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Harnessing the Power of Distributed Energy Resources in Developing Countries:

What Can Be Learned from the Experiences of Global Leaders?

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Abstract

The role of distributed energy resources (DERs) in future power systems is becoming increasingly important due to the ongoing transformation of the electricity sector towards carbon neutrality and higher decentralization. As changes in the demand side continue, such as the adoption of electric vehicles (EVs) and heat pumps, and the connection of DERs to the grid by prosumers and aggregators, coordination between supply- and demand-side resources becomes more critical.

Both developed and developing countries have a strong incentive to deploy DERs. In developed countries, there is a growing demand for cleaner and more sustainable energy sources, as well as a desire to reduce dependence on centralized power grids. As renewable energy sources like solar and wind power continue to gain a larger share of the energy supply, there is a growing need for an optimized and flexible power system that can effectively manage the variability of these sources.

In developing countries, the deployment of DERs has the potential not only to reduce greenhouse gas emissions but also to improve energy access, promote energy security, and mitigate the risks associated with importing fossil fuels. This is why these economies have started to deploy growing DER volumes, particularly distributed solar, battery energy storage, and EV charging load.

Central to this paper is our exploration into the dynamics, opportunities, and challenges of implementing DERs in various energy contexts, particularly underscoring the disparities and commonalities between developed and developing regions. The principal research objective is to unearth the strategic, regulatory, and technological underpinnings that have facilitated the proliferation of DERs in pioneering regions such as Australia, the UK, Germany, and California, and subsequently, to extract actionable insights and tailored recommendations for accelerating the integration of DERs in developing countries. By analyzing the distinct pathways, policy landscapes, and outcomes realized by these frontrunner regions, we aim to distill lessons and strategies that can pragmatically be adapted and applied to the nuanced energy ecosystems prevalent in developing countries. These recommendations cover a range of areas, including end-user tariffs, network access pricing, addressing fixed system costs in the presence of decentralized resources, DER aggregation, enabling DER participation in multiple markets to maximize revenue, reforming electricity distribution utilities, and establishing coordination mechanisms between transmission and distribution system operators (DSOs). The lessons learned can inform developing countries' efforts to integrate DERs and transition to a more sustainable energy future.

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Introduction

Electricity markets are experiencing a rapid growth of DERs (also referred to as non-transmission alternatives, or NTAs, Titenberg and Lewis, 2018), owing to a combination of economic, technological, and sustainability drivers.

These decentralized energy resources are small in scale, connected to the distribution grid, and located on any side of the consumers' meter ('behind the meter' or 'in front of the meter'). Examples of different types of DER include solar photovoltaics (PV), wind generation, biomass-based generation, small-scale hydropower, reciprocating oil and diesel engines, combined heat and power (CHP), battery energy storage systems (BESSs), EV charging, demand response (DR), and combinations of such resources bundled in microgrids.[1]

In 2020, new global DER capacity additions represented already 70 per cent of new centralized generation capacity additions, while the adoption of DERs worldwide is expected to continue throughout the next decade with a global annual market value of about $352 billion by 2030 (Guidehouse Insights, 2020).[2]

The fast-paced technological adoption of distributed energy technologies by electricity consumers – largely driven by policy incentives – has led to systematic cost reductions, particularly in the case of distributed or rooftop solar PV. This has created a significant pull for the creation of DER markets in the US, Europe, Australia, and other developed economies.

However, the deployment of DERs is not just an issue of interest in developed economies. Indeed, these resources provide numerous benefits to developing and middle-income countries, including increased access to electricity, cost savings, energy security, environmental benefits, and job creation. Decentralized renewable energy systems like solar PV, small-scale hydropower, and biomass-based generation can provide cost-efficient and reliable sources of electricity to remote areas and communities, enabling economic growth, improving education, and providing healthcare services. Also, the deployment of DERs can reduce dependence on expensive imported fossil fuels and improve energy security, something of critical importance in developing countries. Furthermore, DERs can help developing countries reduce their carbon footprint as well as address local air pollution, which has become a major issue in many of these countries.

This paper reviews the emerging thinking, evolution, and implementation of new ways of integrating and coordinating demand-side resources, concentrating on countries or markets that are pushing the innovation frontier and demonstrating emerging practices and lessons relevant to emerging and developing economies. While developed nations have indeed amassed substantial experience and evolved best practices in deploying DERs, it is vital to recognize and concede the varied contexts between developing and developed countries in terms of socio-economic, technological, and infrastructural aspects. Nonetheless, this study ardently posits that fruitful lessons can still be drawn from the experiences of developed nations, specifically in the realms of policy and regulation design, grid integration, and capacity building, all of which can be adroitly adapted and tailored to the unique circumstances of developing countries.

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[1] The National Association of Regulatory Utility Commissioners (NARUC, US) adopted the following definition of Distributed Energy Resources: 'A resource sited close to customers that can provide all or some of their immediate electric and power needs and can also be used by the system to either reduce demand (such as energy efficiency) or provide supply to satisfy the energy, capacity, or ancillary service needs of the distribution grid.' (NARUC, 2019)
The Australian Energy Market Commission (AEMC) defines distributed generation as embedded or local generation when electricity is generated from either renewable or non-renewable sources near the point of use instead of centralized generation sources from power plants.
[2] Forecasts on DER growth vary, but even the most conservative estimates set cumulative new DER capacity additions in the next decade at between 50 to 66 per cent of new centralized generation capacity additions (IEA, BNEF data respectively). Guidehouse Insights expects a DER market growth of 12.8 per cent CAGR until 2030 (or a cumulative capacity exceeding 4 TW), compared with a CAGR for the addition of new centralized generation capacity of 2.2 per cent (Guidehouse Insights, 2020).

The principal contribution of this study revolves around the construction of a framework that distinctly delineates the key variables influencing the expansion and integration of DERs, with a spotlight on vital regulatory instruments that are fundamental in steering the integration of these resources at varying stages of penetration in the power sector. This framework is not only developed but also validated through a meticulous review of various case studies, thereby ensuring its robustness and applicability in a real-world context.

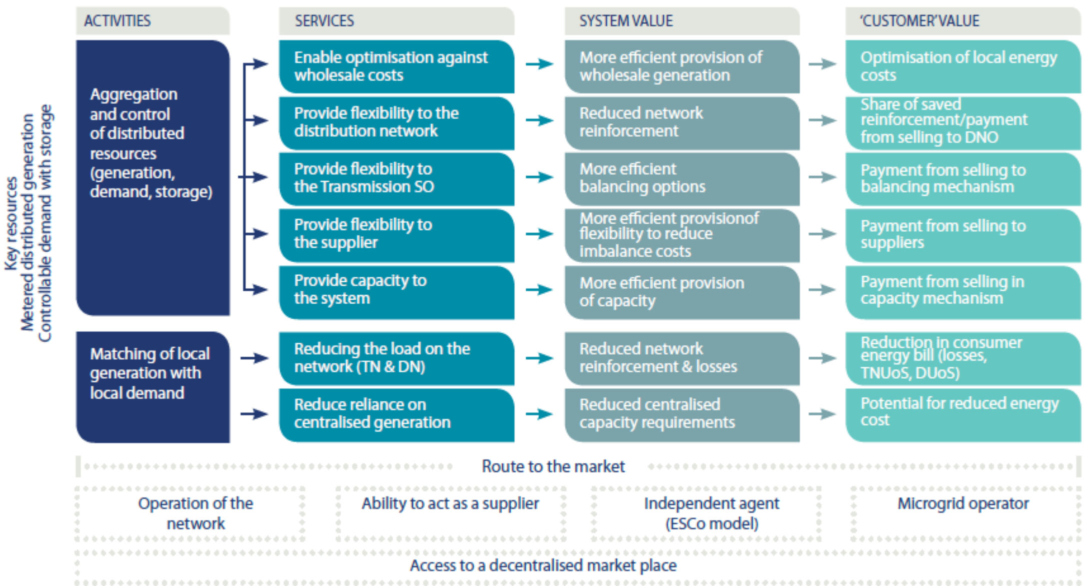
The remainder of the study is structured as follows. Section 1 provides an overview of the expanding array of evidence regarding the economics of DERs. It emphasizes the profound impact of the clean energy transition, with DERs at the forefront, on prompting further adaptations within power sector reforms. Section 2 provides an analytical framework to identify factors affecting the growth and efficient integration of DERs. We apply this framework to select frontier markets (in this case, Australia, the UK, Germany, and California) to analyze their experience, and present the results of our analysis in the appendix. Section 3 elaborates on the relevance of this experience for the future evolution of electricity systems in developing economies. The final section offers concluding remarks.

1. The value of DERs and the new wave of distribution grid-focused reforms

1.1 Emerging evidence on the value of DERs

The burgeoning significance and potential of DERs have increasingly come to light, as elucidated through emerging evidence emphasizing their valuable impact on both the power system and its consumers. DERs can confer this value via two primary modalities: through the aggregation and control of resources or the alignment of local generation with local demand, as illustrated in Figure 1 (Elexon, 2018). However, it is imperative to note that the effective execution of these functions and the realization of the associated benefits are intrinsically tied to the nuances of market design features and prevailing regulatory conditions.

Figure 1: The Distribution Value Framework



Source: ELEXON, 2018

Historically, centralized systems have been anchored in economies of scale. Nonetheless, with the decrease in the cost of renewable energy and storage units, in conjunction with the advent of more sophisticated control systems, decentralized capacities have started to emerge as economically viable alternatives (Xu, 2019). A tapestry of studies has begun to underscore the intrinsic value of DERs for the electricity system. For instance, a study sanctioned by the Maine Public Utilities Commission (US) in 2016 illuminated that a portfolio of Non-Transmission Alternatives (NTAs) was 33 per cent more cost-effective compared with the establishment of a new transmission line over a decadal period (Solar Grid LLC, 2016).

In a separate study conducted in Australia, a thorough economic analysis aimed at evaluating the efficacy of an extensive electricity network transformation to more adeptly integrate DERs revealed that the implementation of structural changes could culminate in markedly higher emissions abatement and substantially diminish costs, with anticipated savings approximating AU$101 billion until 2050, translating to around AU$3 billion annually (CSIRO, 2017). Predominantly, the cost savings were attributable to the more efficient utilization of DERs and concomitant reductions in network peak capacity investment.

Additional economic assessments at the system level have concluded that the incorporation of DER introduces net benefits, particularly when co-optimizing resources connected to both transmission and distribution grids. Notably, a recent evaluation by Vibrant Clean Energy (2020), which employed a fully integrated capacity expansion and production cost model, discovered that the inclusion of DERs could result in cumulative system-wide savings of US$301 billion by 2050, juxtaposing BAU (Business As Usual) vs. BAU-DER scenarios. Moreover, these benefits could potentially escalate to US$473 billion when instituting a 'Clean Energy Standard', which mandates a 95 per cent reduction in emissions from 1990 levels by 2050. These findings are particularly pertinent, given the paucity of modelling tools that incorporate distribution system dynamics and co-optimize supply and demand-side resources.[3]

In the US, various state-level working groups are concurrently developing and experimenting with bottom-up analytical tools to ascertain the available 'hosting capacity' of distribution circuits (termed as Integrated Capacity Analysis, ICA) and to evaluate the locational net benefit of a DER portfolio (dubbed Locational Net Benefit Analysis, LNBA) (Gridworks, 2019). A multitude of preliminary ICAs and LNBAs have begun to unveil the high potential of DERs in delivering net benefits at the circuit level. Moreover, several pilot utility solicitations (auctions) in California aiming to defer or circumvent investments in distribution infrastructure through the application of DERs have been undertaken, addressing the challenge of technical specifications and pinpointing impactful opportunities (Gridworks, 2019).

