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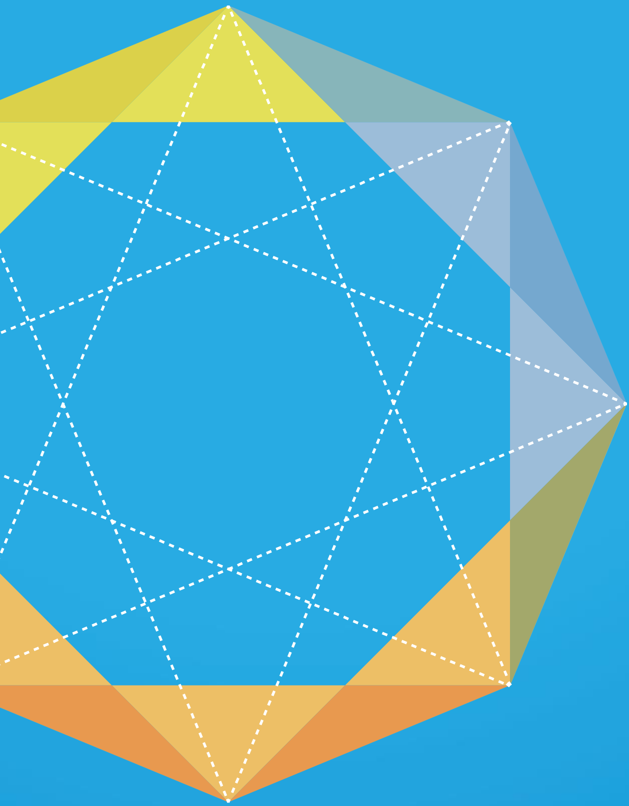
Energy Communities' impact on grids

Energy Community Embedment Increasing Grid Flexibility and Flourishing Electricity Markets



ETIP SNET

European Technology and Innovation Platform
Smart Networks for Energy Transition

ISGAN
INTERNATIONAL SMART GRID
ACTION NETWORK

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Executive Summary

Energy communities have an agenda beyond simply generating electricity or heat from renewable sources. It encompasses environmental, technological and economic aspects of a low-carbon economy by addressing social equity issues. The deployment of energy communities supports the paradigm that society's growth must also occur locally by promoting investment in distributed energy resources and democratising the energy industry.

Climate change and the current energy crisis, along with a hike in electricity prices, have aroused community interest in using local renewable energy sources and creating energy communities. European Union policymakers have adopted legislation to support energy communities in taking responsibility for the energy transition. Still, the challenges and opportunities of deploying such communities are numerous and manifold, from legislation, organisation, socio-economic, market structure, and system-technical to citizen engagement. Therefore, we must ensure that the fair transition to a low-carbon economy happens in a way that avoids displacing energy communities.

Despite the rapid development of technologies that energy communities are experiencing today, technical issues still exist in various forms, mainly known as grid-related challenges. The distributed energy resources that they promote change the electricity landscape.

Since the beginning of this century, even if the electricity sector has experienced profound changes driven by extraordinary technical development (e.g., digitalisation and communications), market rules following new regulatory proposals and policy decisions have overwhelmed the technical ones. For this reason, the traditional structure of power grids needs to be readapted. The emergence of distributed energy resources and the introduction of energy communities to promote integration exacerbate the need to adapt the power grid architecture. Consolidating an appropriate architecture considering the entire power grid - i.e., from the big power plants through the transmission grid, the distribution grid with the distributed energy resources to the consumers and prosumers - is imperative to propel the energy transition realistically.

Distribution and Transmission System Operators could experience many technical challenges in guaranteeing the security and quality of supply after the large-scale implementation of energy communities, which extensively promotes the integration of distributed resources. To overcome this, research and innovation are necessary to introduce fully integrated energy communities, enabling the desired flexibility and resilience. The latter are crucial for grid operators and society facing the energy crisis and climate change.

The current economic processing in the power industry is a mixture of market activities and contracts that do not support the flourishing of viable, fully integrated energy communities. The existing market structure dates back to when electricity was mainly generated in large power plants, fed into the transmission grid, and distributed to customers. The players in the electricity market are limited to large electricity producers, consumers, and energy suppliers, which are few. Fully integrated energy communities will be able to thrive in a market structure that allows all players to participate, regardless of their size.

Three overarching themes are essential for initiating and sustaining an energy community initiative: trust, motivation, and continuity, which impact their governance or self-governance. Each country offers a wide choice of different legal forms of organisations for a newly created entity, which leads to a wildly grown landscape. These energy communities are generally limited to a certain redistribution of cash flow. Their upgrade to fully integrated EnCs, which supports the demand response process at distribution and transmission levels, will require solid organisation forms and business cases.

The top-down approach to introducing energy communities in the energy landscape would be driven by appropriate legislation and measures to overcome grid-related challenges. However, creating and strengthening citizens' awareness is essential for developing a low-carbon social norm. This will take time, which should be considered in all implementation processes.

The new role of energy communities represents both an opportunity and a challenge for DSOs and, consequently, for **TSOs. They can unlock active consumers' flexibility potential and more effectively integrate distributed renewable resources and new technologies**, such as rooftop photovoltaic facilities, electric vehicles or batteries, etc. In contrast, **energy communities must fulfil all related duties and responsibilities when acting as suppliers, active customers or any other existing market role. They must act on equal terms with other market players.**

Abbreviations

AS	Ancillary Service
ATV	Average Trading Volume
BRP	Balancing Responsible Party
BSP	Balancing Service Provider
CAM	Control Area Manager
CEER	Council of European Energy Regulators
CEnC	Citizen Energy Community
CEP	Clean Energy Package
CIM	Common Information Model
CPO	Charging Point Operator
CS	Coordination Schemes
CSC	Collective Self-Consumption
CT	Communication Technology
DER	Distributed Energy Resources
DisCos	Distribution Companies
DR	Demand Response
DTR	Distribution Transformer
DSO	Distribution System Operators
EC	European Commission
EnC	Energy Community
EPO	Electricity Producer Operator
ESCO	Energy Service Companies
ESOS	Energy System of Systems
ETr	Energy trading volume
EU	European Union
EV	Electric Vehicle
GenCos	Generating Companies
HVG	High Voltage Grid
IED	Intelligent Electronic Device
IMD	Internal Market Directive
KPI	Key Performance Indicator
LCOE	Levelized Cost of Electricity
LVG	Low Voltage Grid
MARI	Manually Activated Reserves Initiative
MS	Member States
MVG	Medium Voltage Grid
P2P	Peer-to-Peer
PCC	Point of Common Coupling
PICASSO	Platform for the International Coordination of Automated Frequency Restoration and Stable System Operation
PPM	Peak Power Margins
Pr.	Producer
PV	Photovoltaic
R&D	Research and Development
REDII	Renewable Energy Directive
REnC	Renewable Energy Community
RES	Renewable Energy Sources
SCADA	Supervisory Control and Data Acquisition
SCD	Shared Customer Database
SME	Small- and Medium-Sized Enterprise
St.	Storage
StO	Storage Operators
TERRE	Trans-European Replacement Reserves Exchange
TOU	Time of Use
TransCos	Transmission Companies
TSO	Transmission System Operators
VHVG	Very High Voltage Grid
VPP	Virtual Power Plant

Introduction

The extreme weather situation in 2023, with high temperatures and large fires and storms, rain, and hail in other regions, led to partial blackouts, provoking water supply problems [1] in the European Southern Region. If electricity and water supply in the blackout areas had been powered with resilient local distribution systems, the people there would already have had one less problem. With such resilient systems, some houses would have had electricity and water supply in some regions. All these events underline the importance of local supply and energy communities as crucial elements to increase resilience for citizens.

Historically, the rise of collective consumption, meaning the Peer-to-Peer (P2P) based activity of obtaining, giving, or sharing access to goods and services, has provided the hub for Energy Communities (EnC). The local supply they promote through the Distributed Energy Resources (DER) may achieve broad beneficial economic, social, environmental and governance outcomes. Aware of these opportunities, EU policymakers have adopted legislation to support local communities in taking responsibility for the energy transition. As part of the Clean Energy Package (CEP), the European institutions have recognised the role of EnCs in helping the EU achieve its climate and energy goals while promoting local social innovation. The recast Renewable Energy Directive 2018/2001 (REDII) [2] and the recast Internal Market Directive (IMD) 2019/944 [3], referred to as the Electricity Market Directive, includes the definition of Renewable Energy Communities (REnCs) and Citizen EnCs (CEnCs), respectively. They both contain provisions that establish a supportive legal framework for EnCs. Article 17.2 of the IMD states that DSOs and TSOs treat market participants engaged in aggregating Demand Response (DR) non-discriminately. This also includes EnCs, among other third parties, as reliable providers of flexibility services if such solutions enable more efficient network operation [4].

The EnCs are widely associated with promoting and using DERs, providing customer benefits. Even TSOs and DSOs can benefit from their further deployment. DSOs may procure local flexibility, using the information on energy flows between different connection points to ensure the grid constraints are followed. The demand from DSOs to buy flexibility products is expected to grow. EnCs can unlock the flexibility potential of prosumers and enable more effective integration of distributed resources and new technologies. In the case of flexibility provision, EnCs should be subject to the same relevant provisions as other agents (Article 16.3(b) of the IMD, which states that "*Member States (MS) shall ensure that* ***citizen energy communities are treated in a non-discriminatory and proportionate manner*** *concerning their activities, rights and obligations as final customers, producers, suppliers, distribution system operators or market participants engaged in aggregation;*"). In their role as market facilitators, it is key that DSOs act so that the above principles are met for all parties involved, including EnCs, in providing flexible services and participating in the markets that may exist.

Since the distribution systems are the direct link between all electricity system users, DSOs must recognise the EnC's great potential and help establish a new and more efficient market design in their new role as market facilitators. This new role is relevant as market design is critical to ensure that EnCs have incentives to develop in a way that reduces system costs. There is a risk that, given inefficient incentives, community coordination may lead to increased network use or inefficient market outcomes. An exciting perspective discussed by the Council of European Energy Regulators (CEER) [5] is that most of the issues raised by consumption management and flexibility services are not specific to EnCs, and their existence could change the provision of flexibility to DSOs, where aggregation is already an issue. Indeed, focusing the discussion on social and environmental goals rather than economic gains could result in EnCs being less focused on market-based price signals and thus receiving different considerations vis-à-vis other actors. For example, market participants such as aggregators usually value flexibility in energy markets that are designed to reflect the state of the power system, ensuring that flexibility

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1 https://www.reuters.com/world/europe/europe-sees-another-year-droughts-wildfires-2023-08-09/

2 Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources.

3 Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EU.

4 Energie Impact, 2020, Energy Communities in the Clean Energy Package: Best Practices and Recommendations for Implementation.

5 CEER, 25 June 2019, Report on Regulatory Aspects of Self-Consumption and Energy Communities, Ref: C18-CRM9_DS7-05-03.

is used where and when it is the most valuable to the system. The same could be said of the consumption management of the distribution network, where good practices and customer information are not specific to EnCs either.

Complex interdependencies between economic, political, and social market objectives try to support extensions to market design and bidding strategies [6], especially as electricity is a critical strategic resource of our times. DERs, an increasing captive power generation involving a surge in self-optimising systems, require an entirely different market architecture [7].

On the technical side, remarkable research is being performed to improve the load matching of individual customers and at the community level [8][9][10]. However, none of these studies considers the grid, constraints, challenges, or coordinated operation, so the solutions are not directly practicable on a large scale.

This report first gives a brief overview of EnC developments, followed by an analysis of the impact of large-scale implementation of energy communities on the power grids. It discusses economic processing in the power industry and business organisation, as both are crucial for promoting viable energy communities. Finally, it offers conclusions and recommendations on innovation and research.

Brief overview of developments in energy communities

1.1 Historical development of energy community definition

In general, energy crises have always forced new developments. E.g., the oil crisis in the 1970s was a shock and a wake-up call highlighting Denmark's extreme dependence on imported energy. This crisis sparked interest in harnessing locally available wind energy. Individual enthusiasts, local initiative groups, and small private companies experimented with new wind energy technologies, often with private funds and at personal risk. Denmark was the first country to pioneer in wind energy and local initiative groups, with policies and regulations dating back to the 1970s [11]. In the 2000s, Germany's

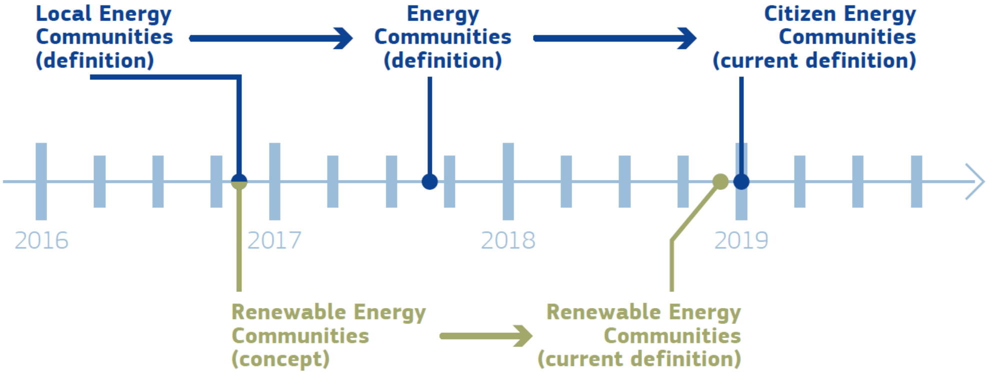

Fig. 1. Changes in the Energy Community definitions in Europe.

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6 Mengelkamp, E.; Staudt, P.; Garttner, J.; Weinhardt, C. Trading on local energy markets: A comparison of market designs and bidding strategies. In Proceedings of the 14th International Conference on the European Energy Market, Dresden, Germany, 6–9 June 2017; pp. 1–6. Available online: https://ieeexplore.ieee.org/document/7981938 (accessed on 9 June 2021).

7 Schleicher-Tappeser, R. How renewables will change electricity markets in the next five years. Energy Policy 2012, 48, 64–75.

8 Rui Amaral Lopes, João Martins, Daniel Aelenei, Celson Pantoja Lima, A cooperative net zero energy community to improve load matching, Renewable Energy, Volume 93, 2016, Pages 1-13, ISSN 0960-1481, https://doi.org/10.1016/j.renene.2016.02.044.

9 A. Chiş, J. Rajasekharan, J. Lundén and V. Koivunen, "Demand response for renewable energy integration and load balancing in smart grid communities," 2016 24th European Signal Processing Conference (EUSIPCO), Budapest, Hungary, 2016, pp. 1423-1427, doi: 10.1109/EUSIPCO.2016.7760483.

10 Matthieu Stephant, Dhaker Abbes, Kahina Hassam-Ouari, Antoine Labrunie, Benoît Robyns, Distributed optimization of energy profiles to improve photovoltaic self-consumption on a local energy community, Simulation Modelling Practice and Theory, Volume 108, 2021, 102242, ISSN 1569-190X, https://doi.org/10.1016/j.simpat.2020.102242.

11 Johansen, Katinka. (2021). Wind Energy in Denmark: A Short History. IEEE Power and Energy Magazine. 19. 94-102. 10.1109/MPE.2021.3057973.

Renewable Energy Sources Act [12] prioritised and enabled the “Energy Cooperative” [13]. At the same time, in the UK, the term "Community Renewable" became part of mainstream energy policy, with funding programs helping various local projects to take off [14]. Later on, the French “Énergies Partagées” [15] emerged. Among these terms, the English term “Community Energy” has received the most attention in the scientific community and has become established.

In November 2016, the “Clean Energy for all Europeans” package was presented by the European Commission (EC), which finally gave a unanimous definition of EnCs at the European level, see Figure 1. It defined the Local EnCs. In September 2017, the Council of the European Union changed the EC proposal by defining EnCs as "a legal entity which is effectively controlled by shareholders or members who are natural persons, local authorities, including municipalities, or small and micro enterprises. At least 51% of the shareholders or members of the entity with voting rights are natural persons. Any actor may participate as long as members or shareholders are not engaged in large-scale commercial activity for which the energy sector constitutes a primary area of economic activity and do not exercise any decision-making power. EnCs can be engaged in electricity generation, distribution and supply, self-consumption, aggregation, storage or energy efficiency services, generation of renewable electricity, or other services to its shareholders or members". This definition removes the geographical limitation of the Local EnC by allowing non-local natural persons and small and micro enterprises to participate in the EnC.

The REDII and the IMD, adopted as part of the European Commission's CEP, provide the current definitions of energy communities by distinguishing between REnC and CEnC. Participation in both types of EnCs is generally open and voluntary.

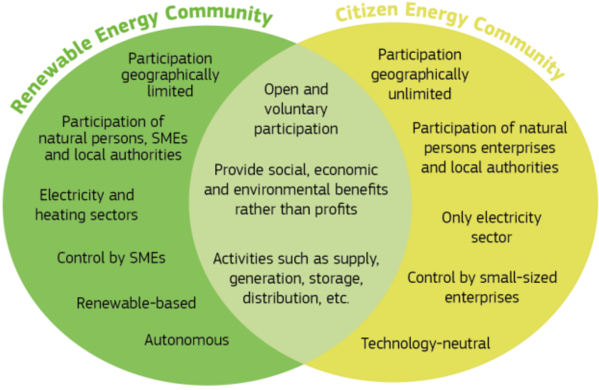

Fig. 2. Similarities and differences between renewable and citizen energy communities.

They aim to provide social, economic and environmental benefits to the community members or shareholders rather than profits. Typical community activities include supply, generation, storage, distribution, etc.

REnCs are geographically limited and organised near renewable energy sources owned and developed by that community, see Figure 2. Natural persons, including low-income and vulnerable households, local authorities and small- and medium-sized enterprises (SMEs), may participate in them. REnCs cover a broad range of activities referring to all forms of renewable energy in the electricity and heating sector.

CEnCs mainly differ from renewable ones in their geographically unlimited character, focus on the electricity sector and technological neutrality. Any actor may participate if members or shareholders are not engaged in large-scale commercial activities for which the energy sector constitutes a primary area of economic activity and does not exercise any decision-

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12 Oschmann, V. (2010). A Success Story – The German Renewable Energy Act Turns Ten. *Renewable Energy Law and Policy Review*, *1*(1), 45–59. http://www.jstor.org/stable/24324586

13 DGRV, Energy Cooperatives in Germany, State of the Sector 2022 Report. https://www.dgrv.de/wp-content/uploads/2022/07/DGRV_Survey_EnergyCooperatives_2022.pdf

14 Walker G, Devine-Wright P (2008) Community renewable energy: what should it mean? Energy Policy 36:497–500. doi:10.1016/j.enpol.2007.10.019

15 Poize N, Ru¨dinger A (2014) Projets citoyens pour la production d’e´nergie renouvelable. IDDRI, Paris. https://www.iddri.org/sites/default/files/import/publications/wp0114_np-ar_projets-citoyens.pdf making power. It is important to note that Member States are required to develop more detailed conditions that will make the full deployment of EnCs possible in each country, as has been the case in some European countries in the last two years.

