation capacities of variable RES are dependent on the availability of the primary energy source (e.g. solar radiation or wind energy). The usual indicators measuring the generator adequacy are based on the probabilistic metrics, such as the loss of load expectations (LOLE) and the expected energy not served (EENS), where the performance of the planned system can be compared with the target values (e.g. a maximum of 24 h per year for LOLE) [51]. Besides the generator adequacy, the system flexibility needs have to be addressed to ensure system stability [52]. Power system stability is typically classified in three categories: rotor angle stability, voltage stability, and frequency stability [53]. In cases where installed capacity of DERs refers to inverter-based PV systems and BESSs rotor angle stability is usually not considered, while in grid-connected energy islands and microgrids, frequency is usually maintained by the utility grid [52]. The focus of this paper is on the techno-economic and environmental evaluation of energy islands considering various flexibility options, meaning that conditions for ensuring system stability and assessment of other stability issues [15] are out of the scope.

The literature overview showed that most studies focused either on methodologies for planning or operation of individual MESs, consisted of predefined energy vectors, without comparatively analyzing value of each energy vector for providing flexibility services to the island energy system. The goal of this paper is to conduct a systematic comparative techno-economic and environmental analysis of different MESs for decarbonization of energy islands, based on chosen indicators and developed MILP models.

Table 2
Summary of the highlighted literature focused on operation of multi-energy systems.

Reference	Energy sources	Energy transform. and storage	Useful energy use	Method	Main indicators
Capuder et al. [1]	Electricity grid Natural gas Ambient heat	Gas boiler EHP CHP Heat storage	Electricity Heat	Techno-economic and environmental modeling based on MILP optimization and minimization of operational cost for MESs.	Operational cost Primary energy savings CO_2 emissions Local emission (NO_X, CO)
Bao et al. [41,42]	Variable RES Gas	Wind turbine Solar power plant CCHP Electricity storage Ice storage	Electricity Heat Cooling	Day-ahead scheduling and real-time dispatching models. For day-ahead scheduling, the uncertainty of variable RES is represented by multi-scenarios and the objective is to minimize expected operation cost.	Operational costs
Mancarella et al. [43]	Electricity grid Natural gas Ambient heat	Gas boiler EHP CHP Heat storage	Electricity Heat Cooling	Participation of MESs on ancillary services market based on energy shifting.	Profit Multi-energy profitability maps
Pepiciello et al. [44]	RES Electricity Natural gas grid Heat grid Hydrogen	Electricity generators EHP Boiler CHP Fuel cell Heat exchanger	Electricity Heat	Methodology is based on extended Affine Arithmetic and enables solving of the optimal scheduling problem in the presence of multiple and heterogeneous uncertainty sources.	Operational costs
Gong et al. [45]	Variable RES	Wind turbine Solar power plant Gas CHP EHP Absorption chiller Schedulable loads	Electricity Heat Cooling	The system uses schedulable loads instead of energy storage, and a collaborative optimization scheduling strategy. A genetic algorithm is employed to optimize the overall performance.	Primary energy GHG emissions Operational costs

3. Method

3.1. Method for techno-economic and environmental assessment of different energy vectors

This research focuses on the assessment of different multi-energy vectors from a techno-economic and environmental perspective in the context of energy islands. It is assumed that energy islands are operated by energy communities with a goal to use local resources, achieve possible synergies, increase self-sufficiency, decrease costs, and decrease environmental impact. The methodology is based on the set of indicators that have a goal to evaluate how sustainable and self-sufficient each multi-energy vector is. To perform a detailed study, an adaptable MILP multi-vector unit-commitment model for each MEC is developed. Furthermore, an extensive case-study analysis considering types and installed capacities of generating units, as well geographical locations is performed. The stability issues are not focus of this paper, analyses focusing on stability aspects can be found in [54], as in this paper it is assumed that energy islands have a grid connection, but their ambition is to increase self-sufficiency, resilience, hedge cost risks and decrease GHG emission intensity and not to operate in islanded mode as a normal operational regime. The indicators described below are presented as the results of annual optimizations and simulations, however the formulations are general so that they can be easily used to calculate values for other time horizons as well.

3.1.1. Energy potency indicator

The key indicator for the assessment of potency of the modeled MECs is an indicator, E_{pot} that evaluates how efficiently a MEC can integrate variable RES. A MEC that is perfectly efficient in terms of no losses, excess or missing energy would have E_{pot} value 0. The energy potency indicator is defined by Eq. (1).

$$E_{pot}^{T} = \frac{E_{missing}^{T} + E_{excess}^{T} + E_{losses}^{T}}{E_{consum}^{T}} \tag{1}$$

where $E_{consum}^{T} = \sum_{t=1}^{T} E_{consum}^{t}$ is the amount of consumed energy in modeled MEC over the observed time horizon, and $E_{consum}^{t}$is the amount of consumed energy in time interval t, $t \in \{1,2,\cdots,T\}$, $E_{excess}^{T} = \sum_{t=1}^{T} E_{excess}^{t}$ is the excess amount of energy that cannot be consumed or stored over the observed time horizon, and $E_{excess}^{t}$is excess amount of energy that cannot be consumed or stored in time interval t, $t \in \{1,2,\cdots,T\}$, $E_{missing}^{T} = \sum_{t=1}^{T} E_{missing}^{t}$ is the amount of energy that is missing in the system to fulfill the end-consumers demand over the observed time horizon and $E_{missing}^{t}$is the amount of energy that is missing in the system to fulfill the end-consumers demand in time interval t, $t \in \{1,2,\cdots,T\}$, while $E_{losses}^{T} = \sum_{t=1}^{T} E_{losses}^{t}$ is the amount of energy that is wasted in the energy transformations in the system to fulfill the end-consumers demand over the observed time horizon and $E_{losses}^{t}$is the amount of energy that is wasted in the system to fulfill the end-consumers demand in time interval t, $t \in \{1,2,\cdots,T\}$. Thereby, energy included in Eq. (1) includes all energy vectors included in the models, such as electricity, gas, hydrogen, or heat. E_{pot} indicator builds on often shown critical excess of electricity production (CEEP) indicator, but goes beyond as it overcomes it's shortage as CEEP does not take into account system losses (so in cases where there are a lot of losses it looks favorable because there could be less excess energy). In addition, it takes into account energy imports making it suitable for island systems. In fact, it adds up all the "inconvenient" energy in relation to a perfectly dimensioned system with local RES.

3.1.2. Self-sufficiency indicator

Due to the fact that electricity production from solar and wind can easily be curtailed, it is insightful to complement the E_{pot} with assessment of the energy self-sufficiency of the analyzed MECs. The energy self-sufficiency indicator (E_{SS}) can be calculated as shown in the Eq. (2).

$$E_{ss}^{T} = \frac{E_{consum}^{T} - E_{missing}^{T}}{E_{consum}^{T}} \tag{2}$$

The terms used in Eq. (2) are described below Eq. (1). To allow comprehensive assessment of energy vectors the E_{ss}^{T} is also shown for the analyzed cases and scenarios in Section 4.

3.1.3. Levelized cost of energy consumed

The third indicator used for the assessment of developed models is an economic indicator Levelized cost of energy consumed ($LCOE_{consum}$), presented by Eq. (3). The analysis includes capital costs, fuel costs, and operation and maintenance costs, as well as costs of missing energy (imported energy). That way the energy community can assess the costs for the used energy and compare different multi-energy vector options.

$$LCOE_{consum}^{T} = \frac{\sum_{l=1}^{L}\left(C_{Il} \cdot CRF_{Il} \cdot \frac{T}{T_Y} + C_{Fl}^{T} + C_{OMl}^{T}\right) + C_{missing}^{T}}{E_{consum}^{T}} \tag{3}$$

where C_{Il} are investment costs in each technology $l, l \in \{1,2,\cdots,L\}$, and CRF_{Il} is a capital recovery factor equaling $\frac{(1+k)^{T_{Il}} \cdot k}{(1+k)^{T_{Il}}-1}$, by which investment costs are annualized using a lifetime of the investment (T_{Il}), and the weighted average cost of capital (k). $\frac{T}{T_Y}$ is the ratio of the observed time horizon T (number of modelled time intervals t) and of horizon of one year (number of time intervals in one year). It is used to scale annualized investment to observed time horizon, and this ratio equals 1 in case when observed time horizon is one year. C_F^T is fuel cost over the observed time horizon equaling $\sum_{t=1}^{T} C_F^t$ and $C_F^t$is the fuel cost in time interval t, $t \in \{1,2,\cdots,T\}$, C_{OM}^{T} is the operation and maintenance cost over the observed time horizon equaling $\sum_{t=1}^{T} C_{OM}^{t}$ and C_{OM}^{t}operation and maintenance cost in time interval t, $t \in \{1,2,\cdots,T\}$, $C_{missing}^{T}$ is the cost of missing (imported) energy over the observed time horizon, equaling $\sum_{t=1}^{T} C_{missing}^{t}$ and $C_{missing}^{t}$ is cost of missing (imported) energy in time interval t, $t \in \{1,2,\cdots,T\}$, and the E_{consum}^{T} is the energy consumed over the observed time horizon, i.e. $E_{consum}^{T} = \sum_{t=1}^{T} E_{consum}^{t}$ and E_{consum}^{t} is energy consumed in time interval t, $t \in \{1,2,\cdots,T\}$.

3.1.4. CO_2 intensity

The fourth indicator used for the assessment of MECs is related to environmental impact, which is an important aspect for energy communities and for energy islands that want to promote sustainable and climate-friendly solutions. As the developed MECs are based on variable RES and low carbon technologies, it is also interesting to analyze effects of GHG emissions. The CO_2 intensity indicator compares the average amount of CO_2 emissions of the modeled MECs. Average emissions for each modeled microgrid are calculated by Eq. (4).

$$CO_{2_{consm}}^{T} = \frac{CO_{2_{prod}}^{T} + CO_{2_{missing}}^{T}}{E_{consum}^{T}} \tag{4}$$

where $CO_{2_{prod}}^{T} = \sum_{t=1}^{T} CO_{2_{prod}}^{t}$ are CO_2 emissions over the observed time horizon caused by the energy production of each MES to fulfill the energy demand and $CO_{2_{prod}}^{t}$ are CO_2 emissions caused by the energy production in time interval t, $t \in \{1,2,\cdots,T\}$, and $CO_{2_{missing}}^{T} = \sum_{t=1}^{T} CO_{2_{missing}}^{t}$ are CO_2 emissions of electricity imported from the utility grid over the observed time horizon and $CO_{2_{missing}}^{t}$ are CO_2 emissions of electricity imported from the utility grid in time interval t, $t \in \{1,2,\cdots,T\}$ There, the lifecycle emissions coming from equipment manufacturing or recycling/waste handling are out of the scope of the analysis. Also, the constant average value of grid emission factor for calculation of $CO_{2_{missing}}^{T}$ is used, as hourly data for grid emission factors are unavailable for many countries.

3.2. Models of multi-energy systems for energy islands

Energy islands are modeled as a sets of energy vectors that can be operated together. The different combinations of energy vectors are tested and evaluated across the scenarios. The assumed useful energy demand relates to indoor space heating and electricity demand for other needs. The modeled time horizon is one year, with the resolution (time interval, $t \in \{1, 2, \cdots, T\}$) of one hour. Modeled energy sources, energy vectors, and energy demand options include solar photovoltaic power plants, wind turbines, battery energy storage systems, gas boilers, gas micro combined heat and power plants, hydrogen electrolysis, hydrogen storage tanks, hydrogen micro combined heat and power plants, electricity consumption, and responsive temperature regulation. However, it should be noted that the presented model in the following sections is general and adaptive, meaning it can easily be expanded by including additional technologies of interest, such as marine technologies on the side of productions or transport as an additional vector on the side of consumption/storage. In this subsection, the mathematical models of operation of different MESs are presented.

In Fig. 1, the modeled energy vectors are presented and marked either as imports/exports, local RES, energy transformations or energy consumption. Lines with arrows indicate the energy flows from local RES, electricity and gas grids to energy transformations and to final energy consumption. In this process, multi-energy vectors can provide flexibility and increase system's ability to integrate electricity production from variable local RES. It can be noted that electricity grid can be used for imports to, and exports from the MEC. Also, generated or imported electricity can be directly used for heating or other purposes, or stored in BESSs, or used for production of hydrogen. The dashed lines indicate further sources and demand sectors that could be added to the model. Of course, additional wide range of emerging energy transformations and storage technologies could also be added, such as use of EVs with storage and V2G, biomass-to-X (liquid, gas, heat), power-to-X, reversible hydro or new storage technologies, or even use of carbon capture, utilization and storage technologies (CCUS). For the sake of clarity and easier understanding, the modelled technologies in this paper are chosen based on the maturity and market readiness of technologies as well as on availability of modelling data.

Based on the presented energy vectors, the three sub-models are developed and modeled separately with the associated scenarios. Even though the mix of all technologies is likely to happen across the interconnected broad energy system, the sub-models of particular multi-energy vectors are modeled separately for the analyzed MECs because the goal is to analyze different transition strategies which are likely to appear on different micro-locations. Also, the aim of the paper is to provide a comparison of different MESs when applied within different energy communities and energy islands. In the remainder of this subsection, the three analyzed models are described. They are divided to: (1) Battery model, where BESSs are used as a main flexibility option and heating is provided by the EHPs, that way simulating the dominant role of batteries for providing system flexibility and increasing potency for integration of RES; (2) Gas model, where the use of natural gas is possible and the heating is provided either by gas boilers or gas micro CHPs, that way simulating the potential of natural gas as a transition fuel; and (3) Hydrogen model, where hydrogen electrolysis and storage is modeled and the heating is provided by the hydrogen micro CHPs, that way simulating the possible significant role of hydrogen vector as a 'missing link' towards the 100% RES energy systems.

3.2.1. Battery model

The Battery model consists of the components depicted in Fig. 2. The model includes wind energy and solar energy as electricity generation from the local RES, following by BESSs that provide flexibility for local demand/supply balancing and EHPs that use ambient heat to produce heat for indoor temperature regulation. Also, imports and exports to the utility grid are possible and the electricity demand for other purposes has to be satisfied. Electricity (blue lines) and heat (red lines) are used as energy carriers. No gas or hydrogen energy vectors are assumed in this model.

The optimization objective in the Battery model is described by Eq. (5).

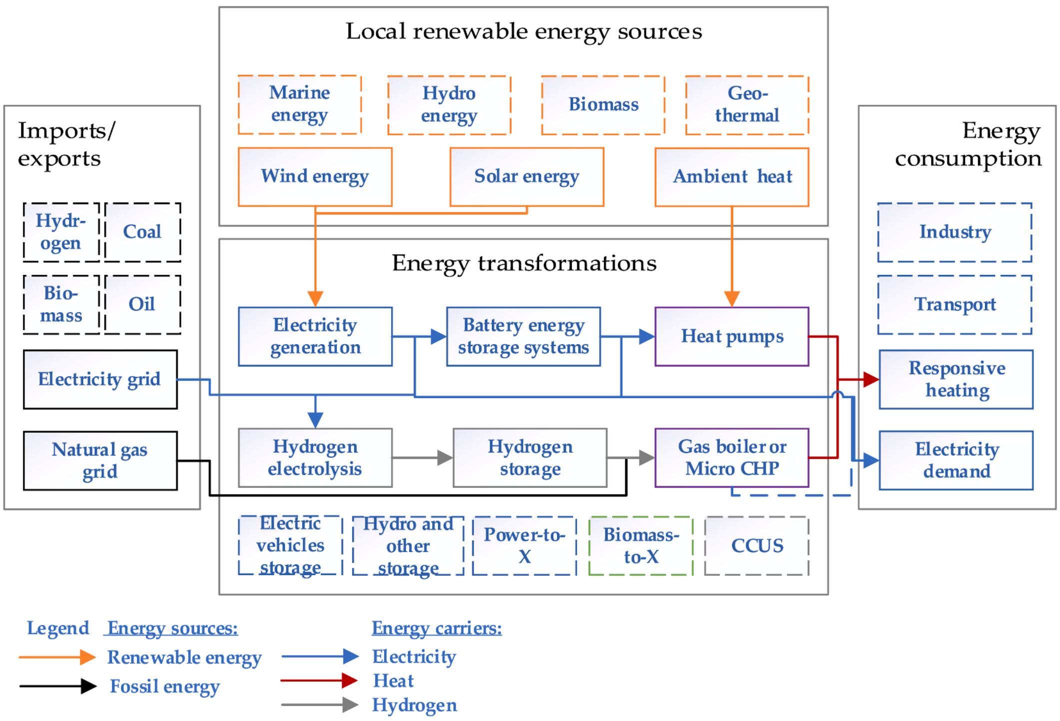


Fig. 1. Energy sources, conversion and storage, and energy demand modeled in the scenarios (solid lines).

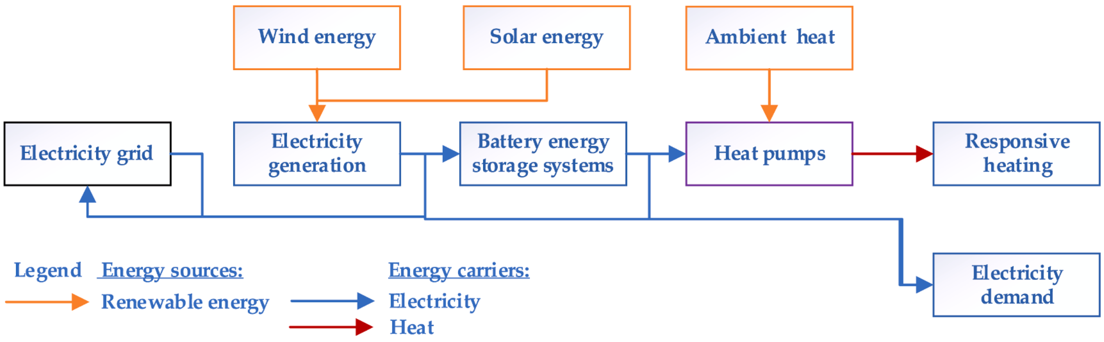


Fig. 2. Energy sources, conversion and storage processes and energy demand in the Battery model.

$$Minimize\left\{\sum_{t=1}^{T}\left(c^{t}_{missing}\cdot P^{t}_{missing}+\sigma^{t}\cdot\rho-c^{t}_{excess}\cdot P^{t}_{excess}\right)\right\} \quad (5)$$

where $c^t_{missing}$ is a fixed price of electricity from the utility grid in time interval t to compensate for the missing electricity, $P^t_{missing}$ is missing electricity in a given time interval t, c^t_{excess} is a revenue for the electricity sold to the utility grid, P^t_{excess} is an electricity that cannot be used or stored in a given time interval t and is sold to the utility grid, σ^t is the temperature deviation from the comfort temperature (in °C), and ρ is the penalty for every degree of temperature deviation [30].

Energy balance constraints are shown in Eq. (6).

$$P^{t}_{consum}=P^{t}_{PV}+P^{t}_{WT}-N\cdot P^{t}_{HP}-P^{t}_{excess}+P^{t}_{missing}+\sum_{j=1}^{N}\left(P^{t}_{dis,j}-P^{t}_{ch,j}\right),\quad\forall t\in T \quad (6)$$

where P^t_{consum} is electricity demand in the energy community in a given time interval t, P^t_{PV} and P^t_{WT} are electricity produced by solar PV plants and wind turbine respectively, N is a number of households, P^t_{HP} is the electricity consumed by each EHP, P^t_{excess} is the excess electricity that cannot be consumed or stored, $P^t_{missing}$ is missing electricity in a given time interval t, and $P^t_{j,dis}$ and $P^t_{j,ch}$ are the discharging and charging electricity of the installed batteries.

The model of household heating system is modified based on the model developed by Zugno et. al. [30]. That way the entire household is represented as a single room, which is heated by an electric pump connected to the water tank. Other simplifications are uniform temperature throughout the entire room, ventilation and humidity influence are neglected, as well as heat released from people and influences of wind and solar radiation. More detailed thermal models are out of the scope of this research, as the goal is to allow assessment and comparison of energy vectors, for which detailed thermal models of houses are not decisive, as they are usually used for short-term operational and market planning (day to week ahead) [43]. The household temperature regulation system has a goal to maintain the room temperature within the boundaries of the given minimum T_{min} and maximum T_{max}. Therefore, it has flexibility to optimize the operation in accordance with the other energy vectors. The model describing heating dynamics uses three variables to calculate the temperature in a room T_{room}: the temperature of a floor T_{floor}, the temperature in a water tank T_{water} (that can be connected to the heat pump or other heat source), and the outdoor temperature $T_{outdoor}$ that presents the influence of external conditions on the T_{room}. The initial values used for T_{room}, T_{floor}, and T_{water} are 22 °C. The mathematical model is presented in Eqs. (7)–(9).

$$T^{t}_{room}=a_{11}\cdot T^{t-1}_{room}+a_{12}\cdot T^{t-1}_{floor}+a_{13}\cdot T^{t-1}_{water}+b_{1}\cdot P^{t-1}_{HP}+e_{1}\cdot T^{t-1}_{outdoor},\quad\forall t\in T \quad (7)$$

$$T^{t}_{floor}=a_{21}\cdot T^{t-1}_{room}+a_{22}\cdot T^{t-1}_{floor}+a_{23}\cdot T^{t-1}_{water}+b_{2}\cdot P^{t-1}_{HP}+e_{2}\cdot T^{t-1}_{outdoor},\quad\forall t\in T \quad (8)$$

$$T^{t}_{water}=a_{31}\cdot T^{t-1}_{room}+a_{32}\cdot T^{t-1}_{floor}+a_{33}\cdot T^{t-1}_{water}+b_{3}\cdot P^{t-1}_{HP}+e_{3}\cdot T^{t-1}_{outdoor},\quad\forall t\in T \quad (9)$$

The parameters used in Eqs. (7)–(9) are taken from [30]. The model is subject to constraints presented in Eqs. (10)–(13).

$$T^{t}_{room}+\sigma^{t}\geq T^{t}_{min},\ \forall t\in T \quad (10)$$

$$T^{t}_{room}-\sigma^{t}\leq T^{t}_{max},\ \forall t\in T \quad (11)$$

$$\sigma^{t}\geq 0,\ \forall t\in T \quad (12)$$

$$T_{water}\leq 80^{\circ}C,\ \forall t\in T \quad (13)$$

where σ^t is the deviation of comfort temperature in a given hour, and (13) limits the T_{water}.

Additional conditions used for the adaptation of the model described in [30] include Eqs. (14) and (15):

$$P^{t}_{HP}\geq 0 \quad (14)$$

$$N\cdot P^{t}_{HP}\leq P^{t}_{excess} \quad (15)$$

where N is the number of households, P^t_{HP} is the electricity used by each EHP, and P^t_{excess} is the excess electricity produced by wind and solar plants, as used in the model presented further in the paper.