The economic impact of aggregators or Virtual Power Plants (VPPs) has also been scrutinized in recent assessments. For example, a study in South Australia revealed that for each additional 50 MW of VPP capacity integrated into the system, the wholesale price would decrease by approximately AU$3 per MWh. Consequently, a 250 MW plant could potentially reduce wholesale prices by ~AU$16 per MWh, translating to consumer savings of approximately ~AU$180 million per annum (Frontier Economics, 2018).

Building upon the established understanding of the economic value derived from DERs, the study by CRA (2017) presents an insightful case, examining the economic impact of independent demand-side aggregators (IDAs) within the UK's balancing markets. The findings showcased a substantial net economic benefit, oscillating between £110-440 million in 2020 and escalating to £160-440 million in 2030, particularly following the removal of barriers that had previously hindered IDAs from active market participation.[4]

In a parallel initiative, the UK's regulating Office of Gas and Electricity Markets (Ofgem), inaugurated a dedicated £500 million fund to bolster projects steered by Distribution Network Operators (DNOs). These projects, which aimed to explore new technologies, operational, and commercial arrangements, are anticipated to cascade benefits valued at £1.7 billion (ENA, 2017).

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[3] A description of the model can be found here: https://vibrantcleanenergy.com/wp-content/uploads/2020/08/WISdomP-Model_Description(August2020).pdf

[4] After allowing for further uncertainty in relation to the capital costs of new peaking capacity, the range widened to £100-530 million in year 2020, rising to £140-580 million in year 2030.

Intriguingly, as the costs associated with energy and digital technology recede, DERs are emerging as preferred energy alternatives in low-income economies, where difficulties in accessing grid-connected electricity are commonplace, and the impacts of suboptimal quality of service on household welfare and commercial or industrial competitiveness are notably significant (Sedai et al., 2021; Nagpal and Perez-Arriaga, 2021).

Theoretically, consumers possess the agency to transition towards alternative energy options, such as distributed energy generation and storage, becoming 'active prosumers' in response to escalating electricity bills or subpar service quality. However, it is pivotal to acknowledge that the willingness to pay for electricity access correspondingly dwindles as household income tapers (Sievert and Steinbuks, 2020).

In several lower-income economies, residential consumers, particularly those either without grid access in urban locales or those underserved by grid services, are becoming the focal point for emerging grid-edge (beneath-the-grid) solutions. These offer tailored services, amalgamating small-scale DER technologies with appliances to accommodate lower consumption and financial capacities. Such 'grid-edge' services, seen as 'pre-electrification solutions', are catering to consumers expected to subsequently transition to higher consumption levels and grid connection. Recent analyses propose that compared with retail tariffs and the costs of fuel oil or diesel-based generators, DER solutions are becoming increasingly competitive in low-income economies (Cunha, 2021).

In conclusion, an evolving repository of knowledge pertaining to the economics of DERs, as well as the associated costs and benefits to both systems and consumers, is being amassed, albeit with information that remains somewhat limited and deeply contextual. At the system level, extant evidence hints at the inherent value in co-optimizing and coordinating resources tethered to transmission and distribution grids. Meanwhile, for prosumers and DER providers, the economics of DERs are finely attuned to market conditions – such as access to wholesale markets – and the willingness and capacity of consumers to pay, juxtaposed against the quality and cost of grid services.

Indeed, the value that DERs confer to both the system and its consumers is intrinsically linked to numerous factors, including the cost and reliability of centralized electricity services, tariff and subsidy designs, the efficiency of network services, and the presence – along with the sophistication – of energy, capacity, and ancillary markets. In a pragmatic context, a fundamental concern is the capacity of DER providers (including aggregators) to 'stack' revenue through participation in a composite of markets, thereby providing a diverse array of services. This exploration into the economics of DERs unveils a multifaceted landscape, wherein the intricate interplay of various factors culminates in the realized value and effectiveness of DER utilization within distinct contexts.

1.2 New wave of distribution grid-focused reforms

The encumbrance experienced by legacy power systems and networks, ill-equipped to adjust to the burgeoning penetration of Variable Energy Resources (VER), DERs, and Inverter-Based Resources (IBR), underscores a palpable challenge amidst lacking compatible market structures, pricing frameworks, system operation models, and digitized infrastructures.

Foster and Rana (2019) encapsulate this predicament, stating: 'Existing global power markets, born from the regulatory climates of the 1990s, did not foresee the technological disruption now permeating the electricity system, especially within the distribution segment.' This nuanced issue necessitates a recalibration of regulatory models, originally crafted for one-way power flows, as two-way power transactions across multiple consumer-sited locations on distribution networks require meticulous coordination. The ensuing complexity significantly challenges traditional electricity market operations.

Five megatrends unveil a novel and rapidly transmuting environment for energy sector institutions, demanding: (i) innovative approaches to planning, operating, and regulating power systems and markets; (ii) adept monitoring and implementation of emerging technological and practical innovations; and (iii) synergistic interactions and partnerships with new energy and digital third-party service providers, such as aggregators and VPPs (World Bank, 2021b).

Li (2020) delineates the intricacies of optimizing diversified energy and flexibility resources alongside large-scale generation. The process not only provides unprecedented challenges for Transmission System Operators (TSOs) to deliver versatile, high-quality energy products but also undervalues small-scale flexibility and DERs through a centralized approach, whilst accruing significant energy balancing and security costs.

Unlike the economically driven first reform wave in the 1990s and the decarbonization-focused second wave in the 2000s (Jamasb and Llorca, 2019), the third wave magnifies its lens on the grid and utility distribution model transformation to nurture DER growth. This wave, melding with the second, engenders a unified trend, recalibrating how electricity services are operated, regulated, and delivered, particularly in a post-COVID-19 era where climate stabilization and universal energy access are pivotal to resilient rebuilding.

Regulatory bodies and system operators across various countries and jurisdictions are commencing the crafting of incentives, protocols, and market architectures essential for the integration of VERs, IBRs, and DERs. Numerous reform proposals are currently under consultation in Europe, Australia, and the US, aiming to design grid transformation roadmaps that intricately weave adjustments to market architectures, operational protocols, and legal and regulatory frameworks (CSIRO, ENA 2017; Gallagher, 2018).

Moreover, energy institutions within middle-income economies have begun exploring operational and regulatory alternatives in anticipation of the forthcoming technological wave within the distribution segment (Batlle, Rodilla, 2019). In several developing economies, the rapid proliferation of rooftop solar is beginning to surpass utility readiness, catalyzing serious considerations towards transitioning to a bidirectional distribution grid, exemplified by Vietnam's formidable addition of 9.3 GW of rooftop solar capacity by December 2020.

On the regulatory front, there is a growing body of literature and research exploring the adjustments that will be necessary to harness grid-connected DERs, ranging from time-of-use (ToU) or dynamic tariffs and locational marginal pricing to network pricing regulation and the access of newly emerging third-party service providers – such as aggregators – to energy, capacity, and ancillary markets (MIT Energy Initiative, 2016; Gomez, Burger et al, 2017, Cossent et al, 2020, Brandsttat and Poudineh, 2020; Batlle, Rodilla, 2019, Gomez, Rodilla et al. 2021).

A pivotal challenge also lies In fostering regulatory and contractual innovations, as in conceiving conditions conducive to private sector-led solutions at the grid edge, such as sandboxes and new public-private partnership formats. [5] The empirical evidence illuminating how grid transformation concepts, strategies, and notably, new market architectures that facilitate the physical and commercial coordination of DERs are developing, remains limited.

Past experiences with power sector reform spotlight that rigid models or prescriptions are seldom universally adopted, indicating multiple viable paths towards enhanced performance. Foster and Rana (2019) articulate a burgeoning sentiment: 'Future reforms should be contextually shaped, outcome-driven, and informed by alternatives.'

Undeniably, the adoption of novel technological solutions will predominantly hinge upon utilities' capacities to assimilate innovations, the introduction of apt valuation and pricing instruments, third parties and aggregators' market access, and system operators' capabilities in leveraging the value from an increasingly multifaceted set of supply- and demand-side resources. This sectoral evolution presents a convoluted yet fundamentally essential roadmap towards establishing an electricity network that is contemporaneously resilient, equitable, and innovative.

[5] Knowledge exchange on contract design and expertise will be key for developing economies to transcend to next-generation solutions.

1.3 Growth of DERs in developing countries

DERs are growing fast in developing economies, although the type, volume, and growth rates of different DERs vary significantly among countries (World Bank, 2021c).

Distributed solar generation is among the most prominent DER in developing economies, driven mainly by net metering and other pricing incentives in emerging markets. China, India, Vietnam, and Brazil are among the top ten distributed solar markets in the world, with installed capacities of 92, 16, 9.7, and 3.2 GW respectively in 2021, and CAGRs in the range of 40 to 100 per cent (Guidehouse Insights, BNEF, 2021).[6] Middle-income economies such as Pakistan, Poland, Mexico, and Turkey are also exhibiting high growth rates in this segment, all with installed capacities above 1 GW today (BNEF, 2021). And there is also an expectation that distributed generation – particularly solar – will grow very fast in the next decade in Sub-Saharan Africa, – with a CAGR of 34 per cent (BNEF, 2021).

Overall, developing countries have 49 per cent of global distributed solar capacity, which by the end of 2020 had reached about 352 GW (Guidehouse, 2021).

In distributed generation, the installation of behind-the-meter (BTM) thermal generation – in the form of diesel and natural gas-based gensets, and microturbines- mainly deployed by commercial and industrial consumers has also been quite large in the developing world. Global installed capacity reached 1.11 TW in 2020 of which 60 per cent was deployed in the developing world, concentrated in China, India, and elsewhere in Asia and MENA countries (Guidehouse, 2021). However, in India, Brazil, and Africa, gensets represent more than 20 per cent of total installed capacity, reflecting the relatively low quality of grid services in some geographic areas or jurisdictions and the need to enhance reliability. As the cost of solar PV and BESSs continues to fall, it is expected that consumers will increasingly compare the economics of these options with that of thermal gensets, particularly in oil-importing countries.

The use of distributed BESSs will grow fast in developed economies in the next 10 years (with a CAGR of 25.7 per cent, compared with a CAGR of 7 per cent in the developing world), although developing countries are expected to catch up as the cost of the technology lowers in the decade after 2030 (particularly in areas where the grid service is unreliable and/ or expensive) (Guidehouse, 2021). Recent analysis shows that the cost of solar-plus-storage is becoming increasingly competitive with gensets and grid supply in some parts of the developing world (World Bank, 2021).

A growing DER in developing economies is EV charging. BNEF (2021) estimates that India and China will increase the EV share of new passenger vehicle sales to about 30 and 70 per cent respectively in the next two decades. China in particular is a powerhouse today, with annual EV sales accounting for 60 per cent of total global annual sales expected in 2021, and more than 500 hundred thousand public charging connectors (BNEF, 2021). Deployment of two-wheelers in terms of volume is also dominated by China, but they will also grow fast in India, Pakistan, Vietnam, Indonesia, Thailand, and the Philippines (BNEF, 2021).

Before the COVID-19 crisis hit the world, the IEA estimated that air conditioning demand in the hottest parts of the world would triple by 2050 (IEA, 2019b). In its most recent analysis (net zero by 2050 scenario), the IEA estimates that 'demand for appliances and cooling equipment will continue to grow, especially in emerging market and developing economies where 650 million air conditioners are added by 2030 and another 2 billion by 2050' (IEA, 2021).

These DER types, solar and thermal distributed generation, solar-plus-storage, EV charging load, and air conditioning load are expected to grow fast in developing economies, and will necessarily require systematic preparation by energy sector institutions to control, manage, and derive value – demand-side flexibility – from this increasing activity (both front-of-the-meter, FOM, and BTM).

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[6] In Brazil, the so-called solar roofs and wind microgeneration installed in buildings (condominiums) has been growing substantially in recent years (under different business models supported by net metering incentives) (Ramos, Del Carpio, Filho and Tolmasquim, 2020).