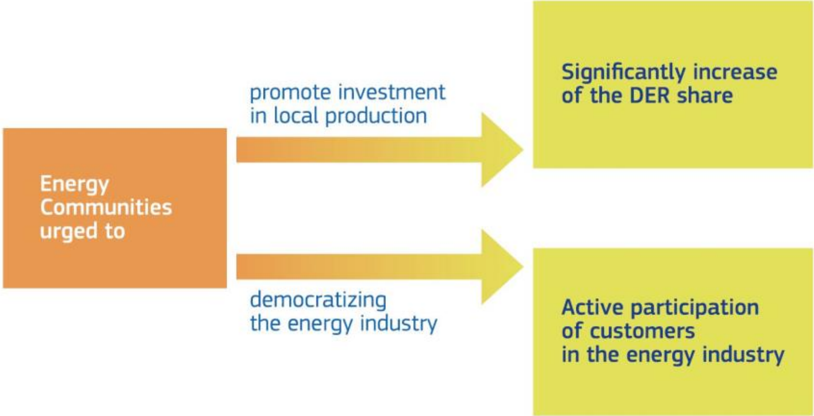

Fig. 3. Reasons for the introduction of the Energy Community concept.

Ultimately, all the new terms describe a new relationship between society and its energy systems. Their definitions express the same approach: promoting investment in distributed energy resources and democratising the energy industry, see Figure 3. Energy communities encompass environmental, technological and economic aspects and address social equity issues. Despite the political motivation and opportunities identified, the barriers and challenges to building EnCs are significant.

1.2 Barriers to the deployment of energy communities

Several EnC types are established in different countries at different stages of development and in different socio-economic, technical, and institutional settings. Four crucial enablers of the EnC have been identified: social engagement, legislation and regulation, adequate market structure and technical solution, see Figure 4. While the first three are rooted in human behaviour and regulations, the last one must obey the physical laws of the power grid. Research projects have identified barriers to establishing and upscaling [14] EnCs in their four enablers.

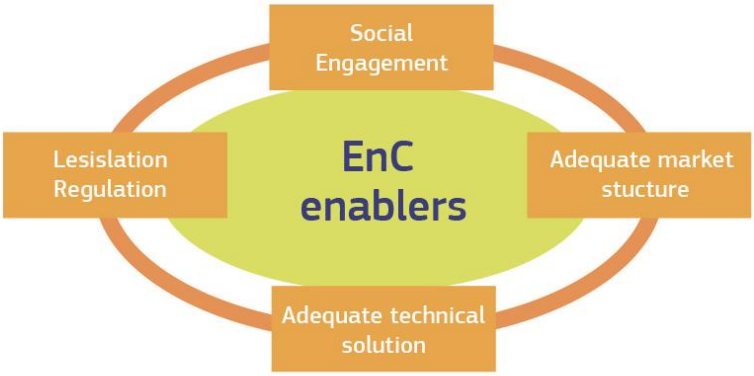

Fig. 4. Overview of the EnC enablers.

However, the **definition of EnCs and the corresponding legislation are still very general and mainly related to basic independent operations**. It does not provide detailed structures for building EnCs that clearly show how they can harmonise with the power grid and transform them into reliable actors. Having a few dominating market actors, large energy companies can be a challenge for local energy communities. **Vague definitions and roles** of EnCs make it hard to find their position in the energy system, access financing sources, and cope with bureaucracy and administration. Competition with or **unclear roles** of commercial aggregators also poses some difficulties.

On a **socio-economic level**, energy communities encounter barriers in managing the complexity of the new organisational form. Developing an adequate governance and ownership structure and establishing strong leadership may be difficult because of a lack of knowledge, expertise, and experience on a technical and financial level. In addition, various risks are perceived, such as a **lack of information** about procedural details in calculations and settlements for members, organisational burdens and structural barriers from other stakeholders on which an EnC depends, such as DSOs, utilities, or third-party providers. The risk is that customers do not follow their expected roles and lack clear benefits, motivation, knowledge, and time. Trust in the actors who organise and plan the EnC and invite citizens to become members is a key aspect in the acceptability of the solutions, especially in areas where local actors have a high impact on decision outcomes and, therefore, hold responsibility. **Social and citizen engagement** have also been identified as a barrier [16]. When people know little about technology, acceptance may mainly depend on trust in actors responsible for the technology as a heuristic or alternative ground to base people's opinion [17]. There can be resistance or indifference to participation from the community, resulting in a lack of members and resources. A barrier to upscaling and replication is a lack of broader citizen participation of lower incomes and more vulnerable groups. Dependency on voluntary work and knowledge or leadership of a few people poses another risk.

The **current market structure does not encourage the creation of energy communities** because direct participation in the market is not possible. Regional and local markets are not planned or foreseen in the existing market structure. As a result, it is nearly **impossible to estimate the cost** of contracting and deploying infrastructure, billing services, and possibly the cost of investing in other technologies for the integrated operation that EnCs normally require. Higher costs are expected for those setting up an EnC for the first time, as unclear conditions are likely to be associated with unforeseen expenses. Non-monetary costs include effort and personal involvement in setting up and managing the EnC (membership acquisition, billing, contracting partners, etc.). There is much uncertainty about the potential costs and benefits of an EnC due to a lack of applied cases and the changing market.

EnCs come across serious **technical system barriers** when there are limitations on grid capacities related to thermal, voltage violation limits, etc. Grid capacity is crucial because it determines the amount of distributed generation that can still be connected to the grid, and thus the fate of EnCs, as they can be rejected by the grid operator, usually because grid expansion is too expensive. Most EnCs are connected to the DSO electricity grid, where they can encounter connection issues or high or unclear grid connection costs. Providing the necessary metering data and installing an IT system brings extra technical challenges.

The **current regulations and state of development of EnCs do not provide adequate interaction and operation potential within the power system**. The promotion of EnC significantly increases the DER share on the grid, posing substantial technical challenges for the reliable operation and planning of the distribution and transmission grid. The main parameters of power systems, voltage and frequency, are affected, and a high level of technical effort is required to keep these parameters within limits specified in the grid codes.

1.3 Phased development and implementation

Developing and implementing EnCs is a lengthy, staggered process in four phases [18], see Figure 5. The **basic operations** of the EnC characterise the first phase. It includes sharing renewable energy produced within the EnCs as part of the Collective Self-Consumption (CSC) [2] [3] schemes. It indicates the current implementation status. Almost all EnCs established so far are in the initial development phase, where only the basic activities are carried out. The second phase –

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16 Stéphanie Petit, Athanase Vafeas, Clémentine Coujard, "BRIDGE Case study #5 Energy Communities: tools to build them and make them thrive", European Commision, July 2022. https://bridge-smart-grid-storage-systems-digital-projects.ec.europa.eu/sites/default/files/case-studies/05%20Energy%20communities_Case%20study_v2.pdf

17 Huijts, N.M.; Molin, E.J.; Steg, L. Psychological factors influencing sustainable energy technology acceptance: A review-based comprehensive framework. Renew. Sustain. Energy Rev. 2012, 16, 525–531. https://www.researchgate.net/publication/251670444_Psychological_factors_influencing_sustainable_energy_technology_acceptance_A_review-based_comprehensive_framework

18 D 5.2. Business cases for INTERACT energy communities, INTERACT project, 19 September 2022. https://www.ped-interact.eu/wp-content/uploads/2022/07/D-4.2-Use-Cases-for-the-integration-of-the-existing-innovative-technologies-with-the-LINK-solution_vFinal.pdf

advanced operation – complements the first by exploiting the flexibility potential of the load-generation balance in the presence of stand-alone or electric vehicle batteries, usually within the EnC limits.

The **integrated operation**, which includes integrating EnCs into the power system, characterises the third phase. It facilitates the local energy market, providing flexibility to the market and the grid and P2P trading. Of course, this can be only possible where there is an adequate regulatory framework in place that allows those activities. The fourth and final phase enables the **fully integrated operation** of the EnC into the energy systems, thus supporting the DR process in distribution and transmission levels.

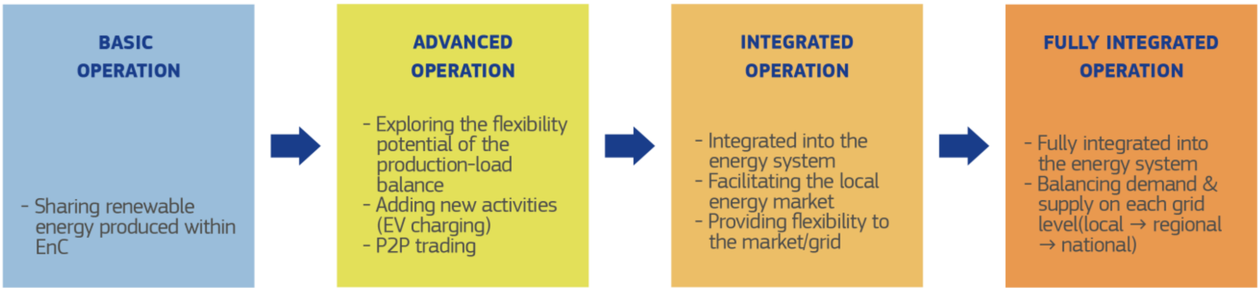

Fig. 5. Possible transition from basic towards fully integrated operation of energy communities.

Impact of energy communities' large-scale implementation on power grids

The power grid of a country may be a unique, vast electromagnetic machine, but it is highly fragmented according to regulatory, geographical and topological structures. The increasing DER penetration makes the reliable operation and planning of the electricity system even more complicated than it already was, posing significant challenges. However, TSOs and DSOs could use distributed generation and consumption for flexible grid purposes and benefit from their wider deployment. DSOs may procure local flexibility, using the information on energy flows between different connection points to ensure the grid constraints are followed. The demand from DSOs to buy flexibility products as an alternative to traditional infrastructure expansion is expected to increase.

1.4 Comprehensive architecture for the technical integration of energy communities

The architectural integration of the EnCs relates to their interaction with the grid. It addresses all electrical appliances the EnC members used to inject, e.g. rooftop photovoltaics (PVs), or consume energy in a controllable way, e.g. cooling or heating facilities, etc.

Significant changes in the electricity system have occurred since the beginning of this century, like market rules, overwhelming technical ones during liberalisation, and the significant increase in distributed generation. These changes require a revision of the traditional structure of power grids.

> *The emergence of distributed energy resources and the introduction of energy communities to promote integration exacerbate the need to adapt the power grid architecture.*

In these conditions, a comprehensive, appropriate architecture is needed to avoid the growing and unmanageable patchwork of unsustainable large-scale grid implementations [19]. It is a global model that structures and organises the

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[19] Taft J, Martini PD, Geiger R (2014) Ultra Large-Scale Power System Control and Coordination Architecture - A Strategic Framework for Integrating Advanced Grid Functionality. U.S. Department of Energy, Washington DC. https://gridarchitecture.pnnl.gov/media/white-papers/ULS%20Grid%20Control%20v3.pdf Accessed 11 May 2021

system to be stable, functional, resilient to changes, and economical. When the architecture is sound, it helps detail its components and applications effectively and it clearly shows the interrelationships between the stakeholders.

Nowadays, power systems are fully interconnected and usually span extensive geographical areas up to a continent or larger. The increase in DER leads to discussions about the appropriate architectural approach to ensure power systems can operate reliably and resiliently in these new conditions.

1.4.1 Decentralised vs. centralised architectural approaches

It is imperative to underline that EnCs would impact the distribution and transmission systems beyond a certain DER penetration level. The policy choice in this direction and its enhancement has to be carefully planned and deployed to maintain the present high service quality standards and avoid stranded costs. In some cases, EnCs might need almost no support from the public power grid. Still, in a more realistic case, the use and role of transmission and distribution grids remain for stability, reliability, quality of service, and contingency management, although energy flows from remote, centralised power plants may be reduced, regardless of the architecture chosen - centralised or decentralised.

Centralised architectures consolidate resources, data, and processing power in a powerful server or data centre. The traditional power system structure is centralised, where the TSO is the system's backbone, while the DSO usually follows the hierarchical instruction from the TSO. The whole market is structured to serve this hierarchical structure. The massive DER penetration changes this but the market structure remains the same. The balancing process between electricity generation and consumption is the first to be influenced and challenged by this structural change. Introducing the balancing groups at the distribution level tries to soften this challenge. Meanwhile, introducting of the virtual power plant (VPP) attempts to mitigate the discrepancy between the new electricity grid structure and the market structure [20].

Decentralised architectures distribute resources, data, and processing power across the power system. The system's robustness is increased by design because of no single point of failure, improving system resilience and reliability. It reduces the latency because data processing occurs closer to users, ensuring faster response times and data protection. The microgrid is one of the concepts driving the decentralised architecture [21]. It has been introduced to address technical challenges posed by DER penetration at the distribution level. The *LINK* architectural paradigm also leads to a decentralised architecture, considering the entire structure of new power systems and the market holistically [22].

However, the coordinated (i.e. whole-system) approach may result in significant additional savings in system operation and investment costs relative to transmission or distribution network-centric models [23]. To realise these whole-system benefits, it will be critical to establish strong coordination between distribution and transmission network operators by clearly defining their future roles and responsibilities and establishing appropriate regulatory and commercial frameworks.

1.4.2 Concepts and paradigms leading to different architectural approaches

Numerous initiatives and projects that deal with the technical integration of DERs promoted by EnCs can generally be divided into three broad categories related to these study scopes: TSO-DSO Intersection, Distribution, and Holistic view.

Figure 6 shows various Research and Development (R&D) projects with different scopes. The Very High and High Voltage Grid (VH and HVG) or transmission grid area is shown in orange. The distribution area includes the Medium Voltage Grid (MVG) area in blue and the Low Voltage Grid (LVG) area in light blue. Individual architecture types are identified in each category, preceding their respective focus areas. Electricity Producers (Pr.) and Storage (St.) are available throughout the grid.

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20 Danny Pudjianto and Charlotte Ramsay and Goran Strbac, Virtual power plant and system integration of distributed energy resources, IET Renewable Power Generation, 2007, vol. 1, pages 10-16, https://api.semanticscholar.org/CorpusID:110699798}

21 D. E. Olivares et al., "Trends in Microgrid Control," in IEEE Transactions on Smart Grid, vol. 5, no. 4, pp. 1905-1919, July 2014, doi: 10.1109/TSG.2013.2295514.

22 A. Ilo, "*LINK*- the Smart Grid Paradigm for a Secure Decentralized Operation Architecture." Electric Power Systems Research - Journal – Elsevier, Volume 131, 2016, pp. 116-125.

23 Pudjianto, D., & Strbac, G. (2017). Assessing the value and impact of demand-side response using whole-system approach. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, 231(6), 498–507. https://doi.org/10.1177/0957650917722381

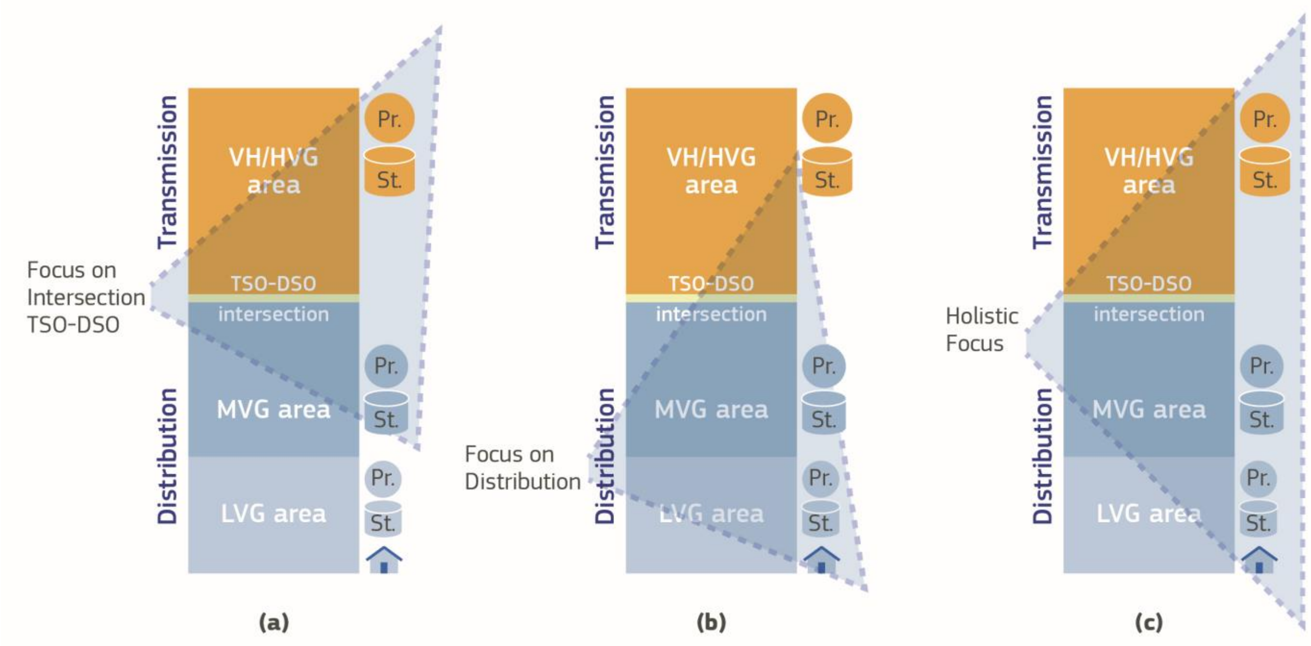

Fig. 6. Various types of R&D projects to address technical issues of EnC with a focus on: (a) TSO-DSO intersection; (b) Distribution; (c) Holistic view.

Figure 6(a) shows p developments using the VPP concept for DER integration. In these cases, the TSO-DSO coordination has particular importance. In comparison, Figure 6(b) shows developments scoping mainly the distribution grids only based on the microgrid concept. Efforts have also been made to combine the VPP and microgrid concepts. In the context of VPP, the microgrid is presented to the host grid at the Point of Common Coupling (PCC) as a single market agent with a prespecified performance; the internal mechanisms and composition of the VPP are hidden from the host power system. It is important to note that the VPP is not limited to the scope of a microgrid; the coordination of multiple distributed generation units throughout a bulk power system is also considered a VPP solution [21]. Initiatives based on the *LINK*-Paradigm [22] consider the entire grid and customer facilities equally, the latter being prosumers or consumers, Figure 6(c).