The energy production from solar PV and wind power plants is modeled as production based on the input data and integrated into the energy balance. The input data vary based on the installed capacities in the energy community.

The electricity demand for other needs (besides for EHP or use of excess electricity for electrolysis or other flexibility options) is imported from the input data and considered in the energy balance.

The BESSs are modeled as described in Eqs. (16)–(18).

$$SoC^{t}_{bs,j}=SoC^{t-1}_{bs,j}+P^{t}_{ch,j}\cdot\eta_{ch}-\frac{P^{t}_{dis,j}}{\eta_{dis}},\quad\forall t\in T \quad (16)$$

$$0\leqslant P^{t}_{ch,j}\leqslant P_{ch,jmax}\cdot N_{chbin,j},\quad\forall t\in T \quad (17)$$

$$0\leqslant P^{t}_{dis,j}\leqslant P_{dis,jmax}\cdot N_{disbin,j},\quad\forall t\in T \quad (18)$$

$$N_{chbin,j}+N_{disbin,j}\leq 1,\forall t\in T \quad (19)$$

$$SoC_{bs,jmin}\leq SoC^{t}_{bs,j}\leq SoC_{bs,jmax} \quad (20)$$

where $SoC^t_{bs,j}$ describes the state of charge of each battery in a given time interval, $SoC_{bs,jmin}$ and $SoC_{bs,jmax}$ are minimum and maximum state of charge of each battery respectively, $P^t_{ch,j}$ is a charging power of each battery at a given time interval, $P^t_{dis,j}$ is a discharging power of each battery at a given time interval, η_{ch} is a charging efficiency and η_{dis} discharging efficiency of each battery respectively. $P_{ch,jmax}$ is the maximum charging power and $P_{ch,j max}$ is the maximum discharging power of each battery. $N_{chbin,j}$ and $N_{disbin,j}$ are binary variables that prevent simultaneous charging and discharging of the batteries.

3.2.2. Gas model

The Gas model consists of the components depicted in Fig. 3. The model includes wind energy and solar energy as electricity generation from the local RES, while flexibility and better local demand/supply balancing as well as heat production are ensured by the gas boiler or micro gas CHP with thermal storage (different scenarios are modelled). For that purpose, the existence of natural gas grid was assumed. Also, imports and exports to the utility electricity grid are possible and the electricity demand for other purposes has to be satisfied. Electricity (blue lines), natural gas (black line), and heat (red lines) are used as energy carriers. No use of BESSs or hydrogen energy storage vectors are assumed in this model.

The optimization objective in the Gas model is described by Eq. (21).

$$Minimize\left\{\sum_{t=1}^{T}\left(c^t_{missing}\cdot P^t_{missing}+\sigma^t\cdot\rho-c^t_{excess}\cdot P^t_{excess}+N\cdot F^t_{CHP}\cdot c^t_{gas}\right)\right\} \tag{21}$$

where $c^t_{gas}, \forall t\in T$ is a cost of gas from the grid, and $F^t_{CHP}, \forall t\in T$ is the gas consumption of each micro CHP unit, and other variables are same as in Eq. (5).

Energy balance constraints are presented in Eq. (22).

$$P^t_{consum}=P^t_{PV}+P^t_{WT}\mp N\cdot F^t_{CHP}\cdot\eta_{ele,CHP}-P^t_{excess}+P^t_{missing}, \quad \forall t\in T \tag{22}$$

where $\eta_{ele,CHP}$ is an electric efficiency of the modeled gas micro CHP. In the case of modeling gas boiler, it equals zero.

The model of household heating system in cases when a gas boiler or micro CHP is a source of heat is similar like the one described in Eqs. (7)–(9), with the adjustment that takes into account the fact that the heat is not produced by the EHP, but CHP that simultaneously produces electricity and heat, and has much smaller efficiency compared to EHP, as described in Eqs. (23)–(25):

$$T^t_{room}=a_{11}\cdot T^{t-1}_{room}+a_{12}\cdot T^{t-1}_{floor}+a_{13}\cdot T^{t-1}_{water}+\frac{b_1}{COP}\cdot\eta_{heat,CHP}F^{t-1}_{CHP}+e_1\cdot T^{t-1}_{outdoor} \tag{23}$$

$$T^t_{floor}=a_{21}\cdot T^{t-1}_{room}+a_{22}\cdot T^{t-1}_{floor}+a_{23}\cdot T^{t-1}_{water}+\frac{b_2}{COP}\cdot\eta_{heat,CHP}F^{t-1}_{CHP}+e_2\cdot T^{t-1}_{outdoor} \tag{24}$$

$$T^t_{water}=a_{31}\cdot T^{t-1}_{room}+a_{32}\cdot T^{t-1}_{floor}+a_{33}\cdot T^{t-1}_{water}+\frac{b_3}{COP}\cdot\eta_{heat,CHP}F^{t-1}_{CHP}+e_3\cdot T^{t-1}_{outdoor} \tag{25}$$

where COP is the coefficient of performance for EHP, $\eta_{heat,CHP}$ is the efficiency of the heat energy distributed from the CHP to a water tank and F^{t-1}_{CHP} is the energy of the fuel used in the CHP, and coefficients are adapted to model the use of gas boilers instead of heat pumps as in Battery model. Equally, as in the case with EHPs, Eqs. (23)–(25) are subject to constraints listed in Eqs. (10)–(13), and used parameters are as listed in [30].

Micro CHP plant is modeled as a gas CHP that produces heat and electricity, where $\eta_{heat,CHP}$, and $\eta_{ele,CHP}$ are the efficiency of the produced heat and electricity from the primary fuel. In the case of a gas boiler, only $\eta_{heat,CHP}$ is used.

3.2.3. Hydrogen model

The Hydrogen model consists of the components depicted in Fig. 4. The model includes wind energy and solar energy as electricity generation from the local RES, while flexibility and better local demand/supply balancing as well as heat production are ensured by the hydrogen production, storage and hydrogen micro gas CHP. Also, imports and exports to the utility electricity grid are possible and the electricity demand for other purposes has to be satisfied. Electricity (blue lines), hydrogen (grey lines), and heat (red lines) are used as energy carriers. No use of BESSs or natural gas energy vectors are assumed in this model.

The optimization objective of the Hydrogen model is described by Eq. (26).

$$Minimize\left\{\sum_{t=1}^{T}\left(c^t_{missing}\cdot P^t_{missing}+\sigma^t\cdot\rho-c^t_{excess}\cdot P^t_{excess}\right)\right\} \tag{26}$$

Energy balance constraint is presented in Eq. (27).

$$P^t_{consum}=P^t_{PV}+P^t_{WT}+N\cdot F^t_{FCCHP}\cdot\eta_{ele,FCCHP}-H^t_{2ch}-P^t_{excess}+P^t_{missing}, \quad \forall t\in T \tag{27}$$

where $F^t_{FCCHP}, \forall t\in T$ is the hydrogen consumption of each micro fuel cell CHP (FCCHP) unit, $\eta_{ele,FCCHP}$ is an electric efficiency of the modeled micro FCCHP, and $H^t_2ch, \forall t\in T$ is electricity used for electrolysis of the hydrogen (H_2).

Further, the production, storage and utilization of hydrogen are modeled. For the hydrogen production, the local electricity production or imports from the grid can be used in the process of electrolysis. The hydrogen production can be calculated by a method described by Mostafaeipour et. al. [55] and modified as shown in Eq. (28).

$$M^t_{H_2}=H^t_{2ch}\cdot\eta_{H_2ch}, \quad \forall t\in T \tag{28}$$

where $M^t_{H_2}$ is the amount of hydrogen produced in each interval (in kWh), H^t_2ch is electricity input for electrolysis (in kWh), and η_{H_2ch} is the efficiency of the process of electrolysis of hydrogen for storage,

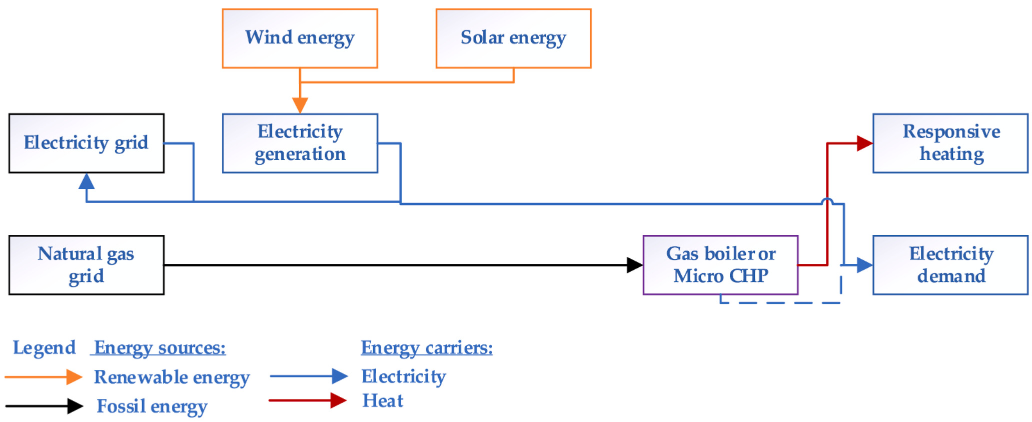


Fig. 3. Energy sources, conversion and storage processes and energy demand in the Gas model.

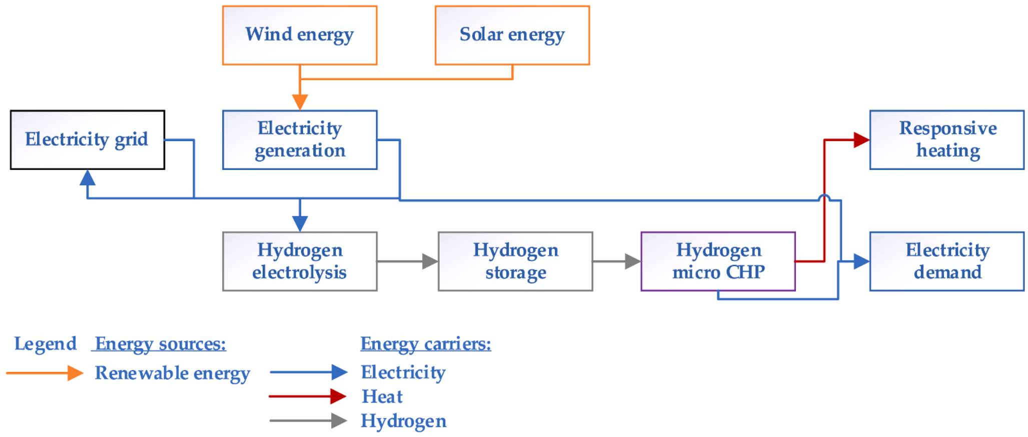


Fig. 4. Energy sources, conversion and storage processes and energy demand in the Hydrogen model.

including efficiency of a rectifier (in %),.

Hydrogen storage is modeled similarly to the battery storage with the difference that it can be both charged and discharge at the same time, as shown in Eq. (29):

$$VH_2^t = VH_2^{t-1} + H_{2ch}^t \cdot \eta_{H_2 ch} - \frac{N \cdot H_{2dis}^t}{\eta_{H_2 dis}}, \ \forall t \in T \tag{29}$$

where VH_2^t is the amount of hydrogen in storage in a given time interval (in kWh), $H_2^t dis$ is hydrogen discharging from the storage in a given time interval (in kWh), $\eta_{H_2 dis}$ is efficiency of discharging hydrogen, and N is a number of households.

Hydrogen consumption for micro FCCHPs can be calculated as shown in Eq. (30):

$$F_{FCCHP}^t = H_2^t dis \tag{30}$$

After the hydrogen is discharged from the storage tank to the micro FCCHPs, useful electricity and heat production in micro FCCHPs are subject to the efficiency of micro FCCHP. The model of household heating system in cases when a micro FCCHP is a source of heat is equal as the one described in Eqs. (23)–(25), with the adjustment that takes into account the fact that the heat is not produced by a micro CHP powered by gas, but micro FCCHP powered by hydrogen. The results are Eqs. (31)–(33):

$$T_{room}^t = a_{11} \cdot T_{room}^{t-1} + a_{12} \cdot T_{floor}^{t-1} + a_{13} \cdot T_{water}^{t-1} + \frac{b_1}{COP} \cdot \eta_{heat,FCCHP} F_{FCCHP}^{t-1} + e_1 \cdot T_{outdoor}^{t-1} \tag{31}$$

$$T_{floor}^t = a_{21} \cdot T_{room}^{t-1} + a_{22} \cdot T_{floor}^{t-1} + a_{23} \cdot T_{water}^{t-1} + \frac{b_2}{COP} \cdot \eta_{heat,FCCHP} F_{FCCHP}^{t-1} + e_2 \cdot T_{outdoor}^{t-1} \tag{32}$$

$$T_{water}^t = a_{31} \cdot T_{room}^{t-1} + a_{32} \cdot T_{floor}^{t-1} + a_{33} \cdot T_{water}^{t-1} + \frac{b_3}{COP} \cdot \eta_{heat,FCCHP} F_{FCCHP}^{t-1} + e_3 \cdot T_{outdoor}^{t-1} \tag{33}$$

where COP is the coefficient of performance for EHP, $\eta_{heat,FCCHP}$ is the efficiency of the heat energy distributed from the FCCHP to a water tank and F_{FCCHP}^{t-1} is the energy of the fuel used in the FCCHP. Equally as in the case with gas-powered CHPs, Eqs. (31)–(33) are subject to constraints listed in Eqs. (10)–(13), and used parameters are as listed in [30].

Micro hydrogen-powered FCCHP plant is modeled as a CHP that produces heat and electricity, where $\eta_{heat,FCCHP}$ is the efficiency of the produced heat from the hydrogen.

4. Case study analysis

The presented methodology and models are used in the comprehensive case study analysis to assess the techno-economic and environmental performance of different multi-energy vectors for decarbonization of energy islands organized as MECs. The models are applied for different geographical locations of island Ærø in Denmark (DK) and island Vis in Croatia (HR), and sensitivity analysis is conducted for different amounts of electricity production from variable RES when compared with electricity consumption. Further, the sensitivity analysis is also conducted for different ratios of installed wind power capacity and solar power capacity for electricity production, with the goal to assess different production potential and locational specificities. In total, there are eight scenarios, two locations, three cases, and six points that define the installed RES capacity based on the ratio of electricity produced and electricity consumed, which in total equals 288 MILP multi-vector unit commitment simulations that were conducted for a time horizon (*T*) of one year with hourly resolution (time interval, *t*, $\forall t \in T$). The simulations are conducted using the Python programming language [56] and Gurobi solver [57], and we used a desktop PC with AMD Ryzen 7 2700 Eight-Core Processor (3.20 GHz) and 16 GB RAM.

4.1. Input data

The overview and features of the scenarios are presented in Table 3. There are eight scenarios in total. The first four scenarios relate to the Battery model, but in scenario B0 there is no BESS available – which makes B0 reference scenario with only responsive heating using heat pumps available as certain flexibility provider. In scenario B1 there is 1 kWh of BESS capacity per 1 kW of installed RES capacity. In scenario B6 there is 6 kWh and in scenario B10 10 kWh of BESS capacity per 1 kW of installed RES capacity available. Scenarios G0 and G1 refer to Gas models, wherein scenario G0 there are gas boilers used for heating and in scenario G1 gas micro CHPs are used. Scenarios H0 and H1 refer to Hydrogen models, wherein scenario H0 polymer electrolyte membrane (PEM) electrolysis is modeled and in scenario H1 alkaline water (ALK) electrolysis is modeled. In all scenarios, electricity is produced by solar PVs and wind turbines, and electricity and heating demands are the same.

The overview of key aspects of country-specific data is presented in Table 4. Thereby, the electricity consumption is scaled to the same total in an analyzed year, based on the electricity consumption of 30 households, but the hourly data is specific for each location. In the models, it is assumed that the energy islands purchase missing electricity for the price which equals price for the final consumers (i.e., with grid and other charges included), and when they sell excess electricity to the energy traders for the price that equals price without grid and other charges (i.

Table 3
Key differences in assumptions across the scenarios.

Item \ Scenario name		B0	B1	B6	B10	G0	G1	H0	H1
Energy sources	Solar energy	x	x	x	x	x	x	x	x
	Wind energy	x	x	x	x	x	x	x	x
	Environmental heat	x	x	x	x				
	Power grid	x	x	x	x	x	x	x	x
	Gas grid					x	x		
Energy transformations and storage	Solar PVs	x	x	x	x	x	x	x	x
	Wind turbines	x	x	x	x	x	x	x	x
	BESSs (kWh per kW RES capacity)		1	6	10				
	H2 electrolysis (type)							PEM	ALK
	H2 storage							x	x
	EHPs	x	x	x	x				
	Gas boilers					x			
	Gas micro CHPs						x		
	H2 micro CHPs							x	x
Useful energy use	Electricity	x	x	x	x	x	x	x	x
	Responsive heating	x	x	x	x	x	x	x	x

Table 4
Key assumptions for country-specific data.

Item	Denmark, island Ærø	Croatia, island Vis
Electricity demand	233,344 kWh (heating not included). Source: national DSO, chart of hourly values available in Fig. 5.	233,344 kWh (heating not included). Source: national DSO, chart of hourly values available in Fig. 5.
Annual wind turbine energy production	3674.45 kWh/kW [58]	2858.11 kWh/kW [58]
Annual solar PV energy production	1068.97 kWh/kW [59]	1567.72 kWh/kW [59]
Average annual outdoor temperature	10.26 °C [60]	17.97 °C [60]
Weighted average cost of capital	6% [61]	12% [61]
Cost of electricity from the grid	0.29 EUR/kWh [62]	0.13 EUR/kWh [62]
Revenue for selling electricity to the grid	0.04 EUR/kWh [63]	0.05 EUR/kWh [64]
Cost of natural gas from the grid	0.085 EUR/kWh [65]	0.038 EUR/kWh [65]
CO2 emission factor electricity grid	0.210 kgCO2/kWh [66]	0.177 kg CO2/kWh [66]
CO2 emission factor natural gas	0.202 kgCO2/kWh [67]	0.202 kgCO2/kWh [67]

e., power exchange price decreased for the trader's margin). It is assumed that fixed prices are defined.

Charts of the hourly values for electricity demand, outdoor temperature as well as of the wind turbine energy production and solar PV energy production are presented in Fig. 5.

Key techno-economic values of the analyzed technologies in the models are presented in Table 5. In all models, it is assumed that there are 30 households, and in each case, the heating output of the used technologies is 10 kW per household. The comfort band of minimum indoor temperature and maximum indoor temperature is set to 19 °C and 24.7 °C, respectively – which was set based on the analyzed group of customers in [30], and the penalty for every °C of temperature deviation is set to 30 EUR [30] to avoid temperature deviations. The assumed capacity of hydrogen storage is 12.000 kWh, and the rated power of the electrolysis 100 kW.

4.2. Results and discussion

Results are grouped in line with the presented methodology, and used indicators are Energy potency indicator, Self-sufficiency indicator, Levelized cost of energy consumed, and CO_2 intensity. The results show values for different geographical locations as well as sensitivity analysis for different installed capacities of variable RES and the sensitivity analysis for different ratios of installed wind and solar power capacity for electricity production. Due to the large number of numerical results for modelled MECs, only graphical representations are shown, while the numerical values are available in Supplementary materials.

4.2.1. Energy potency indicator

The overview of the Energy potency indicator for the analyzed scenarios is shown in Fig. 6. For the DK location, scenario B10 reached the best (lowest) E_{pot} of almost 0.30 for the case where the ratio of installed capacities of wind and solar power plants equals 2:1 (Fig. 6e). Particularly, in the point where RES electricity production equals electricity consumption, E_{pot} reaches a value of 0.32 in scenario B10. It is due to the fact that wind production in DK is significantly higher and correlates well with the demand, which peaks in winter (Fig. 5a and c). Further, the ability of BESSs as a flexibility option allows the efficient storage of surpluses of electricity to be used when there is no adequate production from variable RES. Use of natural gas for heating and electricity production in DK location minimizes the E_{pot} to the level of 0.58 in the cases where the ratio of installed capacities of wind and solar power plants equal 1:1 (Fig. 6a) and 2:1 (Fig. 6e). E_{pot} does not reach lower values primarily because use of natural gas is considered as an import to the location so it's use increases imports and therefore increases indicator E_{pot}. Also, it is evident that the use of micro CHPs (scenario G1) does not significantly improve E_{pot} compared to the use of gas boilers (scenario G0). Use of hydrogen energy vector proves to be less suitable in terms of E_{pot}, as it only in case where the ratio of installed capacities of wind and solar power plants equals 2:1 (Fig. 6e) reaches below 0.60 for the more efficient H1 scenario. Interestingly, in the point where RES electricity production is higher by 20% compared to electricity consumption, due to the fact that significant losses in energy transformations.