While presenting a novel pathway towards a decentralized and sustainable energy future, DERs usher in an intricate web of technical, economic, and regulatory challenges, especially profound in developing countries. The accelerated growth in DERs, notably in distributed solar generation and other resources like BESSs has been primarily fuelled by pricing incentives, technological advancements, and a surge in demand for affordable reliable energy sources. However, the intricacies of assimilating these resources into the existing power systems and regulatory frameworks of developing nations warrant meticulous exploration and strategic mitigation.

Technically, the integration of DERs, especially at high penetration levels, necessitates robust, smart grid infrastructures capable of managing the bi-directional flow of electricity and data, ensuring stability amid the variable nature of distributed resources like solar and wind. A fundamental challenge in developing countries pertains to their existing grid infrastructures, which often lack the requisite resilience and technological sophistication to accommodate a substantial influx of DERs. Moreover, the variability and intermittency of certain DERs, such as solar and wind energy, could pose stability and reliability challenges, especially in regions with already fragile grid networks. Economically, while DERs offer the potential for reduced energy costs and enhanced energy access, the initial investment for technologies and grid upgrades, as well as the potential for tariff imbalances, highlight the need for sound financial strategies and equitable economic policies. Regulatory frameworks, on the other hand, are pivotal in orchestrating a conducive environment for DER integration, necessitating adaptations to accommodate the distinct characteristics and challenges posed by these resources.

Therefore, developing countries must astutely navigate the complexities brought forth by technological advancements and evolving energy markets, strategically leveraging their intrinsic socio-economic and geopolitical landscapes to carve out an energy future that is not merely sustainable and decentralized, but also steadfast, equitable, and inclusive. Central to this endeavour is the imperative to devise adept market and regulatory instruments, as these become the linchpin to seamlessly coordinate the commercial and physical integration of DERs within their power systems.

2. Promotion and integration of DERs: an analytical framework

This section unfolds a framework formulated to champion and weave DERs seamlessly into the electricity system. The realization of this objective is anchored in five pivotal domains: support policies, governance, technology, regulation, and market, all of which serve as essential fulcrums propelling the expansion of DERs. Additionally, the integration of DERs into the energy system is depicted through three illustrative stages, with each one spotlighting key regulatory and market tools essential for the adept coordination of both the physical and commercial operations of these resources.

2.1 Overarching policies to enable the growth of DERs

To enable the growth of DERs, a comprehensive set of capabilities is required, encompassing technical, institutional, regulatory, policy, and market aspects (see Figure 2). We have identified five key pillars for supporting a vibrant DER sector, namely support policies, governance, technology, regulation, and market.

Support policies are crucial not only for providing guidance to the DER sector but also for nurturing the industry during its early stages of development. These policies also play a vital role in enabling consumer participation in the power system, either individually or through energy communities. As the sector matures, the reliance on support policies gradually diminishes.

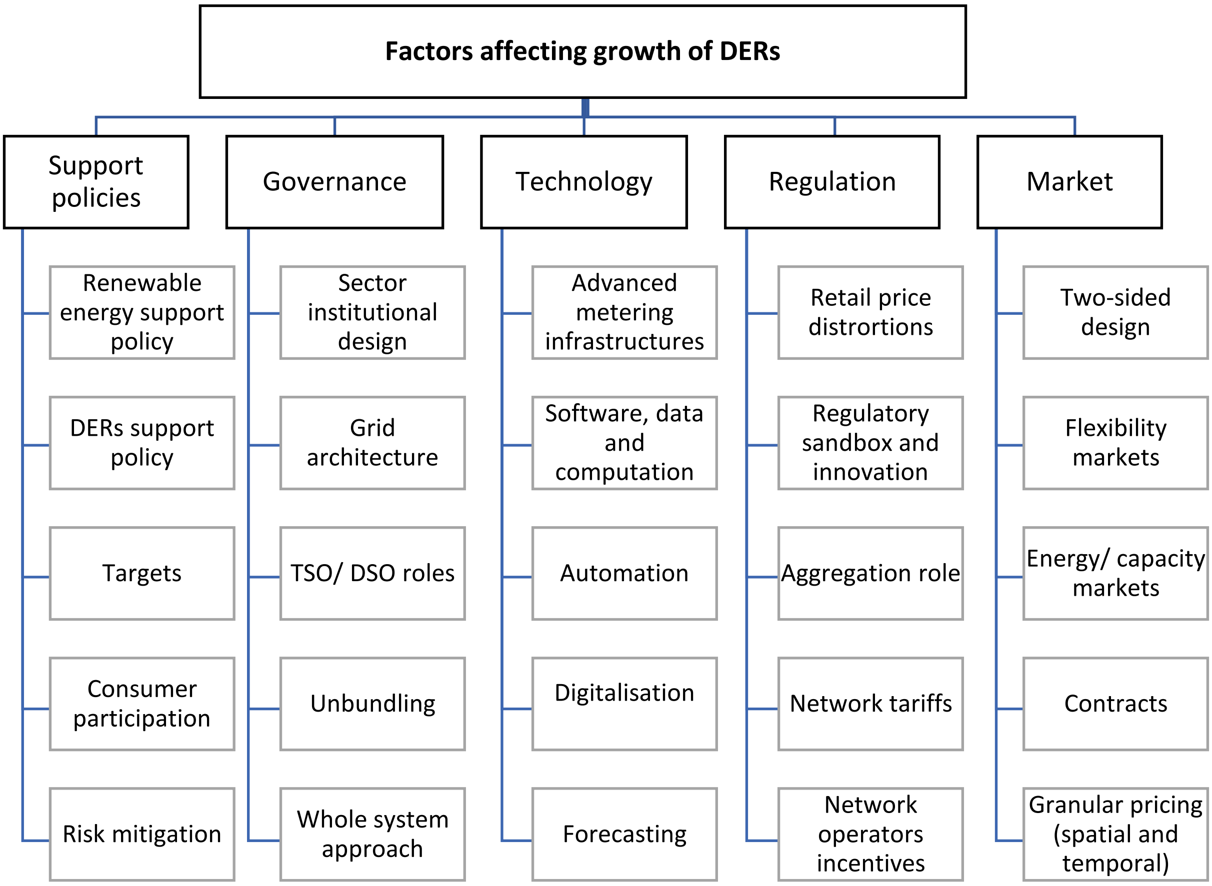
Effective governance of the electricity industry encompasses multiple components, including institutional design, grid architecture, the roles of TSOs and DSOs, as well as considerations like unbundling and comprehensive system planning and operation. Well-designed governance is essential for achieving the efficient integration of DERs, particularly as their penetration levels increase.

Enhancing the technological aspects of electricity system operation is a critical requirement for integrating DERs. This involves deploying advanced metering infrastructures, software, and computational capabilities, as well as digitalization and forecasting tools. Accurate forecasting is particularly important for distributed resources like solar PV and wind power, as it helps identify potential effects on system constraints and other operational challenges, whereas controllable resources like electric storage require effective control mechanisms.

Regulation plays a pivotal role in facilitating the uptake of DERs. It encompasses various areas such as retail price structure and level, establishing a level playing field for all resources (including emerging players like aggregators), incentivizing transmission and DNOs to consider non-wire solutions, and promoting regulatory sandboxes and innovation.

Market design is crucial for enabling the integration of DERs at higher penetration levels. Energy, capacity, and flexibility markets serve as platforms that incentivize investments in DERs. Contracts also hold significance in this context. To encourage the efficient siting and operation of DERs, pricing mechanisms should exhibit spatial and temporal granularity within the framework of a two-sided market. A two-sided market allows direct interaction between supply and demand resources through an intermediary or platform, thereby enhancing power system flexibility, efficiency, and reliability.

Figure 2: Factors affecting the growth of DERs

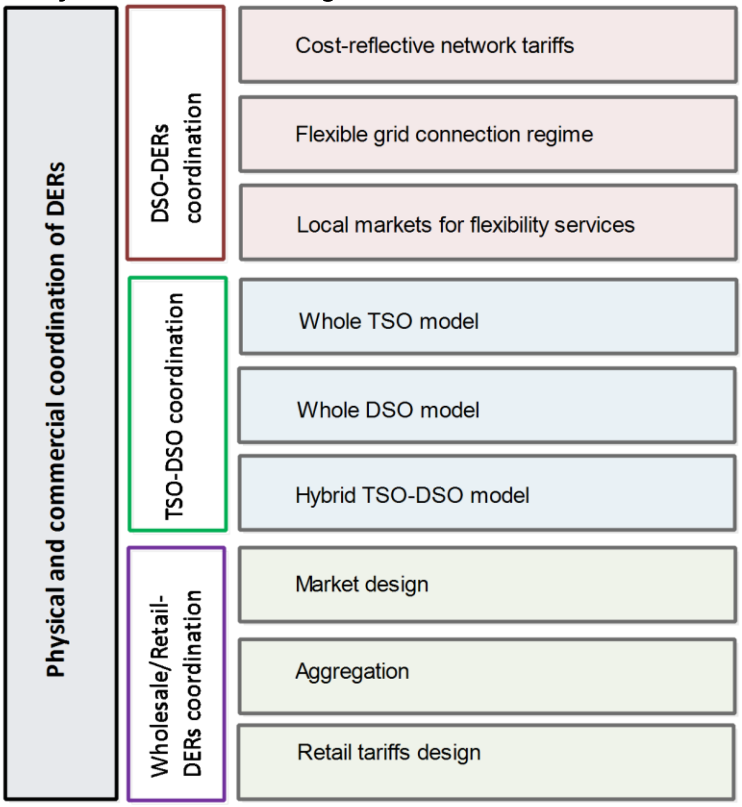


Source: Authors

2.2 Key regulatory instruments to enable integration of DERs

The integration of DERs in the electricity system involves implementing measures that streamline the commercial and physical coordination of these resources, thereby creating value for both the system and resource owners. This coordination encompasses activities at three distinct levels: between distribution networks and DERs, between TSOs and DSOs, and between wholesale/ retail entities and DERs. To enable effective coordination at each level, a comprehensive set of regulatory instruments is required.

Figure 3: key regulatory instruments to integrate DERs



Source: Authors

2.2.1 DSO-DERs coordination

Distribution networks serve as the primary interface for the integration of DERs within the electricity system. To ensure the smooth operation of DERs alongside distribution networks, three key regulatory instruments are necessary.

The first regulatory instrument pertains to network tariffs, which play a crucial role in addressing distribution network issues (Poudineh, 2022). These tariffs should not only recover network expenses but also incentivize the efficient utilization of the grid in both the short and long term. Currently, network tariffs in most countries are often combined with retail tariffs and expressed in volumetric terms. While this aligns with the energy-based nature of commodity electricity, it fails to reflect the actual usage of the distribution grid. Some nations have initiated tariff reforms that incorporate fixed components to recover previous investments and peak-demand-dependent components to account for future network investments (Meeus et al., 2022). These measures improve cost reflectivity, but it's important to acknowledge that designing perfect network tariffs is challenging due to limited information on end-users' willingness to pay, and the influence of equity considerations and historical cost models on pricing efficiency.

The second regulatory instrument involves implementing a flexible grid connection regime. Traditionally, network operators grant firm access to consumers and generators, allowing them to withdraw or inject electricity into the grid within the capacity limits. While firm access simplifies real-time management, it can result in inefficient capacity allocation and delay grid connection for new plants or loads due to conservative criteria. With the rapid growth of DERs, a more efficient and agile grid connection regime is necessary. A flexible grid connection approach relaxes certain access conditions, empowering grid operators to manage end-users' consumption or injection. In return, end-users may receive remuneration, reduced connection fees, faster connections, or the right to connect instead of rejection.

