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Trends in local electricity market design: Regulatory barriers and the role of grid tariffs

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ABSTRACT

New concepts of local electricity markets (LEMs) have led increased focus on the decentralization of energy systems and a raise in local energy communities (LECs). Under the right market-regulatory incentives, peer-to-peer (P2P) electricity trading schemes facilitate direct trade among the prosumers and enable active consumers of energy to share the self-generated electricity and make effective use of flexibility services provided by distributed energy resources (DERs). The paper presents a review of the state of implementation of LEMs and P2P. The research questions are: What grid tariff designs affect the value of peer-to-peer? How does a local energy market benefit from grid tariff designs? To address these questions, the authors survey the latest regulatory frameworks in Europe, focusing especially on Austria, Ireland, and Norway.

1. Introduction

The local sharing of energy between consumers and prosumers in the form of an energy communities (EC) without the requirement of a third party (e.g., an energy supplier) has become an innovative approach to ensure more efficient use of decentralized renewable energy sources and to promote their uptake (Council of the European Union, 2018; Fernandez et al., 2021; Ceglia et al., 2020). This has led to the emergence of new concepts of electricity markets, specifically local electricity market (LEM), in which energy is traded at the local level rather than on established national markets, such as wholesale electricity markets. The trade between prosumers and consumers has been commonly referred to as peer-to-peer (P2P) trading (Lüth et al., 2018a). Several real-life projects have tested local electricity markets and peer-to-peer trading implementations (Park and Yong, 2017; Zhang et al., 2017; Ibn Saif and Khadem, 2020; Pressmair et al., 2021; An et al., 2021). Based on these projects, researchers have focused on local electricity markets and have identified new aspects of market designs (Sousa et al., 2019; Abdella and Shuaib, 2018; Siano et al., 2019; Zia et al., 2020; Khorasany et al., 2018). Bjarghov et al. have reviewed modeling approaches and presented a comprehensive study of challenges related to implementation and operation of local electricity markets (Bjarghov et al., 2021). They note two main challenges in designing local electricity markets: (1) the integration of local electricity markets into established wholesale markets, and (2) the interaction of local electricity markets and the grid through the development of fair electricity costs, respectively electricity tariffs.

At the wholesale level, local renewable energy generation plants compete on the same market as centralized power plants with high capacity. Bids to offer energy on the wholesale electricity market (WEM) cannot be arbitrarily low and therefore power plants must generate a minimum amount of energy to be able sell their energy on the wholesale electricity market. Small decentralized power plants may not be able to generate the required amount of energy to enter the wholesale electricity market, which thus creates a barrier and challenge for their integration (Biegel et al., 2014). Additionally, regular prosumers might lack the required expertise to offer energy on the wholesale electricity market. With the implementation of peer-to-peer markets at the local level, prosumers do not need to compete with central power plants on the wholesale electricity market. As local electricity markets and the wholesale electricity market coexist, and as both markets operate via the same electricity grid, the concept of local electricity markets should be included in wholesale electricity market planning and implemented within the wholesale electricity market. This implies that the definition of new market-regulatory frameworks for the integration of local peer-to-peer markets into the wholesale electricity market should guarantee a coexisting operation of several market types (Zepter et al., 2019).

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Electricity prices are set together of energy-based prices, that are determined by the energy tariff, grid charges which result from certain grid tariffs, and additional fees and taxes. A key factor in the functioning of electricity markets is the role of grid operators, who charge the grid charges based on their incurred costs. The grid charge component of the electricity price can thus be changed by lowering the incurred costs for the grid operator. Central power plants on the wholesale electricity market have to distribute their generated energy via the transmission grid, while local electricity markets aim to use the distribution grid efficiently. Grid charges include the costs of both, the transmission grid and the distribution grid. As only the latter is used for the majority of electricity trading processes in peer-to-peer markets, an inclusion of transmission grid into the grid charges does not reflect the physical use of the grid for peer-to-peer trading. Hence, to allocate the costs incurred fairly, the grid tariffs should only charge for the actual use of the power line. Such innovative grid tariff designs could incentivize peer-to-peer trading by lowering the grid charges at the local level. Innovative grid tariff designs are mainly conceptual, which means that approaches have to be defined and tested theoretically, as well as in demonstration cases. In this paper, we report the testing and implementation of potential innovative grid tariff designs in real-life demonstration cases located in Austria, Norway, and Ireland.

The implementation and realization of local electricity markets in different countries depends on the national laws and regulatory frameworks. The framework for local electricity markets applying peer-to-peer trading is defined at European level and the establishment in national laws is in accordance with guidelines of the European Commission (Council of the European Union, 2018; European Parliament and Council of the European Union, 2019). Due to differences between national laws, local electricity markets are implemented differently in several countries. As we mainly focus on Austria, Norway and Ireland, the regulatory frameworks implemented in these countries are examined more in detail. We look at grid tariff design and analyze their implementation in the three demo-sites, in which possible use cases are investigated in the course of the BEYOND project (Blockchain-based electricity trading for the integration of national and decentralized local markets (BEYOND, 2021b)). The concept of coexisting local electricity markets applying peer-to-peer trading in form of energy communities is given by Fig. 1, which shows each country as having its own regulatory framework, whereas the frameworks are presented as blocks with white background. In Fig. 1, grid tariff design (highlighted in green) is presented as a tool to promote peer-to-peer trading. Furthermore, the implementation of local electricity markets (presented in yellow) in specific wholesale electricity markets (presented in blue) is shown at different levels. Peer-to-peer trading as the lowest level is applied in local electricity markets, which are represented one level above. As a possible application of local electricity markets, Energy Communities are shown above the local electricity market level in the yellow blocks. Additionally, Fig. 1 shows how several Energy Communities leading to several parallel local electricity markets can exist within a country. All Energy Communities are subject to the regulatory framework in their respective country. Grid tariff design as a promotion tool for peer-to-peer trading is assigned to the regulatory level. With an existing regulatory framework, an implementation in a wholesale electricity market is possible. A single wholesale electricity market can operate in multiple countries, like Austria's and Germany's markets are coupled, as presented in "Wholesale Electricity Market #B" in Fig. 1. It follows that the number of countries with a common wholesale electricity market is not strictly limited.

To gain a deeper understanding of possible implementation barriers for local electricity markets, we compared the three case countries with other European countries, as the national frameworks might be advancing differently. The comparison resulted in different implementation possibilities for local electricity markets. The three countries analyzed in this paper are shown in Fig. 2, together with the other European countries analyzed in this paper and whose regulatory frameworks are compared with each other.

The main research objective of this paper is to review and analyze the state of market and grid tariff designs with regard to local electricity markets application of peer-to-peer trading. The focus is mainly on the following points

- *Local electricity markets applying peer-to-peer trading:* Investigation of existing concepts and how it is possible to implement them into the existing wholesale electricity market.
- *Regulatory frameworks:* Comparison of regulatory frameworks for peer-to-peer trading in Europe, and possible implementation differences of local electricity markets.
- *Grid tariff design:* Definition and examination of innovative grid tariffs that can help to promote peer-to-peer trading, for which the implementation can be tested in demo-sites.

2. State of the art and beyond

In this section, the state of the art on local electricity markets and the integration of such markets into the wholesale electricity market are presented. Furthermore, a potential framework for such an integration is defined.

2.1. Local electricity markets applying peer-to-peer electricity trading

Liu et al. consider that local electricity markets that apply peer-to-peer electricity trading is a solution to managing the expected increase in prosumers in distribution grids (Liu et al., 2019). A peer-to-peer approach to electricity trading can potentially aid the expansion of distributed energy resources (DER) and create new markets (Park and Yong, 2017). Furthermore, and as stated by Abdella and Shuiab, successful implementations of peer-to-peer electricity trading markets require the existence of necessary services related to demand response, communication, security of supply, and privacy enforcement (Abdella and Shuaib, 2018). Park and Jong state that viable peer-to-peer electricity trading relies on business models that are beneficial to both prosumers and consumers, with an electricity price that is bounded by the price paid to grid utilities and the feed-in-tariff (Park and Yong, 2017). Moreover, establishment of local electricity markets that apply peer-to-peer electricity trading may impact the relations between electric entities and end-users, in that consumer preferences and interests will be emphasized (Sousa et al., 2019).