Virtual Power Plant-based

The VPP initiatives [24] usually propose a hierarchical architecture, as shown in Figure 7. Figure 7(a) shows a layered control hierarchy using distributed agent technology [25][26]. The VPPs or aggregators need to communicate with the DSO's Supervisory Control and Data Acquisition (SCADA) system and the equipment in the grid to gather information. There is also a need for information exchange between the VPP and market actors. The VPP or aggregator is an intermediary for requests from clients seeking input from the DER units on the process level. Several interfaces exist between the VPP controller, the DER units, and market actors. The design uses semiautonomous agents like Intelligent Electronic Devices (IEDs) and VPP controllers. Each VPP controller receives commands and set points from overlying layers but acts autonomously, considering its operational limitations.

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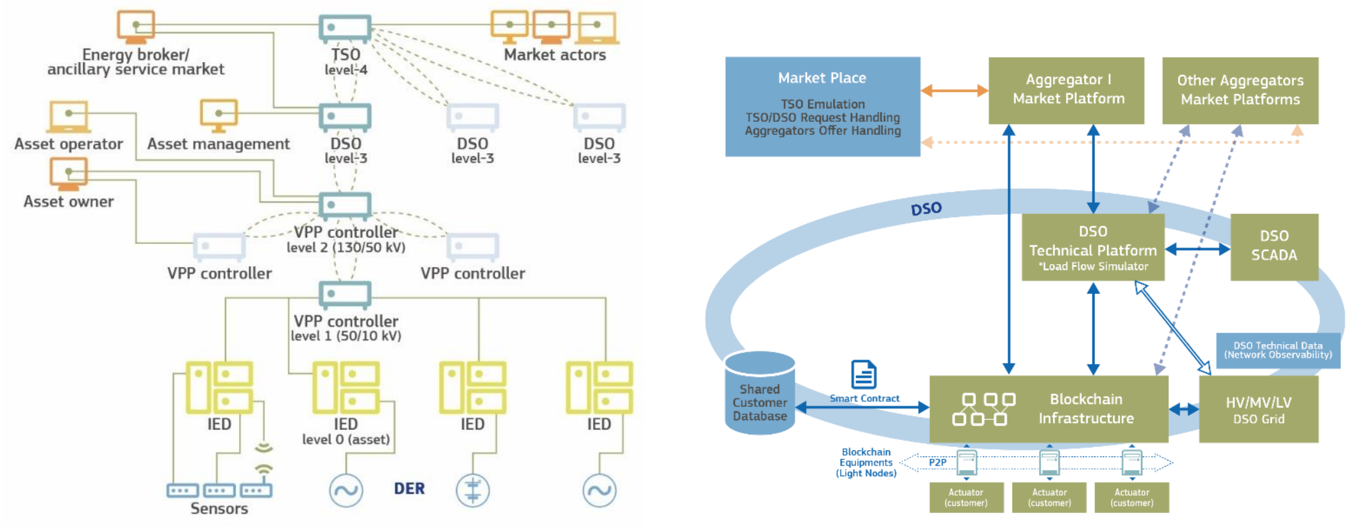
24 C. Kieny, B. Berseneff, N. Hadjsaid, Y. Besanger and J. Maire, "On the concept and the interest of virtual power plant: Some results from the European project Fenix," *2009 IEEE Power & Energy Society General Meeting*, Calgary, AB, Canada, 2009, pp. 1-6, doi: 10.1109/PES.2009.5275526.

25 Lund P (2007) The Danish cell project—Part 1: background and general approach. 2007 IEEE Power Engineering Society General Meeting, Tampa, 24 - 28 June, pp 24–28

26 N. Etherden, V. Vyatkin, M.H.J. Bollen, Virtual Power Plant for Grid Services Using IEC 61850, IEEE transactions on industrial informatics, VOL. 12, NO. 1, February 2016, pp. 437-447.

The VPP or aggregator participates in the energy market with the joint production of all DERs as one unit. However, the interaction with the grid is different for each DER, depending on where it is connected. Therefore, the grid will limit the VPP's ability to participate in the electricity market. Figure 7(b) shows an architecture based on the Blockchain Service Layer [27]. It consists of two blockchain-enabled platforms: (a) The Market Platform, which supports broad geographical area flexibility requests from TSOs and local flexibility requests from DSOs. These are matched with offerings from aggregators resolving conflicts according to pre-defined rules of dispatching priorities. In the Platone project, this platform simulates all the different TSO's flexibility /congestion requests and behaviours, collects the DSO's local flexibility requests, and manages the aggregator's/customer's flexibility offers; and (b) The DSO Technical Platform, which is the framework's core and allows DSOs to manage the distribution grid securely and efficiently. It includes all the tools and services that enable monitoring and control of the grid and observability mechanisms (SCADA and distribution management systems), improving network security, reliability, operational quality levels and resilience. Furthermore, this platform can receive and negotiate flexibility requests from the Market Platform.



(a) **(b)**

Fig. 7. Schematically presentation of two typical architectures based on the VPP concept: (a) Denisch cell project; (b) Platone project.

The Blockchain Access Layer adds further security and trustworthiness to the framework. It is an entry point for the resource in that it collects and certifies the measurements and set points from the field on the Blockchain and sends this data to the Shared Customer Database (SCD). This database archives all the relevant data for flexibility, such as i) energy measurement, ii) baselines, iii) set points, and iv) grid data. As the unique place to collect flexible data, it shares the information with all stakeholders and aims to increase transparency and trust in market mechanisms [28].

All hierarchical architectures based on VPP need massive data exchange between many different actors and, as a result, they need an extended communication system. The VPP participates in the energy market with the joint production of all DERs as one unit. However, the interaction with the grid is different for each DER, depending on where it is connected. Therefore, the grid will limit the VPP's ability to participate in the electricity market.

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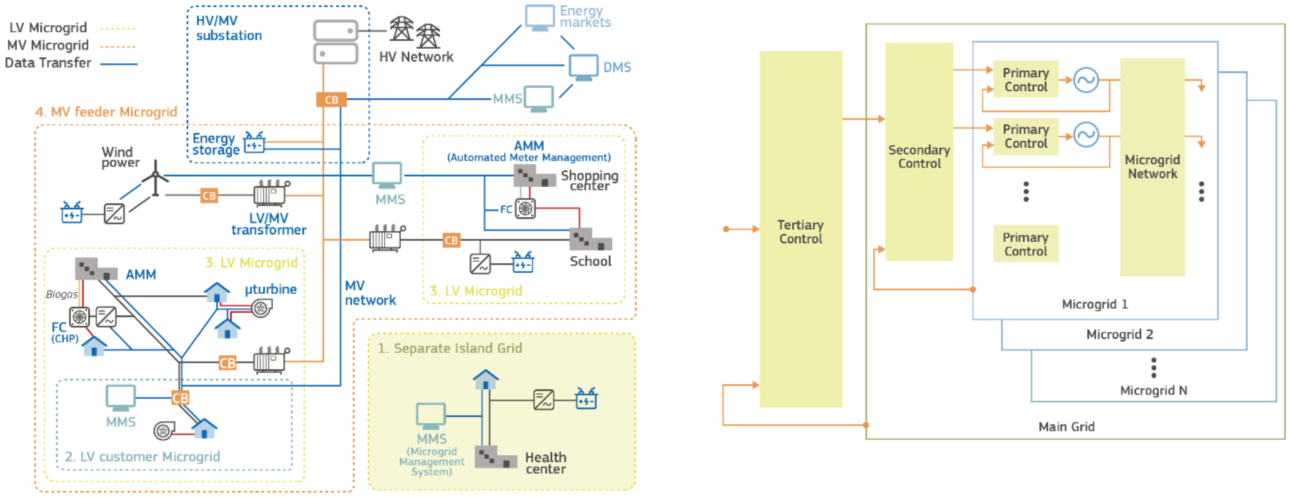
[27] Platone project, D3.9 Report on main results acheieved in the field test. https://www.platone-h2020.eu/Resources/Deliverables

[28] I. Losa et al., "PLATONE: Towards a new open dso platform for digital smart grid services and operation," CIRED 2021 - The 26th International Conference and Exhibition on Electricity Distribution, Online Conference, 2021, pp. 2974-2978, doi: 10.1049/icp.2021.1880.



(a) (b)

Fig. 8. Schematic representation of typical architecture based on the Microgrids concept: (a) Four different types of microgrids: island microgrid, low voltage customer microgrid, low voltage microgrid, and medium voltage microgrid; (b) Hierarchical control levels: primary control, secondary control, and tertiary control.

Microgrid-based

Initiatives scoping mainly distribution grids typically use the microgrid concept and propose the architectures shown in Figure 8. Although microgrids have been researched for nearly two decades and are recognised for their many benefits, such as improving power reliability, security, and sustainability and decreasing power costs for the consumer, they have still not reached rapid commercial growth. The literature and case study analysis confirms that a single standard microgrid model is impossible [29]. The different identified microgrids that may be set up in a power system are anchored in themselves, see Figure 8 (a). It shows the four different types of microgrids: island microgrid, low voltage customer microgrid, low voltage microgrid, and medium voltage microgrid. The coordination of the microgrids with the "main grid" is suggested through the central control scheme shown in Figure 8(b). It consists of three levels of control: primary, secondary, and tertiary. The technical and regulatory relationships between the microgrid and the main grid are still being elaborated. The analysis shows significant technological issues with extremely ramified and complex central coordination, leading to complicated and expensive solutions [21]. These technical challenges are intertwined with regulatory, market, and stakeholder issues, which makes microgrid-based initiatives impossible to implement and paralyses EnC deployment.

LINK-based

The architectural *LINK*-Paradigm and the derived architecture are consistent with fractal principles to create a holistic approach [30]. This **holistic architecture** considers power systems and customer facilities as cohesive electromagnetic entities that capture the whole picture beyond the sub-areas of transmission, distribution, and customer plants, fulfilling the features of holistic architecture as defined in [31]. It gives each part of the power grid and customer assets equal importance and a common purpose, thus ensuring that the power industry realises its full potential.

With its unique and independent elements (power system facilities, automation systems and interfaces), *LINK* architecture sets up a Link technical structure, creating the right conditions for integrating energy systems. Each "Link" may operate autonomously, following the constraints of the neighbours or autarkic (self-sufficient). Each "Link" or "Link bundle" is optimised and adapted locally to achieve the best-coordinated solution for all. Thanks to its fractal properties, the *LINK*

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29 Mariya Soshinskaya, Wina H.J. Crijns-Graus, Josep M. Guerrero, Juan C. Vasquez, Microgrids: Experiences, barriers and success factors, Renewable and Sustainable Energy Reviews, Volume 40, 2014, Pages 659-672, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2014.07.198.

30 A. Ilo, "Design of the Smart Grid Architecture According to Fractal Principles and the Basics of Corresponding Market Structure." Energies 2019, 12, 4153.

31 ETIP SNET, White Paper "Holistic architectures for power systems." 8 March 2019, 1-54. https://smart-networks-energy-transition.ec.europa.eu/sites/default/files/publications/ETIP-SNET_HolisticArchitecture_2019_04_01_Final.pdf applies within the power grid and its consumers, which are organised in EnCs and coupled with other energy vectors such as gas, heating, and cooling (Sector Coupling) [32]. Integrating energy systems involves coordinating the operation and planning of energy systems across multiple pathways and geographic scales to provide reliable, cost-effective energy services with minimal environmental impact, resulting in an Energy System of Systems (ESOS). *LINK* architecture, shown in Figure 9, uses a decentralised control approach combined with "Secondary Control" setups on the grid to coordinate its different levels, producers, and storage regardless of their size and technology. It postulates the market structure to be redesigned (see §4.2.2.2), enabling its harmonisation with the power grid structure. It increases the space granularity [33] of the electricity market, establishing different market categories such as the national/international markets in the transmission area facilitated by TSO, regional markets in the distribution area facilitated by DSO, and the local markets in customer plants alias EnC-area facilitated by EnC [34] (see §4.2.2). The architecture allows customers to participate individually or as EnC members in the local market. It has four main architectural components: (1) Grid-Links, i.e. the HV_, MV_, LV_ and CP_Grid-Links, (2) Producer- and (3) Storage-Links and the (4) market. All Links communicate with each other through the technical "T" and with markets through "M" interfaces.

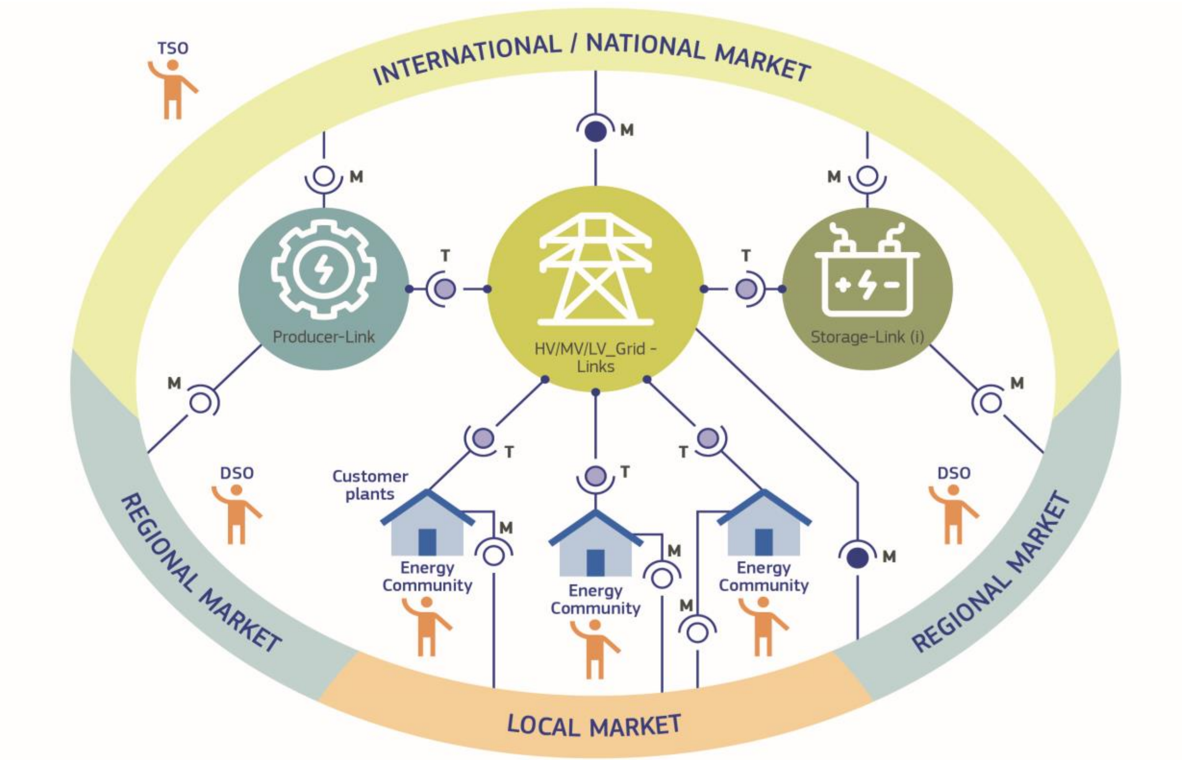

Fig. 9. Architecture designed using the holistic architectural paradigm *LINK*.

In the holistic decentralised LINK architecture, all parts of the electricity grid, transmission and distribution, and customer installations are equally important and have a common purpose. By design, all actors, TSOs, DSOs, EnCs or prosumers may equally provide flexibility and ancillary services to each other in normal operation processes, especially during planned outages and unplanned disturbances. The legislation and the technical and commercial framework conditions between the actors within the ecosystem must be established. The *LINK* holistic architecture, designed to conform to fractality principles of the grid, may be an alternative that enables effective EnC deployment and sector coupling, which is a decisive flexibility source for future power systems. This architecture facilitates TSOs to retain their backbone function for the electricity grid while transforming the DSOs into the hub between the TSOs and the EnCs.

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32 Ilo A., Schultis D.L., A Holistic Solution for Smart Grids based on *LINK*– Paradigm, Springer 2022, 340. ISBN: 978-3-030-81529-5.

33 IRENA, 2019, "Increasing space granularity in electricity markets," International Renewable Energy Agency, Abu Dhabi. Available online: Last access 10.01.2022.

34 A. Ilo, H. Bruckner, M. Olofsgard, M. Adamcova, "Deploying e-mobility in the interact energy community to promote additional and valuable flexibility resources for secure and efficient grid operation. "CIRED workshop on E-mobility and power distribution systems, 2-3 June 2022, Porto, Portugal.

1.5 Technical impact of energy communities on the grid

The large-scale DER deployment promoted by EnC is leading to structural changes. Reverse power flows can occur both in steady-state and during faults, preventing traditional radial distribution grids from functioning as designed. The DERs’ impact on the distribution networks depends on the technology used, the installed power size, the connection location on the grid, and the management of the power flows within EnCs. Violations of voltage limits and malfunction of protection,fault detection and service restoration applications, and so on, may occur. Furthermore, although the EnCs act at the distribution level, the transmission grid is also affected because the behaviour of the entire distribution grid changes drastically. The grid's stability may be affected. The transmission grid, the backbone of traditional power grids, has an intersection point (TSO-DSO intersection) with each distribution grid or sub-grid.

1.5.1 Bi-directional power flow

In traditional power systems, the electricity flows unidirectionally from the transmission grid, where the big power plants connect to the customers through the distribution grid, which has a radial structure. The large-scale DER penetration to be also promoted by EnCs changes the electricity flow direction to bi-directional. Figure 10 illustrates the different levels of impact of the EnC on the grid holistically. Electricity producers and storage are available throughout the grid. Figure 10(a) shows the entire **self-consumption case** envisaged, e.g. by the regulation in France [35]. The distributed generators production, e.g. rooftop PVs, must cover only the load of the customer plant where they are installed. In this case, the grid is unaffected because the electricity flow does not reverse and does not penetrate the superordinated LVG area. In the case of CSC schemes, the grid remains unaffected. Its loading is usually drastically reduced.

Figure 10(b) shows the case when sharing energy, the energy community seeks to increase its social welfare. The **basic operations** of the EnC characterise the first phase. It includes sharing renewable energy produced within the EnCs. It indicates the current implementation status. In countries with a regulation with financial incentives for energy sharing (e.g. Spain [36]), maximising social welfare will also lead to increased self-sufficiency.

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[35] Code de l'énergie : Section 4 : Règles générales pour le raccordement aux réseaux publics d'électricité. Version en vigueur depuis le 01 janvier 2016, https://www.legifrance.gouv.fr/codes/article_lc/LEGIARTI000031749093

[36] Gallego-Castillo, Cristobal; Heleno, Miguel; Victoria, Marta (2021): Self-consumption for energy communities in Spain: A regional analysis under the new legal framework. In: *Energy Policy* 150, S. 112144. DOI: 10.1016/j.enpol.2021.112144.

The second phase of **advanced operation** complements the first by exploiting the flexibility potential of the load-generation balance in the presence of stand-alone or electric vehicle batteries, usually within the EnC limits.