The final regulatory instrument involves the establishment of local flexibility markets, specifically tailored to leverage the services of DERs in addressing distribution grid issues. These markets operate at the local distribution network level and differ from flexibility markets managed by TSOs or those traded in wholesale and ancillary service markets. Typically, DSOs do not account for the flexibility services offered by DERs, such as distributed generation, demand response, or storage operators, to mitigate network congestion. Local flexibility market mechanisms provide a means for accessing DER services, employing strategies like long-term auctions, short-term markets, bilateral agreements, and regulated payments. Several European countries, including the UK, Germany, the Netherlands, Sweden, and Norway, have already implemented such mechanisms (Gómez et al., 2020). However, the design and execution of these local flexibility market mechanisms present challenges such as optimizing DSOs' access to flexibility services, standardizing flexibility products, evaluating aggregation feasibility, managing network topologies and potential competition, and establishing coordination between TSOs and DSOs (Gómez et al., 2020).

2.2.2 TSO-DSO coordination (grid architecture)

The efficient integration of DERs requires a coordination framework between the TSO and the DSO. The current operational paradigm of the power system presents challenges for both entities due to the increasing growth of DERs and decentralization.

For the TSO, several key issues arise. First, there is a lack of visibility over DERs, making it difficult to monitor and manage their impact on the system. Second, the response of these resources to TSO dispatch signals is unpredictable, leading to uncertainties in system operation. Additionally, forecast errors can occur at the interchange areas between the transmission and distribution interface. Finally, the long-term growth scenarios of DERs are often not considered in transmission planning, introducing inefficiency in TSO operations.

Similarly, DSOs face challenges in adjusting the output of DERs to maintain grid reliability. They also encounter the same unpredictability in the response of DERs to dispatch signals. Moreover, the lack of consideration for long-term growth scenarios of DERs in distribution grid planning adds further complexity to their operations. These challenges have resulted in the limited utilization of DERs as service providers in the power system.

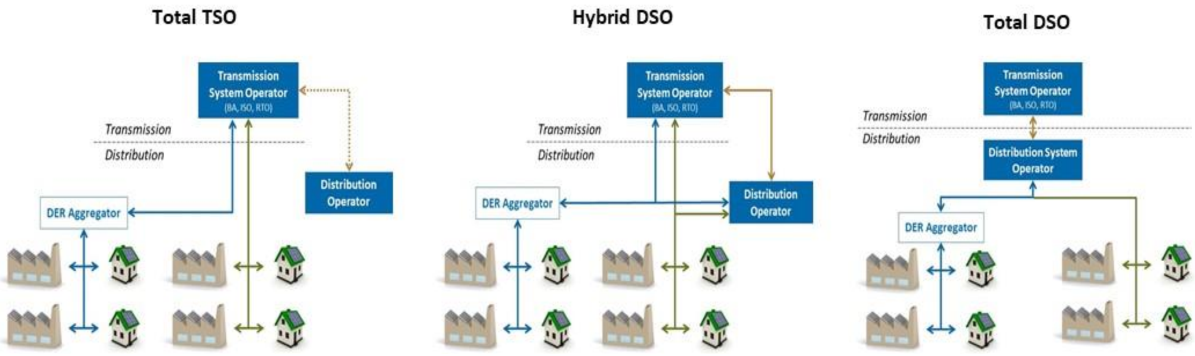
In terms of coordination frameworks between TSOs and DSOs, three stylized models exist (Figure 4). The first model involves the TSO optimizing the entire power system, including the coordination of dispatch for all DERs connected to the distribution system. Aggregators or larger customers connected directly to the distribution networks coordinate with the TSO, bypassing the DSO. In this model, the role of the DSO is to ensure the reliable operation of the distribution network and provide visibility to the TSO.

Conversely, the total DSO model entails the TSO optimizing the bulk power system while observing a single aggregate or virtual resource at each transmission-distribution interface overseen by the DSO. The DSO's task in this model is to coordinate and aggregate all DER services into a single resource at the transmission-distribution interface and in the wholesale market. Aggregators or large customers connected to the distribution grid coordinate exclusively with the DSO, without an operational interface with the TSO.

The hybrid model lies between these two extremes. The TSO is responsible for optimizing the bulk power system as well as all DER resources participating in the wholesale market. The DSO is responsible for optimizing the distribution system and coordinating the dispatch of all distribution-level distributed energy services in coordination with the TSO. In this model, aggregators or large customers coordinate with both the TSO and the DSO.

It's important to note that these models can be combined in various ways, resulting in numerous possible coordination frameworks between TSOs and DSOs.

Figure 4: TSO-DSO coordination models



Source: Kristov et al. (2019)

Note: 'BA' refers to 'Balancing Authorities', 'ISO' refers to 'Independent System Operator' and 'RTO' refers to 'Regional Transmission Organization'. Aggregators combine DERs to operate as a single entity, or VPP, in power or service markets (Kristov et al, 2019).

2.2.3 Wholesale/ retail-DERs coordination

The integration of Distributed Energy Resources (DERs) with wholesale/ retail markets requires the design of effective market arrangements, particularly for the procurement of ancillary services. Barriers to the aggregation of smaller DERs must also be addressed, along with the development of efficient retail tariffs.

Ancillary services are essential for ensuring the reliable and secure operation of the electricity system. They encompass real power services for frequency control, reactive power services for voltage control, and system restoration services for recovering the power system, such as in a black start situation. Balancing markets, typically operated by the TSO), facilitate the provision of ancillary services in many markets, with different markets dedicated to specific services or products. These markets function as monopsonies, where the TSO is the sole buyer, while potential sellers, including DERs, are numerous. To enhance market efficiency and provide additional revenue streams for DERs, barriers to their participation in ancillary service markets need to be eliminated.

To participate in ancillary service markets, resources must meet the requirements set by system operators. Traditionally, these requirements were based on technical properties of thermal generation, which can be considered restrictive in today's power systems. In some developed countries, certain types of DERs, such as demand response, have already started participating in ancillary service markets for contingency reserve and frequency response. The goal is to eventually include all types of DERs in these markets. Removing entry barriers for DER participation is crucial, not only through rules and regulations for eligible products, but also by facilitating the technical capabilities that enable the aggregation of smaller resources.

Aggregation plays a vital role in integrating DERs into the power system, both as a technical capability and a business model. By bundling and controlling distributed assets owned by customers in real-time, aggregators create VPPs capable of offering various services to the electricity system, including the wholesale market, retail market, and power grid. From an operational perspective, VPPs share similarities with conventional power plants and can reduce the need for investments in such plants and network capacity.

In liberalized and competitive electricity sectors, aggregators are typically retailers or independent entities. However, in developing countries, DNOs may also act as aggregators. This arrangement presents challenges as DNOs may lack the incentive and technical expertise to engage efficiently in aggregation efforts. DNOs may be disincentivized by the fact that aggregating DERs reduces the demand for additional infrastructure investments that generate returns for electricity networks. While a competitive market with independent aggregators can enhance efficiency, the direct involvement of DNOs in aggregation can result in better coordination between DER outputs and network conditions. Regulators in developing countries must choose the optimal market structure for aggregation, considering the balance between competition and coordination and the net benefits of each potential model.

Retail electricity prices play a crucial role in coordinating DER activities. They serve as the most important signal received by owners of existing assets and potential investors in future distributed assets. Efficient retail tariffs not only differentiate prices based on time but also location to reflect grid losses and congestion. When consumers respond to such tariffs, adjusting their electricity withdrawal or feed-in based on when and where it happens, it can lead to efficient DER operation and investment. Additionally, this coordination of consumer and producer actions can significantly reduce the need for curtailment of variable generation, such as solar and wind.

Theoretically, the first-best solution for coordinating DER activities is locational marginal pricing (LMP) with appropriate temporal resolution. However, implementing such a pricing mechanism at the distribution level can be challenging due to complexity and equity concerns. There are alternatives that tend to simplify pricing and control mechanisms, providing either broader or decentralized signals to manage DER activities, without necessarily targeting optimal grid conditions. For example, dynamic pricing aligns more closely with LMP by varying prices in real-time or near real-time but typically lacks the locational aspect. It responds to system conditions (for example, high wholesale market prices) but doesn't address local grid constraints. Also, capacity-based pricing charges are based on peak demand, without location specificity. It motivates customers to manage their peak consumption, potentially alleviating stress on the grid without needing intricate locational pricing. Network tariffs, structured to incentivize particular behaviours (for example, peak demand reduction), provide an overarching pricing framework that may lack the dynamic and locational specificity of LMP. Overall, each approach has its own merits and challenges, and the suitability of an approach depends on the specific conditions, objectives, and capabilities of a given electricity system. Some systems may employ a mix of these strategies to balance complexity, equity, and efficiency in coordinating DER activities.

2.3 Three phases of penetration of DERs and corresponding integration instruments

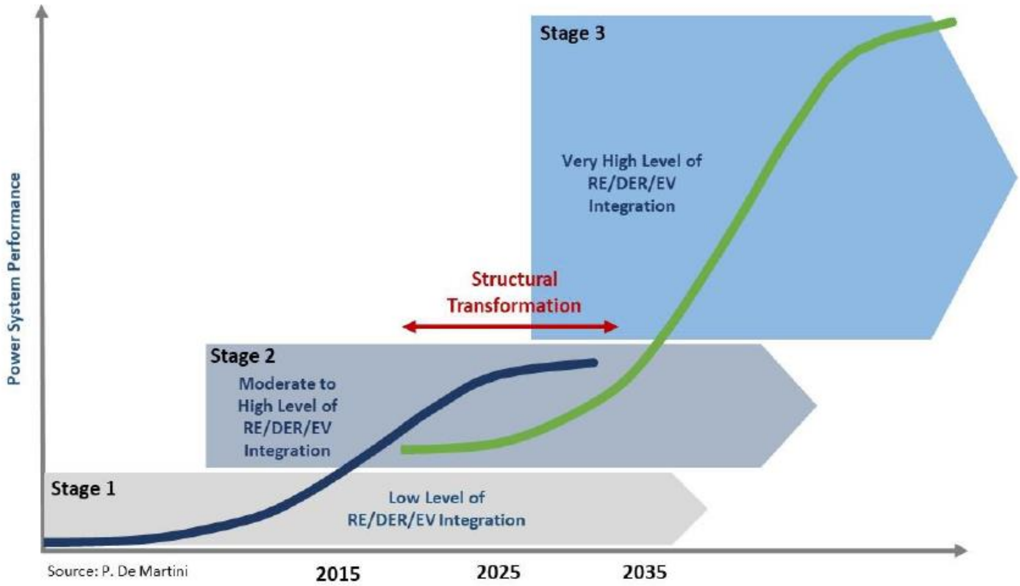
The integration of DERs into the power system occurs gradually in distinct phases rather than all at once. De Martini (2021) has presented an S-shaped curve to illustrate the expected phases in the structural evolution of power systems, similar to the transition observed in the telephony industry from feature phones to smartphones (refer to Figure 5 below). Based on the figure, three distinct stages of DER deployment can be identified.

In the first stage, DER penetration is low, primarily adopted by larger end-users such as commercial and industrial customers, focusing mainly on on-site generation or storage.

The second stage involves a wider adoption of DERs, with a large number of users including smaller residential customers in areas with abundant resources, higher electricity prices, or favourable policy support. This stage is also characterized by an increased presence of EVs and charging infrastructure.

The third and final stage is characterized by widespread DER adoption across all regions and user types.

Figure 5: Electric Industry Structural Evolution



Source: De Martini, (2021)

In regions with a low level of DER penetration, the integration of these resources into the electricity system does not pose significant challenges. However, as countries and jurisdictions experience high growth rates of DERs, it becomes crucial to develop new institutional frameworks, incentives, and grid architectures to ensure the efficient coordination of these resources, both physically and commercially. This is particularly relevant in the transition to stages 2 and 3 of variable renewable energy (VRE), DERs, and integrated battery resources penetration, where market design, regulatory frameworks, information and communications technology (ICT) infrastructures, and grid architecture become important considerations. Grid architecture encompasses both the organizational structure of the institutional setup governing the grid and wholesale market operations, as well as the functions of different institutions responsible for managing different geographic areas and voltage levels.