Challenges related to security of supply may arise when the share of distributed energy resources with volatile generation is high in certain areas. This can cause voltage irregularities that lead to deteriorated power quality (Park and Yong, 2017). Applying a peer-to-peer electricity trading approach might prove complicated in operational practice, as all network nodes in a peer-to-peer system must be responsive to grid conditions, energy prices, local energy supply, and demand (Park and Yong, 2017). A potential solution to such complications is the implementation of energy storage systems that provide flexibility in the system, thus ensuring a stable electricity supply to end-users, despite fluctuating generation (Park and Yong, 2017). With regard to the aforementioned imbalances in generation and related issues, Sousa et al. propose probabilistic matching and queueing theory as a possible solution (Sousa et al., 2019). Furthermore, the scalability of large local electricity markets that apply peer-to-peer electricity trading is considered a challenge (Hashemipour et al., 2021). Research performed by Sousa et al. showed that a hybrid design of peer-to-peer markets, in addition to an existing community management with external actors, is favorable from the perspective of scalability (Sousa et al., 2019).

Park and Jong raise potential future issues related to an increasing share of local electricity markets that apply peer-to-peer electricity trading (Park and Yong, 2017). These issues include grid impact, challenges related to fairness with regard to cost distribution, and

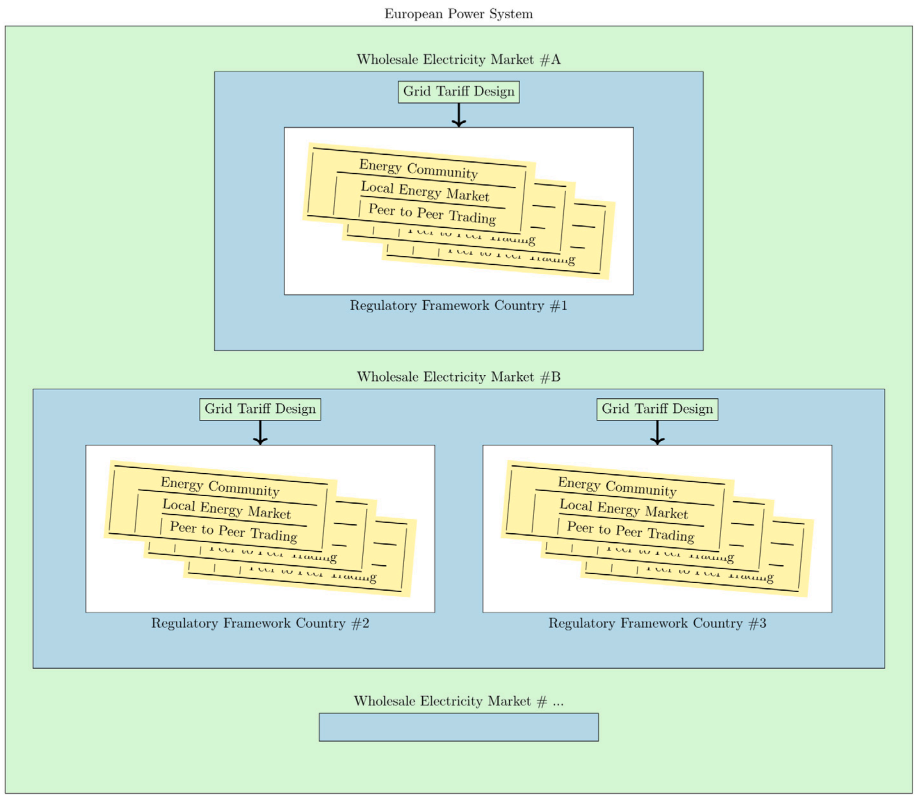

Fig. 1. LEM integration into WEM.

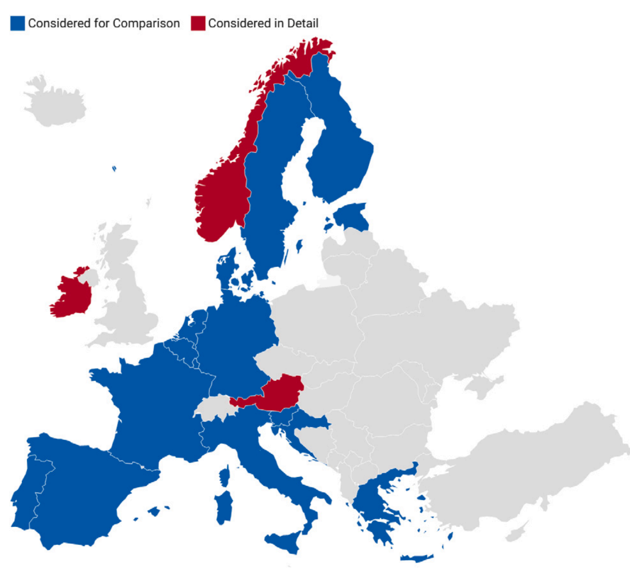

Fig. 2. Countries considered in the comparison of the regulatory framework in the paper, based on Table 6.

the effect of increasing peer-to-peer electricity trading on the centralized power supply system. According to Sousa et al. future research addressing these issues should evaluate how markets that utilize peer-to-peer electricity trading may be efficiently integrated with the existing wholesale electricity market, whilst allowing end-users to engage in local trading, as desired (Sousa et al., 2019). Siano et al. claim that additional analyses of approaches to controlling the interactions between local electricity markets and wholesale electricity markets are needed (Siano et al., 2019). Moreover, further research should focus on enhancing the negotiation processes (Sousa et al., 2019), and legal as well as regulatory frameworks must be clearly defined to ensure effective implementation and operation of local electricity markets (Zia et al., 2020). Bjarghov et al. performed an extensive review of local electricity markets and identified gaps in the literature, including challenges related to integration of uncertainty, coordination of grid and local electricity market resources, scalability of theoretical approaches, and standardization and generalization of methods and topologies (Bjarghov et al., 2021). More research on topics such as distributed generation and integration of demand response is recommended, as the same authors found that analyses had often been performed in an inexact manner (Bjarghov et al., 2021).

2.2. Integration of local peer-to-peer markets into the wholesale electricity market

Conventional power systems consist of large units generating electricity for transmission through the grid to residential, commercial, and industrial end-users. Centralized electricity trading is enabled through the wholesale electricity market (Georgilakis, 2020). The increasing implementation of distributed energy resources and establishment of local electricity markets that apply peer-to-peer electricity trading, in combination with the rising share of electric vehicles (EV) and increasing utilization of energy storage systems, have challenged the original set-up of the wholesale electricity market. For example, Teotia and Bakhar suggest that a disadvantage of the wholesale electricity market relates to liquidity (Teotia and Bhakar, 2016). The participation of smaller generation units on the wholesale electricity market might be hindered by insufficient liquidity and transparency (Yang, 2009), thus inhibiting competition (Teotia and Bhakar, 2016). Hence, regulators and wholesale electricity market operators are developing modifications of the market to ensure fairness, economic efficiency, and power system reliability (Georgilakis, 2020).

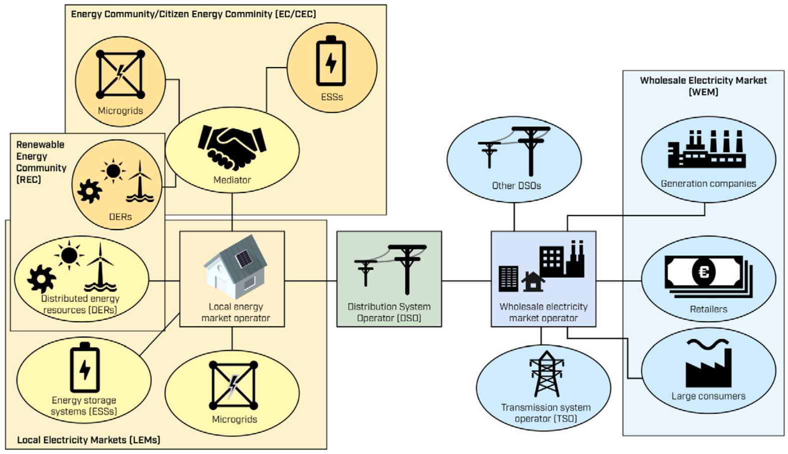

Fig. 3. Potential framework for integrating local electricity markets into wholesale electricity markets (based on Georgilakis (2020)).