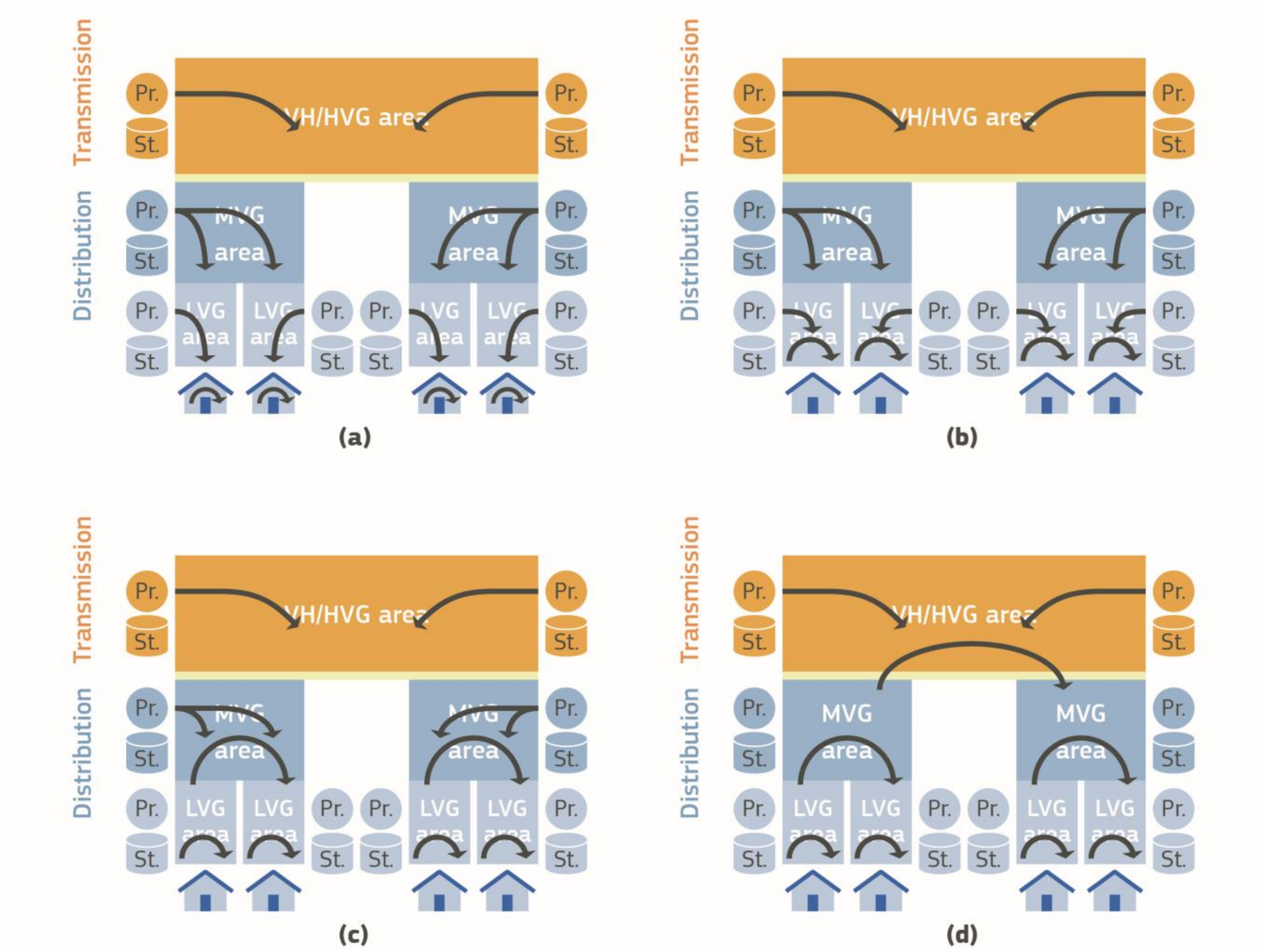

Fig. 10. Different levels of EnC impact on the grid with DERs power flows that: (a) Cover partially or full the customer's load (self-consumption); (b) Penetrate into the superordinated LVG area; (c) Penetrate into the superordinated MVG area; (d) Penetrate into the superordinated HVG area.

Electricity flows in Figures 10(c) and 10(d) correspond to the cases of integrated and fully integrated EnCs. The power flows are bi-directional through the entire distribution grid, reversing the direction in the TSO-DSO intersections and penetrating the transmission grid.

1.5.2 Challenges on distribution grids

DSOs are transforming into a power industry hub because the distribution grid is the direct electrical link between the power system and the customer plants and, therefore, between the power system and EnC. Changing the power flow direction from uni- to bi-directional raises severe challenges in the operation of distribution systems. The latter is designed for radial operation with the possibility of a temporary loop configuration, especially at lower voltage levels (high and medium voltage distribution grids are increasingly more meshed and taking advantage of automatic operation, i.e. automatic reactive control at MV substations or on-load tap changer MV transformers). Significant technical challenges may occur due to extensive DER generation if the local generation and consumption are unfavourably distributed on the grid, such as keeping the voltage within limits, managing thermal congestion in normal and fault conditions, adapting protection and fault indicators, and revising the recovery schemes after blackout events. Therefore, in light of the enormous amount of distributed generation that EnCs promote and the electrification of new users expected in the coming years, the current grid code families, e.g. connection, operation, etc., need to be reviewed and the grid structure updated and expanded.

Violation of upper voltage limit: R&D studies have shown that DER installation and integration require various countermeasures at different integration stages to ensure a reliable and sustainable grid operation [38-41]. The DER installation process may be divided into three phases, as shown in Figure 11. In the **first phase**, the green area, the DER installations in the LV subsystem up to the critical value do not require any countermeasures. Currently, in the legislation of many countries and the corresponding grid codes, PV or DER installation is permitted as long as their power production is smaller or equals the load of customer plants at each point in time. In this case, the voltage profiles of all feeders are partially almost bundled and have an almost straight course. No voltage limit violation occurs. The existing infrastructures are underutilised. In the **second phase**, the yellow area, where the PVs or DERs' installed power exceeds a critical value, voltage violations occur, and countermeasures are needed to guarantee reliable and sustainable operation. All R&D projects emphasise that reactive power control is the most effective means of eliminating voltage violations in radial networks. There are two strategies for reactive power control: distributed and concentrated. The distributed control strategy in radial structures recommends upgrading the customer PV-inverters with different local Volt/var control strategies (*Q*(*U*) [37] or *cosϕ*(*P*) [38]) or their combination [39]. The reactive power provoked by these controls causes an uncontrolled and excessive reactive power flow in the superordinated grids. The concentrated control strategy [40] in radial structures recommends installing *L*(*U*) local controls at the end of the violated feeders. Their combination with the self-supplying customers regarding reactive power (*Q*-autarkic) unloads the grid from the reactive power flow of the load. It reduces the amount of data to be exchanged because DSOs use a couple of inductive devices for voltage control in radial structures. The secure grid operation may be guaranteed by setting up the Volt/var chain control on the superordinated grids [33]. In the **third phase**, the red area, the installed power of the PV systems or distributed generation exceeds the saturation value. The latter means the infrastructure (transformers and cables or lines) is overloaded from this value: more power is generated than the grid may handle. In addition to the countermeasures to eliminate voltage violations, further actions are required to ensure secure infrastructure utilisation in this stage. The steps may be diverse and realised by

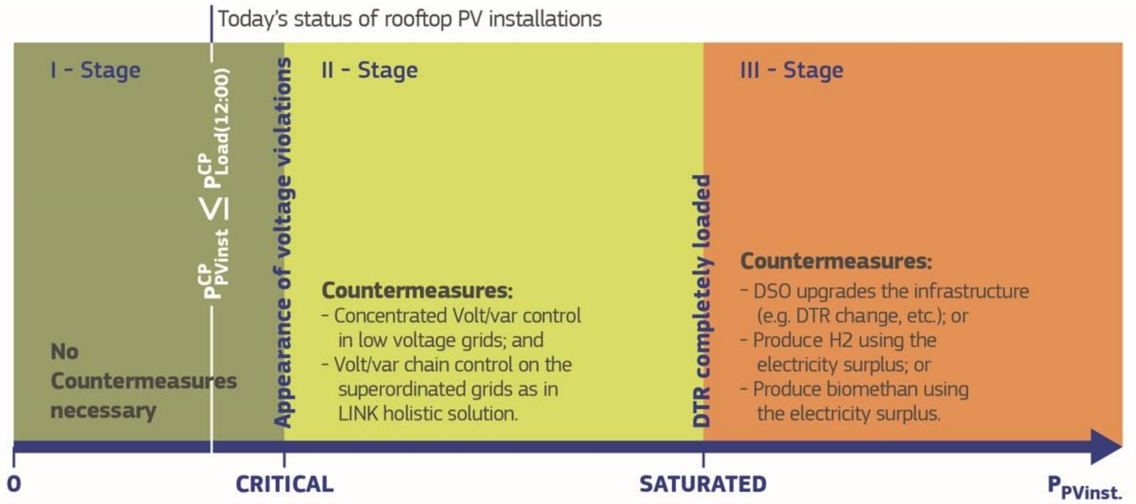

Fig. 11. Critical parameters for the uptake capacity of distributed generation facilities in a radial configuration and the countermeasures for their maximum expansion.

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37 O. Marggraf, et al., U-Control - Analysis of distributed and automated voltage control in current and future distribution grids, in: Int. ETG Congr. 2017, Bonn, Germany, pp. 1–6.

38 F. Zhang, et al., The reactive power voltage control strategy of PV systems in low-voltage string lines, in: 2017 IEEE Manchester PowerTech, Manchester, UK, 2017, pp. 1–6. DOI: 10.1109/PTC.2017.7980995.

39 N. Karthikeyan, B.R. Pokhrel, J.R. Pillai, B. Bak-Jensen, Coordinated voltage control of distributed PV inverters for voltage regulation in low voltage distribution networks, in: 2017 IEEE PES Innovative Smart Grid Technol. Conf. Europe (ISGT-Europe), Torino, Italy, 2017, pp. 1–6. DOI: 10.1109/ISGTEurope.2017.8260279.

40 Ilo A., Schultis D.L., Schirmer C., Effectiveness of Distributed vs. Concentrated Volt/var Local Control Strategies in Low-Voltage Grids. Appl. Sci., 2018, 8, 1382, p. 1-21. https://doi.org/10.3390/app8081382 Accessed: Jul. 01, 2019.

different stakeholders. The DSO may reinforce the infrastructure (e.g. change distribution transformers, etc.), or the EnC may use the surplus of electricity to produce hydrogen or biomethane, thus helping decarbonise the economy [41].

Thermal congestion in normal and fault conditions: Thermal constraints refer to the physical limits of any equipment on the power grid regarding how much power it can sustain in the long (normal conditions) or short (fault conditions) term. These limits result from the fact that when current flows through cables and wires, heat is generated due to the resistance of the metals that make up the conductors. Overheating grid assets causes them to fail and wear out more quickly. In overhead feeders, heat causes conductors to expand and possibly sag, violating safety clearances and increasing the risk of equipment and property damage, line shutdowns, etc. PVs especially pose a risk for the thermal loading of grid assets since they produce power simultaneously; the simultaneity factor is one, while the residential areas have a demand factor lower than one. The increased installed power of distributed generation above the saturated value causes congestion on the distribution grids. The DSO should take countermeasures to avoid exceeding the operation limits in normal and fault conditions. Although quite unusual, operators may be forced to curtail electricity generation if the grid parameters are at risk. System operators need to have enough data to estimate thermal congestion on the grid better and approve the DERs' connection on time.

Phase Unbalances: Installation of one-phase PVs may cause voltage imbalance exceeding the acceptable limits at some nodes in the low-voltage distribution networks [42]. EnCs could act as intermediaries to balance loads and energy production behind the connection point.

Harmonic distortions: Promoting EnC will substantially increase rollout of PV systems with low-rated power in residential areas. Although the harmonic contents of the generated currents from the PVs inverters are too low, the high penetration leads to in high magnitudes of harmonic currents [43]. Additionally, the single-phase PVs give rise to high unbalanced harmonics between the phases, leading to unequal total harmonic distortion values for each phase voltage. Although the transformer may not be overloaded, the increased PV share on the grid may lead to thermal breakdown of the insulation or faster ageing of grid assets due to the increased harmonic currents.

Protection system philosophy: A protection system aims to detect certain system anomalies to ensure power systems' reliable and safe operation. Protective devices, such as circuit breakers and fuses, and fault indicators characterise the protection system of radial-operated distribution grids traditionally set up based on the unidirectional power flow. The exploitation of EnC suggests an extensive integration of the distributed generation located behind and in front of the electricity meter, causing a paradigm shift toward bi-directional power flow (see § 3.2.1 Bi-directional power flow): The actual protection philosophy in distribution grids becomes inefficient. Fault detection and selectivity problems may appear, causing serious miscoordination, damage to grid assets, saturation of the current transformers and failure to detect islanding or unintended islanding. Distribution grid fault diagnoses, such as Fault Location, based on fault indicators may wrongly react because they traditionally indicate that a fault has occurred somewhere downstream from its location, indicating erroneously in the presence of distributed generation: The protective devices, the algorithms of Fault Location, Isolation, and Service Restoration, etc. must therefore be adapted for correct operation in the new conditions.

Revising the recovery plans after blackout events: The large-scale integration of DERs, for example, rooftops in residential areas promoted by EnCs, changes the structure and behaviour of distribution grids, making the actual recovery plans ineffective. System operators continually adapt and update those plans to fit the new conditions.

Temporary self-sufficient operation of grid parts: Another non-negligible concern for DSOs is the undesirable effect of unintended islanding in which distributed generators, mainly connected to medium and low voltage distribution networks, can end up feeding distribution customers if a portion of the network to which they are connected becomes disconnected from the primary source, for whatever reason. This poses a problem for DSOs in managing their network securely and

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[41] Ademollo A., Ilo A., Carcasci C., End-use sector coupling to turn customer plants into prosumers of electricity and gas, CIRED 2023 12-15 June, Rome, Italy, pp 1-5. http://hdl.handle.net/20.500.12708/193578.

[42] M. Nour, J. P. Chaves-Ávila, M. Troncia, A. Ali and Á. Sánchez-Miralles, "Impacts of Community Energy Trading on Low Voltage Distribution Networks," in IEEE Access, vol. 11, pp. 50412-50430, 2023, doi: 10.1109/ACCESS.2023.3278090.

[43] H. Dghim, A. El-Naggar and I. Erlich, "Harmonic distortion in low voltage grid with grid-connected photovoltaic," 2018 18th International Conference on Harmonics and Quality of Power (ICHQP), Ljubljana, Slovenia, 2018, pp. 1-6, doi: 10.1109/ICHQP.2018.8378851.

robustly. Distributed generation and other energy interactions, such as storage and V2G, can also be managed more efficiently and securely, as may be done under the EnCs umbrella.

Planning: DSOs usually require toolboxes comprising different solutions for addressing grid constraints, such as congestion management and voltage instability, to ensure efficient network planning. For this reason, DSOs need a framework to use flexibility, optimise network investment decisions, and handle the challenge of facilitating the integration of renewables into the electricity networks more efficiently [44]. This framework is relevant as market design is critical to ensure that EnCs have incentives to develop in a way that reduces system costs and supports grid operation. There is a risk that, given inefficient incentives, community coordination will lead to increased network use or inefficient market outcomes.

Operation challenges: IMD also mentions that Member States may grant EnCs the right to manage distribution networks in their area of operation. A more atomised network, with new, less specialised agents operating some parts of it, may not be the best solution for achieving more efficient management hand in hand with flexibility.

1.5.3 Challenges on transmission grids

The extensive integration of DERs promoted by EnCs drastically changes the behaviour of the distribution subsystems connected to the transmission grid, thus strongly impacting and challenging the latter's behaviour.

Load-generation balancing process: One of the most essential TSO tasks is performing the injections-with-drawers balancing process to keep the frequency within the limits set by the grid codes. Shortly after the Russian war in Ukraine and the associated increase in energy prices, there has been a massive expansion of DER plants, driven by people's willingness to become energy-autonomous and by legislation. The deployment of EnCs will further propel the integration of DERs. As a result, the load patterns in the connection points TSO/DSO change dramatically, massively impacting the load-generation balancing process.

Load-shedding schemes need adaptations: Although this is not a favourable approach for maintaining the power grid's stability, the TSOs prepare emergency strategies for load-shedding under low-frequency conditions to maintain the grid's security during massive outages. It performs automatic or manual load rejection or disconnection of predefined grid assets. The load-shedding schedules are individually configured and depend on the historical loading patterns of the surrounding grid assets. The extensive integration of DERs promoted by EnCs changes these loading patterns, which become dynamic and dependent on the weather conditions. The current static load-shedding strategies are inaccurate and should be adapted to the new requirements.

Voltage–reactive power management: In many countries, legislation requires DSOs to provide grid access to owners of DERs within a certain timeframe. However, the increasing number of DERs is causing the upper voltage limits in the distribution networks to be violated. According to the Grid Codes, DSOs could apply $Q(U)$ regulation to increase the feeders' intake capacity, creating an uncontrolled reactive power flow in the superordinated grids, that means in transmission grids. TSOs face big challenges in voltage-reactive power management. However, the Grid Code on TSO connection conditions imposes strict requirements, usually $\cos(\phi)$, which puts DSOs in a bind, getting in a vicious circle.

N -1 security calculations: N - 1 security calculations are used to ensure the security of supply, even if a facility of the operating system is out of service for any reason. With the deployment of EnC promoting the increase of DERs, maintaining n-1 safety is a new challenge for the TSOs. The power flows through the interconnection points between TSOs, and DSOs are uncertain because the TSOs do not have an overview of the instantaneous composition of the load that the distribution subsystems represent. Depending on the weather conditions in the regions where these subsystems extend to, they may behave as a load or an injection to the transmission grid.

Impact on power system dynamics: To this day, conventional power plants are essential for power system stability. Their large synchronous generators provide voltage source characteristics and inertia and contain voltage and frequency control to ensure a feasible and reliable power system operation. The immanent active and reactive power dependence of many loads on voltage and frequency acts as system feedback in addition to the control mechanisms and is known as the self-regulating effect. The accurate estimation of the latter plays a crucial role in determining the fast reserve power needs

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[44] Eurelectric, Recommendations on the use of flexibility in distribution networks, April 2020.

[45]. The self-regulating effect will be massively impacted when the fully integrated EnCs are deployed. It includes implementing the DR process, which implies a massive increase in distribution generation and controllable loads. The existing models for considering the self-regulating effect in the system dynamics become questionable. The dynamic equivalent models embrace the entire distribution grid, which is usually connected to the transmission grid at one point. Traditionally, the model equivalents in the literature mainly consider the classical load. Deploying integrated REnCs will increase the number of renewable energy sources (RESs) connected to the distribution grid and energy storage devices, electric vehicles (EV), controllable loads, etc. The used dynamic equivalents are becoming unusable.