In the HR location, E_{pot} reaches the best (lowest) level (below 0.30) in the case when the ratio of installed capacities of wind and solar power plants is equal to 1:2 (Fig. 6d) and for B10 scenario, where BESSs are used as flexibility option. Particularly, in the point where RES electricity production equals electricity consumption, E_{pot} reaches a value of 0.29 in scenario B10. Electricity production from solar power plants (Fig. 5d) correlates well with the electricity demand on a Croatian island Vis, especially during the summer when it is the peak tourist season (Fig. 5a) and outdoor temperatures are high (Fig. 5b), contrary to the DK location. Use of natural gas for heating and electricity production in HR location minimizes the E_{pot} to the level of 0.59 in for the cases where the ratio of installed capacities of wind and solar power plants equal 1:1 (Fig. 6b). Similarly as in the DK location, E_{pot} does not reach lower values

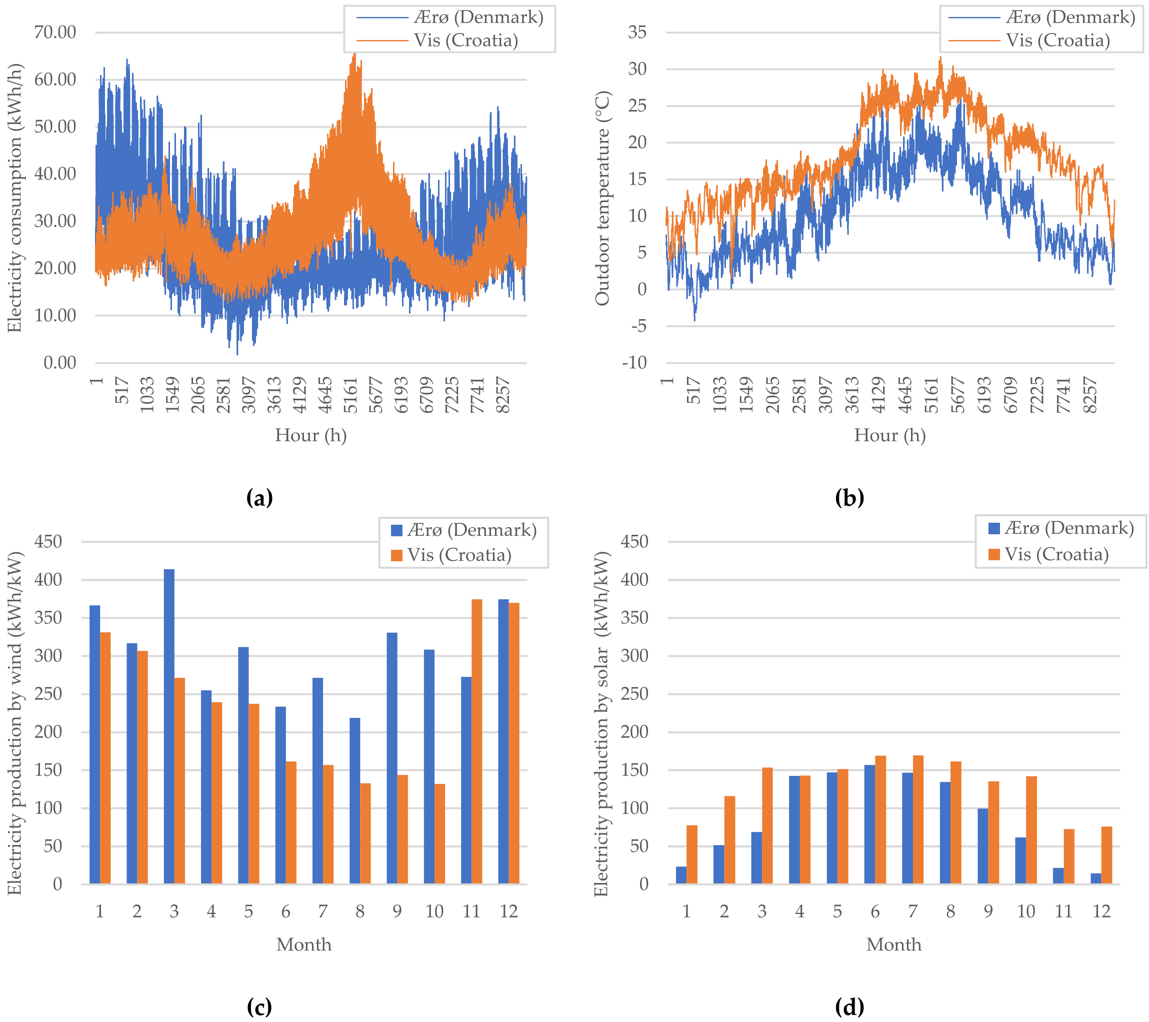


Fig. 5. Comparison of input data for the case study for island Ærø (Denmark) and island Vis (Croatia): (a) Electricity consumption; (b) Hourly outdoor temperature; (c) Monthly specific electricity production from wind power plants; (d) Monthly specific electricity production from solar power plants.

primarily because use of natural gas is considered as an import. Use of hydrogen energy vector proves to be more competitive in terms of E_{pot}, compared with the use of natural gas and compared with the DK location, as it reach the value of 0.56 in case where the ratio of installed capacities of wind and solar power plants equals 2:1 (Fig. 6f) for the H1 scenario, it is due to the fact that hydrogen can be used as a seasonal storage of energy produced during the summer and therefore minimize the missing energy during the winter period.

4.2.2. Self-sufficiency indicator

The overview of the Self-sufficiency indicator for the analyzed scenarios is shown in Fig. 7. For the DK location, scenario B10 show the best (highest) E_{SS} for all ratios of production and consumption and for all cases of ratio of installed capacities of wind and solar power plants (Fig. 7a, c, e). However, for the point where RES electricity production doubles electricity consumption, E_{SS} still does not reach 1.00, but it equals 0.99. It is due to the fact that there are still some energy missing in certain hours. At the end of the chart, in the point where RES electricity production equals electricity consumption times 4, E_{SS} equals 1.00 for scenarios B1, B6 and B10, but not for the scenario B0, as despite the significant overproduction from RES, there are still hours when electricity has to be imported. By the use of natural gas for heating and electricity production in DK location, the self-sufficiency of the MECs cannot be reached if the natural gas is imported and therefore for neither case E_{SS} for scenarios G0 and G1 goes over 0.8. Use of hydrogen energy vector proves to be better in terms of E_{SS} compared to the use of natural gas only after the point where electricity production is higher than electricity consumption, as before that point significant losses in energy transformations lead to more energy imports than in scenarios G0 and G1. Scenarios H0 and H1 are still below scenarios where use BESSs are foreseen (scenarios B1, B6, B10). It is because hydrogen is used primarily for heating and not only electricity production in the modelled scenarios. In the point where electricity production equals consumption, maximal E_{SS} is for the B10 scenario and equals 0.84 in the case when the ratio of installed capacities of wind and solar power plants is equal to 2:1 (Fig. 7e), while the lowest is for scenario G1 and H0 and equals 0.57 in the case when the ratio of installed capacities of wind and solar power plants is equal to 1:2 (Fig. 7c).

For the HR location, scenario B10 also show the best (highest) E_{SS} for all ratios of production compared to consumption and for all cases of ratio of installed capacities of wind and solar power plants (Fig. 7b, d, f). By the use of natural gas for heating and electricity production in HR location, the self-sufficiency of the MECs also cannot be reached if the natural gas is imported, but the indicator comes closer to 1 than in DK case as heating needs and therefore gas consumption are lower. Use of hydrogen energy vector proves to be better in terms of E_{SS} compared to the use of natural gas and compared to the scenario without BESSs (B0), but scenarios H0 and H1 are still below scenarios where use BESSs are foreseen (scenarios B1, B6, B10). Similarly as in the DK case, it is due to the fact that hydrogen is used primarily for heating and not only

Table 5
Key assumptions on the characteristics of technologies.

Item	Specific investment costs	Specific annual operative costs	Lifetime	Additional information
Wind turbine	1350 EUR/kW	32 EUR/kW	25 years	Ref. [68]
Solar PV	1100 EUR/kW	22 EUR/kW	25 years	Ref. [68]
BESS	255 EUR/kWh	3.57 EUR/kWh	10 years	Ref. [68] Roundtrip efficiency: 90% Max SoC: 90%, Min SoC: 0% Capacity at the end of the lifetime: 80% for DK, 70% for HR [69]
EHP	780 EUR/kW th	15.6 EUR/kW th	20 years	Ref. [69] Assumed coefficient of performance: 2.5
Gas boiler	420 EUR/kWth	8.4 EUR/kWth	25 years	Ref. [70] Efficiency: 90%
Gas micro CHP (internal combustion engine)	2400 EUR/kWe	48 EUR/kWe	20 years	Ref. [70] Electrical efficiency: 22% Thermal efficiency: 70%
Hydrogen PEM electrolysis	950 EUR/kW	19 EUR/kW	20 years	Ref. [71] Efficiency (LHV): 60%
Hydrogen ALK electrolysis	620 EUR/kW	12 EUR/kW	20 years	Ref. [71] Efficiency (LHV): 66%
Hydrogen storage tank	14 EUR/kWh	0 EUR/kWh	25 years	Ref. [72]
Hydrogen micro CHP	15,000 EUR/kWe	0.115 EUR/kWhe	20 years	Ref. [68] Electrical efficiency: 37% Thermal efficiency: 52%

electricity production in the modelled scenarios. In the point where electricity production equals consumption, maximal E_{SS} is for the B10 scenario and equals 0.85 in the case when the ratio of installed capacities of wind and solar power plants is equal to 1:2 (Fig. 7d), while the lowest is for scenario G1 and G0 and equals 0.60 in the case when the ratio of installed capacities of wind and solar power plants is equal to 1:2 (Fig. 7d).

4.2.3. Levelized cost of energy consumed

The overview of the $LCOE_{consum}$ indicator for the analyzed scenarios is shown in Fig. 8. The $LCOE_{consum}$ of MESs with the use of hydrogen as an energy carrier is evidently highest in both locations and for all cases. It is due to the high investment cost in electrolysis, storage and hydrogen micro CHP. Therefore, in these scenarios $LCOE_{consum}$ is significantly over the retail electricity price of 0.29 EUR/kWh for DK and 0.13 EUR/kWh for HR (Table 4).

For the DK location, all scenarios show a decrease in $LCOE_{consum}$ from the point where there is no RES installed to the point where the ratio of RES installed compared to electricity consumption equals 1:1. After that point, in scenarios B6 and B10 $LCOE_{consum}$ grows significantly, but in other scenarios only moderately. This can be explained due to the relatively high retail electricity price in DK, low weighted average cost of capital, and high capacity factor for wind power plants, it is economically feasible to install power plants whose energy is primarily intended for the own use at the locations. In the point where electricity produced equals electricity consumed, $LCOE_{consum}$ for H0 and H1 is in range of 1.23 and 1.27 EUR/kWh. For G0 and G1 scenarios it is between 0.16 and 0.23, out of which the lowest is for the case where the ratio of wind and solar installed capacity equals 1:2 and scenario G0, and the highest is in the case where the ratio of wind and solar installed capacity equals 2:1 and in scenario G1. The value of $LCOE_{consum}$ in scenarios with the use of BESSs greatly depend on installed capacities of BESSs, as for example it equals 0.30 in scenario B10 compared to 0.20 in scenario B1 (50% higher) in the case where the ratio of wind and solar installed capacity equals 1:1.

In the HR location, initial electricity cost (without installed wind and solar power plants) is lower compared to the DK case, due to the fact that retail electricity price is lower (Table 4), except in scenarios where hydrogen is utilized. In those scenarios significantly higher weighted average cost of capital in HR (12% in HR compared to 6% in DK, Table 4) leads to the higher $LCOE_{consum}$. Also, it stands out that $LCOE_{consum}$ in HR case grows sharply with the growth of installed RES capacity. It is due to the higher weighted cost of capital and a lower capacity factor of wind power plants, meaning production is lower for higher levelized cost of investments. The capacity factor for solar power plants is higher in the HR case (Fig. 5d) but does not offset lower wind capacity factor and effects of the higher cost of capital. In the point where electricity produced equals electricity consumed, $LCOE_{consum}$ for H0 and H1 in HR location is in range of 1.95 and 1.99 EUR/kWh. For G0 and G1 scenarios it is between 0.19 and 0.27. The value of $LCOE_{consum}$ in scenarios with the use of BESSs greatly depend on installed capacities of BESSs, as for example it equals 0.42 in scenario B10 compared to 0.24 in scenario B1 (75% higher) in the case where the ratio of wind and solar installed capacity equals 1:1.

The scenario where gas boilers are used for heating (Scenario G0) and the scenario where EHPs are used for heating, without BESS (Scenario B0) show lowest $LCOE_{consum}$ in both locations and in all cases. It is due to the fact that in those scenarios, investment costs are lowest which leads to the low $LCOE_{consum}$. On the other hand, E_{pot} and E_{SS} are relatively unfavorable for those scenarios, meaning that the planners have to make decisions according to particular priorities. A compromise solution can be found in the B1 scenario, which shows very good performance in both metrics.

4.2.4. CO_2 intensity

The overview of the CO_2 intensity indicator for the analyzed scenarios is shown in Fig. 9.

For the DK location (Fig. 9a, c, e), initial value of $CO_{2consum}$ (point without RES production) is the highest for the scenarios H0 and H1 (0.29 and 0.28 kgCO2/kWh respectively) due to the fact that highest amount of electricity has to be imported due to high losses in energy transformations. For the scenarios G0 and G1 in that point $CO_{2consum}$ amounts to 0.21 as certain amount of natural gas is consumed, and for scenarios B0, B1, B6 and B10 it equals 0.19 as the use of heat pumps is efficient way for heating and lowest amount of electricity has to be imported. With the growth of the RES production, around point where production equals consumption, $CO_{2consum}$ for scenarios H0 and H1 decrease below scenarios G0 and G1 as impact of electricity imports (in H0 and H1 scenarios) become lower than impacts of consumption of natural gas (in G0 and G1 scenario). Reaching carbon neutrality mostly coincides with the reaching of the energy self-sufficiency for the analyzed MECs.

For the HR location (Fig. 9b, d, f), initial value of $CO_{2consum}$ (without RES) is the highest for the scenarios H0 and H1 scenarios (0.20 kgCO2/kWh), similarly to the DK location, but lower due to the lower emission footprint in the power sector (Table 4). For the scenarios G0 and G1 in that point, $CO_{2consum}$ amounts to the 0.18, and for scenarios B0, B1, B6 and B10 it equals 0.17. When comparing the results for location in DK and HR, the lower difference between the $CO_{2consum}$ is evident between the scenarios for the HR location. It is because heating needs are significantly lower in HR and there is no such a need for seasonal storage in HR meaning that there is less use of hydrogen or natural gas for heating and therefore losses, energy consumptions and CO_2 emissions don't make such a difference between the scenarios in the HR location as in DK location.

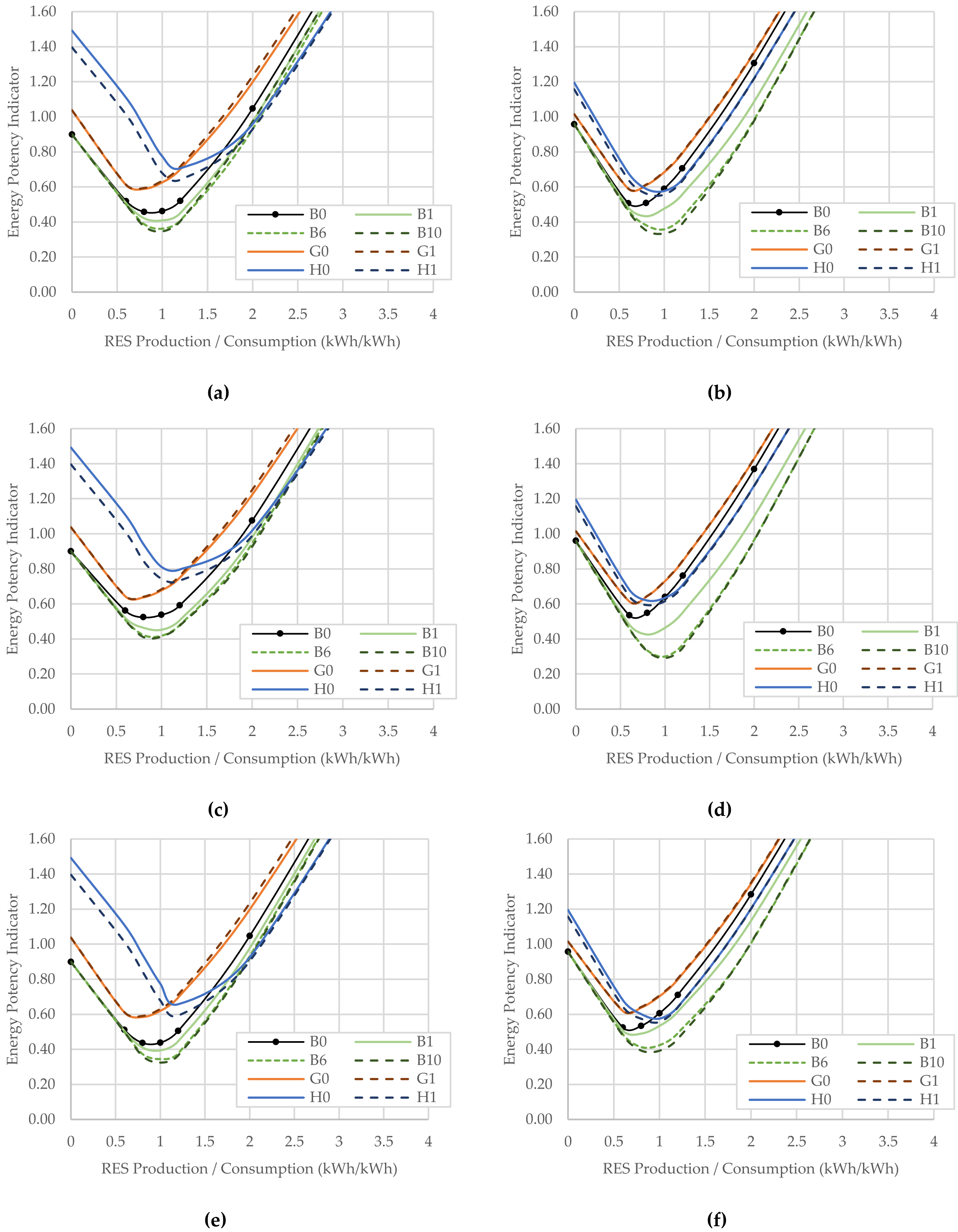
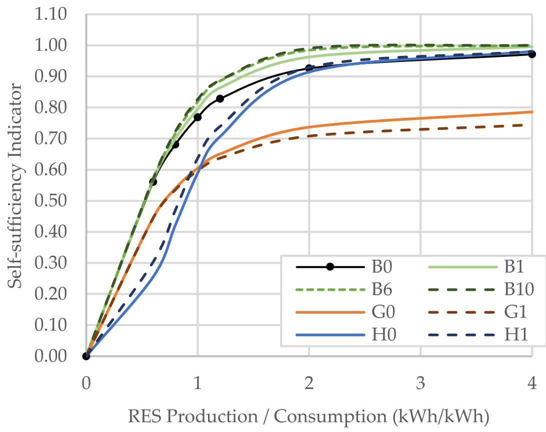


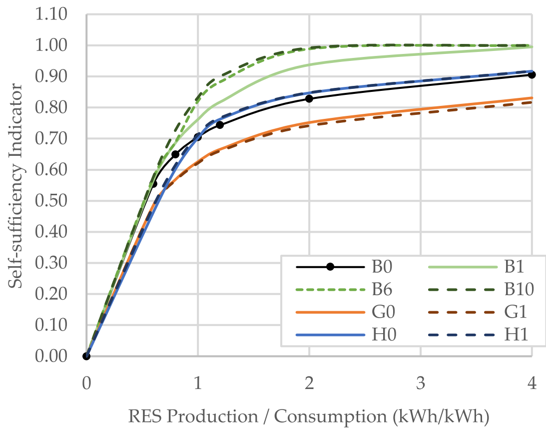
Fig. 6. Analysis of the dependency of the energy potency indicator on the ratio of annual RES energy production and annual energy consumption (kWh/kWh) for different geographical locations, scenarios and ratios of wind and solar installed capacities (hereafter: ratio): (a) DK location, ratio 1:1; (b) HR location, ratio 1:1; (c) DK location, ratio 1:2; (d) HR location, ratio 1:2; (e) DK location, ratio 2:1; (f) HR location, ratio 2:1.

5. Conclusions

The paper defines indicators for estimation of the techno-economic and environmental potential of multi-energy vectors in decarbonization of energy islands. The indicators are calculated from the results of the mixed-integer linear programming unit-commitment models of multi-energy vectors and are assessed in the extensive case study analysis. The case study analysis consists of eight scenarios with different multi-energy vectors and two locations: island Ærø in Denmark and island Vis in Croatia. The results point out that all modeled multi-energy vectors have advantages and disadvantages. The main insights are discussed below:



(a)



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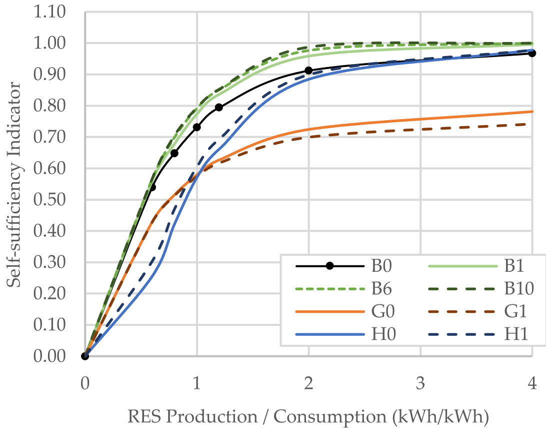

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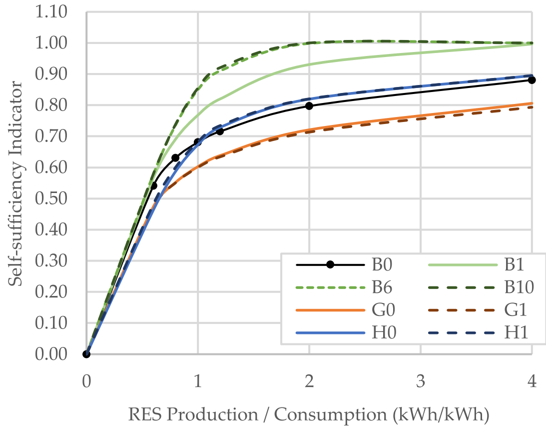

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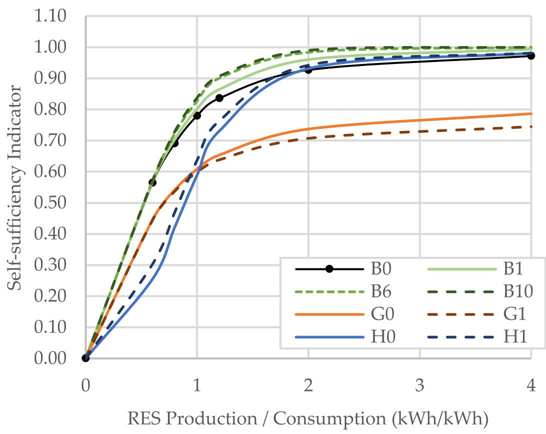
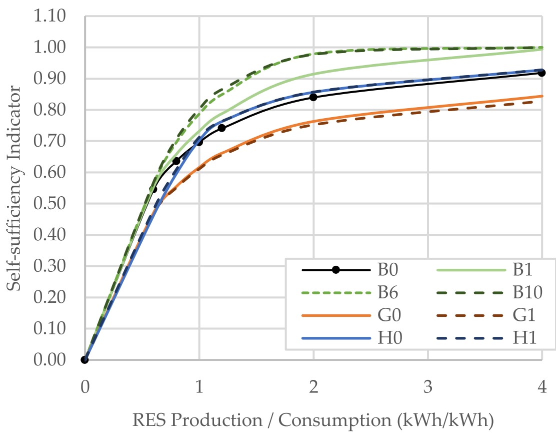


(e)



(f)

Fig. 7. Analysis of the dependency of the energy self-sufficiency indicator on the ratio of annual RES energy production and annual energy consumption (kWh/kWh) for different geographical locations, scenarios and ratios of wind and solar installed capacities (hereafter: ratio): (a) DK location, ratio 1:1; (b) HR location, ratio 1:1; (c) DK location, ratio 1:2; (d) HR location, ratio 1:2; (e) DK location, ratio 2:1; (f) HR location, ratio 2:1.