Local peer-to-peer market participants might experience challenges when they are expected to provide grid services, which could be due to individual capacities being lower than the required minimum and to difficulties related to the management of distributed energy resources (Burger et al., 2017). One solution could be achieved through an aggregator, which aggregates the resources and acts as a single entity that engages with grid operators (Georgilakis, 2020). The flexibility services provided by distributed energy resources and local peer-to-peer markets could aid the distribution system operator (DSO) in performing its primary function as the entity in charge of ensuring an efficient operation of the distribution grid. The DSO would transition from a passive role, in which the main responsibilities include passively operating, maintaining, and expanding the distribution grid (Minniti et al., 2018), to a more active role in which efficient management of the distribution grid and implemented distributed energy resources DSO include taking on the role as operator of local peer-to-peer markets (Rahimi et al., 2016), as opposed to a local peer-to-peer market operator having responsibility as an aggregator, as proposed by Olivella-Rosell et al. (2018). Zepter et al. suggest a framework to integrate local peer-to-peer markets into the existing day-ahead and intraday markets by introducing an exchange platform that serves as a link between the wholesale electricity market and local peer-to-peer markets (Zepter et al., 2019).

A potential future framework for the integration of local peer-to-peer markets into the wholesale electricity market is presented in Fig. 3. The Figure is based on graphics presented by Georgilakis (2020) and considers mediators, distributed energy resources, and microgrids that have the possibility to trade electricity with an local electricity market operator. A DSO serves as a connecting link between the local peer-to-peer market and the wholesale electricity market. Other actors engaging in the wholesale electricity market are large consumers, retailers, other DSO, the DSO, and generation companies.

Potential barriers that might hinder the coupling of local electricity markets that apply peer-to-peer electricity trading with existing retail markets are discussed by de Almeida et al. (2020), and include challenges related to the currently applied single-supplier business models (ELEXON, 2018). Peer-to-peer trading in an local electricity market is based on a multi-supplier business model, wherein community members can obtain electricity from prosumers within the community, as well as from external retailers (de Almeida et al., 2020). The concept of multiple retailers for individual customers could be considered a suitable imbalance settlement process when integrating local electricity markets into existing wholesale and retail markets (Annala et al., 2021).

For a successful inclusion of local electricity markets into wholesale electricity markets, regulatory aspects for market operations within the local electricity markets must be considered. In order to do this, a regulatory framework for local electricity markets must be set as a baseline for the general local electricity market integration framework in Fig. 3.

3. Regulatory framework

Decentralized energy generation is a central aspect in achieving the EU climate targets by 2030 (Council of the European Union, 2018). Currently, EU member countries are creating financial instruments for the uptake of renewable energy generation technologies and promoting new concepts of renewable energy usage. One of these concepts is the sharing of energy by multiple consumers/prosumers in the form of energy communities. Participants in such energy communities can trade their energy in the form of peer-to-peer trading and operate in local electricity markets. The current regulatory framework of the European Union regarding energy communities is anchored in EU guideline 2019/944 (European Parliament and Council of the European Union, 2019). In the guideline, active clients are defined as consumers who are allowed to sell their self-generated electricity and take part in flexibility and efficiency programs. Building upon this, the concept of a citizen energy community has been introduced as a legal entity consisting of persons, who can provide for electric energy generation, distribution, bundling of loads or generation (aggregation), and other energy services to the members. Membership of the citizen energy community is open and voluntary, and the main goals of the communities are environmental, economical, and social benefits for the participants, rather than monetary benefits. Members of citizen energy communities have the right both to use electric energy produced within the community and to receive appropriate grid charges without discrimination, but they still have to make appropriate financial contributions to the overall utilization costs. Renewable energy community concepts, which are defined in EU directive 2018/2001 (Council of the European Union, 2018), include a special concept of community based generation plants. According to the concept, the same provisions apply renewable energy communities as for citizen energy communities, whereby the generated energy in renewable energy communities and thus the shared energy must be obtained from renewable power generation plants and the membership is more restricted and geographically limited. As the concept could have a major impact on the achievement of the EU's renewable energy goals, the EU member states need to create at national level a regulatory framework for renewable energy communities that enables local market introduction and further development. Furthermore, it is necessary to provide information to potential participants in renewable energy communities and to create appropriate subsidies. Another important aspect is how to ensure problem-free cooperation between the DSOs and the members of an energy community.

In the following subsections, the regulatory frameworks of Austria (Section 3.1), Norway (Section 3.2) and Ireland (Section 3.3) are analyzed in detail. Regulatory frameworks are implemented differently, as no detailed schedule and implementation plan is set by the EU guidelines. Due to the lack of uniformity, more administrative work is required, which can be seen as a regulatory barrier from a European implementation perspective of local electricity markets.

3.1. Austria

In Austria, energy generation is mainly based on hydropower plant generation. As the total capacity for hydropower has been exhausted in Austria, other types of renewable energy generation, such as wind and solar power plants are currently being expanded. It is not only necessary to expand these technologies but also to use existing facilities more efficiently. Particularly in the case of smaller decentralized plants, efforts are being made to establish energy communities in order to manifest the aggregation of such plants as a fundamental part of the energy system.

The organization of the energy economy and the guidelines for energy generation, transmission, and distribution of electric energy in Austria are determined in the Federal Act providing new rules for the organization of the electricity sector, the Electricity Act 2010 (ElWOG 2010) (E-Control, 2021). A regulatory framework for the implementation of shared power generation facilities, referred to as community generation plants, in which the rights and obligations of the system operators and distribution grid operators are described, was defined in an amendment to the Act in 2017 (E-Control, 2021). The participants have the right to appoint an operator for the community generation plant. According to the Electricity Act, the main condition for participants to share generation plants is that they are all connected to the electrical distribution network via the same main line (E-Control, 2021).

An implementation of the draft of the Renewable Expansion Act (Austrian Parliament, 2021) into national legislation was decided by the National Council in July 2021. The EU guidelines on energy communities are implemented in this draft legislation (Council of the European Union, 2018; European Parliament and Council of the European Union, 2019). Furthermore, new investment subsidies and market premiums for renewable energy generation plants are stated in the draft legislation, and the Electricity Act ElWOG 2010 will be extended in the course of the implementation of the new Act. Under the Renewable Expansion Act (Austrian Parliament, 2021), citizen energy communities are defined as communities that are allowed to generate, consume, store or sell electricity, and that consist of two or more persons, whose aim must not be to make financial gains, a definition that is similar to the one given in the EU's Directive 2019/944 (European Parliament and Council of the European Union, 2019). The generated energy in renewable energy communities must be obtained from renewable energy sources, as it was also set in Directive 2018/2001 (Council of the European Union, 2018). In Austria, the participants in a renewable energy community have to be connected via either the low voltage grid[1] (local) or the medium voltage grid, which are grid levels seven and five in the (E-Control, 2021). An important aspect is that the members have to be in the same concession area of the distribution grid operator. Thus, formation of renewable energy communities is possible over a larger area than originally defined in the Electricity Act (E-Control, 2021). A major advantage of the new regulatory framework is that the members of renewable energy communities only have to pay the grid charges of the grid levels used (level seven for local usage, and levels five to seven for regional usage). The elimination of the green electricity flat rate may provide an additional financial incentive. For both citizen energy communities and renewable energy communities, DSOs have to be informed about the establishment of an energy community and the members of that community must make agreements on the operation of the plant. Furthermore, the grid operator must provide the measured 15 min mean values to the members of the energy communities. Additionally, Austrian law specifies that the subsidies for renewable energy generation plants defined in the Green Electricity Act of 2012 (Rechtsinformationssystem des Bundes (RIS), 2021) are valid also for renewable energy communities.

3.2. Norway

Currently, Norway's power system is largely dominated by hydropower capacity, with operation perspectives ranging from seasonal to weekly storage cycles. The end-consumer level is characterized by high shares of electric vehicles and electrific heating. Due to low electricity generation costs, grid charges make up about one third of the end-consumers' electricity prices (Norges vassdrags- og energidirektorat, 2020b) (with generation costs and administrative fees accounting for the other two-thirds). Expected developments in Norway incorporate further increases in electrical transportation, electrification of large industry, and increase in solar power capacity. Additional, but as of yet uncertain, trends such as the large-scale roll-out of hydrogen catalysts and increasing (offshore) wind generation capacity show potential to grow in importance in both the Norwegian grid and the Nordic grid as a whole (Norges vassdrags- og energidirektorat, 2020a).