Based on these considerations, we define three levels of DER integration, corresponding to specific stages of DER penetration as illustrated in Figure 5, and requiring different levels of technological, regulatory, and market sophistication. These levels are summarized in Table 1.

Stage 1 represents the initial level of integration, characterized by low DER uptake, primarily through on-site generation by larger consumers aiming to reduce costs or enhance the reliability of their electricity supply. At this stage, the system does not encounter significant integration challenges. The focus of the first level of integration is to incentivize owners/operators of DERs to align their facility operations with the needs of the grid (as in reducing congestion) and electricity markets (for example, balancing supply and demand). This level involves implementing price-based or incentive-based programs to encourage end users to passively or actively modify their consumption or generation patterns.

Stage 2 corresponds to a higher level of DER penetration, with a larger number of smaller consumers adopting decentralized resources such as rooftop solar PV and EVs. This stage is observed in areas with abundant resources, higher electricity prices, or favourable policy support. As a result, the power system is expected to face greater technical challenges, particularly on the distribution side, including reverse power flow, congestion, voltage, and reactive power issues. Stage 2 represents the second level of DER integration, which introduces aggregators in addition to the pricing and incentive-based mechanisms used for larger consumers in stage 1. Aggregation involves grouping DERs owned by smaller electricity customers to act as a single entity on their behalf. An appropriate market design, such as the presence of ancillary service markets in which aggregators can participate, is crucial at this stage. Aggregators can provide real-time resources from the aggregated DERs to participate in the ancillary service market. Furthermore, a coordination framework between TSOs and DSOs is necessary.

Stage 3 represents a mature phase of DER spread, where these resources are adopted by all types of users in all regions and are less reliant on policy support, driven primarily by the market. This stage requires advanced operational tools in addition to the regulatory instruments introduced in levels 1 and 2 of integration. It necessitates an effective grid access regime and the introduction of local markets for flexibility services. DSOs play a more active role in coordinating DERs and utilizing them to optimize power system operation at this stage. Table 1 provides a summary of the specifications for each stage of DER integration.

Table 1: Stages of penetration of DERs, integration level, and corresponding regulatory instruments

Stages	DERs penetration and key features	Integration level and regulatory instruments
Stage 1	• Low level of penetration, • Adopted mainly by large consumers for the purpose of improving reliability and/or lowering electricity bills • No significant challenges to integrate DERs, • Mainly of on-site generation or storage	Level 1 integration • An effective retail tariff design includes components that incentivize efficient behaviour among network users. One approach is the implementation of a ToU tariff combined with a peak-coincident capacity charge. This tariff structure encourages users to adjust their electricity consumption or generation patterns during peak times by offering financial incentives, which can be either positive or negative depending on whether they withdraw or feed-in electricity. • Another option is to implement an incentive-based program where larger DERs are contracted to adjust their output in response to the condition of the system. This approach ensures that the output of these DERs can be modified to align with the needs of the overall power system.
Stage 2	• Higher level of penetration with lots of smaller consumers adopting DERs such as rooftop solar PV or EVs. • DERs adopted by a large number of smaller consumers in areas with abundant resources, higher electricity prices, or favourable policy support. • Higher level of system challenges specifically on the distribution side, due to reverse power flow, congestion, voltage, and reactive power issues.	Level 2 integration • In addition to price and incentive-based schemes in level one, level two introduces the concept of aggregators. • At this level, an efficient market design is crucial, including the establishment of markets for ancillary services that allow DERs to participate through aggregators. At this level, the implementation of an effective coordination framework between TSOs and DSOs is also essential.

Stage 3	• Widespread adoption of DERs by both large and small consumers • The spread of DERs across all regions and consumer types.	Level 3 integration • In addition to the regulatory instruments mentioned in levels 1 and 2, at this stage, there is a need for a more effective grid access regime and the introduction of local markets for flexibility services. A flexible grid access regime can be offered as part of the grid connection conditions. Local markets for flexibility services can be established to procure the services of DERs, addressing grid constraint issues effectively.

Source: Authors

It is important to note that the relationship between different stages of DER penetration and levels of integration is not necessarily one-to-one. In some countries, despite having a high penetration of DERs, the regulatory instruments in place (as mentioned in Table 1) may still be considered inadequate or insufficient for their stage of DERs penetration. On the other hand, a country employing sophisticated integration techniques and regulatory instruments does not necessarily indicate a high level of DERs penetration. Integration instruments can be applied on a smaller scale in preparation for future DERs growth, allowing for the learning experience of adopting new approaches and techniques in optimizing the operation of the power system.

3. Lessons for developing countries

Utilizing the previously detailed framework, we have meticulously examined case studies from Australia, the UK, Germany, and California. Recognized as forerunners in establishing and progressively refining next-generation grid architectures, these regions have been instrumental in seamlessly integrating DERs into their electrical grids. Notably, these jurisdictions find themselves ensconced within either the second or third stage of DERs penetration, presenting an invaluable opportunity for analysis.

Australia, the UK, Germany, and California have witnessed substantial DER adoption, with consumer demographics skewing towards a growing endorsement of technologies such as rooftop solar PV systems, BESSs, and EVs. Furthermore, the successful implementation of policies that underscore DER adoption in these regions has ushered in a spectrum of system challenges on the distribution grid, notably encompassing issues of reverse power flow, congestion, and voltage and reactive power management. As such, these regions stand out as exemplary case studies, offering insights into both the challenges encountered, and the best practices honed in response.

Our exploration into these case studies illuminates several focal experiences, which include:

i) The coordination dynamics between DSOs and DERs.

ii) Emerging trends in the architectural relationships between TSOs and DSOs.

iii) Coordination strategies employed between wholesale/ retail entities and DERs, alongside the incorporation of operational and regulatory innovations to amplify the value of DERs and stimulate the establishment of two-sided markets.

The results deriving from these case studies have been compiled and are presented across Tables A1 to A4 within the Appendix.

As we pivot our focus towards developing countries, this section intricately sifts through the amassed learnings, distilling applicable lessons and strategies from the aforementioned case studies. The aim is to extract actionable insights that can be judiciously applied to catalyze and navigate the nuanced pathway of DER integration within developing nations, cognizant of their unique challenges and opportunities.

3.1 Different contexts

The technical, institutional, governance, and policy contexts in which DERs are deployed in developing countries are often more complex and challenging than in developed countries.

First, developing countries may have less developed power grids and less reliable power generation infrastructure than developed countries. They may also have less access to the latest technologies and expertise in DERs. Therefore, the technical challenges of deploying DERs may be greater in developing countries, particularly in rural areas where infrastructure is often poor.

Second, the institutional landscape in developing countries is often less mature, with less established regulatory frameworks and less transparent decision-making processes. In some cases, this may create barriers to deploying DERs, particularly when it comes to connecting them to the grid and integrating them with existing power systems.

Third, developing countries may have weaker governance structures and less capacity to enforce regulations than developed countries. This can create challenges in ensuring that DER projects are implemented and managed effectively, and that the benefits of DERs are distributed fairly.

Fourth, the policy context in developing countries may differ significantly from that of developed countries. For example, many developing countries have a strong focus on increasing access to electricity and reducing energy poverty, which may require different policy approaches than those focused on reducing carbon emissions. Additionally, developing countries may have fewer financial resources to support DER deployment, which may require different financing mechanisms and incentives.

The stage of liberalization of the electricity sector can also impact the deployment of DERs in both developed and developing countries. In liberalized markets, DERs may have more opportunities to participate in the market and sell their electricity, while in monopolistic markets, the lack of competition and innovation may make it more difficult for DERs to enter the market.

In many developed countries, the electricity sector has been liberalized, meaning that private companies are allowed to generate, distribute, and sell electricity. This has led to increased competition, improved efficiency, and a greater role for market forces in the sector. Liberalization has also opened up opportunities for DERs, as independent power producers and other market actors can participate in the electricity system and sell their electricity to consumers.

In contrast, many developing countries have traditionally had state-owned utilities that have monopolized the electricity sector. This can make it more difficult for DERs to enter the market, as these utilities may not have the incentives or the expertise to integrate DERs into the grid or to allow for third-party participation in the sector. Although many developing countries have begun to liberalize their electricity sectors in recent years, which could create new opportunities for DERs, this process is far from complete.

In many cases, distribution utilities in developing countries are still bundled and operate as regulated monopolies. This means that they have a guaranteed rate of return on their investments in infrastructure and other assets, which can make it difficult for DERs to compete on cost. Additionally, utilities may be hesitant to invest in DERs, as they may see them as a threat to their traditional business model. Also, the financial viability of utility companies in some developing countries may be under threat because of inefficiency, poor management, and subsidized tariffs, among other concerns.

Despite the challenges, the potential benefits of DERs, such as increased access to electricity, reduced reliance on fossil fuels, and improved energy security, have proved them to be worthwhile for policymakers and energy practitioners in these countries to pursue.

3.2 Key lessons for developing countries

Although as mentioned the contexts of the power sectors in developing and developed countries are different, the experiences of the developed world provide valuable insights for developing countries to promote and integrate DERs.

Firstly, developed countries have often been leaders in the development of DERs, and have gained significant experience in designing and deploying these technologies. This knowledge can be transferred to developing countries through technical assistance programs, training workshops, and other capacity-building initiatives.

Secondly, developed countries have often gone through a process of trial and error when it comes to deploying DERs, and have identified best practices and lessons learned along the way. This knowledge can be shared with developing countries to help them avoid common pitfalls and ensure the successful deployment of DERs.

Thirdly, developed countries are often at the forefront of innovation in DER technologies, and may have access to the latest advancements in areas such as the integration of solar PVs, battery storage, and smart grid technology. Developing countries can benefit from these innovations by adopting the latest technologies and using them to leapfrog traditional grid infrastructure.

Fourthly, developed countries have also developed innovative policy frameworks to support the deployment of DERs. Developing countries can learn from these policies and adapt them to their own contexts, creating a more supportive environment for DER deployment.

In what follows we provide ten lessons from the experience of pioneering markets which can help developing countries to integrate DERs in an efficient manner (Table 2). We follow the same framework as applied to the case studies to highlight lessons learned for each category of coordination from the review of international experience.

Table 2: Coordination area and lessons learned from the international experience

Coordination area	**Lessons learned from the international experience**
DSO-DERs coordination	• Aligning the incentives of distribution network companies with the growth and seamless integration of DERs. • Providing incentives for distribution network companies to enhance their cost and technical performance, as well as invest in digitization and grid modernization. • Equity considerations, load and grid defections, and the risk of utility death spiral become important as DERs grow.
TSO-DSO coordination	• A framework of coordination between transmission and distribution system operators is needed.
Wholesale/ Retail-DERs coordination	• Time of use (ToU) tariffs for withdrawal from and injection to the grid. • Barriers to aggregation need to be removed. • Removing pricing distortions, designing efficient retail tariffs to incentivize efficient

	behaviours, and enabling the efficient growth of decentralization. • Removing barriers to the participation of DERs in multiple markets (including ancillary services market) and stacking revenue.
Choice of regulatory instruments	• Applying regulatory instruments for integration of DERs proportional to their stage of penetration. • Incentives for DER deployment: prioritizing cost-efficiency and comprehensive system considerations.

Source: Authors

3.2.1 DSO-DERs coordination

Lesson 1: Aligning the incentives of distribution network companies with the growth and seamless integration of DERs.

The promotion and integration of DERs rely heavily on the presence of an appropriate institutional framework and governance structure within the distribution networks. Failing to adequately prepare energy sector institutions, particularly unbundled distribution companies, to effectively manage and leverage the value of DERs poses a risk of disruption at the grid edge.