Restoration strategies from a blackout: In traditional power systems, where the electricity flows from the transmission to the distribution grids and then to the customers, the operators rely on offline recovery plans developed for selected contingency scenarios. Since the details of a blackout are hard to predict, restoration plans serve as a guide for system restoration. These plans are no longer valid when DERs are in place and even less so when EnCs propel their further integration. The restoration strategies and procedures should be elaborated in the new conditions.

Grid protection: The dual function of grid protection ensures the reliability of the power system and protects the equipment from damage. The protection remains inactive as long as no fault occurs. However, when a fault occurs, the protection relays should respond correctly: Only the faulty devices should be disconnected so that the rest of the system operates reliably. Although the protection schemas in the transmission grids are designed for bi-directional flows, changes, e.g. in the level of short-circuit currents, can affect their correct response. The increased DER presence, driven by EnCs, can drastically affect the superordinated grids' short-circuit currents and nullify the relays' accurate reaction.

Change of the current market patterns: Prosumers and EnCs can change some market patterns because of P2P trading, reducing the energy flows on public grids up to transmission grids.

1.6 Technical opportunities

EnCs will play a vital role in the electrification and decarbonisation of society by providing flexibility and efficiency to the system, and, at the same time, they will increase customer involvement in the energy transition. The following are the technical opportunities the EnC may bring from the whole power system perspective and particularly from DSO and TSO perspectives.

1.6.1 DSO perspective

DSOs, directly connected to the DERs considered in EnCs, have identified the following technical opportunities and good-practice guidelines.

Potential for deployment of new DERs: Developing EnCs may bring some new considerations for DSOs to deploy new DERs when managing connected EnCs. In this regard, DSOs understand their specific situation and are committed to ensuring cooperation. As participants in a common project, members of the EnC together have a more significant potential for both consumption and generation, for example, developing renewable self-generators, managing EVs and providing greater quantities of demand-side flexibility and storage than the adding dispersed individuals. In this regard, E.DSO, the DSO association, has recognised several opportunities for DSOs [46].

Balanced utilisation of the distribution grid assets: The increase of distribution generations in both cases, self-sufficiency or self-consumption and energy sharing between neighbours, reduces the peak power flows in the distribution grid. Therefore, the utilisation of the distribution grid is reduced, thus prolonging the lifetime of the assets such as distribution (MV/LV transformers), supplying transformers (HV/MV transformers), and isolating of the medium and low voltage

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[45] M. Kurth, E. Welfonder, Importance of the selfregulating effect within power systems, IFAC Proceedings, Volume 39, Issue 7, 2006, Pages 345-352, ISSN 1474-6670, ISBN 9783902661081, https://doi.org/10.3182/20060625-4-CA-2906.00064.

[46] EDSO, June 2021, DSOs as facilitators of energy communities.

feeders. This positive effect occurs when measures are introduced to consider the distribution grid within the matching of load and generation [47].

Increasing the operation flexibility: In the event of grid congestion or voltage issues, DSOs may propose to EnCs in real time to adjust their consumption and generation to keep the system secure and stable, thus realising the emergency-driven DR process. The latter should be technically implemented in advance and accompanied by a well-established dialogue with the responsible DSO. By providing flexibility through grid users (such as EnCs), DR offers alternative, robust solutions to tackle grid problems efficiently. The increase in the share of volatile renewable resources and the intensive electrification of the economy makes the DR indispensable. Flexibility solutions could sometimes be temporary, but in any case, they are needed to follow the rapid increase of electrification in our society. In this context, a new grid code for demand response is currently being developed. It will propose the technical framework for deploying flexibility to manage the most relevant challenges for DSOs. It is in this field where EnCs will be able to have a prominent role, constituting themselves as one of the most relevant agents and with a great capacity to provide solutions that improve the exploitation of the networks carried out by the DSOs.

EnCs as reliable providers of flexibility services: DSOs are interested in considering EnCs, among other third parties, as reliable providers of flexibility services if such solutions enable more efficient network operation. EnCs that can actively manage their electricity production and consumption can use their collective flexibility to provide services to DSOs and other network operators. Hence, we can speak of a new type of mutual interaction within the framework of providing greater flexibility to the distribution network, benefiting both parties. DSOs can better control the flexibility of products they purchase and take advantage of a lower risk profile since EnCs are generally supported by regulation and well-established organisations.

Long-term planning: Although planning their network is a recognised task for DSOs, EnCs can provide information that could be used to prevent network congestion and other issues and contribute to planning a more reliable and resilient electricity distribution system. Therefore, good communication between the EnC and the DSOs is paramount.

Improved forecasting for operation planning: Aggregating load and generation profiles at the EnC level makes DSO network operations more predictable and balanced.

Improve the quality of the supply: The close cooperation between the DSO and the EnCs to use the flexibility provided by the latter might support the quality of electricity supply within the community and the closer part of the distribution network.

EnCs acting on equal terms with other market players: Further analysis shows that the new role of EnCs represents both an opportunity and a challenge for DSOs. They can be a means to unlock the flexibility potential of active consumers and to more effectively integrate renewable resources and new technologies, such as EVs or batteries, into the distribution network. In contrast, EnCs must fulfil all related duties and responsibilities when acting as suppliers, active customers or any other existing market role. They must act on equal terms with other market players.

Promoting efficient investments: EnCs can provide information regarding the grid needs at their connection points that can be used subsequently to make efficient investments. A better understanding of the network and profiles with a "built-in" aggregation of network utilisation (through the flexibility of the internal energy community) will help the DSO make the right investment decisions at the right time.

1.6.2 TSO perspective

From the TSO perspective, the deployment of EnCs and as a result of the large-scale integration of the distributed resources, the following technical opportunities are identified:

Increasing operation flexibility: EnC impacts the flexibility of the transmission grid through the increasing flexibility of the distribution grids connected directly to it. Dynamic and coordinated electricity withdrawal from and feed into the transmission grid will enable better balancing injections and withdrawals at the transmission grid level.

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47 Cramer, Wilhelm; Schumann, *Klemens; Andres, Michael; Vertgewall, Chris; Monti, Antonello; Schreck, Sebastian et al. (2021): A simulative framework for a multi-regional assessment of local energy markets – A case of large-scale electric vehicle deployment in Germany. In: Applied Energy 299, S. 117249. DOI: 10.1016/j.apenergy.2021.117249.*

Facilitate frequency control: The more accurate the generation-load balancing is in the distribution level enabled by EnCs, the easier the frequency holding process will become.

1.6.3 Perspective of the entire power system

The following technical opportunities have been identified from the perspective of the entire power system.

Facilitation of recovery process after a total or partial blackout: A power outage interrupts the power supply to end users in large part or the whole of the relevant area for a few minutes to a few weeks, depending on the grid's type and configuration. Outages are serious at sites where the environment, public safety and the maintenance of the technological processes are in jeopardy. The longer the recovery time, the more complex the situation becomes. The wide-ranging DER integration through reliable EnCs offers an excellent opportunity to reduce the recovery time from a partial or complete power outage.

Increasing the resilience of power grids in general and distribution grids in particular: Power systems are considered resilient if they can perform well even after severe, unlikely events such as prolonged droughts and dangerous storms that may become normality in climate change conditions. Security of supply from the reliable hydropower and nuclear power plants could become questionable during potential prolonged and widespread droughts. Centralised structures are not inherently less reliable, but the fact that they bundle large amounts of energy means that a more significant proportion of the supply is at risk in extreme events. With decentralised systems, the quantity at risk is reduced, even if the systems react more sensitively to weather events. With their mission of maximising the DER share, EnCs will play a crucial role in transforming the power systems structure from centralised to decentralised.

EnC facilitator on the transition process: The term energy transition refers to the global energy sector's conversion towards renewable energy sources and energy efficiency, replacing fossil-based, i.e. oil, gas and coal, energy production and consumption facilities. While the latter are directly connected to distribution grids, renewable energy production facilities can be connected to transmission and distribution grids. EnCs promote the comprehensive integration of renewable energy production facilities, and encourage customers to participate actively in flexibility programmes for the grid.

Economic processing in the power industry to promote energy communities

Although the electricity markets are undergoing a radical change, the current re-dispatch process for congestion management is still costly and drives the transmission grid operation to its limits. At the same time, the electricity producers connected to the distribution grid do not have any market access. Meanwhile, DSOs do not participate in the market operation to manage their congestion. Effective DER operation is quite limited. The transformation of the resource mix from fossil fuels to renewables and the rise of distributed resources call for a radical review of the market structures.

1.7 Status quo of the economic processing in the power industry

The two-constituents model of state and market has dominated the energy sector since the 1990s. In recent decades, complex public-private contracts have centralised, privatised, and formalised the energy supply, see Figure 12. The existing market structure dates back to when electricity was mainly generated in large power plants, fed into the transmission grid, and distributed to customers. The players in the electricity market are limited to large electricity producers, consumers, and energy suppliers, which are few. The Control Area Manager (CAM) facilitates the market, whose role is usually taken over by TSOs.

After trading the electricity on the market, the Energy Supplier Companies determine on their own the selling and buying of electricity prices with regard to smaller customers and producers. The latter can buy and sell electricity using various contracting forms. This means that although millions of small customers such as retail customers, etc., and small distributed producers and storage are recognised as market participants, they are practically unable to negotiate. They can only choose between different energy suppliers.

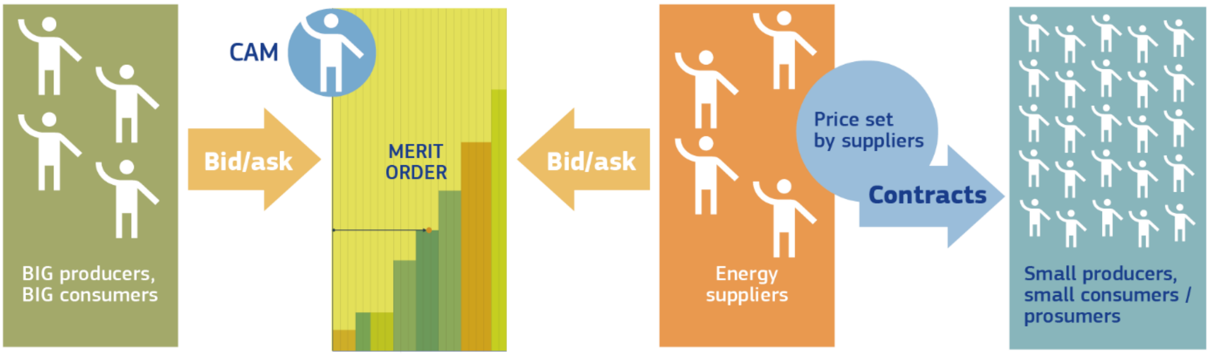

Fig. 12. Overview of the current market structure and pricing mechanisms used in the power industry.

The mixed form of economical processing in the power industry is the source of non-transparent pricing for the end customers and the breeding ground for speculation. New regulatory and policy changes to promote DERs have led to changes in the electricity market, including the introduction of time-based pricing mechanisms and reliability-based incentives. However, no essential structural changes have yet been performed to allow millions of consumers, prosumers, and DERs to participate directly in the market.

1.8 Different economic processes to promote energy communities

The emergence of EnCs challenges the two-constituents model, and a new logic of the third constituent has entered the scene, changing to a three-constituents model State-Market-Civil Society. While the combination of state and market in the past has already blurred the lines between public and private, for-profit and not-for-profit, the emergence of citizen energy initiatives is blurring the lines much more.

Different Coordination Schemes (CS) are designed to facilitate the TSO-DSO coordination and empower EnCs and VPPs integration [48]. Their main goal is to enable EnCs and VPPs access to balancing and Ancillary Service (AS) markets and contribute to these markets by providing their services. The market modelling and design to procure system services depend on the relationship between systems operators and the roles that have been taken up. These CS include a) Centralised AS market model is most compatible with the existing regulation and organisation of AS markets in Europe; b) Local AS market mode, providing a separate local market operated by the DSO; c) Shared Balancing Responsibility model, empowering demand-side flexibility to provide AS to the SO's grid; d) Common TSO-DSO market model, providing a common market for flexible resources that are connected to the transmission and distribution grids; and e) Integrated Flexibility market model, introducing the participation of both regulated SOs and commercial market parties to procure flexibility in a common market.

Scientific works related to the market can be classified into two large groups. One group focuses on adapting existing market structures through different platforms and tariffs. The other focuses on redesigning the market structure.

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48 F. Andren, T. I. Strasser, J. Le Baut, M. Rossi, G. Vigano, G. Della Croce, S. Horsmanheimo, A. Azar, A. Ibanez,Validating Coordination Schemes between Transmission and Distribution System Operators using a Laboratory-Based Approach, PowerTech, June 2019

1.8.1 Adaptation of existing market structures through different platforms and tariffs

1.8.1.1 Traditional Time Of Use tariffs

According to reference [49], local flexibility exploitation occurs in different stages. The first step is to optimally manage and control the EnC flexibility pool for internal purposes via intra-community trading, by which the community should be able to save energy. Any residual generation or demand could be adjusted via balancing mechanisms with the electric supplier(s). In a second step, subsequent to an operational assessment by the competent network operator, the community can respond to incentive ancillary service signals to access further revenue streams.

Traditional Time-Of-Use (TOU) tariffs may be better for customer engagement than more modern newly introduced dynamic tariff structures. In addition, optimal TOU structures should be developed for flexible energy communities so that the higher charge TOU periods are tailored to the highest flexibility periods of the customers. In short, the report recommends that the tariff setting should be closer to the customers and EnC than it has been until now.

1.8.1.2 Integration of distributed resources in ancillary services markets

TSOs have actively assisted in identifying how EnCs can help promote the security of supply, the creation of new market tariffs, and the participation of aggregators in reserve markets as Balancing Service Providers (BSP) or as Balancing Responsible Party (BRP). It was also highlighted that aggregators can participate in congestion management markets as a service provider with a single unit, capacity services, or energy services when it aggregates flexibility from one local CEnC. Also, some CEnCs have stated that an aggregator could participate in these markets if it aggregates flexibility from geographically dispersed CEnC. A common data model has been developed (based on the European Common Information Model (CIM) from the IEC 62325-351 standard) to unify the data interchange with the system operator regarding the procurement of the selected balancing – both manual frequency restoration and replacement reserves – and congestion management services that, due to its technological agnostic nature, accommodates the participation of EnCs in the balancing markets. All these services and data models have been studied in detail. Therefore, the conditions to evaluate the scaling-up of power flexible energy communities’ business models through their participation in the system operator’s balancing services and congestion management markets are now available for fulfilment and testing in the subsequent developments.

TSOs within the ENTSO-E have deployed several projects establishing platforms for standard frequency support services such as the Platform for the International Coordination of Automated Frequency Restoration and Stable System Operation (PICASSO) [50], for automatic frequency restoration reserves; the Manually Activated Reserves Initiative (MARI) [51] for manual frequency restoration reserves; and the Trans-European Replacement Reserves Exchange (TERRE) [52], for replacement reserves. Thus, new players can take advantage of a centralised optimisation of resources to increase supply security, limit emissions, and reduce customer costs.

1.8.1.3 Adopting time-based pricing mechanisms and reliability-based incentive offerings

In this case, the market structure is changed by adopting time-based pricing mechanisms and reliability-based incentive offerings. The entry of DERs into the market realises using load service aggregators [53]. EnCs can access all electricity markets, either directly or through aggregation, in a non-discriminatory manner. This fact invites new stakeholders

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49 H2020 FlexUnity, Report of Market design analysis https://www.flexunity.eu/_files/ugd/3ed137_ef5e40f0ce2f42e5abfd96a2ced32646.pdf

50 PICASSO https://www.entsoe.eu/network_codes/eb/picasso/

51 MARI https://www.entsoe.eu/network_codes/eb/mari/

52 TERRE https://www.entsoe.eu/network_codes/eb/terre/

53 Shen, Bo & Ghatikar, Rish & Lei, Zeng & Li, Jinkai & Wikler, Greg & Martin, Phil. (2014). The role of regulatory reforms, market changes, and technology development to make demand response a viable resource in meeting energy challenges. Applied Energy. 130. 814–823. 10.1016/j.apenergy.2013.12.069.

interested in grid services, resilience enhancement, and innovative business models, similar to the Brooklyn Minigrid in the US.

However, promoting these grid configurations through the market lacks a clear approach. Differentiation is achieved through tariff schemes for different consumer roles in the energy stream. This differentiation has to be addressed when developing the market structures.

Furthermore, regulatory frameworks are often designed for either generators or load curtailment resources, not both, which raises concerns. Microgrids, with their diverse energy management technologies, can provide multiple services simultaneously, but market rules often don't allow this.

1.8.1.4 Regulated Electricity Price Components based on Grid Topology

Regulated electricity Pricing Components, based on Grid Topology, are an alternative pricing system [54], illustrated in Figure 13. The pricing depends on the voltage levels used by participants in the EnC. When two nearby participants share electricity, they incur lower fees than two who live further away or buy electricity from a utility. Thereby, regulated electricity price components incentivise local trading and reduce the stress on the distribution grid. Furthermore, this increases the EnCs' self-sufficiency [48].

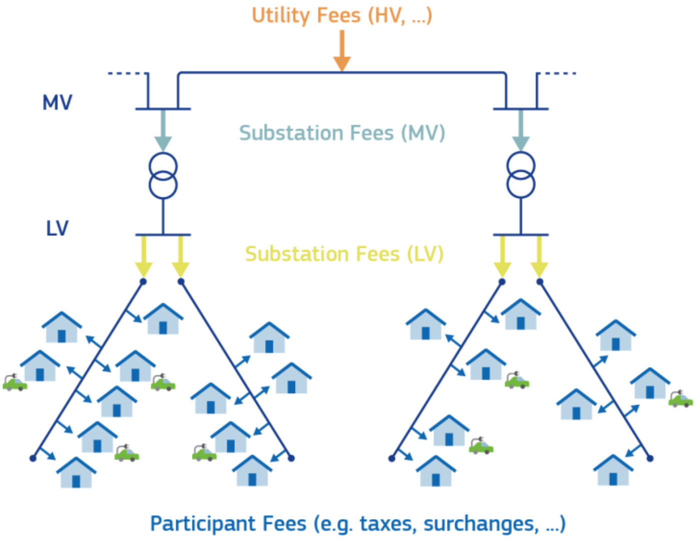

Fig. 13. Exemplary distribution of regulated electricity price components based on grid topology.

Some studies have shown that **considering Power Line Capacities and Voltage Band Compliance** in the matching process can positively impact the utilisation of the whole distribution grid and thus benefit the DSO [55], [56], [57]. However, it requires detailed grid information and increases computational complexity. Striking the right balance is crucial, as overly tight restrictions can reduce the EnC's overall social welfare.

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[54] Schreck, Sebastian; Thiem, Sebastian; Amthor, Arvid; Metzger, Michael; Niessen, Stefan: Analyzing Potential Schemes for Regulated Electricity Price Components in Local Energy Markets. In: Seventeenth Online Stockholm Sweden EEM20.