In Norway, a similar trend towards decentralization like in previously mentioned EU member states can be observed. This is due to Norway being a member of the European Economic Area incorporating EU directives into its national legislation and implementing local power grid optimization. However, Norwegian legislation takes a consumer-centric, individualistic view on this decentralization, with concepts requiring proof of being able to uphold consumer independence and allowing for informed and unbiased decisions by end-consumers (Oslo Economics, 2021). In the case of local markets, both sharing and local trade of electrical energy conflicts with distribution grid ownership and related operation and costs, which has led to a recent surge in discussions of changes to associated regulation as a predecessor and foundation for energy communities and local exchanges (Norges vassdrags- og energidirektorat, 2020b). As specific regulations on design of such exchanges are not defined in EU legislature, associated regulations are decided on national level with Norway's Energy act of 2019 taking a more restrictive position (Norwegian department of petroleum and energy, 2019). Due to the high share of grid charges in the electricity prices, Norwegian authorities expect steep increases in fees for consumers who are fully reliant on the grid, together with increases in local generation and self-consumption. Further, they suggest energy-based tariffs in place of the current capacity-based tariffs as a possible solution (Norges vassdrags- og energidirektorat, 2020b). Further strain on distribution grids emerge due to increases in voltage fluctuations (PQA AS, 2020), which under current regulation must be controlled by grid companies (Norwegian department of petroleum and energy, 2007). Currently, Norwegian authorities accept the associated need for further local flexibility incentives, albeit solely analytical (Thema Consulting Group, 2021) with no specific drafts for regulatory frameworks existing yet.

3.3. Ireland

In 2020, the share of renewables in electricity generation in Ireland reached 43%, which surpassed its target of 40%. Most of the renewable generation comes from onshore wind power plants, while 50% of the electricity generated comes from gas-fired power plants (EirGrid Group, 2021). Thus, the power generation mix (i.e., the electricity generation mix) is predominantly from gas and wind. Residential electricity prices in Ireland has experienced a rise throughout the last decade (Sustainable Energy Authority of Ireland (SEAI), 2021) and it was the fourth

[1] Grid level seven according to E-Control (2021).

highest in Europe in the second half of 2020 (Eurostat, 2021). As of mid 2020 wholesale costs and network costs have accounted for around 38% and 32% of electricity bills respectively (Commission for Regulation of Utilities (CRU), 2021b). Ireland has pledged to source 70% of its electricity from renewables by the year 2030 (Department of Communications, Climate Action & Environment, 2019), with increasing deployment rates for existing and new low-carbon technologies, especially offshore wind farms, solar generation, and storage facilities.

Currently, there is no regulatory framework with respect to energy communities. The energy utility regulator of Ireland, the Commission for Regulation of Utilities (CRU) engaged in a consultation process for drawing up a regulatory framework. Energy communities in accordance with the EU's Electricity Directive (2019/944) (European Parliament and Council of the European Union, 2019) and Renewables Directive (2018/2001) (Council of the European Union, 2018) under EU clean energy package (Directorate-General for Energy (European Commission), 2019) should thereby be regulatory defined. The CRU's consultation paper presents the generalized concept of energy communities, which amalgamates the citizen energy communities from the Electricity Directive and renewable energy communities from the Renewables Directive (Commission for Regulation of Utilities (CRU), 2021a).

The CRU has identified a number of key aspects to facilitate a regulatory framework that encourages the participation of stakeholders in these new endeavors (Commission for Regulation of Utilities (CRU), 2021a). The CRU enumerates all potential energy activities associated with new and existing market participants in the electricity sector. Furthermore, it encompasses existing energy activities, such as consumption, generation, storage, and aggregation, along with new activities such as energy trading/sharing, third-party services, and distribution network management. Another key aspect is the exploration of the possible regulatory approach to address the interactions of aggregators with energy communities and active consumers. Aggregation and participation of aggregated demand-side and generation assets exist in current market arrangements. However, further assessment is necessary to explore the role of aggregators in energy communities' effective participation in the electricity sector.

There is a difference between the proximity requirement defined for renewable energy communities and citizen energy communities. The CRU proposes renewable energy communities as a subset of citizen energy communities, sees distribution network assets (e.g., a single middle voltage substation of certain voltage level) as a way of defining renewable energy communities and keeping citizen energy communities without proximity requirement. A key aspect of the prospective regulatory framework is expected to create a mechanism for energy sharing and trading within energy communities. The trading and sharing of energy can be physical, where participants are required to be located within a certain proximity or virtually on the balance sheet (e.g., virtual power plant Plancke et al., 2015 and peer-to-peer trading International Renewable Energy Agency (IRENA), 2020). Along with above-mentioned key issues, other regulatory aspects have been highlighted in the consultation process, including consumer protection and regulatory oversight, data protection, consumer awareness, and identification of barriers beyond regulatory scope. Given the momentum of the consultation process, it appears that those aspects are expected to be potential components of the regulatory framework and the CRU is in the process of finalizing the draft version of the framework based on the ongoing consultation with stakeholders.

With the regulatory aspects for decentralization and local electricity markets being set, an application of local peer-to-peer markets in real-life use cases is investigated in the next section. Grid tariff design can emerge as a potential tool for promoting such concepts.

4. LEM implementation and the role of grid tariff design

The increasing share of distributed energy resources in the distribution grid, combined with a higher penetration of electric vehicles, heat-pumps, and electricity storage systems, has introduced new challenges related to grid planning and operation. Initial grid investments could be necessary to accommodate the power injected by the distributed energy resources (Méndez et al., 2006). Furthermore, more complex grid control mechanisms (Picciariello et al., 2015) and changes in the long-term grid planning (Picciariello et al., 2015) lead to higher operational costs. Thus, the design of grid tariffs must take into consideration the impacts of increased distributed energy resource implementation and the potential challenges that may occur in the grid in the future. An optimal grid tariff should cover costs of the DSO related to the grid operation, including costs related to grid maintenance and expansion, while also transmitting economic signals to facilitate efficient grid usage and peak load reduction (Picciariello et al., 2015).

The design of grid tariffs is flexible and dependent on the relevant regulations in the specific market area. Thus, tariff design will vary across EU member states, with regard to both tariff regulation and cost allocation. An updated cost allocation methodology is needed to ensure a fair distribution of costs between the consumers and distributed energy resource owners, while considering the supplementary costs and revenues related to the implemented distributed energy resources (Picciariello et al., 2015). Due to the shared nature of the electricity grid, the cost of providing a service to a singular user is dependent upon the behavior of other users (Sakhrani and Parsons, 2010). An example of this effect is given by the Edison Electric Institute (Edison Electric Institute, 2013), where consumers experienced a rise in costs due to incorrect pricing of power produced by distributed energy resources.

When designing a grid tariff, the following principles must be taken into consideration (Picciariello et al., 2015):

- *System sustainability:* Considers cost drivers and ensures that costs related to grid operation are fully covered. Assures all grid users access to the grid (Picciariello et al., 2015).
- *Economic efficiency:* Aims for efficient operation of the grid where services are provided at the lowest possible cost and actors are charged according to their utilization of grid services (Picciariello et al., 2015). Cost-reflectivity is an important principle within the economic efficiency category, which ensures that grid tariffs paid by consumers reflect the costs they impose on the grid (Council of European Energy Regulators, 2020).
- *Customer protection:* Involves the aspects of simplicity, stability, and transparency to present the tariff allocation in an accessible and understandable manner to the customer group (Picciariello et al., 2015).

Challenges may arise when trying to fulfill all principles within the three categories, as some of the principles may be contradictory. An example of contradictory principles is presented by the Council of European Energy Regulators (Council of European Energy Regulators, 2020), which states that the complexities behind a cost-reflective tariff methodology may contradict the principles regarding simplicity and predictability.

Potential challenges occurring within grid tariff design as a result of the increasing implementation of distributed energy resources are evaluated by Picciariello et al. (2015) together with a review of the solution approaches applied. Tushar et al. describe how grid tariffs are utilized to minimize peak loads (Tushar et al., 2020). According to Bjarghov et al. participants in a local peer-to-peer market regulated their consumption based on a subscribed capacity grid tariff (Bjarghov et al., 2020). By charging community members with a reduced grid tariff for electricity sold within the community, the Quartierstrom project in Switzerland aimed to incentivize local consumption (Ableitner et al., 2019). Baroche et al. propose an approach where grid costs allocation

Table 1
Austria use case set-up and assumption summary.