In developed economies, the restructuring efforts of the 1990s led to the separation of the generation segment, which can be competitive, from the transmission and distribution networks, which are considered natural monopolies. For instance, in the UK, electricity distribution is legally and functionally separated from generation, transmission, and retail. Australia followed a similar model, unbundling vertically integrated utilities into distinct entities for generation, transmission, distribution, and retail. Horizontal restructuring and privatization were subsequently introduced to foster competition in the generation and retail segments. The unbundling process is also mandated by the European Union (EU) as part of the regulation for a single electricity market, which member states must adhere to.

The absence of an appropriate form of unbundling makes it challenging to incentivize distribution network companies to integrate DERs. In many developing countries, distribution companies' scope of activities often encompass both network operations and electricity retailing (Poudineh et al., 2021). Consequently, distribution networks in these countries do not stand to benefit from the proliferation of end-user-owned DERs, creating a strong incentive for them to impede their adoption. Moreover, the lack of unbundling can hinder the emergence of innovative business models in the retail segment, as well as hinder the effective integration of DERs into the power system.

A notable example where this issue has created problems for DERs is India. In India, distribution networks are still bundled, with both network and retail functions being performed by the distribution utility. The predicament arises from the fact that distribution utilities rely on energy sales to generate revenue, leading to a misalignment of their economic interests (Poudineh et al., 2021). Essentially, by approving each grid-connected distributed resource, distribution networks are approving a loss of revenue for themselves. Therefore, it is crucial to align the interests of distribution utilities and DERs in order to incentivize the integration of these resources by distribution networks.

Fortunately, this issue is now being recognized, and measures are being taken in India. Private distribution company Tata Power, for example, is implementing 'green' solar-based microgrid projects to support rural industrial and commercial consumers. Initially focusing on 10,000 microgrids, equivalent to approximately 300 MW, the company is exploring the displacement of existing grid lines instead of providing only a temporary solution until the grid is deployed (BNEF, 2021). The cost of electricity from microgrids in this context is approximately 20 per cent less than that of diesel power. For commercial and industrial users in certain rural areas, where diesel power is the only alternative apart from microgrids, this provides a significant advantage. Additionally, in remote areas with dense forests or located on the coast, it is more cost-effective for Tata Power to maintain microgrids instead of power lines spanning long distances. Distribution utilities in Australia and California are also increasingly deploying fringe-of-grid microgrids as a resilience measure and to better serve consumers under their jurisdiction. These examples demonstrate that distribution utilities can deploy DERs in innovative ways to maintain their consumer base while preventing disintermediation and revenue loss.

In the long term, developing countries need to consider the unbundling of distribution networks, as it allows for fair competition among different parties and facilitates the integration of new technologies like DERs into the grid. When generation and distribution are unbundled, third-party companies can more easily provide services such as the installation, maintenance, and operation of DERs. This can result in the faster deployment of DERs, as well as increased innovation and cost savings. However, implementing unbundling in developing countries requires careful planning and management. It is crucial to develop a clear roadmap for unbundling, including timelines, stakeholder engagement, and the regulatory framework. The regulatory framework should define the roles and responsibilities of different stakeholders and establish rules and guidelines for the operation of various entities. Transparency and predictability in the regulatory framework, along with clear mechanisms for dispute resolution, are essential. Developed countries have typically implemented unbundling in stages, with each stage carefully planned and executed. Developing countries can learn from this approach and ensure the existence of a comprehensive plan to guide the unbundling process.

Lesson 2: Providing incentives for distribution network companies to enhance their cost and technical performance, as well as invest in digitization and grid modernization.

Incentivizing distribution networks to improve their costs and performance is of the utmost importance, particularly in many developing countries where these networks often face challenges such as high energy losses and inadequate financial positions that hinder necessary grid investments for modernization. For instance, in India, numerous state distribution companies have yet to fully digitize their operations, aside from implementing a few pilot projects. This lack of digitalization prevents distribution utilities from effectively accommodating DERs or accurately assessing the benefits of these resources in terms of cost savings. Real-time energy loss monitoring is unavailable, preventing them from capturing the positive impact of DERs in reducing losses within feeders with on-site generation.

The financial positions of many distribution companies in developing countries are further strained due to the absence of unbundling, non-cost reflective grid tariffs, cross-subsidies, commercial losses, and a lack of managerial incentives to optimize costs and network operations. Thus, an effective regulatory framework becomes necessary to ensure that distribution networks have both the motivation and capability to integrate DERs when it benefits the power system.

There are several approaches to incentivize distribution network utilities to enhance their cost and technical performance. One such approach is Performance-Based Regulation (PBR), which ties a utility's revenue to its performance against specific metrics such as reducing distribution losses, improving reliability, or increasing DER integration. PBR can incorporate financial incentives for meeting performance targets or penalties for failing to achieve them.

Another method is the use of incentive-based contracts that offer financial rewards for meeting or surpassing performance targets. These contracts can be designed to provide incentives for achieving specific cost or technical benchmarks, such as reducing energy losses or increasing DER integration. Additionally, performance benchmarking can be employed to compare a utility's performance with similar companies. By benchmarking against peers, distribution network companies can identify areas for improvement and strive to achieve better performance.

The experience of the UK in regulating electricity distribution networks provides valuable insights. After liberalization, the network companies in the UK were subject to economic regulation as per incentive-based price-cap regulation, known as the 'RPI-X' model. Under this model, are adjusted in line with the retail price index minus an annual efficiency factor 'X' (Littlechild, 2003). Over time, the UK's regulatory approach shifted from focusing solely on cost efficiency to a more output-oriented framework, driven by advancements in technology and increased capital-intensive investments in the networks (Jamasb, 2020).

To reflect these changing market conditions and encourage innovation and improved outcomes, the regulatory body Ofgem, introduced the RIIO (Revenue = Incentives + Innovation + Outputs) model in 2010. The RIIO model aims to incentivize utilities to innovate and meet the evolving demands of consumers and society. It is widely regarded as the most comprehensive performance-based regulatory system, allowing utilities to capitalize on the growing service economy, including DER companies and other third parties operating at the distribution and retail levels (AEE Institute, RMI, 2018).

The RIIO model comprises four main features to promote innovation and favourable outputs: a multi-year rate plan, the total expenditure (totex) approach, performance incentives, and an innovation fund (AEE Institute, RMI, 2018). The first generation of the RIIO model (RIIO-1) surpassed initial expectations by achieving greater cost efficiencies, meeting performance targets, and fostering the adoption of innovations through the funding provided. However, returns received by network companies were higher than anticipated when the RIIO-1 price controls were set, partially due to lower-than-expected capital costs and information gaps between Ofgem and network companies regarding costs (CEPA, 2018).

In response to the lessons learned from RIIO-1, Ofgem is now introducing the next generation of the regulatory framework, RIIO-2. This new iteration considers previous experience and, more importantly, places a strong focus on preparing the networks for whole-system solutions and achieving net-zero carbon emissions (Ofgem, 2020). By building on the successes and addressing the challenges of the previous model, RIIO-2 aims to further drive innovation and deliver the necessary outcomes for a sustainable energy future in the UK.

Lesson 3: Equity considerations, load and grid defections, and the risk of utility death spiral become important as DERs grow

The penetration of DERs raises concerns about equity. In this context, equity refers to the fair distribution of the effects of DER deployment among different consumer groups, particularly those with low incomes. As more end-users adopt rooftop solar and batteries, their reliance on the grid decreases. However, an inequitable network tariff design may result in a smaller group of users, often those unable to afford DER installations, shouldering the burden of fixed system costs.

Grid defection occurs when DER owners disconnect from the grid and rely solely on their own generation and storage. Load defection, on the other hand, happens when large energy consumers reduce their electricity demand or generate their own power to avoid high retail rates. These actions have significant distributional impacts, affecting the recovery of fixed costs, grid stability, reliability, and the financial viability of traditional utilities. The risk of grid defection is particularly high in countries where the quality of grid services is substandard, and the cost is high. Emerging grid-edge solutions are focusing on residential consumers in urban areas of lower-income economies, who either lack access to the grid or are underserved despite being connected. These solutions provide innovative and customized services using small-scale DER technologies bundled with appliances, specifically designed for customers with lower consumption and willingness to pay.[7] In addition, commercial and

[7] According to the Rockefeller Foundation (RF, 2020), while currently 800 million people lack access to electricity, about 2.8 billion people have unreliable access or are underserved. Providing universal access will require a combination of different electrification modes, including grid extensions, microgrids and stand-alone systems. Microgrids are also used for other purposes than universal access, for instance to improve the reliability of electricity supply of a microgrid connected to the main grid.

industrial consumers that rely on diesel-based gensets are also increasingly adopting emerging DER technology. Furthermore, there is a high risk of grid defection from wealthy consumers in this context.

In the African region, for instance, two features of the electricity sector would hasten the 'utility death spiral' compared with similar circumstances in Europe, North America, and Australia (Hendam et al., 2021). First, users in the topmost consumer category are subsidizing those in the lowest category. When consumers with high energy consumption defect from the grid, the financial shortfall of utilities increases at a much faster rate than the reduction in overall sales volume. Second, when a utility caps 'the equity concern' (distributional impact on low-income consumers), the cost recovery becomes even more difficult to achieve, particularly in the case of 'bundled' discoms.

Ensuring that grid fixed costs are shared among end-users in an equitable manner requires a combination of strategies that take into account the diverse needs and circumstances of different customer groups. Fixed charges, which are a set monthly charge for being connected to the grid, can ensure that all customers contribute to the fixed costs of the grid, regardless of their energy usage. By implementing fixed charges, utilities can ensure that DER owners pay a fair share of the fixed costs of the grid. To prevent the negative effect of fixed charges, the government can provide targeted assistance to low-income customers in order to ensure that all customers have access to affordable energy and that fixed grid costs are shared equitably.

Overall, ensuring that grid fixed costs are shared among end-users in an equitable manner requires a multifaceted approach that takes into account the diverse needs and circumstances of different customer groups. By implementing a combination of rate structures, fixed charges, low-income customer programs, ToU pricing, and energy efficiency measures, utilities can ensure that all customers contribute to the fixed costs of the grid in a fair and equitable manner.

3.2.2 TSO-DSO coordination

Lesson 4: A framework of coordination between transmission and distribution system operators is needed

The current operational paradigm of the power system in many countries is ill-equipped to accommodate the rapid growth of DERs. There is a lack of coordination between TSOs and DSOs in effectively managing DERs. As a result, there is a pressing need to establish a new operational architecture that can orchestrate DERs in a more efficient manner (Atkinson, 2021).

One key aspect is the creation of visibility down to the grid edge. Presently, distribution utilities lack real-time awareness of the output of DERs, including batteries, rooftop solar arrays, and community solar plants. They also lack a comprehensive view of the entire network, spanning distribution substation equipment, feeder circuits, and DERs, which hampers their ability to monitor power flows, voltages, and identify potential bottlenecks. Thus, it is crucial to prioritize the development of software systems that can 'virtualize the grid' and provide real-time monitoring capabilities.

The software system employed by DSOs should facilitate effective communication and collaboration with DER providers, aggregators, and TSOs. DSOs need to enhance their capabilities to support aggregators in mobilizing DERs, registering service offers, and assessing the system impacts of coordinated DER operations. Additionally, the DSOs' software platforms should enable hierarchical control and interoperability. Rather than employing a top-down, command-and-control approach, the DSO can assume a global coordination role, allowing aggregators the freedom to creatively utilize DERs. This approach would resemble the decentralized nature of the Internet's operation.

Developing countries have various models of coordination between TSOs and DSOs at their disposal. However, due to governance structures and the lack of unbundling in many of these countries, centralized schemes are often more effective during the current stage of power sector development. In a centralized coordination mechanism, the TSO assumes responsibility for meeting system demand across transmission and distribution networks, utilizing generation facilities at both levels. The role of the distribution network in this model is to ensure the reliability of the distribution grid and provide visibility to the TSO. As the governance of the distribution sector evolves and distribution networks become more sophisticated, decentralized approaches can be implemented, with DSOs playing a critical role in coordinating distributed energy resources.