- BESSs can provide best energy potency, ensure self-sufficiency with the lowest needed RES production capacity, and can decrease carbon footprint, but the magnitude of benefits is directly reflected in growth of costs. Main impact on the costs comes from the BESSs, while correlation of the supply and demand patterns have key effects on the generated surpluses and missing electricity and therefore on the necessity of the BESSs.
- Use of natural gas as a transition fuel for MECs shows economic attractiveness due to the proven technology and low costs but benefits are offset by the poor energy potency, inability to reach self-sufficiency (in MECs where natural gas is imported) and remaining carbon footprint due to the gas combustion.
- Use of hydrogen energy vector can provide numerous flexibility options, decrease excess of electricity but high transformation losses

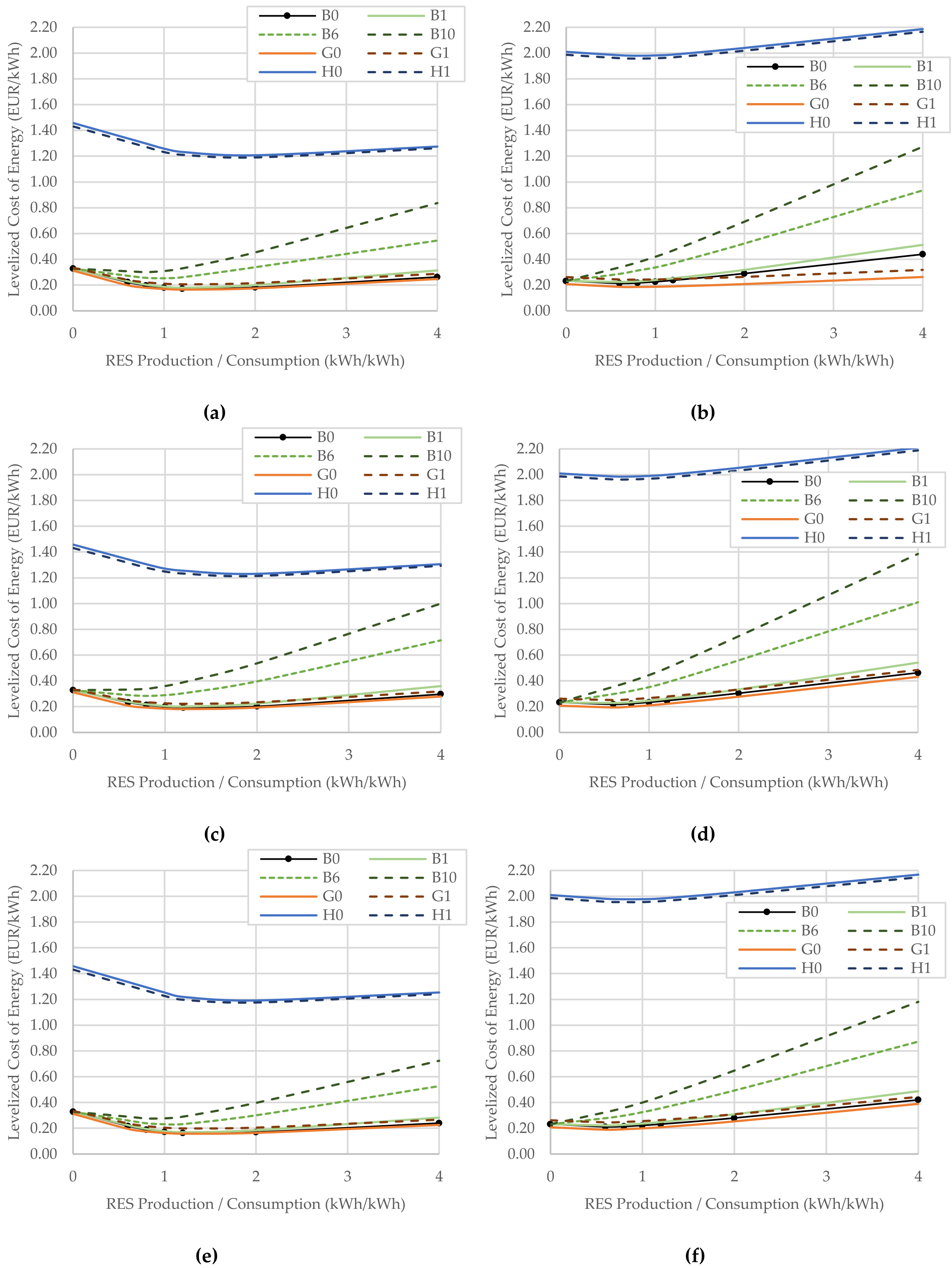


Fig. 8. Analysis of the dependency of the Levelized cost of the energy consumed (EUR/kWh) on the ratio of annual RES energy production and annual energy consumption (kWh/kWh) for different geographical locations, scenarios and ratios of wind and solar installed capacities (hereafter: ratio): (a) DK location, ratio 1:1; (b) HR location, ratio 1:1; (c) DK location, ratio 1:2; (d) HR location, ratio 1:2; (e) DK location, ratio 2:1; (f) HR location, ratio 2:1.

rank the solution near the natural gas in terms of energy potency. However, regarding potential for ensuring self-sufficiency and reduction of carbon footprint, use of hydrogen energy vector proves to be superior to the use of natural gas (even though below use of BESSs). The analysis of the $LCOE_{consum}$ showed high cost for MECs using hydrogen micro FCCHPs as heating devices. However, market reports estimate the potential for cost reductions in the future [68], as there are still significant opportunities for innovation and development.

Geographical locations have significant impacts on the indicators, as different demand patterns and RES supply potential prove to be key for

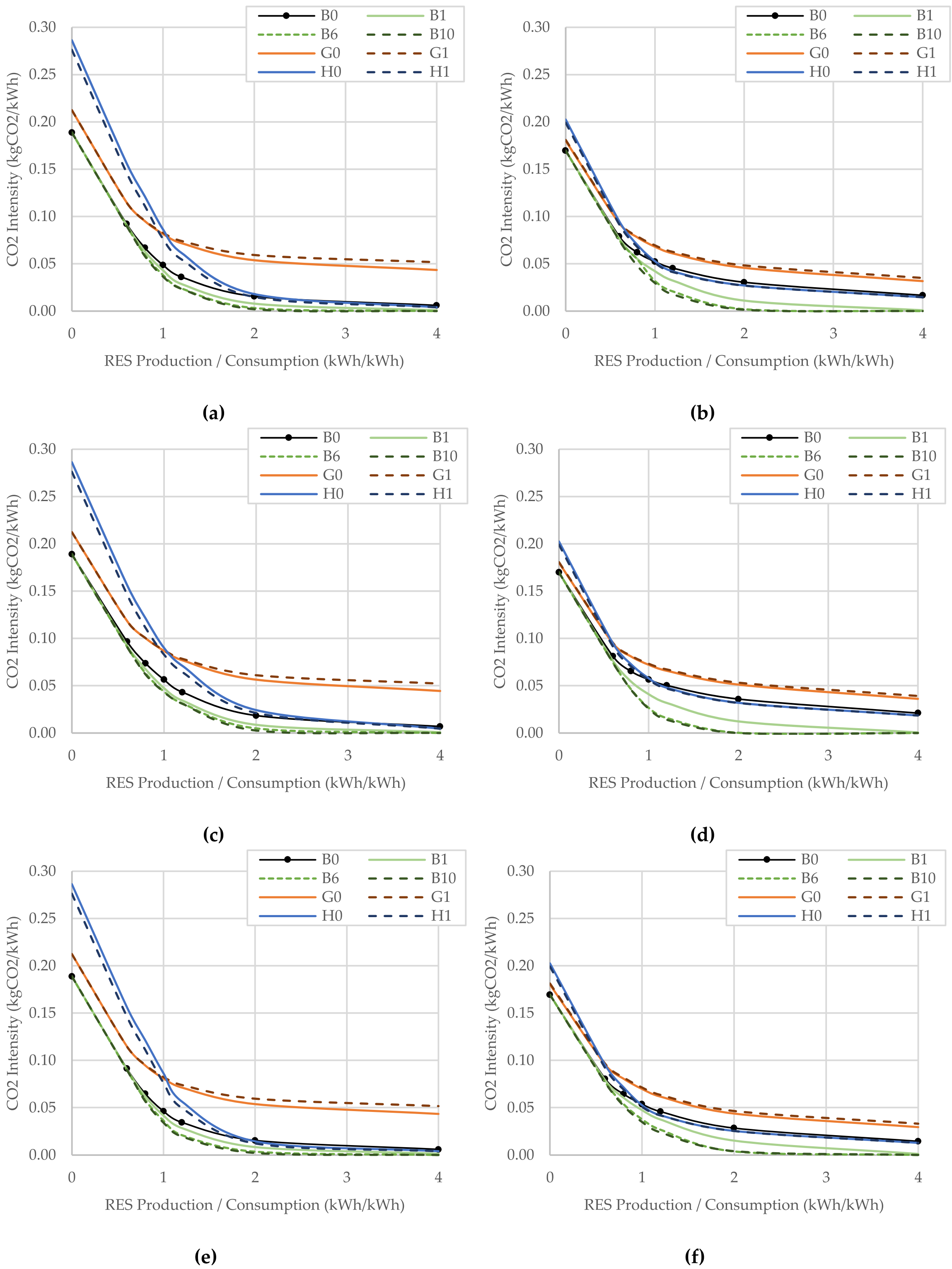


Fig. 9. Analysis of the dependency of the energy CO2 intensity (kg CO_2/kWh) on the ratio of annual RES energy production and annual energy consumption (kWh/kWh) for different geographical locations, scenarios and ratios of wind and solar installed capacities (hereafter: ratio): (a) DK location, ratio 1:1; (b) HR location, ratio 1:1; (c) DK location, ratio 1:2; (d) HR location, ratio 1:2; (e) DK location, ratio 2:1; (f) HR location, ratio 2:1.

determining the potency of different energy vectors for integration of variable RES in MECs. The main differences between geographical locations are summarized as follows:

- The ratio of installed wind and solar capacity 2:1 is more favorable for the DK location, while the ratio of installed wind and solar capacity of 1:2 is more favorable for the HR location, as the peak demand in DK is during the winter period, when there is more wind production, while in HR locations, the peak demand is during the summer period, when there is more solar production.
- Differences in weighted average cost of capital, market electricity prices, and technology capacity factors between locations have

strong impacts on $LCOE_{consum}$ as a chosen indicator of cost-effectiveness of investments in MECs. Decreasing the cost of capital is one of the areas where policymakers can intervene to speed up investments [61], and that would be important measure in HR due to higher perceived risks. In terms of $LCOE_{consum}$, the simplest solutions analyzed in scenarios B0 (no BESSs, only EHPs for heating) and G0 (gas boilers heating) show the best cost performances on both locations, however, the differences with more complex and flexible solutions could be decreasing due to the technological advancements [68].
- Key differences in performances between the analyzed multi-energy vectors in terms of impacts on reducing CO_2 emissions steam from different abilities of energy vectors to reduce fuel combustion, energy losses and energy imports for different supply–demand patterns and heating needs. The lowest CO_2 intensity was found for the HR case where EHPs are utilized as heating sources and BESS as a flexibility option.

Future research directions could include the integration of the transport sector in modeling of MECs, which would mean modelling the use of energy vectors beyond electricity and heating and adding additional flexibility. Additionally, the presented long-term models could be experimentally validated and fine-tuned in a real-life setup for operational purposes, focusing on shorter time steps, and details of technical constraints and uncertainties. Further, application of innovative transactive energy management systems [73] could be studied for MECs, as well as potential grid stability issues.

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CRediT authorship contribution statement

Lin Herenčić: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Matija Melnjak:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing - original draft, Writing - review & editing. **Tomislav Capuder:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data curation, Writing - review & editing, Supervision, Project administration, Funding acquisition. **Ivan Andročec:** Validation, Resources, Data curation, Writing - review & editing. **Ivan Rajšl:** Validation, Resources, Data curation, Writing - review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enconman.2021.114064.

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Overview of the main challenges and threats for implementation of the advanced concept for decentralized trading in microgrids

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***Abstract*—Current trends of decentralization, digitalization, decarbonization and democratization in the power sector enable new business models featuring active participation of the distributed energy resources and distributed storage systems. Moreover, individual and small market participants acting as peers want to trade electricity within local communities. Peer-to-peer decentralized electricity trading in microgrids using distributed ledger technology could be a solution for establishing local markets and accelerating the integration of distributed energy resources. In this paper, main technical, economic, social and regulatory challenges and threats for implementation of the peer-to-peer concept for electricity trading in microgrids are stated and discussed.**

***Keywords*—blockchain, electricity, microgrid, peer-to-peer, trading**

I. INTRODUCTION

Important, relatively novel features of the power system development are decentralization, digitalization, decarbonization and democratization. They are reflected in indicators such as growth of the number of distributed energy resources (DERs) [1], development of the smart grids [2], growth of the renewable energy sources (RESs) [3] and increase in the active participation of citizens [4]. By the active participation, consumers/prosumers can improve their economic position but also contribute to the power system stability. Consumers are becoming providers of flexibility and positive effect of their active participation can lead to the balancing of the local grid and rest of the power system, as well as on increasing the potential for integrating RESs [5].

To facilitate these trends, electricity markets will have to adapt [6]. These trends are recognized and further fostered by the European Union's (EU's) "Clean energy for all Europeans" package [7] where a set of legislative changes has been proposed with a view to put consumers in the first place ([8] defines term "active customers") and with a goal to continue pursuit for the long-term climate-energy objectives of the EU. The package is characterized by the support for flexible and decentralized production, increased dependence between the system and the ability of end-users to actively participate in the power market by means of demand response, energy storage, own energy production, etc. Some of the provisions are also important for the revised responsibilities of the distribution system operators (DSOs).

The aforementioned benefits for power system and citizens can be achieved through the coordination of consumers/prosumers, which is commonly realized through the concept of virtual power plants (VPPs) and aggregators. There are various strategies for consumer/prosumer management by aggregators. However, common disadvantages, examined in [9], include requirement for top-down design and top-down management from a subject which is often not in the best position, doesn't have all the data or is not motivated enough to use full potential of coordination of active consumers and to incorporate their features and preferences in management strategies.

A solution to the aforementioned challenge could be a concept that allows users, such as consumers, producers or prosumers (acting as peers) to trade electricity within community microgrids. Moreover, the idea of a federated power plant (FPP) as a VPP formed through peer-to-peer (P2P) electricity trading between self-organizing prosumers has been introduced to address the issues faced by top-down strategies for coordinating VPPs and to tap into the potential value added of P2P electricity trading [9]. This concept could be achieved through a P2P trading platform using distributed ledger technology as an information system for processing and recording of the transactions in a trusted and decentralized way [10].

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On this track, the new Directive (EU) 2018/2001 on the promotion of the use of energy from renewable sources [11] explicitly defines P2P trading of renewable energy and stipulates that P2P trading of market participants should not be subject to discriminatory or disproportionate procedures and charges.

Moreover, an advanced P2P concept for electricity trading (P2PCET) was proposed in [12] with the following key features: automated execution and settlement of transactions between the peers in a microgrid based on the contracts with conditions that are dynamically defined to ensure both supply and demand side management, while satisfying system constraints, and realize an economical, sustainable, and reliable operation of microgrids. Therefore, the pricing algorithms that set conditions for fine-tuned contracts should be integrated into the P2PCET and take into account and/or manage optimal power flow (OPF), grid congestion, flexibility, supply and demand balance, forecasting, storage facilities, balancing activates, demand-side management and socio-economic preferences of the peers. The proposed concept allows different kinds of peers to be included in P2P trading, such as DERs, distributed storage systems (DSSs), electric vehicles (EVs), households, electricity-heat boilers, etc. [12]

The first implementation of the concept, similar to the P2PCET, was applied in limited scope in 2016 in Brooklyn Microgrid project in New York where P2P electricity trading between neighbors was enabled [10]. To date, many new pilot projects have been initiated and research is ongoing [13]. Existing research papers discuss various aspects of P2P microgrid electricity trading, such as necessary market components [10], P2P platform architecture and bidding system [14], energy-sharing models with price-based demand response [15], capabilities of blockchain technology [16], potential of game-theoretic approaches for P2P trading [17], energy management for P2P trading [18], etc.

The latest research papers list areas which need further research, such as optimal market design and needed regulatory changes for P2P electricity trading [9]; allocation and pricing mechanisms for P2P electricity trading that values market participants' utility functions and effects on the power flows and energy balancing [10], [18]; socio-economic impact on participants in the P2P energy trading [10]; scalability of P2P energy trading platforms [18]; technological evaluation of smart contracts and distributed ledger technology as information and communication technology (ICT) used for microgrid energy markets [17].

The purpose of this paper is to present an overview and analysis of key technical, economic, regulatory and social challenges with the goal of detecting key requirements and barriers for the implementation of the P2PCET. Challenges are grouped based on a proposed four-layer system architecture for P2P energy trading platforms [14]. The listed layers are the power grid layer; the ICT layer; the control layer; and the business layer as depicted in Fig. 1.

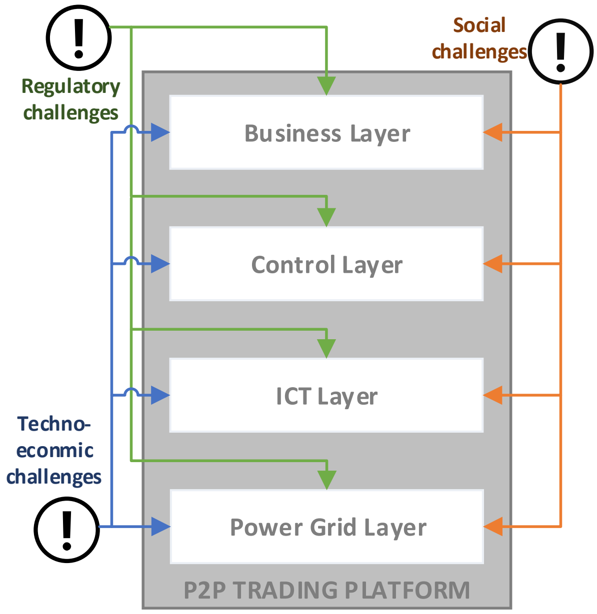

Figure 1: Overview of the layers and types of challenges for the implementation of the P2PCET

II. POWER GRID LAYER

The power grid layer was defined in [14] as physical elements of the power system, which include grid, transformers, loads, DERs, DSS, etc. These elements form the physical basis where P2P energy trading can be implemented.

A. The ability of grid infrastructure to facilitate grid connection and operation of loads, DERs and DSSs

According to [9], different types of platforms support P2P energy trading: 1) retail supplier platforms; 2) vendor platforms; 3) microgrid and community platforms and 4) public blockchain platforms, but not all of them imply P2P trading within the microgrids as it is understood in the P2PCET [12].

There are various definitions and classifications of microgrids [19], out of which broadly cited definition was defined for the U.S. Department of Energy by the Microgrid Exchange Group and associated researchers and experts [20], as follows: "[A microgrid is] a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island mode." According to [19] three conditions follow from this definition: 1) it has to be possible to locate the internally interconnected part of the power system around where the clear electrical boundaries can be drawn; 2) the resources and loads within that microgrid have to be operated in harmonization with each other; and 3) that microgrid can function in island mode and grid-connected mode. The definition doesn't set rules on types or capacities of connected resources and technologies in the microgrid.

In modern distribution grids, DERs and DSSs are common, but it should be noticed that traditionally distribution networks have been designed to passively take power from higher voltage levels and distribute it to end customers at lower voltage levels. They were dimensioned for specific maximum peak load under the assumption of known power flow direction. Moreover, the usual DSO network planning and investment strategy were conceived without DERs, DSSs or prosumer's behavior in mind. Under such investment principles, DSOs preferred to address the requirements of increased demand by investing in grid development, often leading to over-investment and low utilization of the network [21]. The impact of DERs, DSSs, and vehicle-to-grid (V2G) can have positive effects on the grid [22], but also bring challenges [23]. Benefits can include improvements in areas such as reactive power support, active power regulation, tracking of variable RES, load balancing, and current harmonic filtering [22]. Based on these technologies, ancillary services, such as voltage and frequency control and spinning reserve can be provided. To support these functions, distribution equipment and ICT should be installed to actively support grid operation, which is discussed in more detail below in ICT and control layers. Therefore, challenges could be in possibility of the grid infrastructure to facilitate the bidirectional power flows and connections of the loads, DERs and DSSs.

On a regulatory level, grid codes are a technical specification that defines the parameters a facility connected to a public electric grid has to meet in order to ensure the safe, secure and economic proper functioning of the electric system. Since the P2PCET aims to provide better management and control of individual grid users, more DERs could be connected to the power grid by implementing the P2PCET. Therefore, grid codes should be amended to facilitate more advanced interactions of grid users and third parties.

B. Installed power capacity of DERs and DSSs in the microgrid

To fulfill the condition for the microgrid [20] to be able to operate in the island mode, DERs must be in the microgrid. DERs can be classified on various grounds, such as whether they are conventional or non-conventional [1]; renewable or non-renewable [1]; variable or dispatchable [24]; inverter-based or synchronous-based [23]. DERs include renewable solar photovoltaic systems, wind power plants, hydropower plants, biomass and biogas power plants but also non-renewable thermal power plants can be parts of the microgrids. In the grid-connected mode of the microgrid, the main grid functions as a flexible generator and, if bidirectional power flows are allowed, it serves as a flexible load/storage system.

Trends and studies [25] suggest that by 2050, 50% of EU residents could be generating their own renewable energy. However, past installations of DERs were mainly driven by support schemes for RES and there were significant differences across the countries on policy mechanisms [3] and which led to significant differences in installed power capacity and types of RES. Lack of or relatively low installed capacity of DERs (in comparison with the demand in particular microgrids) can be an important barrier in many potential locations for implementation of P2PCET. Moreover, support schemes usually result in DERs that do not actively participate in electricity markets (e.g. feed-in systems) and/or may have additional limitations.

To facilitate the integration of variable RES, such as solar and wind power plants, DSSs can be of great value. There are various technologies for DSSs [26], among which batteries are increasingly becoming an economically affordable technology [27] for demand shedding and for the regulation of power system operation by providing fast frequency response (FFR). Given their scalability, they stand out as a suitable solution for application in microgrids and with their favorable response times at the millisecond scale they could reduce the need for physical inertia by providing virtual inertia through FFR. Therefore, DSSs are an important part of the implementation of the P2PCET even though their role can be compensated with the other providers of inertia and flexibility on generation-side and on the demand side, such as dispatchable generation units and demand-side management as well as V2G.