	Austria	Norway	Ireland
Type of analyzed grid tariff	Distance-dependent grid tariff that incentivizes community trades within the same low voltage electricity grid branch	Fixed grid fee with variable tariffs for energy (transferred electricity) and power (available capacity)	Static time-of-use tariff having day and night rates.
Grid impact, DSO perspective	The grid impact is not considered in the presented analysis, because no flexibility options are assumed for the considered participants.	Only joint peak demand management as a community	Not explicitly, only peak demand
Topology and set-up	30 residential consumers, 15 with solar PV	Industrial site with multiple buildings. 5 building complexes with large demand	20 prosumers, each having batteries and 9 of them having solar PV
Runtime [days]	365	365	30
Asset overview	15 PV systems 1.5 kWp to 6 kWp	total PV capacity: 777 kWp, CHP systems, load shifting, EV parking lot	PV 2 kWp to 2.2 kWp and batteries-10 kWh/3.3 kW
Peak generation [kW]	37.1	752	16.1
Peak load [kW]	52.6	1500	21.2

is determined based on electrical distance between agents and zones to reduce stress on the grid (Baroche et al., 2019).

Grid tariff design based on distance could potentially incentivize participation in local electricity market. Baroche et al. propose a cost-sharing methodology for a peer-to-peer community where grid charges are allocated either uniformly, based on the electrical distance between agents, or by zones (Baroche et al., 2019). The authors applied a test case using an IEEE 39 bus test system in order to evaluate the effect of the investigated methodology on trading and grid utilization within the peer-to-peer community. Baroche et al. conclude that distance-dependent grid charges can potentially reduce strain imposed on the grid by the peer-to-peer market (Baroche et al., 2019).

Although there are a variety of potential grid tariff structures, these have not been widely rolled out yet. In this paper, different use cases in Austria, Norway, and Ireland are described that investigate such grid tariff designs in real-life implementations. Grid tariff design impact on local market operations is additionally investigated. Grid tariffs are defined in the use cases in such way that peer-to-peer trading can be an opportunity for market operators to reduce their incurred costs. Even though the use cases in the countries consider different grid tariff designs, they all have the same goal to reduce stress on the grid by promoting peer-to-peer trading. In this context, grid peak power reductions, cost reductions due to local market operations, and the amount of locally traded energy are investigated in the use cases. Table 1 summarizes the analyses in the use cases and the taken assumptions.

4.1. Austria

In Austria, a real-life case, developed within the BEYOND project, is currently being used to investigate the impact of distance-dependent grid tariffs on trading within an energy community. The case is based on the Klima- und Energie-Modellregion Retz in Lower Austria, a region where an increase of about 500 kWp PV is expected. The case participant group consists of 30 private households distributed among different low voltage grid branches. 15 participants own a PV system with a combined peak production of 37.1 kW. The use case set-up is illustrated in Fig. 4.

The distance-dependent grid tariff incentivizes electricity trades within the community (*B* in Fig. 4) by providing a tariff reduction compared to external electricity purchases (*A*). Trades within the same low voltage grid branch are charged with an even lower grid tariff to encourage local usage of RES production.

A linear optimization model is used to identify the optimal electricity trades among community participants. It is implemented with the

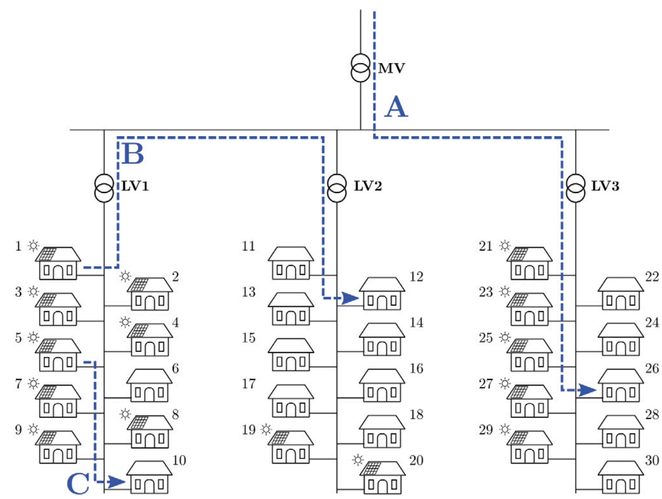

Fig. 4. Use case set-up for the simulation-based analysis. *A* corresponds to purchases from the supplier, *B* to trades within the community and *C* to trades within the same low voltage grid branch.

Femto simulation framework presented in Schwabeneder et al. (2021) using the Julia programming language (Bezanson et al., 2017). The model takes time series for PV production and electricity load as input and depicts all possible trades among community participants and external purchases and sales. The objective function minimizes the total electricity procurement cost of the community, given by the sum of the cost of each participant. Quarter-hourly time series data from the year 2019 are considered in this analysis.

To observe the impact of forming a community and the effects of a local grid tariff the following three set-ups are investigated and compared in the BEYOND model:

- *No Community:* There is no community and no trading among end-users.
- *Community Regular:* End-users form a community, but have to pay the regular grid tariff for all trades.
- *Community Reduced:* End-users are charged a reduced grid tariff for trades within the community and an even lower tariff for trades within the same low voltage grid level.

Table 2
Tariff assumptions in cEUR/kWh for different set-ups in Austria. The internal price is the price at which electricity is traded among community members. It is irrelevant for the optimization model results. However, it is chosen in a way that both buyer and seller benefit equally compared to trading with the supplier.

	No community	Community regular	Community reduced
Supplier tariff p_s	7	7	7
Supplier feed-in tariff p_f	4	4	4
Grid tariff supplier (A)	4.9	4.9	4.9
Grid tariff community (B)	–	4.9	4.2
Grid tariff local (C)	–	4.9	3.1
Fees	2.5	2.5	2.5
Internal price	–	$(p_s + p_f)/2$	$(p_s + p_f + \text{grid savings})/2$

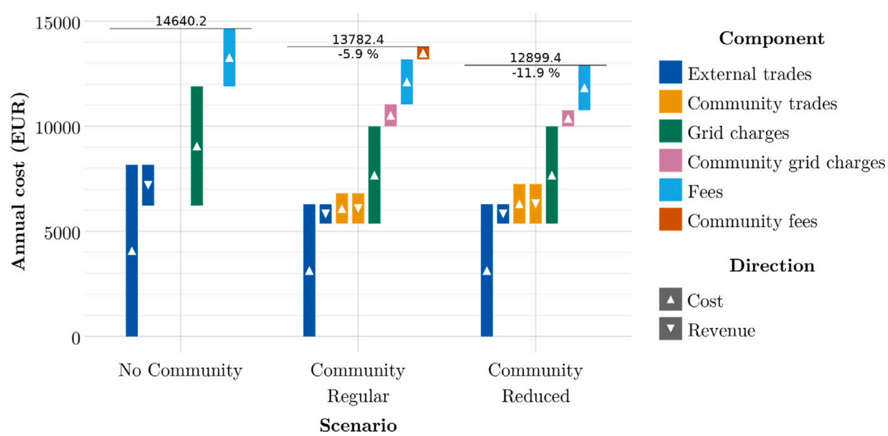

Fig. 5. Total community cost components in different set-ups in the Austrian BEYOND model.

In Austria, the grid charges make up about one fifth of the total electricity price. The tariff assumptions in the set-ups are listed in Table 2.

Fig. 5 shows the total cost of the considered community in different set-ups. The introduction of an energy community results in a cost reduction of approximately 860 EUR for the entire community or 28.6 EUR per household. This is achieved by avoiding the spread between supplier tariff and supplier feed-in tariff. Hence, with higher spreads the cost reduction will also be higher. The introduction of a local grid tariff further reduces total community cost by approximately 880 EUR or 29.4 EUR per household. This yields a total cost reduction of approximately 1470 EUR or 58 EUR per household compared with the *No Community* set-up.

Fig. 6 shows the community benefits per household and the average benefits for each low voltage electricity grid branch. Each individual end-user achieves a cost reduction with the introduction of a community and a further cost reduction with the reduced grid tariff. However, the benefits differ significantly among customers. Household 15 has a significantly higher electricity load than the other households. Its annual demand is about 3.5 times the average annual demand of all households. Hence, it can buy more electricity from other community members and benefits more from the introduction of a community. With reduced grid tariff trades within the same low voltage grid branch are incentivized. Thus, household 15 mostly buys electricity from the PV owners 19 and 20. This results in higher benefits for these participants.