In summary, effective coordination between TSOs and DSOs is essential to address the challenges posed by the growing presence of DERs in power systems. By establishing a new operational architecture, enhancing visibility down to the grid edge, fostering collaboration with DER providers and aggregators, and implementing hierarchical control and interoperability, countries can navigate the evolving energy landscape and unlock the full potential of distributed energy resources.

3.2.3 Wholesale/ Retail-DERs coordination

Lesson 5: ToU tariffs for withdrawal from and injection into the grid

ToU pricing is a valuable tool for integrating DERs as it effectively reduces the need for curtailing variable generation by coordinating actions between consumers and producers (Poudineh et al., 2021). By shifting consumption and injection to periods when the system value is highest, ToU pricing lowers the requirement for investment in generation capacity, reserves, and network strengthening associated with peak demand.

Recognizing the significance of ToU pricing, many developing countries have started experimenting with this approach. Brazil, for instance, has implemented ToU tariffs and an incentive-driven demand response program (DRP) to encourage demand response from consumers across different voltage levels (Cunha, 2021). The aim of the DRP is to reduce and time-shift demand load, displacing thermal generation in the centralized merit order. However, Brazil's experience highlights the challenge of ensuring consumer participation and compliance with ToU schemes. Initial results showed limited consumer engagement in load reduction auctions due, in part, to complex rules. Efforts are underway to recalibrate the DRP and attract a larger number of participants. Encouragingly, recent surveys have shown increased consumer interest in the program.

Developing countries can learn an important lesson from developed countries regarding the significance of customer education when implementing ToU tariffs. It is crucial to communicate clearly and effectively with customers, as ToU tariffs may be unfamiliar to those accustomed to fixed-rate electricity pricing. Additionally, a reliable metering infrastructure is necessary to accurately measure energy consumption at different times of the day, which may require investments in new metering infrastructure.

The implementation of a ToU tariff can have social impacts, particularly on low-income households. High peak period rates may pose challenges for low-income households to shift their energy consumption to off-peak hours. Therefore, it is vital to consider the potential social impacts and implement policies to mitigate any negative effects. Flexibility in tariff design may be necessary to address the unique needs of different customer groups. For instance, offering distinct ToU tariff options for residential, commercial, and industrial customers can incentivize energy efficiency across different sectors.

Lesson 6: Barriers to aggregation need to be removed

Aggregation plays a crucial role in enabling the participation of smaller distributed energy resources (DERs) in the electricity market, although its implementation lags behind in many parts of the world, particularly in developing countries. However, the importance of aggregation is increasingly being recognized.

In Brazil, for instance, the pilot DRP associated with ANEEL Resolution n° 792/2017 has explicitly included aggregators as eligible entities, whether they are distribution companies or independent aggregators (CCEE, 2021). Various institutions, such as the Chamber of Electric Energy Trading (CCEE), have conducted simulations to assess the impact of DER aggregation on distribution networks in the presence of appropriate price signals.

While aggregation has not yet actively participated in the Brazilian wholesale market, there are ongoing discussions about how the system can be restructured or adjusted to accommodate a future scenario with high levels of VRE and DERs, which is quite plausible. The Brazilian Association of Electric Energy Distributors (ABRADEE), for example, has supported research activities through its 'Research and Technological Development Program of the Electric Energy Sector regulated by the National Electric Energy Agency (ANEEL)' that explore the interaction between transmission and distribution system operators through aggregators (Ramos, Del Carpio, Filho, and Tolmasquim, 2020).

The concept envisions the entry of aggregators, or VPPs, directly participating in wholesale markets under a 'Hybrid DSO model' to provide a range of services. These services include peak shaving for the market, system flexibility and balancing services for the TSO, network decongestion and voltage control services for the DSO, and services for Balancing Responsible Parties (BRPs). In this concept, a VPP can be managed by aggregators, BRPs, or third parties.

Aggregation of DERs offers benefits beyond participation in electricity markets, particularly in contexts where such markets may not exist. In developing countries, for example, bundled DERs present a valuable solution to promote electrification and enhance access to electricity. Mini-grids, in particular, can serve communities located 'under the grid' and eventually connect to the main grid, transforming into embedded mini-grids and contributing as distributed resources (Graber et al., 2018).

However, many developing countries face challenges in establishing a regulatory framework that supports DER aggregation. The absence of clear rules and guidelines makes it difficult for aggregators to enter the market and for DER owners to participate in aggregation schemes. Moreover, the technical infrastructure necessary for effective DER aggregation, including communication systems, data management platforms, and control systems, may be inadequate in many developing countries.

In addition to regulatory and technical barriers, innovative business models are essential to attract DER owners to participate in aggregation schemes and create value for aggregators. Developing countries can draw lessons from the experience of developed countries in DER aggregation, identifying successful business models and adapting them to suit their unique contexts. By learning from these experiences, developing countries can foster an environment conducive to DER aggregation and leverage its potential benefits.

Lesson 7: Removing pricing distortions, designing efficient retail tariffs to incentivize efficient behaviour, and enabling efficient growth of decentralization

Price distortions, such as taxes, levies, and subsidies, significantly impact the growth of DERs. In developed economies, high retail electricity prices are driven by substantial taxes and surcharges aimed at recovering the costs of environmental and social policies. Interestingly, this has driven the adoption of residential rooftop solar PV systems as homeowners seek to offset their high energy costs.

In contrast, developing countries face a different scenario. In India, for instance, tariffs for residential, institutional, and agricultural customers are intentionally set below the average cost of service, or ACS. These subsidies are partly funded through transfers from the state's exchequer, but primarily through cross-subsidy surcharges imposed on commercial and industrial customers, or C&I. Additionally, discoms are burdened with legacy power purchase contracts that require fixed payments even when there is no demand for the power.

These distortions not only undermine the competitiveness of DERs but also contribute to a detrimental cycle of financial instability for distribution companies. The result is poor operation and maintenance of distribution assets, insufficient investment in grid infrastructure modernization, and declining service quality. This situation further increases the risk of disintermediation, as consumers increasingly turn to BTM solutions, mini-grids, or local energy markets as the costs of DER technologies continue to decline.

Addressing price distortions is crucial for the success of DER promotion initiatives. However, there are various barriers to designing and implementing efficient retail electricity prices in developing countries, particularly if these tariffs result in increased costs for certain customers. Resistance from customers, politicians, and other stakeholders can arise due to concerns about the impact on constituents.

Additionally, developing countries may lack the necessary institutional and regulatory frameworks to support the implementation of efficient retail electricity tariffs, and regulatory agencies may lack the capacity or authority to enforce tariff regulations.

Customer awareness is also a critical issue. Customers in developing countries may have limited awareness and understanding of the benefits of efficient retail electricity tariffs. Without a clear understanding of these benefits, customers may resist changes to their tariff structure.

Furthermore, there are other challenges to consider. Retail electricity tariffs rely on accurate and up-to-date energy consumption data, which can be difficult to obtain in developing countries. Limited metering infrastructure and data collection systems hinder the accurate tracking of energy consumption and the implementation of efficient tariffs. Technical expertise may also be lacking in some developing countries.

Developing countries can learn from the experiences of developed countries in terms of tariff design, transparency, stakeholder engagement, data analytics, and supportive regulatory frameworks. By adapting these lessons to their own contexts, developing countries can unlock the potential benefits of retail electricity tariff reform, including reduced energy consumption, improved affordability, and increased energy access.

Lesson 8: Removing barriers to the participation of DERs in multiple markets (including ancillary services market) and stacking revenue

The value of DERs, both to the power system and consumers, relies on several factors, including the cost and reliability of centralized electricity services, tariff and subsidy design, efficiency of network services, and the existence and sophistication of energy, capacity, and ancillary markets. A crucial aspect is the ability of DER providers, including aggregators, to 'stack' revenue by participating in multiple markets and offering a range of services.

To effectively stack revenues, DER owners and operators must carefully manage the operation of their assets to ensure they can participate in multiple markets without compromising performance or reliability. This often necessitates sophisticated control systems and coordination with other market participants. In a well-designed electricity market, DERs can participate in wholesale electricity markets by selling the excess energy they generate. They can also provide capacity as needed or offer grid services such as congestion management and reactive power support. These services can be sold to the grid operator, and DERs generating renewable energy can sell renewable energy credits to utilities or entities striving to meet renewable energy targets. With the right regulatory and market framework, technical expertise, and financial resources, revenue stacking from multiple markets becomes feasible.

Developing countries can learn from the experiences of developed countries in facilitating the participation of DERs in electricity markets. Standardizing technical requirements is an important step, encompassing communication protocols, data exchange, and monitoring and control specifications for DERs. Encouraging the aggregation of DERs is also key, as it increases their size and capacity, making them more appealing for market participation. By combining smaller assets, aggregating DERs can provide the necessary capacity to engage in the market.

To eliminate barriers to market participation, developing countries can simplify market rules and procedures, reduce transaction costs, and ensure fair compensation for service providers with access to reliable and accurate market data. This may entail developing new market structures and regulations, implementing market-based pricing mechanisms, and establishing performance standards for service providers.

By adopting these strategies, developing countries can foster an environment conducive to DERs' active participation in multiple markets, facilitating the building of a more reliable and sustainable power system. Standardized technical requirements, the encouragement of DER aggregation and VPPs, capacity-building support, and streamlined market rules and procedures are crucial elements in realizing the full potential of DERs in electricity markets.

3.2.4 Choice of regulatory instruments

Lesson 9: Applying regulatory instruments for integration of DERs proportional to their stage of penetration

Integrating DERs into the power system requires a phased approach that aligns the level of regulatory instruments with the share of DERs in the system. This approach allows for the gradual adjustment of technological, market, and regulatory aspects, providing sufficient time for power system planners to adapt. By applying regulatory instruments in proportion to the penetration of DERs, unnecessary complexity can be avoided until it is truly needed. This is not only pertaining to the type of regulatory instruments but also the strength of the incentives provided through regulation.

Rapid and extensive changes to the power system can introduce complexity and risks. A phased approach allows utilities and stakeholders to leverage existing infrastructure and resources, reducing the costs associated with building new infrastructure. It also facilitates the identification of potential challenges and opportunities in DER integration, informing subsequent phases and optimizing DER deployment. Moreover, it enables a systematic evaluation of the impacts of DERs on the power system, allowing for the adjustment of regulatory instruments to maintain system stability.

Developing countries must assess their current electricity system in terms of capacity, demand, and reliability to determine the potential for DER integration and the required regulatory instruments. Establishing an appropriate regulatory framework that supports DER integration at each stage of penetration is crucial. This framework should address interconnection, pricing, incentives, aggregation, technical requirements, and reliability, among other relevant aspects.

In summary, a phased approach to integrating DERs enables developing countries to achieve their energy goals in a cost-effective and sustainable manner. It promotes improved energy access, reduces carbon emissions, and mitigates the risk of large-scale system failures and unexpected impacts on the grid. By applying regulatory instruments proportional to the stage of DER penetration, developing countries can navigate the challenges of DER integration and unlock the benefits of a decentralized and resilient power system.

Lesson 10: Incentives for DER deployment: prioritizing cost-efficiency and comprehensive system considerations

Incentives and subsidies for the deployment of DERs should be aligned with broader market integration strategies, ensuring that the enhanced capacity corresponds with market demand, grid assimilation capabilities, and technological preparedness, preventing issues like overcapacity.

Although we did not formally review the case of Spain in this research, its experience is a testament to the complexities inherent in DER integration and the indispensability of well-coordinated, adaptive, and balanced strategies in promoting sustainable and robust growth in the DER sectors, avoiding pitfalls such as overcapacity, fiscal strains, and investor reticence.