In the case of operation of the microgrid in grid-connected mode, the main grid can provide inertia and functions of a flexible generator and if bidirectional power flows are allowed, as a flexible load/storage system. Hence, favorable locations for the implementation of the P2PCET are microgrids with DERs and/or DSSs.

Moreover, multi-energy systems and conversion of electricity to other forms, such as power-to-heat, power-to-gas or power-to-hydrogen can be considered for more advanced systems as a means of demand-response and energy storage with a goal to facilitate higher integration of variable RES.

C. The connection of the microgrid with the main grid

The definition of a microgrid [20] implies an ability of microgrids to operate in connection with the main grid as well as in the island mode. The P2PCET was foreseen to operate in a grid-connected mode, mainly so that the microgrid can participate in the frequency control and ancillary service markets and provide grid stability and system security to the main grid through the fine-tuned energy trading which can provide added value for the users. In the cases where microgrids operate in island mode, the P2PCET can be implemented, but in scope reduced for the ability to provide services to the rest of the grid. Moreover, lasting inability to use the main grid for the regulation of the microgrid would set the more stringent requirements for the security and regulation in the microgrid which could lead to higher investment and operation costs.

The challenges of facilitating bidirectional power flows can be visible on the connection points of the microgrid with the main grid. The integration of RES and consequent bidirectional power flows can lead to power quality issues and a need for additional investments in the grid infrastructure. The major power quality issues are voltage and frequency fluctuations in such a low-inertia power system with non-firm RES capacity and lack of physical inertia. Other power quality issues involve harmonics produced by power electronic devices used in renewable energy generation [28] and significantly more switching initiated by the P2PCET.

III. ICT LAYER

The ICT layer consists of computers and other electronic equipment and systems to collect, store, use, and send data electronically. Therefore, meters and sensors collect information from the grid layer and make it possible for the ICT layer to use them.

A. Implementation and functionality of the "smart meters" between the users and the microgrid

The "smart meters" should be installed between users and the grid to facilitate the measurement and data exchange in near real-time and with a resolution that is small enough for the P2PCET. The "smart meters" can be defined in several ways. U.S. Energy Information Administration defined advanced metering infrastructure in [29] as "Meters that measure and record usage data at a minimum, in hourly intervals and provide usage data at least daily to energy companies and may also provide data to consumers. Data are used for billing and other purposes. Advanced meters include basic hourly interval meters and extend to real-time meters with built-in two-way communication capable of recording and transmitting instantaneous data." In EU smart metering system is defined as "an electronic system that can measure energy consumption, providing more information than a conventional meter, and can transmit and receive data for information, monitoring and control purposes, using a form of electronic communication" [8].

Installing smart meters on a large scale can be a significant challenge in many countries. Another question is whether such devices are technically and technologically ready to have a key role in the P2P electricity market. Also, the challenge can pose the question of ownership, as meters are usually owned by the DSOs, who set the technical specifications and install the meters, and linked to that, the challenges can be in data access and protection.

To overcome this barrier and ease the implementation of P2P trading, some projects proposed use of the "smart readers" [30], as an alternative or addition to "smart meters", which can identify appliances and their energy consumption, cost less than "smart meter" and can be incorporated with communication infrastructure to support the dynamic pricing and operation of P2P platform. However, it is still unproven if such devices would be appropriate and economically justified in a larger scale.

B. Monitoring and control devices at the user level, "behind the meter"

The sensors and control devices are needed to facilitate active demand response and leverage the flexibility potential of the electricity consumption and of DERs and DSSs that are integrated "behind the meter" [31]. Every type of load has its characteristics such as the potential for demand response, capacity and load signature [32]. In case there is no, or a small proportion of users have sensors and control devices, active participation of the peers would be limited as the peers could hardly participate in demand response.

C. Monitoring and control devices in the grid

Due to integration of DERs and monitoring and control devices into the grid, it is expected that future distribution networks will become interactive systems with connected flexible power nodes [33], "offering" part of their consumption/production to be moved in time; in return, they can receive favorable fee for provided system service. For this concept to materialize the grid should be transformed into the "smart grid", which is in [2] defined as "a modern electric power grid infrastructure for improved efficiency, reliability and safety, with smooth integration of renewable and alternative energy sources, through automated control and modern communications technologies."

Currently, in many countries, there is a lack of monitoring and control devices particularly on low-voltage (LV) distribution networks and distribution networks are mostly passive with a little information on the events downstream from distribution network substations. This lack of visibility hamstrings the capability of system control and contingency handling within regional areas, thus presenting a potential barrier for implementation of the P2PCET.

D. Communication infrastructure

Without the appropriate communication infrastructure between the metering and control devices, the P2PCET cannot be established. Therefore, it is necessary to implement the optimal technology for communication between meters and control devices "behind the meter", "smart meters" and within the "smart grid" infrastructure. Communication technologies can be divided into wired and wireless technologies. Wired technologies, such as DSL and fiber optics, have a higher data transmission rate and reliability but come at a higher installation cost. On the other hand, wireless technologies, such as Zigbee, Z-wave, GSM, and Wi-Fi are easier to deploy and with the lower installation cost. Due to the use of ever more sensors and controllers in microgrids, wireless technologies are recognized as better candidates primarily due to their lower implementation costs [34].

E. Security and speed of data storage and analytics

Secure data storage and communication and resilience to the cyber-attacks is a key requirement for the implementation of the P2PCET. The information system should have the capability of fast operation and data exchange within the system and on external inputs, e.g. on weather forecast, etc. The application of blockchain technology could be a solution to the issue. The consensus protocols to agree on ledger content combined with cryptographic hashes and digital signatures for ensuring the integrity of transactions could be the solution to minimize the system requirement and time of verification of transactions [10]. However, novelty and unproven track record in the application of the technology in the energy sector, as well as the question of scalability and trust can be a barrier for the implementation.

IV. CONTROL LAYER

The control layer should provide control functions in the microgrids. In this layer control strategies should be defined to preserve and/or increase the quality of electricity supply, system stability, the reliability of power supply and control the network power flows [14].

A. Energy management trading system

The P2PCET must integrate functions of energy management systems (EMSs) for microgrids to facilitate both supply and demand side management, while satisfying system constraints, and to realize an economical, sustainable, and reliable operation of microgrids. EMSs provide many benefits, such as generation dispatch, energy savings, reactive power support, frequency regulation, reliability to loss of load, cost-reduction, energy balance, GHG emission reduction, and enhance customer participation and customer privacy [34].

The P2PCET should provide these functions by the energy management trading system (EMTS) [10]. EMTS's main purpose is to secure the energy management in the microgrid while incorporating functionalities of EMS with the P2P trading. As a main management system of the P2PCET, EMTS needs access to the (near real-time) demand and supply data of its market participant and constant integration with the pricing mechanism to secure the reliable operation of the microgrid. EMTS should allow communication with the main grid and rest of the market to maximize the benefits for the peers in the P2PCET. Automated transactions within the P2PCET could improve management of distribution networks, reduce costs, improve security and efficiency of the distribution network by reducing unplanned power flows, grid congestion, voltage, and frequency variations. Consequently, the distribution grid becomes more flexible. Moreover, the EMTS should take account on needed capital and operation and maintenance cost for the microgrid infrastructure and incentivize the development of production capacities to ensure the short-term security and long-term adequacy and quality of power in the microgrid.

Barriers can be in data access and unproven possibility of efficient decentralization of the EMTS. Moreover, positioning of the EMTS on the power market and coordination with the roles of suppliers, aggregators or DSOs should be considered and harmonized.

V. BUSINESS LAYER

Business layer determines the rules, mechanisms, and algorithms how electricity is traded among peers and with the third parties. Various business models could be designed in a business layer to foster the P2PCET. Characteristic of this layer is that it is closely related to legislation that regulates energy markets, market participants and their roles.

A. Market organization and mechanism

Market mechanisms define the market's allocation and payment rules and provide an employable bidding language and a clearly defined bidding format [35]. Generally, P2P market models are still unproven and unevenly defined. The market mechanism should be tailored to best fit the purpose of the P2PCET with the small-time resolution to incentivize the constant demand response and optimization in the microgrids. However, it should be compatible with the market mechanisms in place for that particular grid or electricity market. Inappropriate design of market mechanism can lead to obstacles for the users and to unfulfillment of the full potential of the P2PCET. The P2PCET market mechanism must facilitate fast intraday, near-real-time negotiation and automated execution of the contracts between the peers at the favorable prices.

On a regulatory level, the P2PCET must adhere to electricity market rules to function within the (wholesale) market and/or auxiliary services market but can provide additional modes of operation for its peers. However, where existing market organization and rules restrain the potential for the implementation of the P2PCET in full scope, there could be a case for adapting them (if justified considering other impacts).

B. Electricity pricing mechanism and rules

To seize the potential of the P2PCET, appropriate algorithms for dynamic pricing should be defined and implemented to incentivize demand response and grid services by the peers. Most of the existing pilot projects implemented static pricing with the ex-ante defined price for P2P trading [10]. In theory, the aim of the P2PCET is achievement of the *strong equilibrium.* This means central clearing of the market and P2P settlement through the blockchain. If peers should and could bid with *strongly optimal* supply functions [36] in the P2PCET, is a question which needs further investigation. The significant uncertainty in demand forecasting is the issue which could be resolved with finding *supply function equilibria* (SFE) since it has been proved that supply function equilibria exist when there is demand uncertainty [37]. This enables firms to define their supply functions before they know the demand values. Also understanding of the behavior and flexibility of various DERs both temporally and spatially should be understood and integrated into the algorithms.

On a regulatory level, to support the P2PCET, dynamic pricing should be promoted as well as network charges fine-tuned to actual and proportional network usage. Currently, in many countries, DSOs are not ready for the active role of final users [21]. The P2PCET would be more viable if the energy portion of the end price is more significant and demand-response/ancillary services are valued higher. Moreover, adaptation of taxation policy (VAT, excess duty, levies) could foster the viability of the P2PCET, but like any other major policy change it could have complex impacts and it has to be done in line with allowed state aid rules ([38] defines the State aid for environmental protection and energy 2014-2020 in the EU).

C. Value added for the users

There should be a clear added value in terms of cost, security, social and/or environmental aspects for users to be motivated to take part in the P2PCET. Economic benefits could be provided by finding the SFE and usage of *strongly optimal* supply functions, while the social and environmental added value can be provided, inter alia, by allowing users to set their preferences on electricity they are willing to trade with regard of source and/or location. Practical uses of the P2PCET should demonstrate the economic benefits of DERs, DSSs and/or monitoring and control devices to motivate users to invest in equipment and participate in the P2PCET. Therefore, the implementation should be thoroughly tested and analyzed in simulations, laboratory environment and pilot projects before scaling the implementation.

VI. DISCUSSION

The P2PCET goes well with the actual trends of decentralization, decarbonization, digitalization and democratization in the energy sector since it incorporates automated initiation of electricity transactions between peers in the microgrid, integrated with an energy management system for secure load-supply and operation in the microgrid.

As analyzed above, it is evident that important challenges still exist for the implementation of the P2PCET - in the technical, economic, regulatory and social domain, as well as in each layer for P2P trading platform architecture. Most prominent issues include the still unproven functionality of P2P trading platforms, often missing ICT infrastructure in the grid and at the user level, together with the regulatory framework that can restrict the implementation and potential benefits of the P2PCET.

Future work includes the development of a simulation model of a microgrid; a laboratory setup for testing P2P concepts for electricity trading in small-scale microgrids; and real-life testing in a community microgrid. Also, challenges and barriers will be periodically reassessed and recommendations to deal with them developed.

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Peer-to-Peer Electricity Trading in Distribution Grid: Effects of Prosumer's Elasticities on Voltage Levels

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***Abstract*—Peer-to-peer electricity trading between consumers, producers and/or prosumers located in a low voltage distribution grid is a concept that goes well with the trends of democratization, decarbonization and decentralization in the power sector. However, the impacts of peer-to-peer electricity trading on voltage levels in distribution grids are still in the early stage of research. The aim of this work is to investigate effects of a near real-time peer-to-peer electricity trading in a distribution grid on voltage levels. It is analyzed if a contribution to the sustention of the voltages under limits can be achieved without security-constrained dispatch calculations for the observed time horizon and each trading period. The peer-to-peer electricity trading is simulated as an auction-based local market and implemented in the modified IEEE European Low Voltage Test Feeder where the impacts on voltage levels are analyzed for different elasticities of demand bidding curves.**

Keywords—electricity, peer-to-peer, trading, voltage stability, distribution grid, renewable energy sources

I. Introduction

Ongoing transition of the power sector from centralized system based on conventional power plants towards decentralized system based on renewable energy sources (RESs) [1], energy storage systems (ESSs) [2], information and communication technology (ICT) [3], and active participation of citizens [3] enables development of innovative business models in the power sector. Peer-to-peer (P2P) electricity trading at local energy markets (LEMs) is a concept that should provide an opportunity for electricity trading between peers (consumers, producers, prosumers) [4] in local low-voltage distribution grid [5]. That way, added value to the participants (increased global welfare), integration of RESs, improved grid stability, and auxiliary services to the rest of the power system [6, 7], could be provided. LEMs can be organized as P2P electricity trading, electricity trading through a mediator, or combination the both [4]. Further, the organization of LEMs can have only a business layer but can include also grid constraints in trading algorithms [4]. There, the application of advanced ICT and control systems are decisive [6, 8]. However, many barriers and challenges still have to be overcome to accelerate the implementation of P2P electricity trading in practice and in wider scope. Recognized challenges include management and control of P2P electricity trading to remain under network constraints and to further contribute to the stability in distribution grid, P2P electricity trading market design, market-clearing approaches and integration trading within the electricity markets [4, 9, 10, 11, 12].

Important stability concerns in grid-connected microgrids refer to voltage stability [13], and the line power flow constraints have to be respected [14]. When microgrid control functions are observed from the market design perspective, the attention has to be paid to timeframes of certain activities, as stability issues vary from milliseconds to minutes/hours. In contrast, the time intervals for electricity trading on markets are commonly not lower than 15 minutes, only in some cases the near-continuous trading is conducted, where energy is dispatched every 5 minutes [15, 16]. Therefore, only some of the control functions have the same timeframe as the electricity trading (unit commitment, economic dispatch, optimal power flow and Volt/VAr control), while the other control functions can be further regulated by grid codes [17], market for the auxiliary services [18], added control loops [19], and/or by the deployment of energy management systems [20]. The existing papers that investigate impacts of P2P electricity trading on distribution grid proposed various means of supervision and/or control. The existing proposals include role of DSOs for reviewing of the orders in the periods between the gate closure and the energy exchange [10], pricing based on game theory that would support demand peak shaving [21], P2P electricity based on the multiclass energy management concept to allow trading between prosumers with beyond only financial preferences [12]. Further, a methodology was proposed based on the network sensitivity analysis that should facilitate P2P energy trading under low-voltage (LV) distribution grid constraints [22]. That methodology is compatible with the continuous double auction (CDA) market mechanism.

In this paper, it is analyzed what are the effects on the bus voltage levels if a near-real-time P2P electricity trading is implemented. It is researched if a contribution to the sustention of the voltages under limits can be provided without time-demanding security-constrained unit commitment (SCUC) calculations for the analyzed time horizon (for example one day) and without security-constrained economic dispatch (SCED) calculations for every trading period (for example every five minutes). The simulated P2P electricity trading is organized as a local power-exchange where supply and demand offers are aggregated and market clearing prices and quantities are calculated [23]. Further, it is analyzed what are the effects of demand elasticities on voltage levels in the environment of P2P electricity trading in LV distribution grid.

To get the results, the scenario analysis of the impacts of different demand offering curves of the peers is conducted in

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the case of the IEEE European LV Test Feeder [24]. Near-continuous (5 min trading period) P2P electricity trading is simulated using the double-auction trading mechanism for estimation of equilibrium prices and volumes. The results are compared with the reference results simulated on the IEEE European LV Test Feeder without P2P trading. The implemented method is briefly described in Section 2. The case study analysis is presented in Section 3. Finally, the conclusions are discussed in Section 4.

II. Method for Simulation of Peer-to-Peer Electricity Trading and Estimation of Effects on the Voltages in the Grid

For the investigation of the effects of different trading strategies and offering curves on voltage stability, the centrally aggregated double auction P2P electricity trading mechanism was implemented based on the EUPHEMIA [25] mechanism approach. The market is simulated over 24 hours, and the resolution of trading intervals is five minutes. Unit commitment of the peers is obtained from the trading mechanism based on the estimated equilibrium prices and volumes. The dispatched energy of the peers is applied as an input in the IEEE European LV Test Feeder [24, 26]. That approach allows analysis of the power flows and voltage levels. A more detailed explanation with the flowchart of the method is available in [23]. The method can be divided into four steps. Firstly, peers in the distribution grid make projections of their supply possibilities and demand needs. Secondly, they define elasticity and volumes of energy demand as well as production volumes and offering prices. Thirdly, those supply and demand offers are submitted to the double-auction market, where bids are aggregated, and market equilibrium volumes and prices are determined. In the last step, the least-cost dispatch of the peers is sent to the IEEE European LV Test Feeder grid, and there the impacts of P2P electricity trading on voltage levels can be analyzed. The simulation in the IEEE European LV Test Feeder is carried out based on a five-minute energy dispatch from the previous step, and in a resolution of one second.

Besides the reference scenario, analysis is carried out for two cases, where peers' demand offering curves simulate high to low demand elasticity in the local energy market. The detailed explanation of the used method can be found in [23] where the implementation code is also available.

III. Case Study

In this section, the effects of different demand offering curves are assessed. The study is conducted for the case where supply offer strategies reflect moments of high electricity prices and scarcity of supply, i.e. the case where producers bid with the costs over their short-run marginal costs. Contrary, the demand biding curves are varied between scenarios to allow the analysis of the effects of changing demand elasticity of the peers.

A. Input Data and Scenarios

The analysis is conducted for the cases where producers practice high markup intending to achieve added revenue on top of production cost and are even ready to curb the production. The impact of strategies of demand peers is analyzed for two cases: (1) higher elasticity, where flexibility and demand response of the peers is assumed higher, and (2) lower elasticity, where flexibility and demand response of the peers is assumed lower. It can be noticed that in the area where supply and demand curves cross, the demand of the peers is inelastic (absolute value of elasticity < 1), which is in line with the usual elasticity of electricity demand [27, 28].

Based on the assumed different behavior of the peers, the two scenarios are created and analyzed (scenarios S1-S2). Also, those scenarios are compared with the reference scenario (SREF), where the production is presumed maximal. It is a conceptual case that simulates the effects of feed-in tariffs for electricity production from RES. Moreover, in the SREF scenario, the demand is assumed inelastic, to represent the common behavior of the peers in traditional electricity LV distribution grids, which can be summarized by the slogan 'use it when you need it'. The main differences in the simulated and analyzed scenarios are shown in Table 1.

TABLE I. Key differences of the analyzed scenarios and input data for individual peers, where "High" supply price is set at 0.075 EUR/kWh and "Low" supply price at 0.025 EUR/kWh.

Item \ Scenario	SREF	S1	S2
Maximal supply offering price	NA (feed-in-tariff)	High	High
Price elasticity of demand	Perfectly inelastic (passive demand)	Increased*	Decreased*

* Compared to one another (Fig. 2).

In all scenarios, the initial demand needs are same as in the the default IEEE European LV Test Feeder [24], but it is assumed that every fourth peer has a PV system installed with the nominal power capacity of 4 kW. The applied approach resulted in total of 14 solar single-phase PV systems among 55 peers, where 5 solar PV systems are located at phase A, 6 solar PV systems at phase B, and 3 solar PV systems at phase C, as depicted in the Fig. 1.

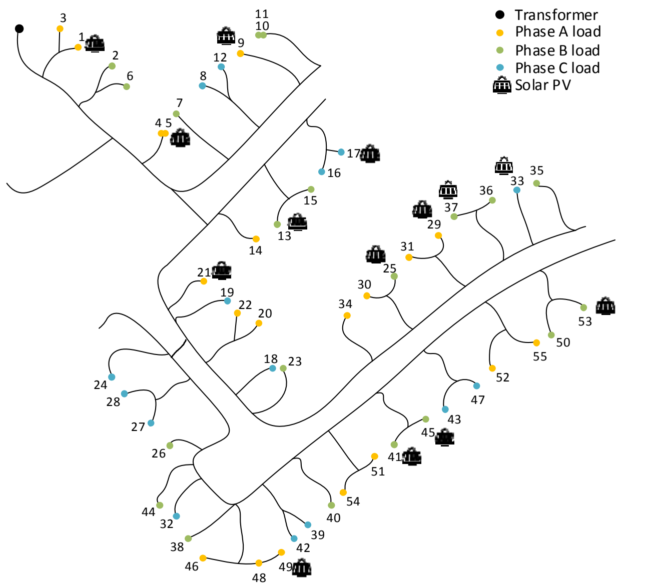


Fig. 1. Topology of the IEEE European LV Test Feeder where simulation of the P2P electricity trading was conducted.

The potential maximal production from the PV systems for each five-minute interval for the assessed day was obtained from [29] for June 1st. Same as in [23], the minimal volumes of the offering blocks are rounded to 0.5 kW. The creation of offering blocks for the peers is based on the approach in [23] and is performed accordingly with Equation (1) and Equation (2) for supply and demand offers, respectively. The principle for creation of offering blocks is also depicted in Fig. 2.

$$p_{s,t,b,i} = \frac{p_{N_{s,t,i}}}{q_{MAX_{s,t,i}}} q_{s,t,b,i}\,, \quad \text{where: } 0 \leq q_{s,t,b,i} \leq q_{MAX_{s,t,i}} \tag{1}$$

$$p_{d,t,b,i} = -\frac{2 \cdot p_{N_{d,t,i}}}{1+k} q_{d,t,b,i} + \frac{p_{N_{d,t,i}} \cdot 2 \cdot q_{MAX_{d,t,i}}}{1+k}, \quad \text{where: } 0 \leq q_{d,t,b,i} \leq q_{MAX_{d,t,i}} \tag{2}$$

where $p_{N_{s,t,i}}$ is the nominal supply price (final price in the supply curve) of the peer i in period t, $p_{N_{d,t,i}}$ is the nominal demand price of the peer i in period t. There, $p_{N_{d,t,i}}$ is assumed equal as the price from the upstream grid, i.e., 0.100 EUR/kWh. Values for reference consumption $q_{N_{d,t,i}}$ of the peers (i) in time periods (t) are obtained from the IEEE European LV Test Feeder and can be increased by the k blocks where each block equals 0.5 kW, i.e., $q_{MAX_{d,t,i}} = q_{d,N_{t,i}} + \frac{1+k}{2}$ (kW). The described approach for creation of supply and demand bids is sam as in [23] and allows transparent analysis based on the modification of supply prices $p_{N_{s,t,i}}$ and slopes of the demand curves around price $p_{N_{d,t,i}}$ (Fig. 2). Illustration of varying slope around the price $p_{N_{d,t,i}}$ of the demand curves are shown in Fig. 2.