Fig. 7 illustrates the electricity trades among community members between the low voltage grid branches in the two community set-ups. It clearly shows that the internal trades increase significantly with the introduction of a reduced distance-dependent grid tariff.

Table 3 provides a summary of the results in the Austrian use case analysis. In the current configuration, this analysis does not provide any results for impact on the DSO's operation, because no flexible technologies are considered here. The investigation only focuses on optimal trading of residual electricity production and consumption in the community. However, it shows that reduced grid tariffs provide incentives for local trading. Hence, flexible customers with batteries, heat pumps, or electric vehicles are encouraged to use flexibility to increase local use of RES production and this can also affect transformer loads.

4.2. Norway

In Norway, commercial and industrial customers face a peak power charge and are billed for the highest peak drawn from the grid each month. The objective is to incentivize consumers to reduce their power demand in order to ensure efficient grid utilization. Commercial and Industrial customers make up the largest part of the power demand (e.g., energy intensive production processes). Hence, these end-users are the front-runners or possible early adopters of local electricity market frameworks. A recent study of a local electricity market for an industrial site highlights the benefits of peer-to-peer for this type of community (Sæther et al., 2021). The real-life case is based on an industrial site located in Norway and has an overall yearly demand of 6 GWh. It consists of five large building complexes representing: food processing plants, construction, forestry, mechanical workshops, and other businesses. This industrial community of buildings considers various local electricity market designs to understand the value and role of peer-to-peer trading.

In the case, the consumers are subject to the same electricity price per kWh (flat tariff), regardless of when it was delivered or at how high the power. This energy-based tariff consists of a fixed term and an energy term. The fixed term is a yearly cost (EUR/year) independent of the energy delivered (e.g., investments and government taxes). The energy term reflects the costs for energy procured from the grid, such as losses. In addition, large consumers are subject to a peak power demand charge (refer to Sæther et al., 2021). Hence, the Utility Tariff (UT) includes a power term based on the peak power drawn from the grid in each billing period, as described in Eq. (1). The power term is usually high as it aims to reflect that peak demand might create stress to

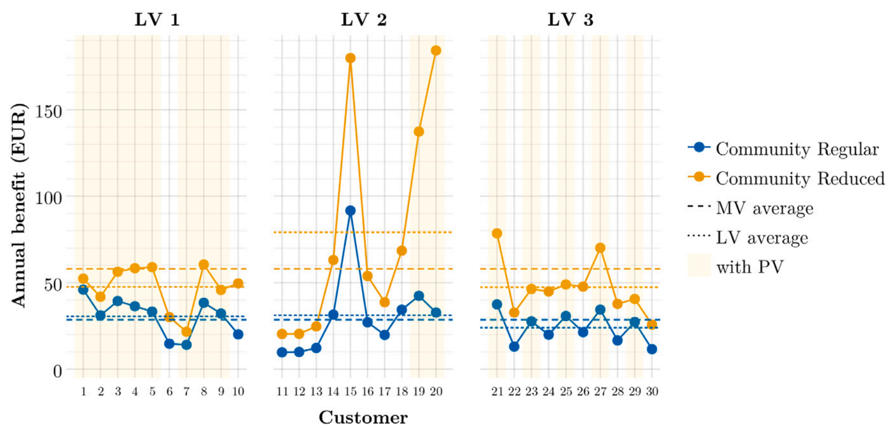

Fig. 6. Cost change for individual households compared with the *No Community* set-up in the Austrian BEYOND model.

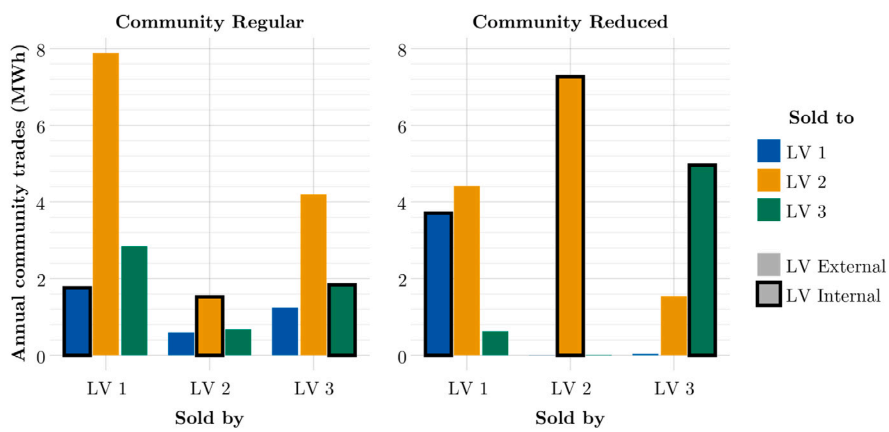

Fig. 7. Electricity trades in Austrian use case between different low voltage electricity grid branches in different set-ups.

Table 3
Summary of the results of the Austrian use case analysis.

	No community	Community regular	Community reduced
External electricity purchases [kWh]	80,240	57,668	57,668
External electricity sales [kWh]	43,104	20,529	20,529
Total electricity exchanged within the community [kWh]	–	22,573	22,573
Electricity exchanged within the same low voltage grid branch [kWh]	–	5,123	15,932
Total annual cost for electricity [EUR]	14640.2	13782.4	12899.4

the grid. The incentive is to shave the peak demand by minimizing the cost of the power term (The Norwegian Water Resources and Energy Directorate (NVE), 2018; Energi Norge, 2018).

$$\text{Consumer Utility Tariff (UT)} = \text{Fixed term} + \text{Energy term} + \text{Power term} \quad (1)$$

Based on this tariff configuration and the industrial site features, the model by Sæther et al. (2021) and Lüth et al. (2018a) analyses specifically joint peak management in local energy trading (i.e., a joint energy arbitrage optimization in combination with community peak time management). The time-span of the analysis is one year with 2017 data. Table 4 illustrates central results of this case related to the benefits of local sharing versus no community on a monthly basis. There are potential cost savings of 7.5% mainly from better joint peak management for the community as whole (cost of peak power reduces by 15%). Community energy sharing decreases grid imports by 1.9% which contributes to these overall savings. Also solar PV is better used locally (grid feed-in reduced by 67%) and flexibility assets (e.g., electric vehicles and load shifting) shave jointly the community peak as well as increase the peer-to-peer energy traded.

Table 4
A collaborative community via P2P in a Norwegian industrial site. Monthly average.

	No community	P2P in the community
Monthly cost (EUR) of grid import	21,641	20,018 (−7.5%)
- Cost of peak power	9,330	7,930 (−15.0%)
- Cost of UT energy term	1,492	28 (−1.9%)
- Cost of UT fixed term	679	0
- Cost of energy spot price	10,140	9,947 (−1.9%)
Revenues of grid feed-in	248	86 (−65.3%)
Community export to grid [kWh]	9,195	3,034 (−67.0%)
Curtailed Solar PV [kWh]	1,309	0
Grid imports [kWh]	320,087	314,005 (−1.9%)
P2P export [kWh]	–	17,184

For this industrial community the potential savings calculated and the grid tariff structure play a meaningful role to establish a local electricity market. A similar study by Dynge et al. (2021) designed a local electricity market formation in Norwegian residential buildings where authors estimated that the value of setting up a peer-to-peer community brings savings of around 3%. This is much lower than the industrial site (7.5%). The difference is because the power term creates an important value in the local electricity market (joint peak management) and the power term is not part of the grid tariff in the residential case.

4.3. Ireland

In continuation of previous use cases, this section presents a simulation-based analysis of the peer-to-peer market under static time-of-use tariff for a real-life energy community in Ireland BEYOND (2021a). The use case examines the synergy of static time-of-use grid tariff and residential energy storage system (ESS) on the operation of residential customers along with the consequences of introducing peer-to-peer market under such scenario.