[55] Zocher, Julius; Trageser, Marc; Schreck, Sebastian; Alvarado, Axel; Ulbig, Andreas (2021 - 2021): Consideration of Power Line Capacity and Impact on Voltage Band Compliance in Local Energy Markets. In: 2021 IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe). 2021 IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe). Espoo, Finland, 10/18/2021 - 10/21/2021: IEEE, S. 1–5.

[56] Khorasany, Mohsen; Mishra, Yateendra; Ledwich, Gerard (2020): A Decentralized Bilateral Energy Trading System for Peer-to-Peer Electricity Markets. In: *IEEE Trans. Ind. Electron.* 67 (6), S. 4646–4657. DOI: 10.1109/TIE.2019.2931229.

[57] Guerrero, Jaysson; Chapman, Archie C.; Verbic, Gregor (2019): Decentralized P2P Energy Trading Under Network Constraints in a Low-Voltage Network. In: *IEEE Trans. Smart Grid* 10 (5), S. 5163–5173. DOI: 10.1109/TSG.2018.2878445.

In summary, the DSO can benefit from both schemes as they reduce the distribution grid utilisation without impeding EnCs. However, the DSO must actively cooperate with them by communicating price components and the grid model.

1.8.1.5 Peak Power Margins

Peak Power Margins (PPMs) and regulated electricity price components use price incentives or cost penalties to encourage the energy community to reduce the utilisation of the distribution grid. The market platform can also check for distribution grid constraints by receiving a grid model from the DSO. This model includes thermal limits for lines and transformers and voltage band restrictions for matching.

PPMs aim to reduce the maximal power consumed at the PCC of a market area. If the market is oriented on the power grid, this can reduce the utilisation of transformers. PPMs are costs that apply for the peak load at the PCC within a year and have been presented and investigated in [58], [59], [60].

PPMs can act in three phases, see Figure 14. In the first phase, the grid operator defines a cost factor applying to the PPMs at the beginning of a year. This cost factor will apply to the maximal load of an energy community at the PCC. The costs need to be high enough to incentivise the end customer to shift their load, but they should be low enough not to impact the energy sharing too much.

In the second phase, the market platform considers the PPM costs within the day ahead or intraday matching. The market platform forecasts the expected load required by the energy community over the PCC. If the load exceeds the last peak load, the market platform checks different operations to avoid PCC costs. In the third phase, the grid operator determines the maximal load at the PCC ex-post and invoices. the PCC costs to the market platform or end customers.

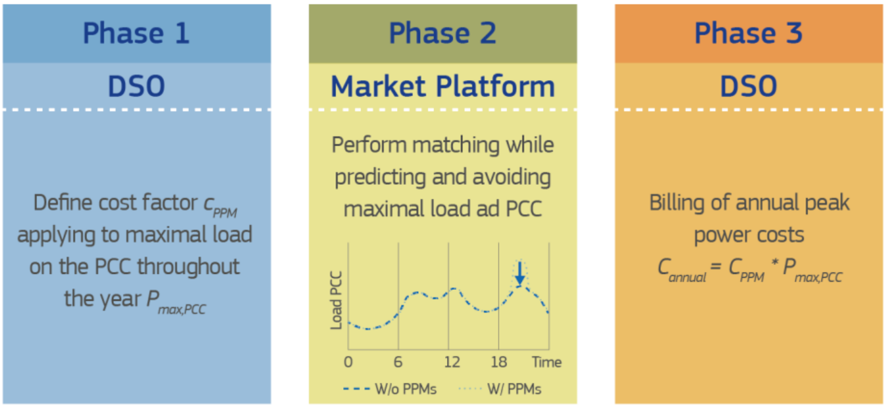

Fig. 14. Three phases of the process of PPMs.

1.8.2 Redesign of market structure: The rise of the local market

The potential of local energy markets is considered very high in the literature: Nearly all publications identify them as crucial to promoting the integration of large-scale renewable DERs and creating viable EnCs. The local energy market [61] can provide ancillary services and relieve the balancing market needed to meet electricity demand. It opens doors for the interactive grid and customer participation. An efficient local market strives for advantageous market prices, a high rate

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58 Moret, Fabio; Pinson, Pierre (2019): Energy Collectives: A Community and Fairness Based Approach to Future Electricity Markets. In: IEEE Trans. Power Syst. 34 (5), S. 3994–4004. DOI: 10.1109/TPWRS.2018.2808961.

59 Cramer, Wilhelm (2021): Bewertung lokaler Energiemärkte. Ph.D. disseration. RWTH Aachen, Aachen, Germany. Institute for High Voltage Equipment and Grids, Digitalization and Energy Economics. https://www.eonerc.rwth-aachen.de/cms/e-on-erc/forschung/publikationen/~dmwf/details/?file=835194&lidx=1

60 Schumann, Klemens; Schmitt, Carlo; Blank, Andreas; Kollenda, Katharina; Moser, Albert; Ulbig, Andreas (2022): Local Energy Market Designs to Relieve the Transmission Grid. In: 2022 19th International Conference on the European Energy Market (EEM).

61 Valarezo, O.; Gómez, T.; Chaves-Avila, J.P.; Lind, L.; Correa, M.; Ulrich Ziegler, D.; Escobar, R. Analysis of New Flexibility Market Models in Europe. Energies 2021, 14, 3521. https://doi.org/10.3390/en14123521 of self-consumption and a large amount of traded energy to increase its self-sufficiency and liquidity [6]. But, despite all the developments and progress, many challenges [62] have been identified. They are mainly related to coordination within the power grids (between transmission and distribution), the power grid with the customer, and the new local market structure. For example, significant voltage and loss challenges may occur due to extensive local PV generation if local generation and consumption are unfavourably distributed on the grid. Local markets could exacerbate these challenges.

1.8.2.1 Local energy markets involving aggregators

The electricity market structure under the wholesale competition is shown in Figure 15. The market participants include Generating Companies (GenCos), Transmission Companies (TransCos), Distribution Companies (DisCos), customers and the TSO. Generating companies compete to sell electricity connected to the high-voltage transmission network to competing buyers (DisCos and large customers). DisCos provide bundled services to consumers. TSOs provide non-discriminatory open access to the transmission network to all users, manages congestion and network constraints, provide ancillary and balancing services, and manage energy loss. DSOs provide access to the distribution network to the supplier (retailer) who delivers electricity to the end user. The drawbacks of the wholesale market are eliminated by giving access to the consumer to choose the retail service. The retail market becomes more competitive as free entry to retail is provided. Consumers can change their retailers for better services and prices.

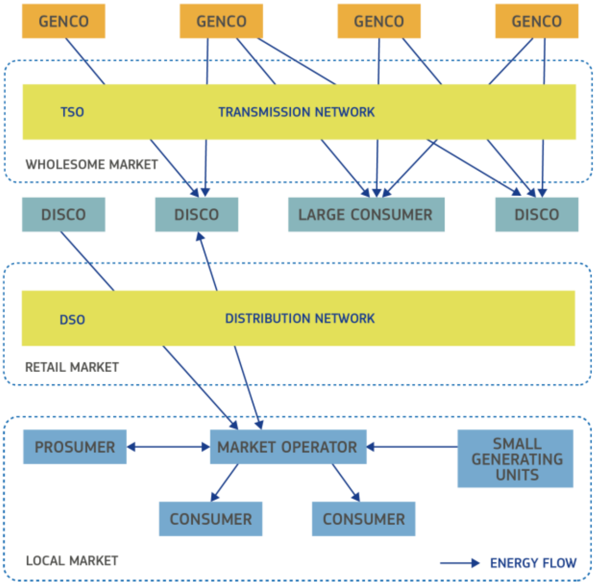

Fig. 15. Electricity market structure.

Therefore, the major driver is the local electricity grid tariffs used on the EnC exchanges. For example, the EU requires tariffs to be cost-volumetric, which entails paying only for the actual voltage-level used for distribution within the community [63]. While some countries develop local tariffs specifically for renewable energy communities (Austria, Wallonia, Italy), other countries (France, Portugal and Spain) also allow CSC initiatives to use the public grid to which specific tariffs will equally apply. The development of local grid tariffs for REnCs generally involves a reduction of volumetric elements of the grid tariff (e.g. in Cyprus, Spain, etc. [64]) and, in some cases, additional taxes and charges unrelated to the costs of the public grid. These developments show two fundamentally different motivations for local tariffs. The first is cost reflectiveness, and the second is the support of CSC and REnCs. Both motivations are embedded in the EU

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62 Y. Ruwaida et al., "TSO-DSO-Customer Coordination for Purchasing Flexibility System Services: Challenges and Lessons Learned from a Demonstration in Sweden," in IEEE Transactions on Power Systems, vol. 38, no. 2, pp. 1883-1895, March 2023, doi: 10.1109/TPWRS.2022.3188261.

63 Nicolás Morell-Dameto, José Pablo Chaves-Ávila, Tomás Gómez San Román, Tim Schittekatte, Forward-looking dynamic network charges for real-world electricity systems: A Slovenian case study, Energy Economics, Volume 125, 2023, 106866, ISSN 0140-9883, https://doi.org/10.1016/j.eneco.2023.106866.

64 EURELECTRIC, Network Tariffs, Position paper, March 2016 13 pages.
https://cdn.eurelectric.org/media/2012/network_tariffs__position_paper_final_as-2016-030-0149-01-e-h-5AF7DC88.pdf

framework, though in different pieces of legislation. Roughly, reductions of the tariff element for grid use can serve cost-reflectiveness, while the reduction of renewable support charges falls under the supportive nature. However, grid tariff reductions represent reduced costs and can thus be expected to have a supportive nature. Therefore, in practice, the boundary between policy goals and energy market regulation cannot be drawn clearly. The REDII also highlights this for electricity consumed on-site. At the same time, Member States should "generally not apply charges to electricity produced and consumed within the same premises". They "should be allowed to apply non-discriminatory and proportionate charges to such electricity if necessary to ensure the financial sustainability of the electricity system" [56].

There is also a trade-off between privacy and market efficiency, i.e., an exchange between sharing demand, supply, and price data with a limited number of agents and the electricity price level. Real decentralisation without any central authority and a high level of privacy might only be offered by a privately negotiated P2P energy market. In contrast, order book markets have the potential to find the lowest feasible market prices. The way of handling privacy challenges and data security in local energy markets will likely influence the success of such markets immensely [6].

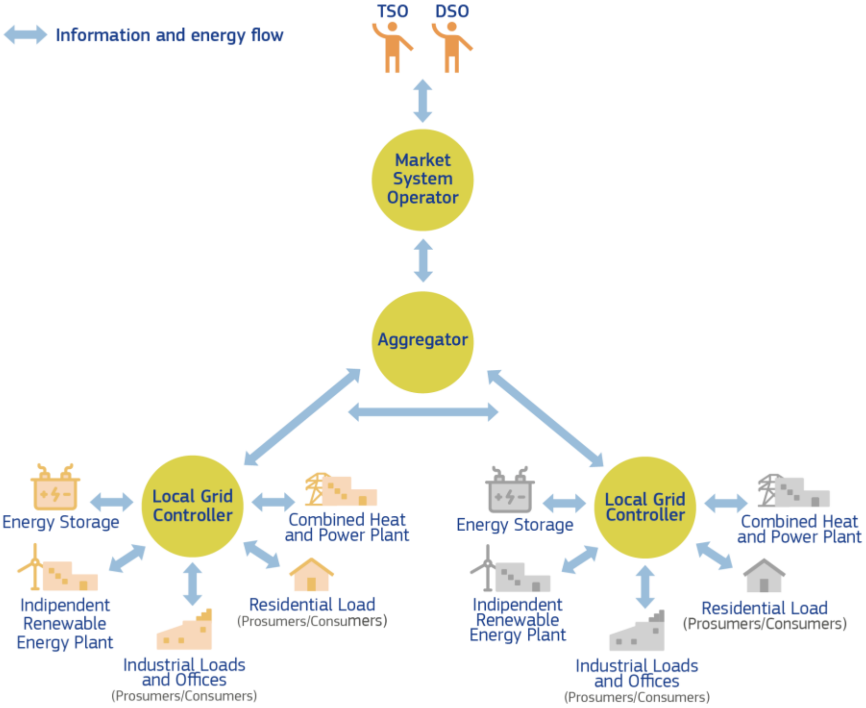

Fig. 16. Local market design involving aggregators.

A new market mechanism design is given for a local energy configuration, where the prosumer/consumer sends the power demand and the generation to the local grid controller [65]. The latter prepares the auction while the bidding is done by the final users of the grid and the aggregator, considering the energy price and volume. The market system operator matches the bid and power requirement through an aggregator and the TSO/DSO. The TSO/DSO deals with day-ahead and real-time markets, and the intra-market helps in adjusting the clearing real-time market via an aggregator. After market clearance, the results are passed on. The aggregator provides the service and power purchased or delivered to the prosumers through the local grid controller. This type of market allows market power mitigation, brings consumers flexibility and security, manages demand response, and provides ancillary services. It also reduces the operating costs and supports medium-size renewable power plants, allowing them to compete through the local market scheme.

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65 F. Teotia and R. Bhakar, "Local energy markets: Concept, design and operation," 2016 National Power Systems Conference (NPSC), Bhubaneswar, India, 2016, pp. 1-6, doi: 10.1109/NPSC.2016.7858975.

1.8.2.2 Fractal-based market restructuring

Redesigning the market in line with the structure of the power grid and adjusting its mechanisms is necessary to realise the democratisation of the power industry, enable demand response and meet today's requirements. The fractal-based market restructuring aims to provide consumers with reliable, environmentally friendly electricity at the lowest possible cost and to promote EnCs and sector coupling. It has pursued two main objectives in the design. The first objective of the restructuring is operation efficiency, making the best use of existing resources. The second objective is to stimulate capital investment by providing appropriate incentives for its efficient use. Efficient capital investments are usually prompted by suitable price mechanisms, e.g., spot prices. However, electricity is not an ordinary commodity but a unique property with high reliability. It requires a power reserve to meet demand when supply and demand uncertainties would otherwise create electricity shortages. Intelligent pricing mechanisms should be developed to take this into account. A capacity market could also coordinate investments.

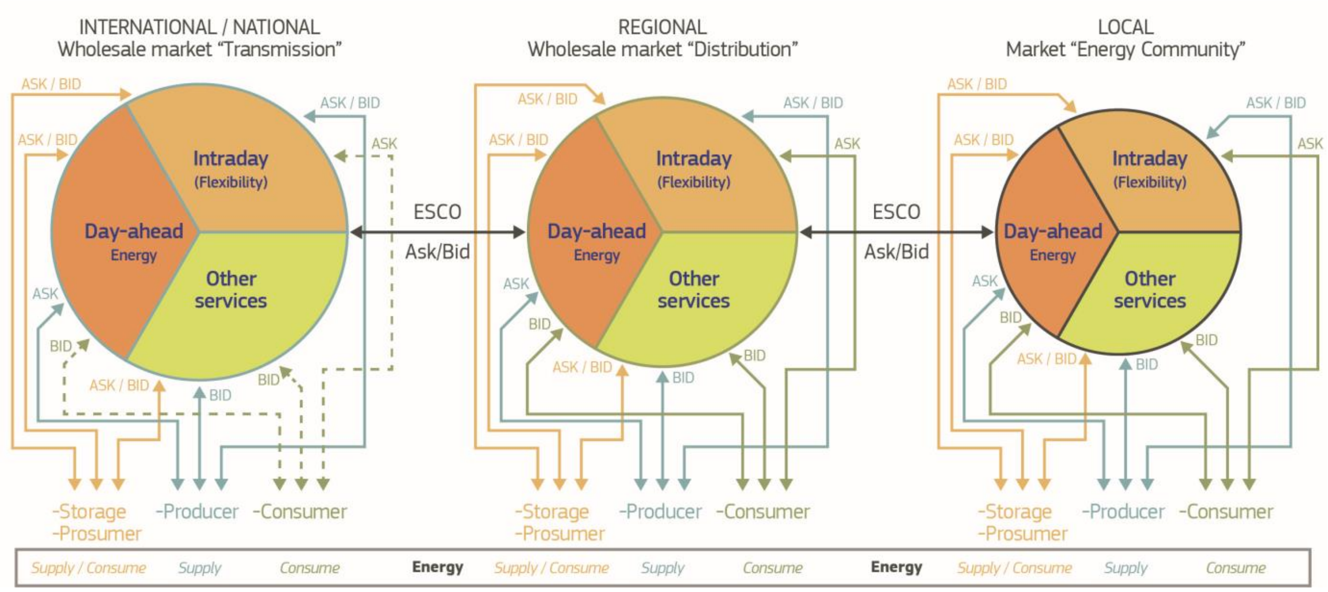

Fig. 17. Overview of the electricity market structure derived from the fractal *LINK*-structure.

The new market design, shown in Figure 17, is harmonised with the fractal structure of smart grids. It increases the space granularity of the electricity market, establishing different market categories such as the national/international markets in the transmission area, regional markets in the distribution area, and the local markets in customer plants EnC-area. It is set up in line with the fractal principle: Similar market patterns [35] and shapes repeated in ever-smaller sizes. The market structure is simple because it is derived from the fractal structure of smart grids. It promotes the direct and equal participation of all actors in the market regardless of the size of their units, making it fair.

Splitting markets at the national/international, regional, and local levels significantly reduces the current complexity due to the variety and economics of the resources, their uncertainties, and power system constraints. Furthermore, an efficient welfare-maximising outcome is achieved by optimising each market area and the area's coordination. The trading volume defines the market size. It refers to the total energy traded during a specific period. The Average Trading Volume (ATV) is calculated by dividing the total Energy Traded (ETr) in a period by the period. The result is the average daily trading volume per unit of time.

$$ATV = \frac{E_{Tr}(Period)\cdot 24}{Period} \quad \text{[GWh], [MWh], [kWh]} \tag{1}$$

The ATV for the national market ranges to GWh; the TSO facilitates it. For the regional one, facilitated by the DSO, the ATV goes to MWh, while the local market, facilitated by the energy community, ranges to kWh [66].

TSOs, DSOs, and EnCs enable the corresponding markets in all segments, such as energy (day ahead), flexibility (intraday) and other services. Market participants have a similar nature in all three market categories. Based on *LINK*-Architecture, production and storage facilities are available in all smart grid fractal levels. Their operators participate in all three market categories. Producers supply energy and ask in the day-ahead market, ask and bid in the intraday market, and bid for other services. Storage supplies or consumes energy, and its operators ask and bid on all market segments. Markets have two peculiar additional participants: prosumers and consumers. Prosumers behave in the market similarly to storage operators because they can supply or consume energy, i.e. they ask and bid in all market segments (prosumers are treated as black boxes in the *LINK*-Solution). In contrast, consumers only consume energy, bid in the day-ahead and intraday market, and ask for other services. Energy Service Companies (ESCO) bid and ask between markets.