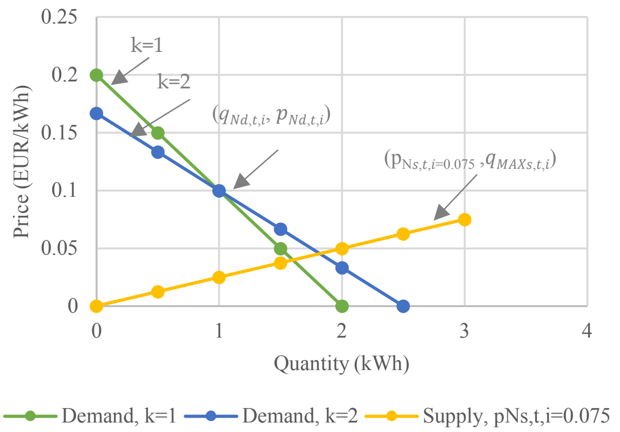


Fig. 2. Depiction of the demand bidding curves of the peers for the cases where $p_{N_{d,t,i}}$= 0.100 EUR/kWh, $qD_{N_{t,i}}$= 1 kWh and the differences relate to the slope of the curves which is defined by the factor k, where (1) k=1 and (2) k=2. At the same time, the supply curve is defined with the $q_{MAX_{s,t,i}}$= 3 kWh and the nominal supply price is defined by the $p_{N_{s,t,i}}$=0.075 EUR/kWh.

Besides through the P2P electricity trading, peers have the option to purchase the electricity from the upstream grid, but with the assumed supply price of 0.100 EUR/kWh, while the price of selling to the utility grid is assumed at 0.050 EUR/kWh. For the case study, the time horizon of 120 min is analyzed when demand and PV production are available at the same time. The simulation was implemented via the MATLAB software package [26].

B. Results of the First Stage of the Simulation: Equilibrium Quantities and Prices

The results of the first stage of the P2P electricity trading are the equilibrium (market clearing) prices and volumes, based on the least-cost market mechanism. The calculated quantities are input for the second stage, where analysis of the impacts on voltage levels in the IEEE European LV Test Feeder is performed. The aggregated values of volumes traded between 55 peers are displayed in Fig. 5.

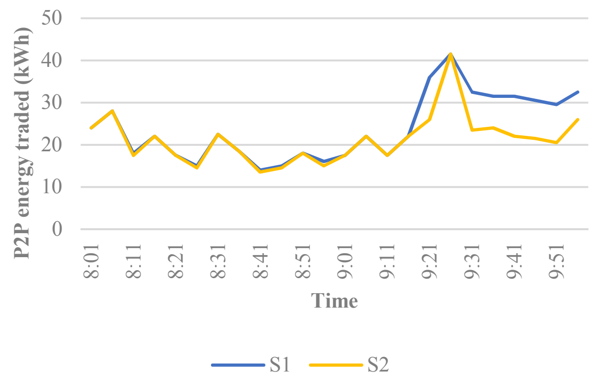
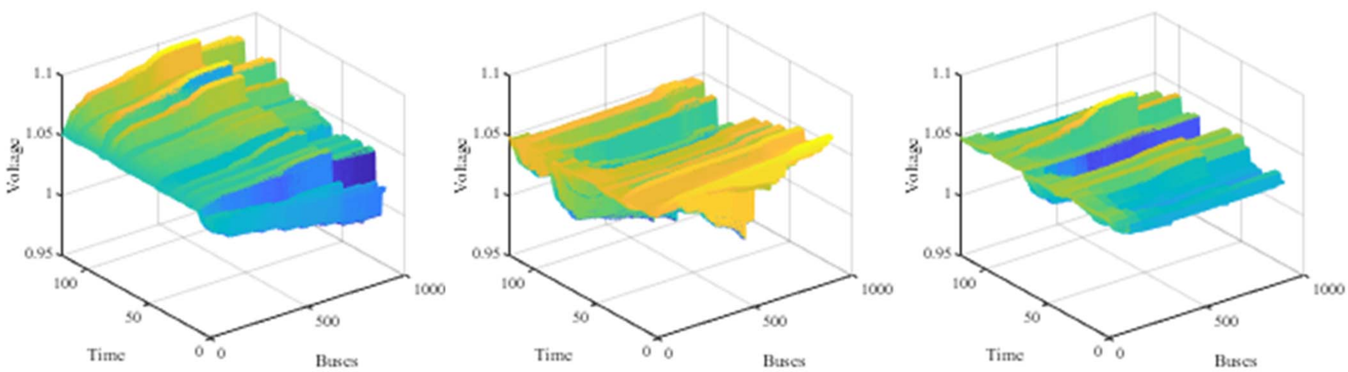


Fig. 3. The quantities of P2P energy traded in the analyzed time-span.

The scenario S2 compared to the scenario S1 (Fig. 3), has less quantities traded at higher prices. This is due to decreased demand elasticities which enable producers to withhold some production to achieve higher markup consequently increasing equilibrium prices and decreasing equilibrium quantities.

C. Results of the Second Stage of the Simulation: Voltage Levels

The impact of the market-clearing on the voltage levels in the IEEE European LV test feeder is quantified and presented in Fig. 4-6 and Table 2-3. In Fig. 4, three-phase voltage profile is shown over 120 min. In Fig. 4(a) - 4(c), voltage profiles for the reference scenario (SREF) are shown. In Fig. 4(d) – 4(f) voltage profiles for the scenario S1 are shown and in Fig. 4(g) – 4(i) the voltages profiles for the scenario S2 are shown. Due to a large amount of data (voltages for 906 buses × 7.200 s × 3 phases × 3 scenarios), 3D graphs are for a brief insight.



(a) (b) (c)

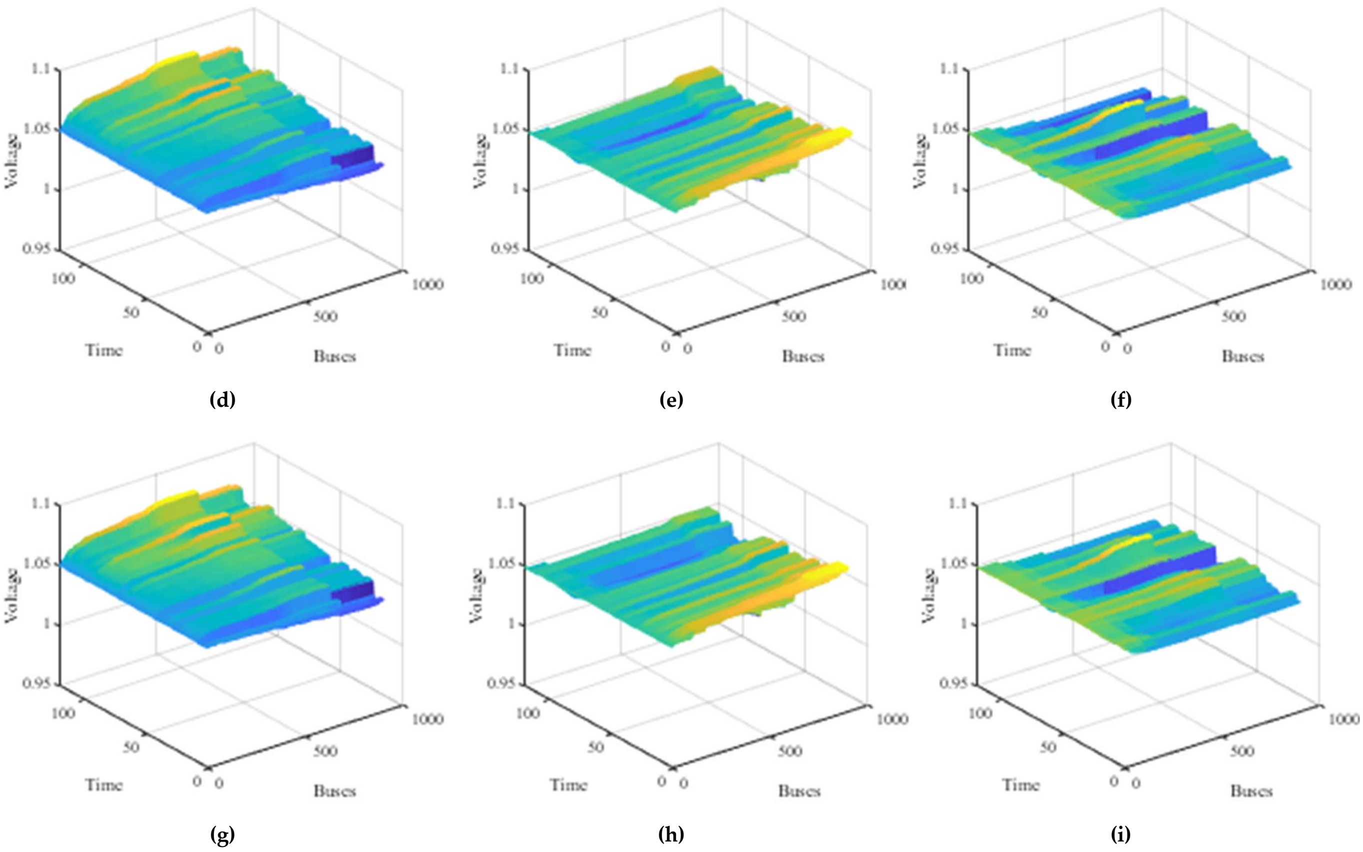


Fig. 4. Voltages profiles (p.u.) over 120 minutes**:** **(a-c)** Voltage in reference scenario SREF for phases A-C; **(d-f)** Voltage in scenario S1 for phases A-C; **(g-i)** Voltage in scenario S2 for phases A-C.

The average voltage levels and differences from the nominal voltage in the analyzed scenarios are shown in Table 2 and Fig. 5. It can be noticed that on average, in SREF scenario, voltages in phase A are 0.781% above nominal voltage, while in phase B and phase C are 1,166% and 1,071% below nominal voltage, respectively. The differences of voltages in S1 and S2 scenarios compared to the nominal voltage are smaller. In phase A, the voltages decrease, while in phases B and C voltages increase. Those results can be explained as the effects of the decreased energy consumption and decreased imports from the upstream grid, which steems from the high equilibrium prices and activation of the flexibility of the peers that participate in the P2P electricity trading. In the S2 scenario (Table 2 and Fig. 5), voltage levels are nearer to the nominal voltage than in S1 scenario. Reasons for this are in lower consumption, production and P2P energy traded, which initiated lower power flows on lines compared to S1 scenario, resulting in lower deviations from the nominal voltage (as set on LV side of the transformer substation).

TABLE II. AVERAGE VOLTAGE LEVELS AND DIFFERENCES IN COMPARISON WITH THE NOMINAL VOLTAGE IN ALL SCENARIOS.

Item	Phase	SREF	S1	S2
Average voltage level	A	1.05820	1.05755	1.05695
	B	1.03776	1.04913	1.04868
	C	1.03875	1.04264	1.04387
Average voltage level difference from the nominal	A	0.781%	0.719%	0.662%
	B	-1.166%	-0.083%	-0.125%
	C	-1.071%	-0.701%	-0.584%

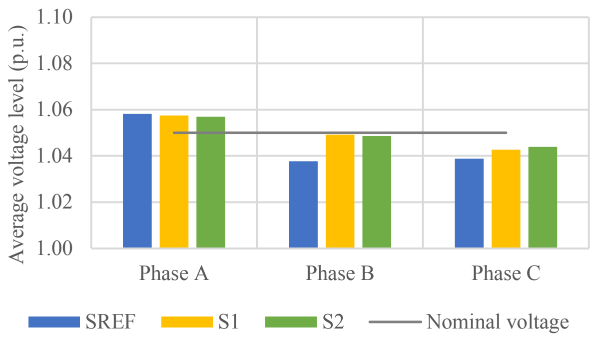


Fig. 5. Average voltage levels in the analyzed scenarios.

Further, differences between voltage deviations in comparison with the nominal voltage are calculated using the mean absolute error (MAE) across the scenarios. That quantification allows comparisons and provides insights into the impacts of demand elasticity on voltage levels and voltage deviations. The calculation of the voltage deviations using MAE is conducted for all voltage deviations (dU), positive voltage deviations (dU+), and negative voltage deviations (dU−). The data is shown in Table 3 and Fig. 6,.

From Table 3 and Fig. 6, it is evident that in the SREF scenario, MAE for all voltage deviations is between 1.18% and 1.46% of the nominal voltage, across the phases. Thereby, negative voltage deviations are dominant (in scope of 1.10% to 1.74% across the phases for negative compared to scope of 0.35% to 1.30% across the phases for the positive deviations). In scenarios that simulate P2P electricity trading (scenarios S1–S2), MAE is approximately halved for all voltage deviations and for all phases, except for phase B in S1 and S2 scenario. In the S1 scenario (high supply prices, higher demand elasticity), MAE of all voltage deviations ranges in the scope of 0,53%-0,83%, with the greater contribution of positive voltage deviations (0.18%-0.86%) and lower contribution of the MAE of negative voltage deviations (0.45%-0.77%). The impacts of lower demand elasticity in the S2 scenario resulted in a decrease of voltage deviations (all, positive, and negative) (Table 3, Fig. 6) on average across the phases when compared with the S1 scenario. At last, it can be noticed that the MAE of voltage deviations across the scenarios that simulate P2P electricity trading are, on average, 48% lower than in the SREF scenario for all voltage deviations, 23% lower for positive voltage deviations, and 57% lower for negative voltage deviations across the phases, meaning P2P trading could stabilize voltage levels nearer to the nominal voltage and decrease voltage fluctuations.

TABLE III. MAE BETWEEN MICROGRID VOLTAGE AND NOMINAL VOLTAGE FOR EVERY PHASE (FOR ALL DEVIATIONS, POSITIVE DEVIATIONS, AND NEGATIVE DEVIATIONS) IN THE ANALYZED PERIOD AND BUSSES. FOR THE SAKE OF CLARITY OF THE RESULTS, MAE IS DIVIDED BY THE NOMINAL VOLTAGE AND EXPRESSED AS A PERCENTAGE.

Item	Phase	SREF	S1	S2
MAE (all voltage deviations) (%)	A	1.26%	0.83%	0.77%
	B	1.46%	0.53%	0.55%
	C	1.18%	0.75%	0.63%
MAE (positive voltage deviations) (%)	A	1.30%	0.86%	0.81%
	B	0.51%	0.86%	0.46%
	C	0.35%	0.18%	0.18%
MAE (negative voltage deviations) (%)	A	1.10%	0.45%	0.38%
	B	1.74%	0.60%	0.64%
	C	1.25%	0.77%	0.64%

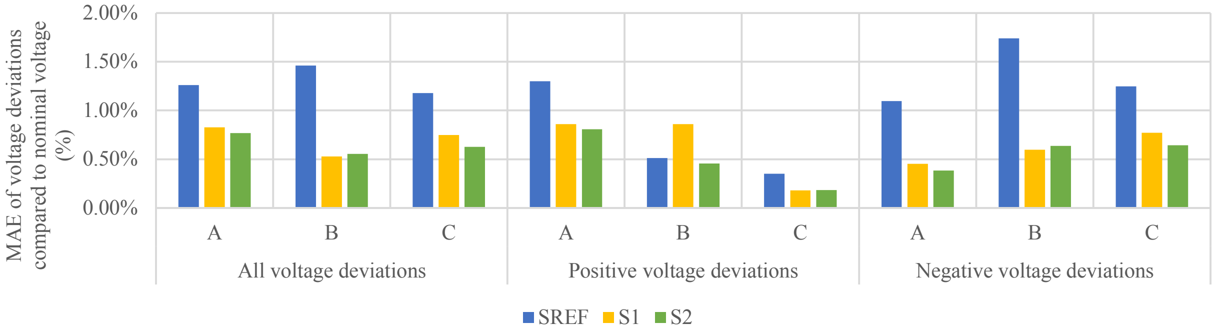


Fig. 6. MAE of the voltage deviations from the nominal voltage across the phases (for all deviations, positive deviations, and negative deviations) in the analyzed period and busses. For the sake of clarity of the results, MAE is divided by the nominal voltage and expressed as a percentage.

IV. Discussion

The method for simulation of P2P electricity trading was utilized in the paper and effects on voltage levels in the IEEE European LV test feeder were analyzed for different elasticities of demand bidding curves of the peers. The results point out that local P2P electricity trading can provide a contribution to the stabilization of voltage levels nearer to the nominal voltage and decrease the voltage fluctuations. In a simulated P2P electricity trading, the demand bidding strategies of the peers have an important effect on equilibrium prices and volumes on the market. Consequently, local electricity production and consumption are affected, and finally, that defines power flows and voltage levels in the grid. The simulated scenarios showed that a decrease in demand elasticity caused a decrease in market-clearing prices and quantities. Further, the analysis pointed out that the P2P electricity trading can provide listed positive effects without SCUC and SCED calculations for the used input data. Those insights can have important implications for designing of the P2P electricity trading and associated market and control mechanisms.

Future work includes research and implementation of strategies for optimal coordinated operation of variable RES and controllable ESS based on the game theory [30, 31, 32] for the peers that participate in the P2P electricity trading. Also, in the IMPACT project [33], testing of P2P electricity trading is foreseen in the laboratory environment as well as in the real-life distribution grid.

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Impact of Producer's Offering Prices in Peer-to-Peer Electricity Trading on Power Flows in Distribution Grid

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***Abstract*—The business models for peer-to-peer electricity trading are emerging but number of challenges still must be solved to allow large-scale deployment. The aim of this paper is to investigate effects of producer's offering prices on power flows within a distribution grid where peer-to-peer electricity trading is simulated. The peer-to-peer electricity trading is simulated as a near real-time auction-based local electricity market and tested on the IEEE European low voltage test feeder. That way, the effects on peak load requirements and local energy balance are studied. The results point out that peer-to-peer electricity trading can enhance participation of prosumers which leads to better local demand/supply balancing and reduction of peak demand from the upstream grid.**

Keywords—electricity, peer-to-peer, power flow, distribution grid, renewable energy sources

I. Introduction

Peer-to-peer (P2P) electricity trading is a concept that allows local electricity trading (LET) between different peers (decentralized generation, prosumers, consumers) [1, 2] in a local distribution grid [3]. P2P electricity trading could contribute to increased power system stability, easier operation [4, 5], and it could allow active participation of households [6, 7]. Expected benefits include reduced peak demand and lower network losses [8]. On the other hand, many challenges still have to be solved to accelerate implementation of P2P electricity trading in practice and in a wider scope such as market design [1], congestion [9], and ICT solutions [10, 11]. P2P electricity trading can improve economic dispatch, unit commitment, voltage stability [12], congestion management [13] and Volt/VAr control. Additionally, grid codes [14], auxiliary services markets [15], control loops [16], and/or energy management systems [17] could also be used to regulate and control P2P trading.

In this paper the effects on power flows and local energy balance are analyzed in case where near-real-time P2P electricity trading is implemented. It is studied if a contribution to the reduction of peak load requirements and better local supply/demand balancing can be achieved based on a local market principle. Specifically, the impact of different producer's supply prices on the power flows in the grid is analyzed. The simulated P2P electricity trading is organized as an auction based local market in the distribution grid where supply and demand is aggregated. The result of the auctions is clearing price and quantities [18].

To conduct the research, scenario analysis of the impacts of different supply offering curves of participants is performed on the IEEE European LV Test Feeder [19]. In this IEEE distribution grid, a near-continuous LET is assumed based on the EUPHEMIA algorithm [20] with 5 min trading period for which we assumed that it behaves as a P2P market. In this way we can analyses the impact of P2P on power flows by analyzing a near-continuous double auction LET which simplifies the market modelling issues. For more on approach for calculation of equilibrium prices and volumes used here consult [18]. The applied method is briefly described in Section 2. The case study is described in Section 3, based on which the discussion is presented in Section 4.

This work has been supported in part by Croatian Science Foundation under the project IMPACT – Implementation of Peer-to-Peer Advanced Concept for Electricity Trading (grant No. UIP-2017-05-4068).

II. Simulation Method for Peer-to-Peer Electricity Trading and Estimation of Impacts on the Grid

To investigate the implications of different trading strategies and offering curves on power flows the P2P electricity trading is approximated with a near real-time double auction based local electricity market. Trading is done over 24 h with 5-minute trading intervals resulting in five-minute interval time series of equilibrium prices and volumes and five-minute unit commitment. This dispatch of committed peers is used as an input to the IEEE European LV Test Feeder [19, 21] to analyze the impact on power flows. The flowchart of the applied method and more detailed explanation is available in [18]. Firstly, peers create demand and supply offers, which are then sent to the double-auction market. There, offers are aggregated, and equilibrium volumes, prices are calculated, and least-cost dispatch is obtained and sent to the IEEE European LV Test Feeder grid, where impacts of electricity trading on power flows is analyzed. The simulation on IEEE European LV Test Feeder is conducted with one-second resolution using a five-minute dispatch from the previous step [18]. In order to get broader perspective, two scenarios of peer offering curves with different elasticities are used.

III. Case Study

In this chapter the impact on power flow of different offering strategies is quantified. These offer curves strategies reflect moments of high electricity prices and scarcity of supply in one scenario and low electricity prices and oversupply in another scenario. The demand is defined by demand offering curve.

A. Scenarios and Input Data

The two producer's strategies by peers are: (S1) higher markup which means additional revenue on top of actual cost (S2) when they bid with the lower prices which are close to the short-run marginal costs (SRMC). Demand is defined by the demand curves and is the same for both scenarios. Generally, the demand is assumed inelastic in the point of

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demand and supply curves intersection (similar to real life electricity market [22, 23]).

Additionally, the reference scenario (SREF) is also created and in ordered to obtain comparative analysis. SREF assumes maximal production and inelastic demand. In this scenario feed-in tariffs for renewable energy sources and inelastic behavior of peers is assumed. The main features of scenarios are given in Table 1.

TABLE I. KEY DIFFERENCES OF THE ANALYZED SCENARIOS AND INPUT DATA FOR INDIVIDUAL PEERS.

Item \ Scenario	SREF	S1	S2
Maximal supply offering price	NA (feed-in-tariff)	High, 0.075 EUR/kWh	Low, 0.025 EUR/kWh
Price elasticity of demand	Perfectly inelastic (passive demand)	Elastic	Elastic

The consumption profiles are taken from the IEEE European LV Test Feeder [19]. In this analysis the 4 kW solar PV is added at every fourth peer. The applied approach resulted in total 14 solar PV system among 55 peers, as depicted in Fig. 1. The simulation is done in MATLAB [21].