Currently, there exists a day–night retail electricity pricing scheme in Ireland for smart meter users along with a traditional flat pricing scheme. The price of each unit of electricity during the night is almost half of each unit during the day. This retail pricing comprises the wholesale energy cost, supplier's cost, grid tariff, government taxes and levies (Commission for Regulation of Utilities (CRU), 2021b). The reduced night rate in the day–night tariff scheme is realized not only by the usually low energy price during night hours in the wholesale market but also by significantly lower distribution grid tariff (due to low electricity consumption). In 2020, domestic consumers in Ireland with day–night pricing, had to pay a distribution grid tariff of 5.4 cEUR/kWh and 0.7 cEUR/kWh for energy supplied during the day and night time respectively (ESB Networks DAC, 2020). This indicates that the current distribution grid tariff in Ireland is intended to encourage customers to shift their demand to the night hours passively. However, this approach is static and time-of-usage in nature. As the grid tariff is not coupled with real-time grid conditions, it fails to stimulate demand response in near real-time to avoid grid congestion or critical peak events. In Ireland, grid charges account for around one third of total electricity prices (Commission for Regulation of Utilities (CRU), 2021b). The distribution grid tariff comprises a volumetric component (cEUR/kWh) as well as a fixed component (EUR/year) and does not have a power component. Therefore, end-users cannot be incentivized or penalized based on their power usage.

The Irish use case involves 20 residential households, each of which is equipped with 10 kWh/3.3 kW peak lithium-ion batteries. Out of the 20 households, 9 with rooftop PV facilities are acting as prosumers. The pilot site is located under one of the substations with a 10 kV feeder with an overhead grid. All the 20 households are located under the same 10 kV feeder. Results presented in this section consider two set-ups as described below:

- *No Community:* Each household is equipped with a home energy management system operating the assets to minimize the electricity bill of individual end-users. They do not engage in peer-to-peer trading.
- *P2P in the community:* This set-up envisages that the households form a community with the provision of peer-to-peer trading within the community.

The peer-to-peer market has been formulated as a multi-period linear optimization model to minimize the total procurement cost of the entire energy community from the energy supplier by incentivizing the peer-to-peer energy trading among community members. Details of the formulation of the market model can be found on Lüth et al. (2018b). Demand and solar PV production profiles used as inputs to the model are in hourly resolution. To incentivize electricity trading on a local level, the electricity price in the P2P trading is assumed to be lower than the day-time rate of electricity but higher than the feed-in-tariff. The results illustrating the impact of peer-to-peer trading within the community compared with the base case, no community set-up, are summarized in Table 5. The analysis was conducted for an entire month, June 2020. Due to the large computation time for the optimization, the analyzed period in the Irish use case is shorter than in the other use cases. The choice of June 2020 for simulation is because it gives the most prospective result as this month has the highest self-autarky with 27.7% of demand is supplied from locally generated energy.

Table 5 shows that the implementation of the peer-to-peer market reduced the total cost to the community by 11% associated with electricity exchange with the grid. It was due to the preference of trading among peers within the community rather than importing from and/or exporting back to the grid, as reflected in the statistics in Table 5. It is observed that both grid imports and exports have been reduced due to the peer-to-peer market. The grid dependency of the community has experienced a reduction of 9.2% as locally generated electricity is being utilized more effectively in the peer-to-peer market environment. However, the adverse impact of the peer-to-peer market arrangements causes the aggregated peak demand to increase by 9.1%. It is due to the fact that the charging operation of energy storage systems for energy arbitrage using the opportunity of differential tariff scheme. This phenomenon is particularly of interest to the DSO, as it highlights the need for additional constraints from DSO-side to postpone its grid reinforcement. The results also demonstrate the critical relationship of energy storage and static time-of-use grid tariff on the benefits brought by peer-to-peer market provision to the energy community.

All three use cases showed that the implementation of peer-to-peer trading can help to reduce peak power and further reduce the costs for consumers operating in local electricity markets. Grid tariff design is thus an effective tool to promote peer-to-peer trading in local electricity markets.

5. Discussion

Regulatory frameworks on local electricity markets and investigations regarding grid tariff design were introduced as important foundations for the implementation of local electricity markets. Building upon these, first regulatory frameworks in EU countries are compared and analyzed based on their implementation level. For a real-life implementation, potential barriers for grid tariff design might emerge, that are also analyzed in this section.

5.1. Comparison of the regulatory framework in EU countries

The first part of this discussion analyzes and compares the EU countries that have already defined a regulatory framework for energy communities as a concept for peer-to-peer energy trading or in which a regulatory framework is currently emerging. The countries' approaches to energy communities are summarized in Table 6. Table 6 shows how far advanced their regulatory frameworks are, the proximity of the energy communities, the grid levels over which the establishment of a community is possible, and whether innovative grid tariff designs, where only the grid charges for the actually used power lines are charged, have been considered.

From Table 6 it can be seen that energy community concepts are not equally implemented across the EU. A major difference is in the possible proximity of energy communities. In some countries, such as Sweden, the proximity is limited to the same grid connection point (under the same sub-station), while other countries allow participation over wider areas. A more strict limitation is implemented in some countries. For example, in Denmark local energy trading is only allowed over private grids. Overall, the considerations regarding the proximity and grid levels differ significantly, as some countries consider the connection of the consumers through the electricity grid, specified by the location within the grid levels, and other countries (e.g., France and the Netherlands) make the assignment based on geographical conditions. This variation occurs due to the fact that there are no clear guidelines from the EU

Table 5
A collaborative community via P2P in an Irish pilot.

	No community	P2P in the community
Electrical energy imports from grid [kWh]	5,817	5,282 (−9.2%)
Electrical energy exports to grid [kWh]	604	0
Total cost of electrical energy imports [EUR]	642	523
Variable cost of electrical energy imports [EUR]	N/A	N/A
Revenue from electrical energy exports [EUR]	54	0
Total cost from energy exchange with grid [EUR]	588	523 (−11%)
Locally exchanged electrical energy [kWh]	0	871
Peak demand [kWp]	77	70 (−9.1%)

Table 6
Comparison of regulatory frameworks in EU countries (based on Frieden et al. (2019), Jasiak (2019), Gouvernement Wallon (2019), Verbraucherzentrale Bundesverband e.V. (2018), Ministry of the Economy Luxembourg (2018), Inês et al. (2020)).

Country	Regulatory framework	Proximity	Grid level	Innovative grid tariffs
Belgium	Only citizen energy communities	Grid connection points	Middle/Low voltage	Possible in the future
Croatia	Only citizen energy communities	No specific	No specific	Premium tariffs
Denmark	Limited	Private grid	Private grid	No
Estonia	Limited	Same metering points	Low voltage	No
Finland	Limited	Industrial or estate grid	Industrial or estate grid	No
France	Yes	c. 1 km	Low voltage	Grid tariffs
Germany	Yes	Not clear	not clear	Not mentioned
Greece	Yes	50% of participants must be in same building	Not clear	Not mentioned
Italy	Only citizen energy communities	Not clear	Not clear	Premium tariffs/tax reduction
Luxembourg	Yes	Grid connection branch	Low voltage	Not mentioned
Netherlands	In development	Postal codes	Postal codes	Not mentioned
Portugal	Emerging	Not clear	Not clear	Price reduction
Slovenia	Yes	Metering point of low voltage grid	Low voltage	Not mentioned
Spain	Yes	Nearby customers	Low voltage/internal grid	Not mentioned
Sweden	Limited	Grid connection point	Low voltage	No

regarding the proximity of energy communities. Innovative grid tariff designs have been discussed in various countries, but not implemented, as no real concepts have been tested on a large scale yet.

Differences occur in the energy community participation limits. All EU countries listed in Table 6 allow energy trading between apartments that are located within the same building. The next step, taken by some countries (e.g., Belgium), is to include small or medium-size companies, as well as local authorities, in energy communities. Generally, if the regulatory framework of a country is limited or emerging, participation in energy communities is mainly limited to apartments within the same building.

Based on the findings in the comparison, Austria is among the countries with an existing framework for citizen energy communities and renewable energy communities. Peer-to-peer trading in renewable energy communities can be done over either the low voltage grid or middle voltage grid, which will also determine the proximity in which a renewable energy community can be founded, while the grid tariff concepts should be designed in such a way that only the grid costs of the used grid levels for energy trading are cleared. The Irish regulatory framework is still under development. Trading is allowed in the form of physical and virtual trading. While renewable energy communities are limited to the distribution grid sections, citizen energy communities have no proximity requirement. Norway has to be considered as different from the other countries, as its regulatory framework for local electricity markets is set only at a national level without reference to the EU guidelines. The necessary framework concept for the energy system in Norway is not defined by the European regulations. Energy and grid tariff adaptions are needed in general, but not as an innovative concept.