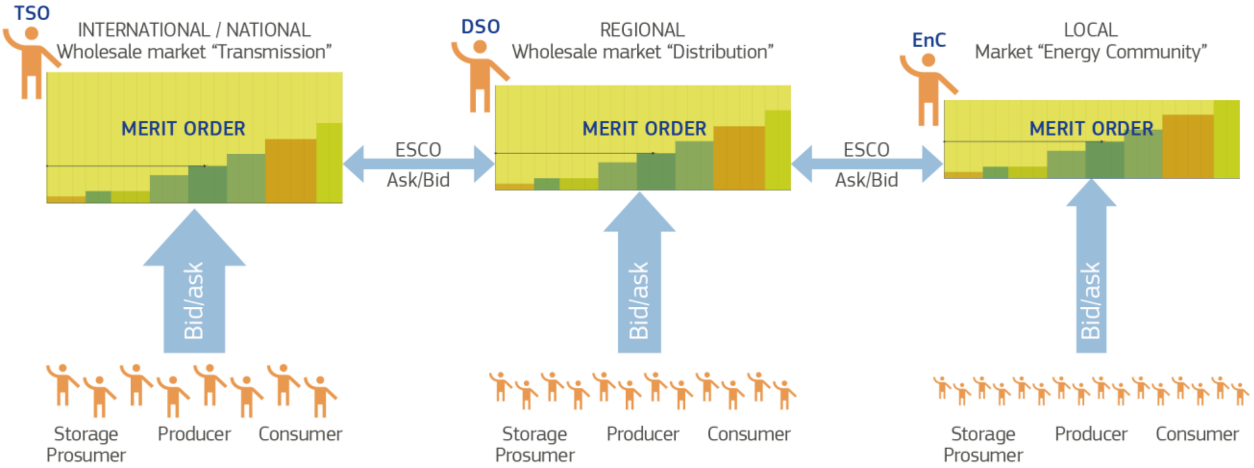

Fig. 18. Overview of the pricing mechanisms used in the different fractal structures of the market.

Each market category is defined as a pricing area, as the largest geographical area in which each market participant trades without capacity allocation: I.e., a Link-Grid area where congestion at the boundaries are controllable through the *LINK*-control strategy. The regulator, and the TSO, DSO and EnC define these areas. The components to be defined to construct a market mechanism are the format of the bids, the clearing rule, the pricing rule and the information the market participants have access to [45]. The pricing mechanism refers to the process where forces of demand and supply determine the prices of commodities and the changes therein. It is the buyers and sellers who determine the price of an item. The Merit Order mechanism has long been established in the electricity market. Figure 18 shows an overview of the pricing mechanisms used in different fractal structures of the market. The Merit Order mechanism is used in the international, regional, and local markets based on the main fractal principle of repeating the same shape and features in various structure sizes. It enables demand and supply market forces to play freely. However, this mechanism may create severe social problems in times of political and economic troubles. Other pricing mechanisms may be needed to make goods affordable for the broad population.

The local EnC market is designed to allow neighbours to supply each other with electricity and democratically set the pricing rules. This approach makes them more independent of international and regional electricity market developments.

The EnC, as a facilitator of the local retail market, has a portfolio of pricing mechanisms. The EnC entity democratically decides which pricing mechanisms from its portfolio to use for a given period. It involves its members, an executive board and eventually a supervising board. The EC should formally inform the controlling body, e.g., the energy authority, of any change in the pricing mechanism and the application period. It has the following portfolio of pricing mechanisms, which may be applied in different circumstances: Merit Order based on arbitrary price offers, Merit Order based on Levelised Cost of Electricity (LCOE) price offers, and Power Purchase Agreements.

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66 INTERACT project, D 4.3 Market structure and its interfaces with the Energy Community, November 2022. https://www.ped-interact.eu/wp-content/uploads/2022/11/D-4.3-Market-structure-and-its-interfaces-with-the-Energy-Community_vfinal2.pdf

1.9 Development of regulation

In Europe, although there is a common core legislation, significant differences in deployment depending on the country may exist since national regulation has an essential role in setting practical implementation; for example, tariff schemes are the responsibility of national regulators.

Since the current power system is conceived on a centralised architecture, this is also the basis for cost recovery of energy transport infrastructures and remuneration of energy flexibility (reserve, peak generation, balancing services, etc.); the burden sharing of such costs is socialised across all end users, with criteria partially related to objective parameters (energy consumption, load profile, connection capacity), complemented by socio-economic policies across different categories of end users. Therefore, going beyond certain thresholds of grid independence would require an overhaul of the existing regulation and tariffication schemes. It is the same problem for system general costs, typically paid through grid tariffs and other tariff components calculated on a per kWh consumptions and a per kW connection capacity.

The current regulation on EnCs provides the basic definitions and requirements for the first and second phases of EnC developments (see § 2.3 Phased development and implementation). These phases cover the basic and some advanced operation modes of the EnCs where the grid is not significantly affected. The regulation is worded so that the existing grid is not aggravated, preserving its traditional structure. Conversely, there are a few guidelines on how EnCs can be integrated into the energy system and the energy market, which should enable phases three and four of the EnC development, the integrated and fully integrated EnCs. The following is a concise overview of the state-of-the-art regulation. However, the EU framework provides details of the implementation process to be developed at a national level, resulting in various criteria and measures within the EU.

As a first regulatory step, the CEP publication acknowledges the EnCs' role in helping the EU meet its climate and energy objectives while driving local innovation. The recast REDII and IMD include the definition of REnCs and CEnCs, respectively, and both contain provisions that establish a supportive legal framework for EnCs. It is also important to note that the regulatory framework highlights the relevance of increasing flexibility to maintain grid stability and manage grid congestion in the energy system. Significantly, the DSOs are becoming increasingly receptive to engaging third-party services, such as flexibility services from third parties through market-based mechanisms. Article 17.2 of the IMD states, "Member States shall ensure that TSOs and DSOs when procuring ancillary services, shall treat market participants engaged in the aggregation of demand response in a non-discriminatory manner alongside producers based on their technical capabilities".

The community structure is not considered a legal entity, which is essential for the EnCs' participation in the electricity markets. The first element relevant to market structures is the type of energy used and traded in the community [67]. Many Member States focus on electricity when implementing REnCs and CEnC, with some explicitly foreseeing a potential future expansion to other energy forms. The generation capacity limits of the EnC are another critical point. Maximum generation capacities for energy communities or CSC schemes differ considerably between regulations. These distinctions also vary, with some referring to the total power within an entire initiative and some referring to the power of individual installations. For example, in Greece, the maximum power capacity for an installation within an energy community is limited to 1 MW. In Italy, individual power plants must not exceed 200 kW. In Slovenia, the sum of RES production should not exceed 80% of the coupling capacities included in the collective scheme. In France, the maximum total power that may be installed within a CEnC scheme on the continental metropolitan territory is 3 MW.

Interestingly, in Switzerland, a minimum production capacity is defined (10% of the grid connection capacity of the community). Depending on the limits, the EnC could see faster or slower growth of the projects due to the number of participants needed to comply with the requirements. Some national regulations, such as in Finland, require the DSOs to provide measuring services, net value calculation, and a simple value-sharing mechanism for the EnC. However, an EnC still needs an operating entity to manage contracts among members, allowing it to remove or add a member. Therefore, an operation entity or related regulation is missing.

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67 D. Frieden, A. Tuerek, C. Neumann et al, Collective self-consumption and energy communities: Trends and challenges in the transposition of the EU framework", Technical report, December 2020,. DOI: 10.13140/RG.2.2.25685.04321

In general, the regulatory measures asses the mentioned barriers during the initial stages of the EnC planning to avoid the need for retrofitting. For example, Article 11.2 of the 2019/944 Directive underlines that the Member States shall ensure that the suppliers fully inform final customers of the opportunities, costs and risks of such dynamic electricity price contracts and shall ensure that suppliers are required to provide information to the last customers, accordingly, including concerning the need to have an adequate electricity meter installed. The directive also requires the regulatory authorities to monitor market developments, assess the risks that the new products and services may entail, and deal with abusive practices.

With the progressive detachment from the common network-based configuration, there is also a need to consider consequential network cost burden splitting to other grid users. Indeed, the shift to microgrids should never be enacted only (or mainly) to escape from system costs, which, by definition are of a general nature and must be borne, with proper splitting principles, by all electricity end users.

Several papers have highlighted a gap between the cost of financing smart grid development and the funds private parties are willing to contribute [68]. Moreover, since DSO/TSO revenues are regulated in an incentive-based regulatory regime, these revenues are not likely to increase significantly due to the use of innovative technologies or processes unless specific regulatory incentives for innovation are in place. Hence, "the funding gap of innovation activities carried out by network operators tends to be larger than that of similar innovation conducted by deregulated actors. The size of this financing gap depends on each technology. It can be determined by carrying out the same cost-benefit analysis that potential private investors would undertake before committing to any R&I project [69]."

Therefore, several position papers [70][71][72] have highlighted the urgency of complementing the results obtained by pilot projects with comprehensive approaches for estimating the costs, benefits, and impacts of the large-scale deployment of the innovative solutions tested in the projects [73].

Business organisation

Three overarching themes are essential for initiating and sustaining an EnC initiative: trust, motivation and continuity [74], impacting their governance or self-governance. It is often unclear who exactly the "I" or the "other" is; therefore, it is unclear which actors are responsible for which aspects. A multi-actors perspective is discussed, followed by their roles, structure, and organisation.

To design a business organisation, specific rights and obligations [75] will be needed to the existing generic definition of REnC [2][3] to ensure its integrated operation and make it a reliable stakeholder in the energy landscape.

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68 M. Murphy e P. Edwards, «Bridging the Valley of Death—Transitioning from Public to Private Sector Financing» National Renewable Energy Laboratory, 2003

69 GRID+ consortium, «D3.6 Preliminary assessment on existing financing schemes. Report for Portfolio of possible financing schemes» 2012

70 Giordano V, Onyeji I, Fulli G, Sanchez Jimenez M, Filiou C. Guidelines for cost benefit analysis of smart metering deployment. EUR 25103. Luxembourg (Luxembourg): Publications Office of the European Union; 2012. JRC67961

71 Vitiello S, Flego G, Setti A, Fulli G, Liotta S, Alessandroni S, Esposito L, Parisse D. A Smart Grid for the city of Rome: A Cost Benefit Analysis. EUR 27158. Luxembourg (Luxembourg): Publications Office of the European Union; 2015. JRC95273

72 European Commission BRIDGE 2020 Annual Report Replicability and Scalability Task Force, April 2021, https://energy.ec.europa.eu/system/files/2021-06/bridge_tf_replicability_and_scalability_report_2020-2021_0.pdf

73 Valiati, R. ERGEG position paper on Smart Grids. An important dimension for cost-efficient investments

pres., Florence Forum 11 June 2010

74 F. Avelino et al.. (2014). The (Self-)Governance of Community Energy: Challenges & Prospects. DRIFT PRACTICE BRIEF, Dutch research institute for transitions. DOI: 10.13140/2.1.1297.0242 . Accessed 21 November 2022

75 INTERACT Project, D4.1 Design of the Energy Community Organization according to the LINK-Solution, January 2022. https://www.ped-interact.eu/wp-content/uploads/2022/06/D-4.1-Design-of-the-Energy-Community-Organization-according-to-the-LINK-Solution-vfinal.pdf

An integrated EnC means a legal entity: (a) Which is based on open and voluntary participation; (b) It is autonomous and effectively controlled by shareholders or members that are located near renewable energy sources, owned and developed by that legal entity or its members; (c) Where the shareholders or members are natural persons, SMEs or local authorities, including municipalities; (d) With the primary purpose of providing environmental, economic and social community benefits for its shareholders or members or for the local areas where it operates rather than financial profits; (e) Which establishes and operates local markets in harmony with the grids and other markets to enable the active energy trading of the shareholders or members.

1.10 Multi-Actors perspective

The multi-actor perspective shows that the (self-) governance of EnC involves a variety of actors. Figure 19 gives an overview of the actors relevant to integrated EnC and of how their interactions and roles. EnC can interact with many profit and non-profit actors such as customers, distributed Electricity Producer Operator (EPO) or Storage Operator (StO), Charging Point Operator (CPO), authorities, regulators and market facilitators. Concerning EnC member's roles, it is essential to distinguish between external and internal tasks.

Internally, the EnC interacts with its members, such as the customers (consumers or prosumers), distributed EPOs and StOs, and the DSO(s) to whose grid its members' facilities are connected, see Figure 19(a). It coordinates the energy and flexibility trading in the local market, the long-term planning of facilities, the day-ahead and short-term operation planning, and all legal and organisational issues. Additionally, the EnC fulfils community services, e.g. it cares about the members' concerns, brings them together, promotes knowledge share, etc. Externally, it interacts with many actors in the energy sector, Figure 19(b). These are DSOs (in the role of the technical or wholesale market "Distribution" operator), authorities, and regulators.

1.11 Roles and responsibilities

In general, the role is related to the function or position the actor has or is expected to have in an organisation, society, or relationship. It is essential to distinguish between the roles of other energy sector actors, the role they will play within the EnC, and the members' roles. EnC interacts with many internal actors, Figure 19a) and with many external energy sector actors or stakeholders, Figure 19b). It should cooperate with local, regional, national and EU authorities for the smooth development of the organisation. Close cooperation with regulators should be the order of the day to guarantee compliance with competition rules by all local market participants. A crucial role is to coordinate with the DSO, acting as a technical operator and operator of the wholesale market "Distribution" when applying the *LINK* solution. The coordination with the DSO as a technical operator should achieve a reliable and secure grid operation in normal and non-normal conditions, and it should facilitate the recovery process after a blackout. The coordination with the DSO as an operator of the whole market "Distribution" succeeds in trading between the wholesale market "Distribution" and the local market, which is established and handled by the EnC. The EnC's significant role is to recruit and consult non-EnC members such as customers, EPOs, StOs, and CPOs.

Representing a novel concept, EnCs will expand within the existing energy system. While energy communities can perform several activities, energy sharing is one of the most discussed activities that will be used within energy communities [76]. In energy sharing, participants can share self-generated electricity (e.g. from PV systems or wind power plants) with other participants, thereby increasing the community's self-sufficiency and reducing electricity costs. Energy sharing can be accomplished through local energy markets as a market platform for matching generation and load. Participants can use their flexibility (e.g., battery storage or EVs) to align load and generation and maximise social welfare within the community [77].

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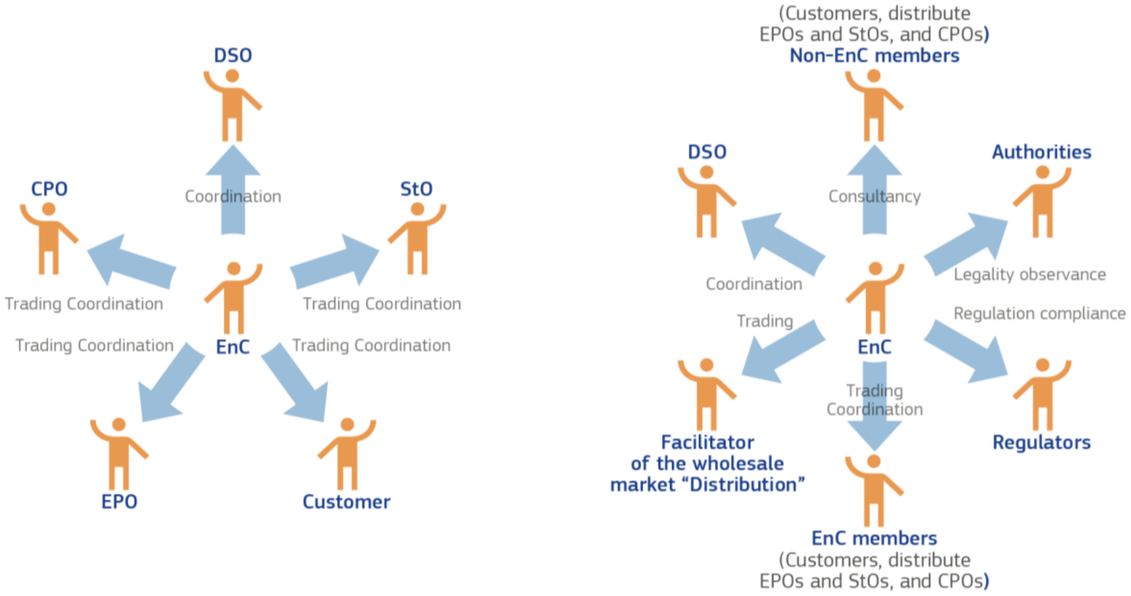
76 Caramizaru, Aura; Uihlein, Andreas (2020): Energy communities. An overview of energy and social innovation. Luxembourg: Publications Office of the European Union (EUR, 30083).

77 Mengelkamp, Esther; Schönland, Thomas; Huber, Julian; Weinhardt, Christof (2019): The value of local electricity - A choice experiment among German residential customers. In: *Energy Policy* 130, S. 294–303. DOI: 10.1016/j.enpol.2019.04.008.

Adjusting the load of end customers can lead to changed power flows on the power grid, especially on the distribution grid. These changed power flows can be an opportunity but also a challenge for DSOs by leading to reduced or increased utilisation of the distribution grid.



(a) **(b)**

Fig. 19. Overview of the EnC actors and their roles: (a) Internal; (b) External.

When sharing energy, the energy community seeks to increase its social welfare. In countries with a regulation that economically encourages energy sharing (e.g. Spain [37]), maximising social welfare will also increase self-sufficiency. Furthermore, increasing self-sufficiency can reduce the peak power flows over the PCC, which can often be the LV/MV-transformer or MV/HV-transformer, depending on the definition of local market areas. However, the positive effect does not occur in all cases, but it can be encouraged by introducing specific measures for considering the distribution grid within the matching of load and generation [48].

1.12 Structure and Organisation

Each country offers a wide choice of different legal forms of organisations for a newly created entity. The analytical credit dataset of the European Central Bank lists in its 2.6 version of the "list of legal forms" 958 different legal forms in the 28 countries covered [78]. Due to the community aspect of the EnC, sole proprietorships are excluded.

The following aspects can generally classify the different ownership models: 1) The influence of the owners on the business; 2) From direct influence and participation in daily business to indirect influence without participation in day-to-day business; 3) The liability of the owners resulting from the business: Full or limited personal liability; The formality of the ownership model: Registration of a separate legal entity or taxation of the owners or taxation of the organisation; and 4) The duration of the ownership model: Ending expected (e.g., departure of a partner) or not (e.g. death of a partner).