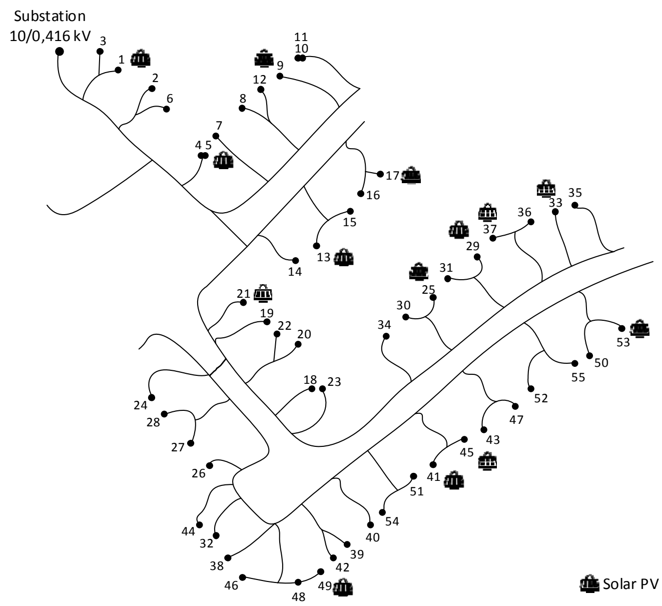


Fig. 1. The IEEE European LV Test Feeder used here

The PV production profiles are from [24] for June 1st. The analyzed is 8 a.m. to 10 a.m. when enough demand is available and PV production is also available. The minimum bidding steps are 0.5 kW [18]. The varying slopes of curves are shown in Fig. 2. The price of electricity used from the upstream grid is 0.100 EUR/kWh, and the price of selling to the upstream grid is 0.050 EUR/kWh. The aggregated supply and demand curves are shown in Fig. 3 for the time interval 9:35–9:40 a.m. for high and low-price scenarios.

B. *First Stage Outputs from the Simulation: Equilibrium Volumes and Prices*

In the first stage of approach prices, volumes, and least-cost dispatch calculation is calculated. The least cost dispatch is then input to the IEEE European LV Test Feeder. Then this feeder is analyzed for power flows. Figure 5(a) shows the total volumes in the LET and in Fig. 5(b) the market prices are shown for scenario S1 and S2.

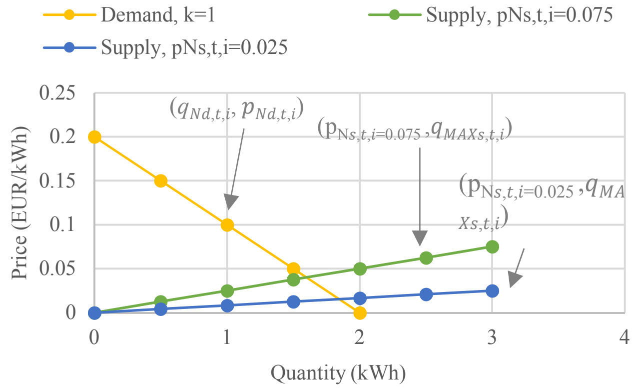


Fig. 2. Dmand and supply curves for the cases: (1) demand curves nominal price $p_{N\,d,t,i}$= 0.100 EUR/kWh, nominal demand $qD_{N\,t,i}$= 1 kWh and the slope of the curves is defined by the factor k; (2) supply curves maximal quantity $q_{MAX\,s,t,i}$= 3 kWh and the differences relate to the nominal supply price are defined by the nominal price $p_{N\,s,t,i}$.

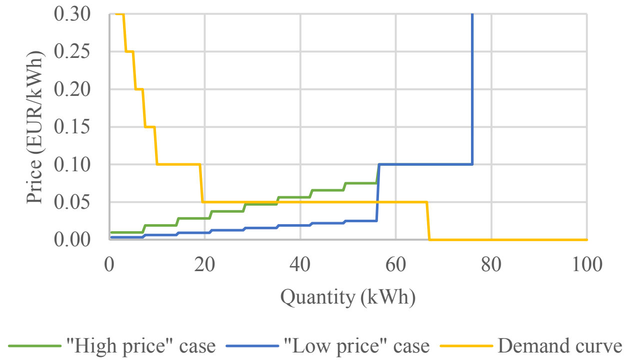


Fig. 3. Merit order supply and demand curves in the time interval 9:35 a.m. – 9:40 a.m.

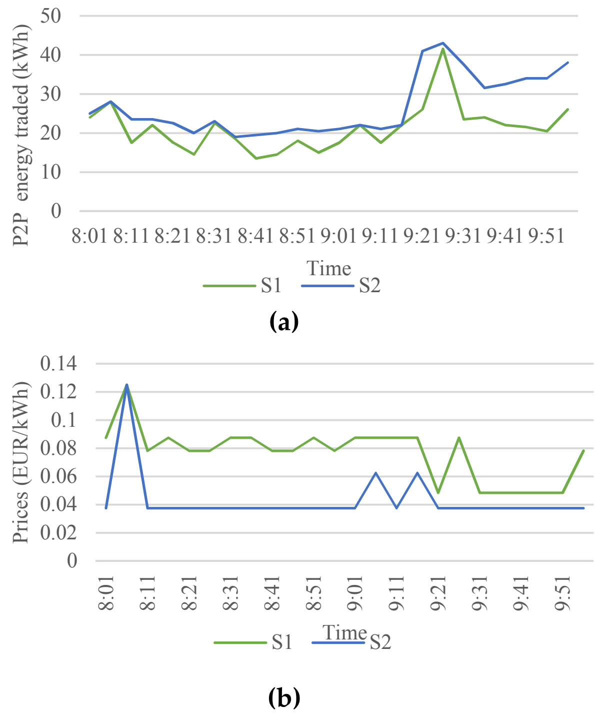


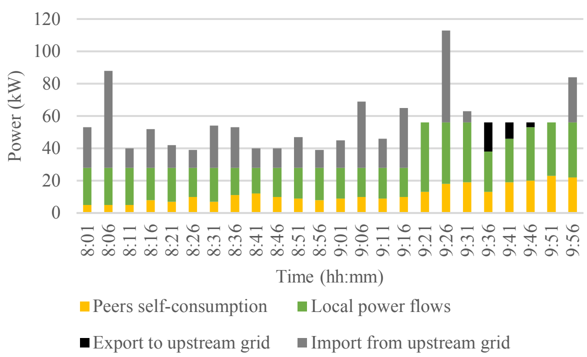
Fig. 4. Outputs of the market clearing: (a) market prices in analyzed time horizon, (b) volumes of P2P energy traded in analyzed time horizon.

C. Results: Power flows

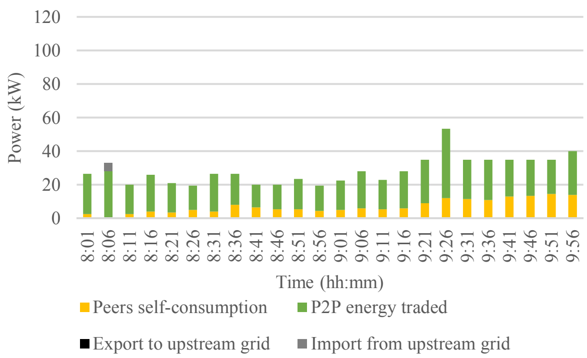
The impact of the P2P dispatch on demand/supply balance, import/export to upstream grid is shown in Fig. 5 for scenario SREF, S1 and S2. The energy balance in Fig. 5 is divided on: (1) Peers self-consumption, (2) traded P2P energy in the distribution grid which is the energy produced by the PV systems of the prosumers and not self-consumed but traded, (3) export to the upstream grid and (4) import from upstream grid.

Interesting insights are observed in reference scenario SREF (Fig. 5(a)). In this scenario the total consumption is at the maximal values. The total electricity production is also at maximal values but not enough to cover it by other production peers in the grid. Consequently, a significant share of energy is imported from the upstream network. Compared to the previous case the scenarios with implemented P2P trading (Fig. 5(b)-(c)) have lower total consumption due to introduction of price signals to consumers which is done by bidding the demand curves, which enables a decrease of consumption and avoidance of extreme market prices is possible depending on demand elasticity values and market prices (Fig. 2 and 3).

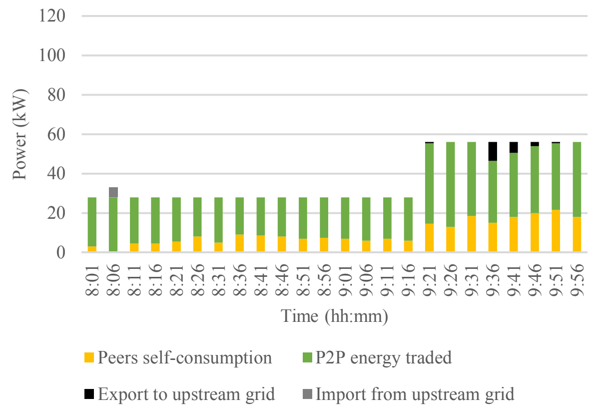
The Fig. 5(b) shows the power balance for the S1 scenario. This is the P2P electricity trading case with high producer markup (i.e. offer prices) and higher than average demand elasticity. This all resulted in decrease of total consumption and decrease in production compared to the SREF scenario. All combined, it resulted in decrease of imports from the upstream grid while exports to the upstream grid perished. On the other hand, in scenario S2 shown in Fig. 5(c) the lower producer markup (i.e. lower supply prices) resulted in the increased consumption and traded volumes in P2P market. Also, the exports to the upstream grid are observed in this scenario.



(a)



(b)



(c)

Fig. 5. Energy balance of the feeder: (a) Energy balance in reference scenario SREF; (b) Energy balance in the S1 scenario; (c) Energy balance in the S2 scenario.

In Fig. 6, the feeder self-sufficiency is shown, which is calculated as a share of total energy produced and total energy consumption of the feeder.

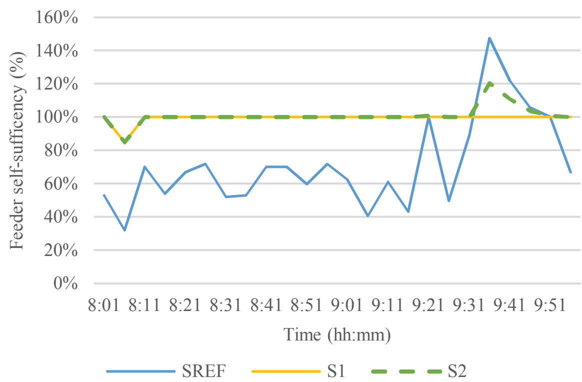


Fig. 6. Self-sufficiency of the prosumers located at the anlyzed distribution grid feeder.

The results in Fig. 6 clearly show that the P2P trading increases the self-sufficiency of the distribution grid, except in the times (around 9:41 am) when in the SREF scenario there are exports to the upstream grid. It can be pointed out that the implementation of P2P electricity trading nears the feeder self-sufficiency ratio towards 100%, subject to technical and economic constraints.

IV. Discussion

The effects of different elasticities and prices in offering curves of the peers participating in the P2P electricity trading on power flows, self-sufficiency, consumption and production in the distribution grid were studied here. The results show that P2P electricity trading can contribute to the increase of local supply-demand balance, it can increase self-consumption rates and decrease imports from the upstream grid. The producer's strategies for supply curves have significant impacts on market-clearing prices and quantities, i.e., local consumption and production, and thus power flows. In the observed scenarios, the decrease supply prices resulted in the decrease of equilibrium prices and increase traded volumes. The results are valuable from the point of view of peers that can participate in the P2P electricity trading and from the point of view of policy makers and planners that will work on the design and implementation of markets for P2P electricity trading. Planned future work will be related to creation of demand and supply offer curves that will ensure optimal bidding based on the game theory [25, 26, 27]. Further, an implementation of P2P electricity trading is foreseen in the laboratory setup and in pilot-project in real-life distribution grid [5, 28] accounting for RoCoF issues in grids with high wind penetration levels [29].

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Local Energy Trading Under Emerging Regulatory Frameworks: Impacts on Market Participants and Power Balance in Distribution Grids

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***Abstract*—Local energy trading is a concept that allows trading between distribution grid participants such as consumers, producers, and prosumers on a local level in a transparent and competitive way. This can provide better local demand-supply balancing, decrease voltage deviations, and improve social welfare. However, economic feasibility of implementation of such a concept greatly depends on regulatory framework, as certain regulatory provisions can either lead to barriers and costs that can undermine the potential benefits of local energy trading, or support implementation of such projects. In this paper, feasibility of local energy trading under different variations of regulatory framework are assessed and implications on market participants and energy balance in distribution grids analyzed. It is shown that regulatory provisions have high influence on potential benefits and implementation of local energy trading in wider scope.**

Keywords—energy trading, renewable energy resources, distribution grid, regulatory framework, energy communities.

I. INTRODUCTION

The emergence of distributed energy resources (DERs) increases the importance of management and power system optimization in a distribution grid [1], both at low voltage (LV) and middle voltage (MV) levels. Development of information and communication technologies (ICT) supports the development of innovative management solutions [2]. Local energy trading (LET) is a concept that allows peer-to-peer (P2P) and centralized electricity energy trading of prosumers, consumers, and producers regarded here as trading peers or trading nodes in LV distribution grid [3]. Application of this market-based mechanism can lead to better local demand-supply balancing, decreased voltage deviations from their nominal values, and improved social welfare [4, 5, 6, 7]. The existing literature have proposed different approaches to LET, including centralized auction-based trading [8], bilateral contract networks [9], or centrally coordinated trading or sharing [10]. The assessments of challenges and barriers for feasibility of LET beyond theoretical dimension identified provisions in regulatory framework as possible stumbling blocks for wider implementation and realization of potential benefits of the concept [11]. There, due to the complex influence of regulatory provisions in the power system, regulatory changes must be carefully designed, and impacts assessed.

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A. Development of the regulatory framwork in the EU

The debate on upgrading the legal framework is increasingly present to facilitate rapid changes in the sector, but it is noticeable that the process takes considerable time. The reasons for this come from the fact that changes in the legal framework must involve a large number of participants throughout the electricity supply chain, often encountering obstacles [12]. Some countries are experimenting with regulatory sandboxes to explore the impacts of possible regulatory changes which would foster implementation of new business models [13]. Further, the EU has set the definition of peer-to-peer (P2P) trading of renewable energy as: "the sale of renewable energy between market participants by means of a contract with pre-determined conditions governing the automated execution and settlement of the transaction, either directly between market participants or indirectly through a certified third-party market participant, such as an aggregator" [14]. As evident, a mediator can also be facilitator of the P2P electricity trading. Mediators or energy dealing businesses can be any other player on the market besides sellers or buyers, e.g. distribution system operators (DSOs), aggregators, market operators, smart energy service providers [15], energy traders, auctioneers [16], local operators [17, 18]. Moreover, the trading can be facilitated by a P2P trading platform which would demand administration and maintenance from the third party as a minimum [19]. Most of the pilot projects examine P2P trading over P2P trading platforms [20, 21].

As an important novelty in EU's regulatory framework, the emergence of 'citizen energy communities' and 'renewable energy communities' [14] as new legal terms should be highlighted [22], as those could allow special local regulatory provisions, without changing the whole regulatory landscape. As of the end of 2020, most of the countries were in the phase of drafting of the new laws and bylaws with the aim to transpose general mandatory provision set in the EU directives to the national regulatory frameworks [22]. Since EU directives set the general framework, different approaches can be seen. Term collective self-consumption (CSC) is used for "jointly acting renewables self-consumers" [14], i.e. situations where at least two prosumers cooperate, either in the same building or multi-apartment block, or within wider premises if allowed. Through that concept, a group of households could partially cover their own energy needs by installing PV systems and sharing or trading energy between them [23]. While the focus of CSC is on the specific activity, the focus of energy communities (ECs) is on certain organizational format [22]. Local energy trading or sharing, in principle, can be conducted within ECs or ECs could be trading peers in wider-range trading. In practice, member states (MSs) have to decide, inter alia, on spatial limitations, allowed capacities, local grid tariffs, or conditions for use of public grid [22]. Introduction of local grid tariffs and reduction of other surcharges could have a potential to significantly improve cost-effectiveness of LET [24]. An example from the United Kingdom, where the feed-in tariff for solar PVs lower than 4 kW were abolished, showed how the installation of panels on household roofs have become significantly less commercially viable. Although different trading options are emerging, the question is whether investing in this direction is profitable [25]. However, the extent of the subsidies that would be given for such installations have yet to be determined given that P2P trading could bring improvements in terms of network constraints. The authors conducted an analysis and concluded that subsidized P2P trading is promising mechanisms in the transition towards the post-subsidy period that could gradually reduce the support needed for solar PV installations [25].

B. Scope of the paper

The goal of this paper is to evaluate feasibility of LET under different regulatory environment. Also, the goal is to assess the implications on different market participants, such as transmission system operator (TSO), DSO, trading peers participating in LET, and other taxes and levies affected by the LET. To perform the research, the LET is simulated as a market with local trading coordinator (LTC), where volumes are determined based on the optimal unit commitment (UC) dispatch model of the participants, and the prices are determined ex-post based on the supply and demand ratio (SDR) [26]. Therefore, this paper contributes with (1) LET market clearing model applicable for different regulatory set-ups; (2) assessment of the different regulatory set-ups on the economic feasibility of LET. The rest of the paper is organized as follows: in Section II the method is described, in Section III the input data and results of the case study are presented, and in section IV main conclusions are listed.

II. Method

The method consists of the LET mechanism including LTC and application on the modified IEEE European LV Test Feeder [27], with added solar PV systems and battery energy storage systems (BESSs). The focus of the analysis is on the economic effects on different market participants and power balance and energy self-sufficiency of the feeder.

A. Local energy trading mechanism

To simulate LET, a centrally coordinated local energy trading mechanism is implemented with a goal to minimize operating cost but here it's complement is used which is to maximize the cumulative revenues for the participants in the LEM. It is assumed that LTC operates the available flexibility provisions of the participants. In the model availability of BESSs is assumed, while the model can be expanded to include also other options, like heat storage, electric vehicles, or hydrogen production. The operation scheme is shown in Fig. 1.

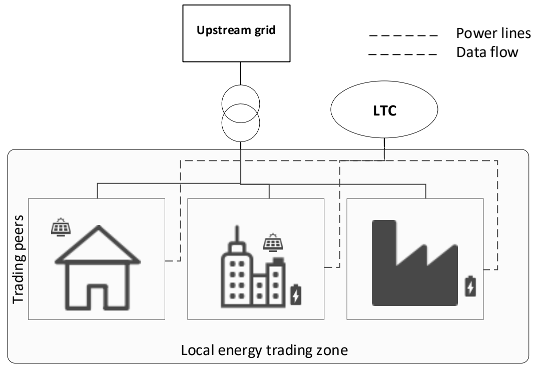


Fig. 1. Local energy trading scheme with local trading coordinator.

The optimization objective is defined with (1).

$$\max\left\{\sum_{t=1}^{T}\sum_{p=1}^{P}\left(E_{t,p}^{g,s}\cdot\pi_t^{g,s}-E_{t,p}^{g,b}\cdot\pi_t^{g,b}-E_{t,p}^{l,b}\cdot C_t^{l,b}-C_p\left(P_{t,p}\right)\right)\right\} \quad (1)$$

where $\pi_t^{g,s}$ is the price of electricity (depending on the regulatory set-up, can be defined to cover system fees, taxes or levies) which is sold (exponent s) at the amount of $E_{t,p}^{g,s}$ by a peer p to the upstream grid (exponent g) in interval t; $\pi_t^{g,b}$ is a price of electricity (usually includes system fees, taxes or levies) bought (exponent b) at the amount of $E_{t,p}^{g,b}$ by a peer p from the grid (exponent g) in interval t; and $C_t^{l,b}$ is the cost added to the local electricity traded (e.g. DSO fee, VAT, or other fees and levies) which is bought (exponent b) at the amount $E_{t,p}^{l,b}$ by a peer p from the LEM (exponent l) in interval t. $C_p\left(P_{t,p}\right)$ is the operating cost of peer p (typically quadratic) and is a function of its real output power $P_{t,p}$ in interval t. Index sets are $p\in\{1,2,\dots,P\}$ and $t\in\{1,2,\dots,T\}$ where P is total number of peers and T is number of time intervals in time horizon.

Optimization objective is subject to constraints defined in (2) – (11). There, in (3) energy balance constraint is defined, the (2) is LET constraint, (4) is solar PV production constraint, (5) – (6) are transformer substation (TS) active power capacity constraints, and (7) – (11) constraints of BESSs. The inequalities and equations in (3) – (11) are defined for every t and every p ($\forall t\in\{1,2,\dots,T\}$, $\forall p\in\{1,2,\dots,P\}$) while (2) is defined for every t:

$$\sum_{p=1}^{P}E_{t,p}^{l,s}=\sum_{p=1}^{P}E_{t,p}^{l,b} \quad (2)$$

$$\mathrm{D}_{t,p}-P_{t,p}=-E_{t,p}^{g,s}+E_{t,p}^{g,b}-E_{t,p}^{l,s}+E_{t,p}^{l,b}-E_{t,p}^{ch}+E_{t,p}^{dis} \quad (3)$$

$$0\le P_{t,p}\le P_{t,p}^{max} \quad (4)$$

$$0\le\sum_{p=1}^{P}E_{t,p}^{g,s}\le P_t^{g,s,TSmax} \quad (5)$$

$$0\le\sum_{p=1}^{P}E_{t,p}^{g,b}\le P_t^{g,b,TSmax} \quad (6)$$

$$SoC_{t,p}=SoC_{t-1,p}+E_{t,p}^{ch}\cdot\eta_{ch}-\frac{E_{t,p}^{dis}}{\eta_{dis}} \quad (7)$$

$$0\le E_{t,p}^{ch}\le E_{t,p}^{ch,max}\cdot N_{t,p}^{ch,bin} \quad (8)$$

$$0 \leq E_{t,p}^{dis} \leq E_{t,p}^{dis,max} \cdot N_{t,p}^{dis,bin} \quad (9)$$

$$N_{t,p}^{ch,bin} + N_{t,p}^{dis,bin} \leq 1 \quad (10)$$

$$SoC_{t,p}^{min} \leq SoC_{t,p} \leq SoC_{t,p}^{max} \quad (11)$$

where $D_{t,p}$ is demand, $P_{t,p}$ is electricity production, $E_{t,p}^{ch}$ is electricity charged to BESSs, and $E_{t,p}^{dis}$ is electricity discharged by the BESSs, for $p \in \{1,2,\dots,P\}$, $t \in \{1,2,\dots,T\}$. P_p^{max} is maximum possible production for $p \in \{1,2,\dots,P\}$, $t \in \{1,2,\dots,T\}$. Where $P_t^{g,s,TSmax}$ and $P_t^{g,b,TSmax}$ are available power capacity of TS which constraints the sold and bought electricity to the upstream grid for $t \in \{1,2,\dots,T\}$. $SoC_{t,p}$ is the state od charge of BESSs, $SoC_{t,p}^{max}$ is maximum state of charge of BESSs, $E_{t,p}^{ch,max}$ and $E_{t,p}^{dis,max}$ are maximal charging and discharging power of BESSs, $N_{t,p}^{ch,bin}$and $N_{t,p}^{dis,bin}$ are binary variables for charging and discharging respectively, for $p \in \{1,2,\dots,P\}$, $t \in \{1,2,\dots,T\}$. The price determination for LET is based on supply-demand ratio (SDR) as proposed in [26].