All of the above-discussed aspects lead to the conclusion that regulatory barriers for the implementation of energy communities can occur due to the limited proximity or participation possibilities. Innovative grid tariff structures that would promote the energy community concept are discussed theoretically at best. Furthermore, the regulatory differences between the countries might also hinder the implementation of energy communities.

5.2. Barriers to implementation of innovative grid tariffs

In Section 4, the main aspects of grid tariff design are mentioned as system sustainability, economic efficiency, and customer protection. Considering the results from the investigations in Austria, Norway, and Ireland, possible implementation barriers to innovative grid tariffs have been analyzed. For system sustainability, the costs related to the grid operation must be fully covered (Picciariello et al., 2015), which means that if the total costs for the DSO are not decreasing, lower grid tariffs for customers applying peer-to-peer trading can result in higher costs for customers who are not involved in the local electricity market mechanism. This would conflict with the non-discrimination approach of energy communities in EU Directive 2018/2001 (Council of the European Union, 2018), which means that cost savings for energy community members must not lead to higher costs for others customers that do not participate in energy communities. One of the possible solutions to overcome this barrier is to implement the grid tariff design in such a way that the reduced grid tariffs for peer-to-peer trading should be covered by the long-term cost savings for the DSO due to the decrease in the maximum power provided by the grid to each customer. Such peak power reduction could prevent future grid expansion for the DSOs. The discrimination problem for non-participating customers also fits in the customer protection category, and therefore it can be seen that the most important aspects regarding grid tariff design are intertwined.

Applying peer-to-peer trading with reduced grid tariffs should be provided as simply as possible by the DSOs. Otherwise, barriers could be created if the DSOs fail to provide such a service easily. In addition, economic incentives for peer-to-peer trading are required. The investigations of the demo-site in Austria, Norway, and Ireland, which are described in Section 4, mainly focus on the economic efficiency of peer-to-peer trading. In all of the cases, innovative grid tariffs for local electricity markets lead to cost savings. As found in the Austrian case, the cost savings for a single person were rather low (36 EUR per person per year). The cost savings that arise through the peer-to-peer trading with reduced grid tariffs should be determined based on the total cost savings for the whole community when considering the overall economic benefits of the energy community. Customers might not consider the benefits to the whole community, but rather just their own benefits, in which case the cost savings provided by innovative grid tariffs might not meet the expectations of the consumers. Therefore, there is a need for tariff structures that can provide additional incentives for peer-to-peer trading.

Moreover, a main goal of grid tariff design is the allocation of the costs incurred by electricity trading, based on the physical load flows caused by electricity trading. Hence, it is assumed that only medium and low voltage (MV/LV) lines, as well as the corresponding transformers are used in peer-to-peer trading processes, so that the grid charges for high voltage (HV) lines and transformers are not intended to be charged for peer-to-peer trading. Applying Kirchhoff's law, the currents and thus the load flows are divided across all connected power lines depending upon the distance dependent impedances of the connected power lines. The power line to the closest consumer, whose consumption profile just matches the generation profile of the prosumer, will be the most heavily loaded, even if the consumer is not involved in peer-to-peer trading and draws the energy. This is due to the difference between energy billed on the balance sheet and energy physically procured. In addition, load flows of lower dimension over other connected power lines emerge, which are not directly required for the peer-to-peer trading process. These load flows occur because the impedances of the power lines are not infinitely high. Peer-to-peer trading results in a load on the electrical equipment beyond the local level. Thus it is apparent that innovative grid tariffs do not exactly represent the physical load flows, which can emerge as additional implementation barriers. Along with these barriers, the literature reviewed for this paper shows that the most important technical issues in relation to the grid stability and power quality of the network have been overlooked (Dudjak et al., 2021; Dynge et al., 2021). It is expected that the peer-to-peer or local electricity market will help to increase the clean energy trading over the distribution network, which might increase the voltage/frequency fluctuation, imbalance, and harmonics in the network as well due to rising amount of distributed energy resources and increased distribution grid load for local energy trading. However, it not clear, how this issue will be managed with regard to the administrative boundaries of energy communities. In such cases, DSOs will always have to play an important role either directly or indirectly to maximize or limit the energy trading over the network.

6. Conclusions

Regulatory frameworks for energy communities are derived from EU regulations, their actual implementation still differs within the individual member countries of the European Economic Area. In Austria, the Renewable Expansion Act including the concepts of citizen energy communities and renewable energy communities, was implemented in the federal law in July 2021, while in Norway a trend of increasing decentralization is faced with consumer-centric legislation with an individualistic view. In Ireland, regulations on the formation of citizen energy communities and renewable energy communities are currently in the consultation process.

One of the characteristics in framework design is that of proximity, where authorities are considering both physical and geographical boundaries. In case of physical power grid boundaries, the issues in relation to the negative grid impact could be overcome, but special attention should be given in cases of geographical boundaries, as participating customers may trade energy beyond their substation areas. DSOs should have an active role in situations. Reduced grid tariffs are an effective means of creating incentives (e.g., the existing framework for Austria and Germany for pumped hydro storage plants for ancillary services such as frequency containment reserve or frequency restoration reserves) and thus can fulfill the role of the promotion of energy communities. However, in the case of energy-based grid tariffs, these grid tariffs for external purchases can continue to increase due to higher self-consumption of localized energy. Thus, the contribution to grid financing further unevenly distribution between participants in energy communities and other consumers. Due to the increasing expansion of decentralized energy generation and the increase of electrification of energy systems by sector coupling, power-based grid tariffs are increasingly discussed. This power-based grid tariff system is highly important as on the one hand, it will help to keep the grid expansion as low as possible and on the other hand, to change the behavior of the consumers towards more grid friendliness (under the heading peak load shaving). However, with power-based grid tariffs, there is also less incentive for self-consumption, since the grid component of the retail electricity price usually decreases, thus lowering the levelized costs of electricity for energy. In order to still provide incentives for energy communities, virtual metering points must be introduced for energy communities. However, this reduction in the economic incentive of self-consumption is increasingly offset by rising electricity prices. A power-based grid tariff can be a grid-friendly incentives for use of flexibilities (e.g., battery storage). Therefore, the economic incentives for the use of battery storage increase, on the one hand due to an increasing spread between retail price and feed-in tariff and on the other hand due to the reduction of the peak load pricing of the power-based grid tariffs. An increased use of battery storage also decreases the amounts of electricity to be traded. This has disadvantages for pure consumers in the energy communities or promotes the incentives to invest in generation and storage themselves. Therefore, energy communities will also experience an economic saturation level of decentralized generation and storage. In order to not promoting this individual optimization, as mentioned, virtual metering points are needed to make the benefits of battery storage available to all participants of energy communities. This means that energy communities will also require to have a common peak load calculations, which would then result in a reduction compared with the individual metering point billing if the energy communities reduce the total peak load in the network section. This would lead to a coordinated operation of the energy communities and most likely to a more optimal economic result.

Preliminary results from the BEYOND project case studies in Austria, Norway, and Ireland demonstrate the economic benefits leveraged by the community after implementing peer-to-peer markets under existing electricity retail pricing. The economic benefit mainly stems from reductions in grid dependency of the energy community. This highlights the need for further investigations into possible future grid tariff designs which facilitate the assumptions about peer-to-peer pricing and understanding of its impact on customer, community, and system level.

On top of the regulatory framework and grid tariff design comes the problem of market connection between local and wholesale electricity market. In this case, transmissions system operator–distribution system operator coordination will play a crucial role.

Further, based on the EU focusing on consumer-centric European smart grids, the national regulations for energy communities should also be adjusted to the grid requirements at national and EU level.

CRediT authorship contribution statement

Matthias Maldet: Conceptualization, Methodology, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Review organization. **Frida Huglen Revheim:** Conceptualization, Methodology, Formal analysis, Investigation, Resources, Writing – original draft, Writing – review & editing, Visualization. **Daniel Schwabeneder:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Georg Lettner:** Conceptualization, Methodology, Formal analysis, Investigation, Resources, Writing – original draft, Writing – review & editing, Project administration, Funding acquisition. **Pedro Crespo del Granado:** Conceptualization, Methodology, Formal analysis, Investigation, Resources, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Aziz Saif:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing. **Markus Löschenbrand:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Shafi Khadem:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, 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.

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