As per definition, the REnCs may have a vast spectrum of organisational forms. Cooperatives [6][7] are the most common form adopted by EnC initiatives. They constitute democratic structures that follow a set of internationally agreed principles and make decisions on a one-member-one-vote basis; an elected board governs day-to-day operations. "Limited" or "joint

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78 E. C. Bank, "AnaCredit," European Central Bank, Apr. 28, 2021. https://www.ecb.europa.eu/stats/money/aggregates/anacredit/shared/pdf/List_of_legal_forms.xlsx (accessed Dec. 03, 2021).

and several" Partnerships [79][80] or Corporations [81][82] that, in contrast with the first form, is a legally approved single entity that acts as a legal person before the law. Associations [83] are individuals or legal persons who agree to form a typical structure and pursue a common goal or purpose. They can be registered or non-registered. Associations can vary from small, informal, local hobby groups to large multinational interest groups. This type of diverse organisation and self-governance raises questions about their reliability to be integrated into the existing power systems structures [84].

Depending on the size and strategic target of EnCs, they might either be attached to an existing entity or organised by setting up a new entity. Existing entities with a high degree of trust that can add EnCs to their portfolio are local municipalities and municipality-owned companies. When establishing a new company, there are several options available under the law, which differ in terms of the influence of the owners on the company, the owner's liability, the degree of formality and the planned duration of the organisation. In large groups, we identified partnerships, corporations, cooperatives, community trusts and foundations, and associations as the possible legal structure of an EnC. Depending on the chosen organisation of the EnC, ownership of assets is possible. Community-owned assets can be differentiated into non-electrical and electrical assets. The non-electrical assets mainly cover Communication Technology (CT) infrastructure, land, buildings and intellectual property, whereas, electrical assets mainly cover electricity grids, production facilities, and Electrical Vehicle (EV) loading- and storage facilities.

EnC work according to an agreement between members to provide environmental, economic or social community benefits. In this regard, EnC need a reliable entity to assist their operation, including managing the agreement between members, adding or removing members, measuring consumption and production, calculating the added value of the community, determining the value-sharing strategy among members, and billing process. In addition, these entities can be equipped with a one- or two-level energy management system to control or reschedule smart consumption to optimise costs or provide flexibility or ancillary services in the energy market.

In addition, operating EnCs requires a dedicated platform to provide related services. Therefore, a service provider or a company that provides software as a service has an undeniable role in the practical working of an EnC. An EnC service provider can provide more sophisticated services, such as energy management systems at a single customer and community levels. It can also aggregate the flexibility potential of each EnC to participate in flexibility (ancillary service) markets [85].

Conclusive remarks

EnCs represent an intriguing new way of organising energy systems that put active customers and citizens at the centre and promote DERs for more sustainable developments. Despite considerable regulatory support, their story challenges

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79 European Commission, Joint Research Centre. Energy Communities: An Overview of Energy and Social Innovation. 2020. Available online: https://op.europa.eu/en/publication-detail/-/publication/a2df89ea-545a-11ea-aece-01aa75ed71a1/language-en (accessed on 5 November 2021).

80 European Committee of the Regions and Milieu Ltd. Models of Local Energy Ownership and the Role of Local Energy Communities in Energy Transition in Europe. 2018. Available online: https://op.europa.eu/en/publication-detail/-/publication/667d5014-c2ce-11e8-9424-01aa75ed71a1/language-en (accessed on 4 November 2021).

81 JuraForum. Gesellschaft Mit Beschränkter Haftung/GmbH Gründen–Alles zur Haftung, Geschäftsführer und Auflösung. Available online: https://www.juraforum.de/lexikon/gesellschaft-mit-beschraenkter-haftung (accessed on 13 December 2021).

82 Investopedia. What Is AG (Aktiengesellschaft)? Available online: https://www.investopedia.com/terms/a/ag-aktiengesellschaft.asp (accessed on 13 December 2021).

83 Dictionary.com. Definition of Association. Available online: https://www.dictionary.com/browse/association (accessed on 13 December 2021).

84 Flor, A.; Rick, B.; Niki, F.; Sanne, A.; Philip, B.; Jesse, H.; Geerte, P.; Bonno, P.; Daniel, S.; Julia, W. The (Self-)Governance of Community Energy: Challenges & Prospects; Drift Practice Brief, Dutch Research Institute for Transitions: Rotterdam, The Netherlands, 2014; pp. 1–34. Available online: https://www.researchgate.net/publication/265694629_The_Self-Governance_of_Community_Energy_Challenges_Prospects (accessed on 21 November 2022).

85 T. G. Papaioannou and G. D. Stamoulis, "An Optimization Framework for Effective Flexibility Management for Prosumers," 2022 IEEE International Conference on Communications, Control, and Computing Technologies for Smart Grids (SmartGridComm), Singapore, 2022, pp. 103-109. https://ieeexplore.ieee.org/document/9961040 the existing structures and raises many questions about (self-) governance, technical compatibility with the grid, energy exchange participation, etc.

Energy Communities locally support the growth of society by promoting investment in DERs and democratising the energy industry.

EnCs introduce a new relationship between society and its energy systems. They promote investment in distributed energy resources and democratise participation in the energy industry. EnCs encompass environmental, technological and economic aspects and address social equity issues. Energy sharing provides its members with financial benefits from the local presence of renewable and decentralised generation plants.

The implementation of EnCs in the different Member States after the publication of the CEP is far from complete. While REnCs have already been recognised in many of the Member States, CEnCs have so far received less attention in national legal processes. This may pose some challenges that should be adequately addressed to allow the benefits of EnCs to develop in a way compatible with the idea of a more cost-efficient operation of distribution grids.

EU policymakers have adopted legislation to support ***Energy Communities*** *taking responsibility for the energy transition. Their* ***practicable implementation requires further legislative support****.*

The current economic processing in the power industry is a mixture of market activities and contracts, which doesn't facilitate the flourishing of viable EnCs. E.g. the new fractal-based market structure, with the national, regional, and local markets harmonised with the grid, encourages the direct participation of small customers and DERs in the energy market, §4.2.2.2 Fractal-based market restructuring. The results of this work may help policymakers, regulators, and industry representatives set out new energy policies and processes related to research and development programmes for implementing fully integrated renewable EnCs, as well as detailing the steps for integrating them on a large scale. Their development and implementation will be a long process.

First of all, a level playing field must be guaranteed, and EnCs should be subject to similar opportunities but also to similar responsibilities and regulations as the rest of the market actors performing similar activities [4]. In the case of flexibility provision, EnCs should be subject to the same relevant provisions as other agents (Article 16.3(b) of the IMD states that "*Member States shall ensure that* ***citizen energy communities are treated in a non-discriminatory and proportionate manner*** *with regard to their activities, rights and obligations as final customers, producers, suppliers, DSOs or market participants engaged in aggregation*. In their role as market facilitators, it is key that DSOs act in such a way that the above principles are met for all parties involved, including ECs, in providing flexible services and participating in the markets that *may exist.*

The current electricity market structure analysis shows that EnCs and other smaller entities cannot participate. This market structure was created when the electricity system was almost unidirectional, and smaller entities only consumed electricity. With an increasing number of DERs and local entities also producing electricity and being able to provide further supporting services to the grid, this market structure does not seem adequate anymore.

The new role of ***Energy Communities*** *represents both an opportunity and a challenge for DSOs and TSOs.*

Their technical integration requires a coordinated operation and control of the entire power grid, including transmission and distribution, and the end users. Additionally, being reliable actors, EnCs should be included in the investment planning process. They should be designed to fully incorporate the potential and modalities of providing system services in operational flexibilities and overall resilience improvements.

Wherever EnCs are set up, they will still need to transport energy to or from distances regardless of size or load density. The solution should be complementary rather than as a competitor to transmission or distribution grids; the challenge is to strike the right balance between a distributed resources system, optimising their exploitation, and the comprehensive system necessary to balance out the fluctuations of weather-dependent generation over large areas.

Sharing system costs (especially the fixed ones, asset-based) among all users of the power system in an equitable way remains to be tackled. Indeed, the shift to EnCs should never be enacted only (or mainly) to escape from system costs, which are general and must be borne, with proper splitting principles, by all electricity end users. Going beyond certain thresholds of grid independence would require an overhaul of the existing regulation and tariffication schemes. It is the same problem for system general costs, typically paid through grid tariffs and other tariff components calculated on a per kWh consumptions and a per kW connection capacity.

> ***Energy Communities*** *can* ***unlock active consumers' flexibility potential****, integrating distributed renewable resources and new technologies more effectively.*

Being a democratic entity built by the End-Users, EnCs entities should be considered reliable and trustworthy. They have great potential to mobilise customers, get them involved and actively ensure the flexibility of energy systems through the effective use of new technologies.

> *To achieve the desired maturity,* ***energy communities need to be viable by becoming reliable players*** *so that DSOs can better integrate the flexibility and other services they acquire into their processes without compromising the quality of the power supply.*

EnCs can be considered an essential player in the future customer-driven multi-energy ecosystem and enhance the roles of current key players involved in the operation of distribution networks. They bring economic, social, and environmental benefits to their members, and in doing so, they also contribute to distribution networks in the form of necessary flexibility. However, to ensure the proper functioning of the energy system, EnCs must have the same rights and obligations as other market players. Therefore, regulatory authorities must propose adequate schemes to develop and promote EnCs, considering their valuable contribution to a decarbonised energy system. A detailed organisation structure, with a description of all rules and responsibilities, and the use and business cases, would need to be developed as a next step for its development.

Another relevant aspect is the special relationship between DSOs and EnCs regarding the operation of distribution networks. IMD also mentions that Member States may grant EnCs the right to manage distribution networks in their area of operation, leading to undue operation distortion. To avoid this, it is strongly recommended that in these cases, EnCs take on the same responsibilities and obligations (such as maintenance, metering, connection, billing and licensing) as DSOs, ensuring that individual rights and obligations for consumers within the community are fully respected.

> ***Establishing a holistic functional architecture*** *considering the entire grid, customer plants and market that describes the properties of the architectural elements involved and their relationships, behaviours and dynamics, and giving multiple complementary and consistent views of the system* ***will help to develop a standardised, replicable and repeatable solution.***

The first appearance of the VPP and Microgrid concepts dates back to 2000, with VPP a little earlier and microgrids shortly afterwards. They are still being scientifically defined. The analysis shows significant technological issues with extremely ramified and complex coordination, leading to complicated and expensive solutions [30]. These technical challenges are intertwined with regulatory, market, and stakeholder issues, making the related initiatives challenging to implement and delaying EnC deployment. The *LINK* holistic architecture designed to conform to the fractality principles of the grid may be an alternative that enables effective EnC deployment and sector coupling, which is a decisive flexibility source for future power systems. This architecture helps TSOs to retain their backbone function for the electricity grid while transforming the DSOs into the hub between the TSOs and the EnCs.

The top-down approach to introducing EnCs in the energy landscape should be driven by appropriate legislation and measures to overcome grid-related challenges. However, creating and strengthening citizens' awareness is essential for developing a low-carbon social norm. This will take time, which should be considered in all implementation processes.

Recommendations on innovation and research activities

Although many successful studies have been conducted, the convergence of their results is questionable. The following roadmap is proposed to ensure convergence of R&D results and to enable the development of fully integrated EnCs.

1. Preparation and Pilot Phase

The preparation and pilot phase extends over six years. Establishing a holistic architecture enabling a comprehensive solution is crucial in this period. It is important to adapt the regulation at EU level. A European strategy/initiative that guides Member States will effectively avoid any lack of EU-level coordination that would lead to European inequalities. This stage may extend over one or two years; it aims to prepare the framework at the European level.

EnCs should be established as viable and reliable entities. Legislation should be developed to adapt the current market structure to mirror the physical flows of electricity better and incentivise its implementation. Detailed standards should be developed for creating and operating local energy markets and transparent market rules for integrating new market structures. All grid challenges described in § 3.2 should be investigated, and the appropriate countermeasures should be defined. The development of technologies is the core of this stage. Additionally, it should develop standards for technology providers and manufacturers to incorporate features envisaged from the selected architecture. Finally, in this stage, the establishment and motivation of pilot implementations as best practices through supporting structures (policy, umbrella organisations, etc.) should be promoted. Fully integrated EnCy pilots should be launched in suitable locations for proof of concepts.

Promising technical solutions that can be delivered to improve the capacity of the networks to integrate the energy communities are:

1a. Establishing a holistic architecture enabling a comprehensive solution

EnCs transform the power grid structure through the massive promotion of the DERs. The need to integrate them has brought many concepts with the most prominent VPPs and microgrids on stage. Although they have been elaborated for over twenty years, they still deliver very complex and hardly practicable solutions, neither repeatable nor scalable [86][87].

Meanwhile, the question is whether to continue with R&D with these concepts or take a pragmatic way, enabling the required power system transformation as soon as possible. In the following, we give insights into a pragmatic way to help in the fast development and implementation of fully integrated energy communities.

A study or a project should be launched to analyse and evaluate the circulating concepts or paradigms - i.e., VPP, microgrids, cellular approach, web-of-cells [88][89], and *LINK* - and architectures derived from these concepts or paradigms.

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86 A. Bose, Smart transmission grid applications and their supporting infrastruc-ture, IEEE Trans. Smart Grid 1 (June (1)) (2010) 11–19.

87 A. Ilo, "Are the Current Smart Grid Concepts Likely to Offer a Complete Smart Grid Solution?" Smart Grid and Renewable Energy Journal, Vol. 08, No. 07, 2017, pp. 252 - 263. http://dx.doi.org/10.4236/sgre.2017.87017

88 G. Kariniotakis, L. Martini, C. Caerts, H. Brunner, N. Retière. “Challenges, Innovative Architectures and Control Strategies for Future Networks: The Web-of-Cells, Fractal Grids and Other Concepts”. CIRED 2017 - 24th International Conference on Electricity Distribution, Jun 2017, Glascow, United Kingdom. pp.2149 - 2152, ff10.1049/oap-cired.2017.1287ff. ffhal-01518368f

89 L. Martini, H. Brunner, E. Rodriguez, C. Caerts, T. Strasser, G. M. Burt, “Grid of the future and the need for a decentralized control architecture: the ELECTRA Web-of-Cells concept”, 24th Int. Conf. on Electricity Distribution CIRED, Glasgow, 12-15 June 2017. https://digital-library.theiet.org/content/journals/10.1049/oap-cired.2017.0484

In the analysis and evaluation process, the following should be considered:

- The architectural concepts or paradigms must have independent, unique and timeless elements; and
- The proposed architecture should:
    - Describe comprehensively the properties of various elements involved;
    - Show relationships between different elements;
    - Detail the behaviours and dynamics of architecture's elements, ensuring the safe, reliable and feasible operation of the whole power system;
    - Give multiple views of the system (complimentary and consistent), flourishing the market and enabling the smooth deployment of EnCs and Sector Coupling being key factors for increasing the flexibility and resilience of the system;
    - Accommodate equally all actors (TSOs, DSOs, EnCs, End-Users), avoiding discrimination; and
    - Guarantee the data privacy of all actors and the cybersecurity.

Once the adequate holistic architecture has been defined, meaning the interoperability challenge to increase seamless integration and data exchange between the systems is solved, the following steps [90] will be necessary:

1.b. Solutions to mitigate grid-related challenges

All grid-related challenges must be investigated in detail, and the countermeasures needed to overcome them should be addressed holistically to guarantee their comprehensive implementation on a large scale.

- Challenges in distribution grids:
    - Violation of upper voltage limit;
    - Thermal congestion in normal and fault conditions;
    - Unintended islanding;
    - Phase Unbalances;
    - Harmonic distortions;
    - Protection system philosophy;
    - Revising the recovery planes in blackout cases;
    - Temporary self-sufficient operation of grid parts; and
    - Planning.
- Challenges on transmission grids:
    - Load-generation balancing process;
    - Load-shedding schemes need adaptations;
    - Voltage–reactive power management;
    - N -1 security calculations;
    - Impact on power system dynamics;
    - Restoration strategies from a blackout;
    - Grid protection; and
    - Change of the current market patterns.

1.c. Scalability and Replicability and Cost Benefit Analysis

The results obtained in the pilot projects (notably the measured Key Performance Indicators (KPIs) shall be used as input to perform comprehensive cost-benefit, scalability, and replicability analyses. These analyses aim to provide an ex-ante evaluation of the potential economic and technical benefits that can be obtained when the pilot projects are deployed at a larger scale or in different boundary conditions. These results are necessary to elaborate reliable business plans and discuss with the National Regulatory Agency the adaptations required to exploit the benefits of innovative solutions. The

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90 INTERACT Project, D.6.1. Roadmap for the implementation of the designed INTERACT Energy Community in general and for the specific local perspectives, January 2023. https://www.ped-interact.eu/wp-content/uploads/2023/01/D6_1_roadmap.pdf scalability and replicability analysis should include different aspects of the innovations: system architecture and the characteristics of local grids, local markets, regulatory schemes and stakeholders' characteristics.

Comprehensive methodologies to perform the cost-benefit, scalability and replicability analyses have not been fully developed so far; the Joint Research Centre [70] and the BRIDGE H2020 task force [72] have issued general guidelines that should be followed to perform these assessments.

Several projects have used these guidelines to develop project-specific approaches for conducting these analyses based on the local characteristics and the use cases implemented in each pilot project [91] [28].

2. National strategies

The stage of the National Strategies extends over one or two years: It aims to prepare the framework at the national level after the European strategy is consolidated. In this period, the specification of instructions about the roles of and within fully integrated EnC and their structures should be made. It should guarantee the legal framework and resources to deploy fully integrated EnC. At the same time, the technology and the standards developed during the first stage should be finalised. It should also enable and engage stakeholder participation through clear participation models with defined responsibilities, supported through local, trusted intermediaries, and participatory processes and capacity building at all levels. A campaign to disseminate the results and verified benefits to support the large-scale roll-out should be promoted.

3. Fast Promotion

The stage, Fast Promotion, spans five years to advance large-scale implementation of fully integrated EnCs rapidly. In this stage, local schemes and standards for the support and facilitation of EnC deployment will be established. Local electricity markets should be launched to enable EnCs to participate in the market. Regular revision of technical norms, further R&D, etc. will be promoted, facilitating the upgrade to automatically integrated technology at the customer level. Stakeholder engagement will proceed further, accompanied by adequate dissemination of the information and procedures for a large-scale roll-out of the fully integrated EnCs.

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91 I. Losa, R. C. (2016). Scalability and replicability analysis of smart grids demo projects: An overview of selected European approaches. Economics and policy of energy and the environment (2), 56-82.

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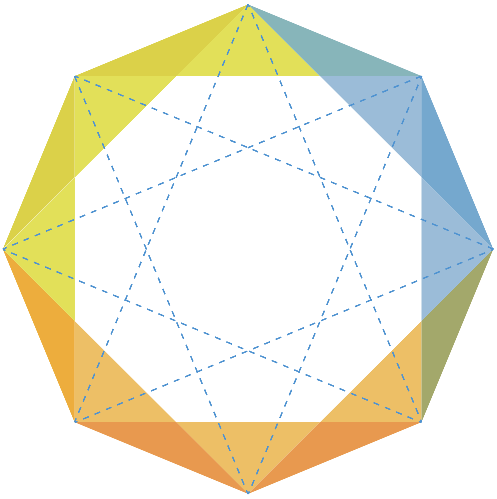

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