B. Distribution network model

The application of the local energy trading mechanism is applied on the IEEE European LV Test Feeder [27], which was modified to include solar PV systems and BESSs. It is a radial distribution feeder at the voltage level of 416 V (phase-to-phase) and a base frequency of 50 Hz, which is typical for the European low voltage distribution systems. The application of the test feeder enables analysis of time-series rather than only static power flow solutions. This is becoming ever more important for studying dynamic behavior of different market and control concepts on the distribution network, such as integration of DERs, Volt/VAr control, operation of BESS, etc. [27], as well as for application of simulations with various timeframes. Further, represents well the typical topology of the distribution grid in Croatia, where the LET plans be implemented under the IMPACT project [4].

III. Case study

For the case study, several scenarios with different regulatory set-ups are analyzed and impacts on different market participants assessed. The energy consumption input data are based on IEEE European LV Test Feeder [27]. The energy consumption data are supplemented with the data that allow simulation of electricity production with PV systems and energy storage with BESSs.

A. Scenarios and input data

As elaborated in the Introduction, the regulatory landscape in EU is increasingly changing to facilitate the energy transition [22]. There are fine nuances across the member states and no single solution fits all locations. For the case study, the current regulators provisions governing prosumers in Croatia are analyzed, namely individual net billing scheme, which is applicable for the entrepreneurship sector in Croatia, and individual net metering scheme, which is applicable for the households' sector in Croatia [28]. The main difference between those two are that in case of net billing, the energy exported from prosumers to the grid is valued just for the price of energy (without transmission and distribution fees, and other taxes and levies), while in the case of net metering, the bills are netted for the unit value of the total cost of electricity for prosumers (including transmission and distribution fees, and all taxes and levies). In practice, additional correction factors can be applied, but in the case study additional corrections are not analyzed for the purpose of clarity. Since there are currently no additional provisions for energy communities or similar local organizations in Croatia, those two cases are expanded with additional three cases. Those are collective net billing and collective net metering schemes, simulating the operation of the feeder as an entity 'behind the meter' or stimulating effects in case of adopting that kind of regulatory provision to support LET in public distribution grids. The final, fifth case, simulates the advanced and more considerate customized provision that defines individual net billing and LET tariff, under which there is no RES levy and no transmission fee for the energy locally traded or shared. The idea behind this provision is to encourage local energy trading but without depriving system operators for their fair fees for grid operation. The input expressions for modelling analyzed regulatory frameworks by (1) and (2) are listed in Table I. The profit margin of the intermediary (e.g., supplier) is not analyzed and the single tariff model is applied as one of the existing options in Croatia.

To allow implementation of different regulatory provisions, tariffs and allocations of regulated electricity price components (REPCs) [24], a general formulation of specific costs is shown in Table I, where c_t^g is the cost of energy from the grid (supplier) in time interval t, λ^{dist} is a distribution fee, λ^{trans} is a transmission fee, λ^{sur} is unit cost of surcharges (e.g., RES surcharge), λ^{tax} is the tax on electricity (e.g. value added tax) in percentage points.

TABLE I. Analyzed cases and input expressions

Case	$\pi_t^{g,s}$	$\pi_t^{g,b}$	$C_t^{l,b}$
Individual net billing	c_t^g	$(c_t^g + \lambda^{dist} + \lambda^{trans} + \lambda^{sur}) \cdot (1 + \lambda^{tax})$	N/A
Individual net metering	$(c_t^g + \lambda^{dist} + \lambda^{trans} + \lambda^{sur}) \cdot (1 + \lambda^{tax})$	$(c_t^g + \lambda^{dist} + \lambda^{trans} + \lambda^{sur}) \cdot (1 + \lambda^{tax})$	N/A
Collective net billing	c_t^g	$(c_t^g + \lambda^{dist,b} + \lambda^{trans,b} + \lambda^{sur,b}) \cdot (1 + \lambda^{tax,b})$	0
Collective net metering	$(c_t^g + \lambda^{dist} + \lambda^{trans} + \lambda^{sur}) \cdot (1 + \lambda^{tax})$	$(c_t^g + \lambda^{dist} + \lambda^{trans} + \lambda^{sur}) \cdot (1 + \lambda^{tax,b})$	0
Individual net billing and LET tariff	c_t^g	$(c_t^g + \lambda^{dist} + \lambda^{trans} + \lambda^{sur}) \cdot (1 + \lambda^{tax})$	$(\lambda^{dist}) \cdot (1 + \lambda^{tax})$

The input data on prices and fees are taken from a real-life examples in Croatia: c_t^g is 0.058 EUR/kWh [29], $\lambda^{dist,b}$ 0.029 EUR/kWh [30], $\lambda^{trans,b}$ is 0.012 EUR/kWh [30], $\lambda^{sur,b}$ is 0.013 EUR/kWh [31], and $\lambda^{tax,b}$ is 13 % [29]. Also, to simplify the method and still retain satisfying level of accuracy for the purpose of analyzing the impacts on power balance and other market participants under local energy trading and different regulatory frameworks we assumed that the production peers are an identical PV power plants with the zero operating costs.

The energy demand and supply input data are based on IEEE European LV Test Feeder [27], which was modified to include solar PV systems for each third prosumer with installed capacity of 4 kW, and BESSs for each sixth prosumer with installed capacity of 13.5 kWh and maximum charging and discharging power of 5 kW. The network topology of the test feeder and locations of the solar PV systems and BESSs are shown in Fig. 2. Besides BESSs, an inelastic demand is assumed.

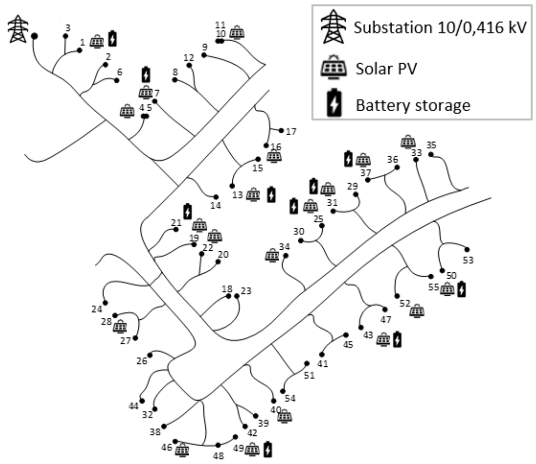


Fig. 2. Feeder with PVs and BESSs

B. Results and discussion

The time horizon of the case study is one day, and the interval of the LET is assumed as nearly real-time 5 min. The results are divided to effects on dispatch and power flows, and effects on economic indicators for participating parties.

1) Effects on dispatch and power balance

The dispatch and power balance in the observed time horizon for all intervals are shown in Fig. 3. The feeder self-sufficiency indicator is calculated as share of energy imports in total demand and is shown in the Fig. 4. In the case of the individual net billing there is an economic incentive for maximizing individual self-consumption to minimize the energy bought from the grid. On the other hand, there is no economic incentive for local energy sharing or trading. Therefore, in this case in hours when there is no solar PV production, there are no local power flows and the operation of BESSs is motivated only to increase self-sufficiency of individual prosumers (Fig. 3(a)). Feeder self-sufficiency indicator (Fig. 4) in this case is 38.9 %, which is the third best. In the case with individual net metering, there is no economic incentive for the operation of BESSs, as the upstream grid serves as virtual energy storage where generation surpluses can be 'stored' and used afterwards for the same price. In this case, local power flows happen only when there are local surpluses and missing energy between prosumers at the same time (Fig. 3(b)). That leads to the highest energy imports and exports, and lowest feeder self-sufficiency of 28.0 % (Fig. 4). The power flows indicators for cases with collective net billing and collective net metering are identical (Fig. 3(c)), as economic incentive is the same in both cases, There, the feeder self-sufficiency is maximized to 47.1% (Fig. 4), and energy imports and energy exports minimized, due to the fact that no system costs, taxes or levies are associated with local energy trading. In the final case with individual net billing and LET tariff, there is an economic incentive for maximization of self-consumption and minimization of imports from the grid (Fig. 3(d)), but as the LET is charged with the DSO fee and taxes, the incentive for minimizing grid self-sufficiency is lower. In this case the individual self-consumption is the highest, while the feeder self-sufficiency equals 42.6 % (Fig. 4), or third best after cases with collective net billing and collective net metering schemes.

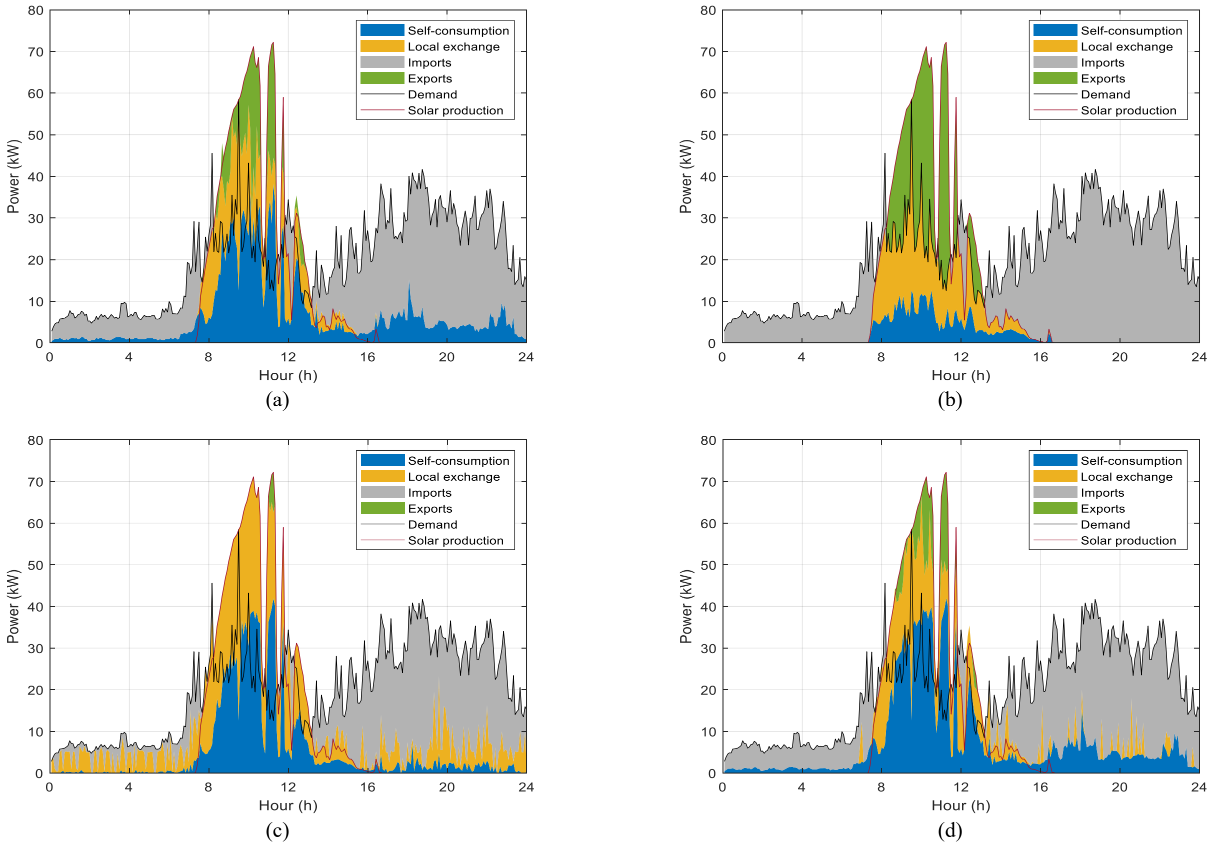


Fig. 3. Feeder power balance in the observed time horizon and for all trading intervals, across the analyzed regulatory framworks: (a) Individual net billing; (b) Individual net metering; (c) collective net billing and collective net metering, (d) Individual net billing and LET tarif.

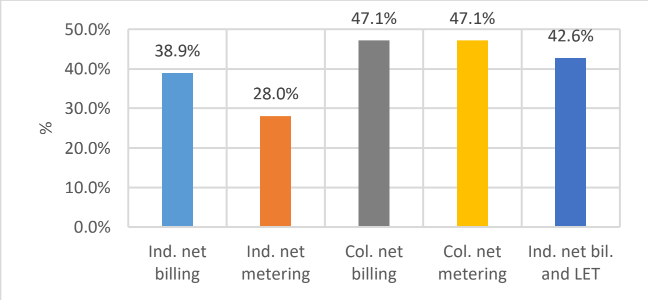


Fig. 4. Feeder self-sufficiency

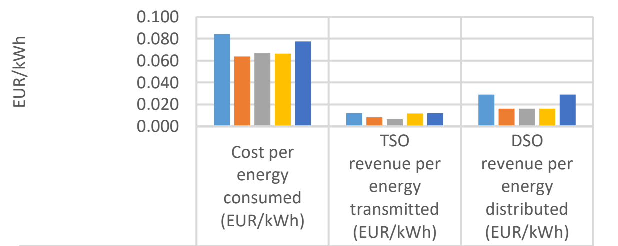
2) Effects on economic indicators for the parties

The effects on net revenues or costs of the participating parties are shown in Table II, and the unit costs and revenues per energy consumed and transmitted/distributed are shown in Fig. 5. The biggest impacts of the regulatory provisions are seen for the system operators TSO and DSO. The individual net metering scheme reduces TSO's and DSO's revenues by 36.4 %, when compared with individual net billing scheme (Table II.), leading to concerns about 'utility death spiral' [32]. Similar results are evident in the Fig. 5, as unit revenues per energy transmitted/distributed are reduced by 24.3 % for the TSO and 44.5% for the DSO respectably. Collective net billing and net metering schemes can improve the picture for the TSO in terms of unit revenues per energy transmitted, as less energy is imported and exported from the upstream grid, but there is no improvement for the DSO as those schemes would allow local energy trading in public grids, without fee for the DSO (Fig. 5). The fifth case shows considerably fairer unit revenues both for the TSO and DSO - equal to the individual net billing case (Fig. 5). On the other hand, in absolute terms TSO's revenues in this case are lower by 27.6 % compared to the individual net billing case (due to the lower energy imports) and DSO's revenues are even slightly higher by 0.2 % (due to the more use of BESSs and local energy trading). Similar effects can be seen on the surcharges and tax revenues, whether those are included in the unit costs or not.

TABLE II. REVENUES FOR THE ANALYZED PARTIES

Case	Supplier	TSO	DSO	Sur-charges	Tax	Pro-sumers
Ind. net billing	14.41	4.57	11.05	4.95	5.55	-40.54
Ind. net metering	14.06	2.91	7.03	3.15	3.53	-30.69
Col. net billing	14.64	3.05	7.37	3.31	3.70	-32.07
Col. net metering	14.64	3.03	7.32	3.28	3.67	-31.94
Ind. net bil. and LET	14.51	3.31	11.07	3.59	4.79	-37.27

From the perspective of the prosumers, of course, the individual net metering scheme proves to be least costly (24.3 % lower cost when compared with the net billing scheme) (Table II and Fig. 5). The collective net metering and net billing schemes are just slightly more costly than individual net metering scheme (if BESSs are used), while the individual net metering scheme with LET tariff could prove to be a 'golden mean' where utilities are not deprived of revenue, but the prosumers can yield some benefits (8.1 % lower total and unit costs). It has to be mentioned however that investment costs are not analyzed. The attractiveness of investments in PV systems considering regulatory options in UK are analyzed in [25].



	Cost per energy consumed (EUR/kWh)	TSO revenue per energy transmitted (EUR/kWh)	DSO revenue per energy distributed (EUR/kWh)
Ind. net billing	0.084	0.012	0.029
Ind. net metering	0.064	0.008	0.016
Col. net billing	0.067	0.007	0.016
Col. net metering	0.066	0.012	0.016
Ind. net bil. and LET	0.078	0.012	0.029

Fig. 5. Unit costs or revenues for prosumers, TSO and DSO

The local energy trading price, calculated in accordance with the SDR [26], is shown in Fig. 6. Since the focus of this paper is on cumulative benefits of certain categories of parties - prosumers, DSO, TSO, taxes and surcharges, the costs and benefits of individual prosumers are not observed in detail, as they depend on demand/supply curves and whether they have solar PV systems and/or BESSs. The analysis of different price determination mechanisms for energy communities can be found in [33].

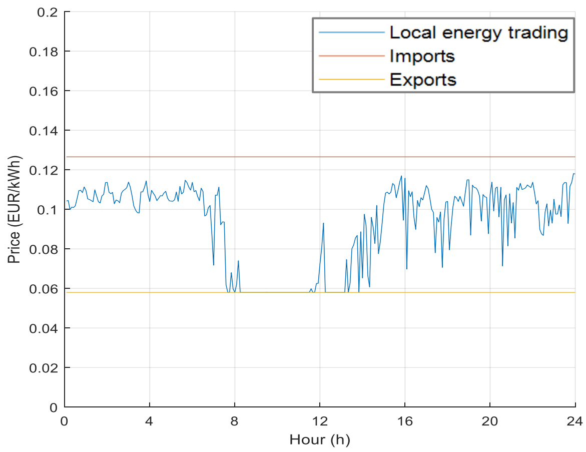


Fig. 6. Local energy trading price in case with individual net billing and LET tariff

IV. Conclusion

In the paper, it is shown that economic feasibility and achievement of possible benefits of local energy trading greatly depends on the regulatory framework. It is shown that currently existing provisions of individual net billing and individual net metering does not provide economic incentive for LET. Some possible regulatory set-ups, like collective net billing and collective net metering can have substantial impacts on economic benefits for prosumers participating in LET, but at the same time, very negative effects on the revenues of the system operators and could prove to be unsustainable in a larger scale and in long term. More advanced provision, like LET tariff and adjustment of levies and taxes for LET, can be a 'golden mean' leading to increased economic attractiveness of LET, while not depriving the system operators. Well-designed regulatory provisions can have positive impacts also on the energy balances and optimization of the operation of the distribution system. Even though collective net billing and collective net metering scheme led to highest feeder self-sufficiency in the analyzed case study, the scheme with individual net billing and LET tariff led to just slightly lower feeder self-sufficiency but to the highest individual self-consumption and lowest peak exchange power in the substation transformer. For the future work, the additional regulatory landscapes could be studied, as well as control of voltages and system dynamics with LET. Further, a laboratory setup for testing LET concepts in small-scale microgrids, and real-life testing in a community microgrid is foreseen in the scope of the IMPACT project [4].

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Biography

Lin Herenčić received his master's degree in electrical engineering and communication technology in 2011 at the Faculty of Electrical Engineering and Computing, University of Zagreb, and master's degree in economics at the Faculty of Economics and Business, University of Zagreb in 2013. Since 2011 he has been working in power industry and as a consulting associate in the field of climate and energy where he has participated in many research and consulting projects in Croatia and Southeast Europe. Since 2018, he has been employed as a researcher in Department of Energy and Power Systems at Faculty of Electrical Engineering and Computing, University of Zagreb.

His research interests include local energy markets in distribution networks, multi-vector energy systems, and modelling, policy assessment and optimisation of pathways towards climate neutrality of national economies. His research activities focus on the development of the innovative business models that engage local flexibility options considering electrical distribution network constraints and increase social welfare. He was awarded for the outstanding graduate thesis in the field of energy by the Croatian Energy Association. He has been involved as a researcher or project coordinator in several scientific research projects funded by Croatian Science Foundation, the European Union, and other sources.

Lin has been involved in teaching activities as a teaching assistant in courses Electric Power Systems 1, Energy Efficiency and Demand Side Management, Economics of Energy, and has been supervising students in development of bachelor and master thesis.

Lin has been a member of the Croatian presidency team before and during the Croatian presidency of the Council of the European Union in the first half of 2020, in the area of climate and energy. He has published several conference and scientific journal papers and worked on a number of technical studies for the industry. He is also a member of professional associations IEEE and CIGRE.

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Životopis

Lin Herenčić magistrirao je elektrotehniku i informacijsku tehnologiju 2011. godine na Fakultetu elektrotehnike i računarstva Sveučilišta u Zagrebu te magistrirao ekonomiju na Ekonomskom fakultetu Sveučilišta u Zagrebu 2013. godine. Od 2011. godine radi u elektroenergetskoj industriji kao suradnik u području klime i energetike gdje je sudjelovao u mnogim istraživačkim i konzultantskim projektima u Hrvatskoj i jugoistočnoj Europi. Od 2018. godine zaposlen je kao istraživač na Zavodu za visoki napon i energetiku Fakulteta elektrotehnike i računarstva Sveučilišta u Zagrebu.

Njegovi znanstveni interesi uključuju lokalno tržišta električnom energijom na razini distribucijskih mreža, više-vektorske energetske sustave te modeliranje, procjenu politike i optimizaciju puteva prema klimatskoj neutralnosti nacionalnih gospodarstava. Njegove istraživačke aktivnosti usmjerene su na razvoj inovativnih poslovnih modela koji uključuju aktivaciju lokalnih opcija fleksibilnosti na način koji uvažava ograničenje distribucijskih mreža i povećava društveno blagostanje. Dobitnik je nagrade Hrvatskog Energetskog društva za istaknuti diplomski rad iz područja energetike. Sudjelovao je ili sudjeluje je kao istraživač ili voditelj na nekoliko znanstveno-istraživačkih projekata financiranih od strane Hrvatske zaklade za znanost, Europske unije i drugih izvora.

Lin je uključen u nastavnu djelatnost kao asistent na kolegijima Elektroenergetski sustavi 1, Energetska učinkovitost i upravljanje potrošnjom, Ekonomija u energetici, te nadzire studente u izradi preddiplomskih i magistarskih radova.

Lin je bio član hrvatskog tima uoči i za vrijeme predsjedanje tijekom hrvatskog predsjedanja Vijećem Europske unije u prvoj polovici 2020. godine, u području klime i energije. Objavio je više konferencijskih i znanstvenih radova u časopisima te radio na nizu tehničkih studija za industriju. Također je član stručnih udruga IEEE i CIGRE.