In 2007 and 2008, Spain witnessed a remarkable boom in solar PV deployment, propelled mainly by a generous feed-in tariff (FIT) (del Río & Mir-Artigues, 2014). However, this rapid expansion was followed by a drastic bust, marked by a governmental rollback in FIT due to unsustainable costs, leading to a crisis in the sector. The FIT, initially aimed at promoting solar PV deployment, did foster short-term growth, but the lack of cost control mechanisms marred its long-term effectiveness, resulting in a detrimental impact on Spain's domestic industry and overall renewable electricity contribution.

Key flaws in the FIT design contributed to this, including overly generous rate structures and the absence of subsidy 'degression' options to modulate support in accordance with the variable costs of solar PV projects. The failure to swiftly and adaptively align policies with the rapidly decreasing costs of technology and external economic variables like fluctuating currency exchange rates and investment shifts intensified the crisis.

The ill effects of this policy turbulence were extensive. The solar PV sector, despite receiving a massive portion of renewable energy subsidies, contributed only a minor part to the total renewable electricity generation. The subsequent policy changes, considered retroactive by many, along with inconsistent amendments, undermined investor confidence, impacted industrial viability, and led to significant job losses in the sector.

The crucial lesson gleaned from Spain's experience emphasizes the importance of vigilant cost control in renewable energy subsidy designs. The policies should be resilient and adaptive to the mutable nature of technological costs, economic factors, and global market dynamics to foster a sustainable and resilient renewable energy sector.

Conclusions

DERs such as rooftop solar PV, battery storage, EVs, and demand response are increasingly recognized as important tools for developing countries to enhance their energy systems. These countries often face challenges in providing reliable and affordable electricity access for their citizens, and DERs offer a range of benefits that can help overcome these challenges.

In this paper, we examine the experiences of countries and regions such as Australia, the UK, Germany, and California regarding the integration of DERs. These examples provide valuable insights and serve as models for developing countries seeking to adopt DERs in their energy systems. The reviewed countries have already made significant progress in integrating DERs into their energy infrastructure. They have formulated policies, regulations, and technical solutions to overcome the challenges associated with DER integration into the grid. Moreover, they have implemented programs to incentivize households, businesses, and utilities to embrace DERs. By drawing from the experiences of these countries, developing nations can learn from best practices and expedite their transition towards a more sustainable, affordable, and reliable energy future.

We outline several key lessons for developing countries considering the integration of distributed energy resources (DERs) into their electricity systems. The significance of addressing institutional misalignments, specifically through the unbundling of distribution companies, cannot be emphasized enough when it comes to incentivizing the integration of DERs into distribution networks. The absence of unbundling can create economic conflicts of interest between distribution companies and DERs, impeding the adoption of DERs. Additionally, there is a need to provide incentives for distribution network companies to enhance their cost and technical performance, as well as invest in digitization and grid modernization. This becomes particularly crucial in developing countries, where distribution networks often suffer from high energy losses and poor financial conditions.

Two key mechanisms, namely ToU tariffs and DER aggregation, play a critical role in facilitating the grid integration of DERs. However, alongside reducing transaction costs, the implementation of ToU tariffs requires customer education and careful consideration of potential social impacts, especially on low-income households. On the other hand, DER aggregation allows smaller DERs to participate in the electricity market and offer a range of services, including peak shaving, system flexibility, and network decongestion. Developing countries can greatly benefit from the experiences of developed nations in terms of DER aggregation, as it can facilitate the integration of DERs into their electricity systems.

Efficient retail electricity pricing is a crucial element for the success of DER promotion initiatives. However, designing and implementing efficient retail electricity tariffs face barriers, particularly if tariff reforms lead to increased costs for certain customers. Additionally, customer awareness plays a vital role, as end users may lack knowledge and understanding of the advantages associated with efficient retail electricity tariffs.

As the deployment of DERs expands, it is essential to address equity considerations, the potential for load and grid defections, and the risk of a utility death spiral. The impact of grid and load defections on distributional costs and the financial viability of traditional utilities can be significant, especially in countries with inadequate grid services and high costs. Developing countries can gain valuable insights from the experiences of developed nations by recognizing the importance of tariff design, transparency, stakeholder engagement, data analytics, and supportive regulatory frameworks. By applying these lessons within their own contexts, developing countries can unlock the potential benefits of retail electricity tariff reform, such as reduced energy consumption, improved affordability, and increased energy access.

To successfully integrate DERs, establishing a coordination framework between transmission and distribution system operators is crucial. It is also important to develop software systems that visualize the grid, enable hierarchical control and interoperability, and standardize technical requirements for DERs. Developing countries should strive to remove barriers to DER participation in multiple markets by simplifying market rules and procedures, reducing transaction costs, and ensuring fair compensation for the services provided.

Also, integrating DERs into electricity grids poses challenges and necessitates a coordinated approach that takes into account technological, market, and regulatory aspects. Implementing changes too rapidly or on a large scale can entail significant risks, which is why a phased approach is recommended for developing countries. This approach allows utilities and stakeholders to leverage existing infrastructure and resources, identify potential issues and opportunities related to DER integration, and systematically evaluate the impacts of DERs on the power system. Developing countries should assess their electricity systems to identify the potential for DER integration and develop an appropriate regulatory framework to support integration at each stage. Overall, a phased approach to integration can help developing countries achieve their energy goals in a cost-effective and sustainable manner, while simultaneously improving energy access, reducing carbon emissions, and mitigating the risk of large-scale system failures.

Finally, incentives and subsidies for the deployment of DERs should be strategically aligned with broader market integration objectives, ensuring congruence between enhanced capacity, market demand, grid compatibility, and technological readiness to avoid issues such as overcapacity. Learning from the experience of global leaders, a crucial takeaway is the imperative need for rigorous cost control in formulating subsidies and incentives for renewable energy. Policies should be dynamic, adaptable, and resilient against the ever-changing landscape of technological costs, economic variables, and global market trends, to promote a robust and sustainable renewable energy sector.

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Appendix

Table A1: Australia

Country	Area of coordination	Regulatory instrument	Summary of key points
Australia	DSO-DERs coordination	Cost-reflective network tariffs	• In Australia, DERs face varying distribution network charges based on location and local tariff structures, including fixed demand, and energy charges. • Stakeholders express concerns that current pricing structures are not fully cost-reflective of DERs, potentially leading to unfair charges and discouraging DER uptake. • To address concerns, proposals include implementing time-of-use tariffs, locational pricing, and access fees based on system size or capacity. • There's ongoing debate on the transparency and comprehensiveness of the methodology used to calculate network charges and the value compensation provided to DERs. • A rule change submitted in March 2020 to the Australian Energy Market Commission (AEMC) seeks to establish nationally consistent minimum technical standards for DER, focusing on inverters and demand response standards.
		Flexible grid connection regime	• Australia allows both firm and non-firm connection options for DERs, dependent on various factors like size and location. • Allows small-scale solar PV systems to connect to the grid on a non-firm basis; network operators can curtail the export of electricity if needed. • In some regions, new solar PV systems up to a certain size are required to have inverters that can be remotely controlled to limit electricity exported to the grid during oversupply or network constraints. • Some network operators offer incentives or payments for DER owners who opt for a non-firm connection option.
		Local markets for flexibility services	• Various initiatives in Australia allow DER owners to offer flexible services to DNOs. • Australia has several VPPs that aggregate and manage networks of DER assets as single entities, allowing owners to sell excess energy to the grid. AGL Energy's VPP connects 1,000 households in South Australia for this purpose. • Supported by the Australian Renewable Energy Agency (ARENA), TEM allows DER owners to sell energy and flexibility services to DNOs and other market participants. Currently being piloted in Western Australia with plans for national rollout. • Some DNOs are exploring becoming Distribution Market Operators (DMOs), creating market platforms for DER owners to offer their flexibility services to the grid. AusNet Services is developing a DMO platform aimed at creating a more flexible and efficient energy system.

	TSO-DSO coordination	TSO-DSO coordination models (total TSO, total DSO, hybrid DSO)	• Open Energy Networks (OpEN) Project launched to create a customer-centric roadmap for Australia's electricity network and enhance coordination among AEMO, TOs, and DOs for effective DER integration. • Identified four models, Single Integrated Platform (SIP), Two-Step Tiered (TST), Independent Distribution System Operator (IDSO), and a Hybrid Model, to enable market access for participants while maintaining system integrity and security. • A three-year trial through Project EDGE aimed at creating a prototype market for DERs, focusing on efficient delivery of both wholesale and local network services within secure limits. • Emphasis on integrating private electricity grids, like industrial parks and shopping centres, which recently gained access to retail markets.
	Wholesale/ retail-DERs coordination	Market design	• DERs over 30 MW can directly participate in the Australian National Electricity Market (NEM), those between 5 MW and 30 MW can participate on a non-scheduled basis, and DERs under 5 MW can participate in aggregated form when affiliated with an electricity retail business. • The Australian Energy Market Operator (AEMO) has programs to enable DER participation in energy or ancillary services, with participation requirements varying depending on the DER specifics, such as size, type, and technical capabilities. • The ancillary services market may be dominated by a few large players, making it difficult for new and innovative technologies, such as DERs, to enter and compete. • Proposals for promoting greater DER participation include changes to market design to better value DER capabilities, revising the frequency control ancillary services (FCAS) market, streamlining registration and compliance requirements, technology-specific reforms like creating a new market for distributed battery storage, and introducing new technical standards for DERs.
		Aggregation	• Aggregators are crucial for enabling the participation of DERs in the electricity market, unlocking their value by providing services like FCAS to the NEM. • The participation of aggregators in the NEM faces challenges such as an evolving regulatory framework, significant upfront investment, and the need for technical expertise and infrastructure. Data-sharing arrangements between grid operators and aggregators are also still developing, impacting effective participation. • Continuous adjustments to market design and regulation may be necessary to accommodate aggregators, including new market mechanisms allowing aggregators to bid into the FCAS market, simplification of registration processes, and improvements in data transparency and access. • At high levels of DER growth, proper coordination measures are crucial to avoid increased system costs, and well-coordinated regulatory frameworks are needed to ensure the efficient operation of DERs through aggregation. • Without proper coordination and mitigation measures, the operation of aggregators like VPPS and the growth in passive rooftop solar PV could lead to exceeding local technical limits and reduced ability to maintain transmission network flows within secure limits, causing increased costs borne by consumers.
		Retail tariffs design	• In Australia, most retail tariffs are volumetric, charging customers based on the amount of electricity consumed. This structure doesn't financially incentivize DERs to provide grid services during peak demand, leading to suboptimal grid management and higher consumer costs.

			• Reforms including ToU tariffs, which vary pricing based on the time of day, have been introduced in some states to address the issues, providing accurate price signals and incentivizing service provision during high demand or supply constraint times. • Trials of ToU tariffs in South Australia and New South Wales have been successful in reducing demand during peak periods, with some reducing their peak demand by around 20 per cent. However, concerns have been raised about the impact on vulnerable customers unable to adjust their consumption to off-peak rates. • The implementation of ToU tariffs has sparked concerns about their impact on vulnerable customers, leading to calls for more support and adjustments to help them adapt to the new pricing arrangements and mitigate adverse effects.

Table A2: UK

Country	Are of coordination	Regulatory instrument	Summary of key points
UK	DSO-DERs coordination	Cost-reflective network tariffs	• DERs are subject to various charges, including connection charges (one-time charges upon connecting to the network), fixed charges (ongoing charges covering the fixed costs of maintaining the network), use of system charges (based on the actual usage of the network), and triad charges (apply to large consumers, based on usage during the three highest-demand half-hour periods). • Ofgem introduced reforms to make network charges more reflective of actual costs, initiating a Targeted Charging Review (TCR) to address cross-subsidies among network users and phase out certain universal charges, replacing them with charges that accurately reflect the costs of using the network at different times and locations. • Considerations include forward-looking charging arrangements and changes from a first-come-first-served capacity allocation method to more market-based approaches, allocating capacity to those who value it most and recovering costs from those who cause it. • Ofgem has proposed locational charging for distribution networks to align charges paid by DERs more closely with the actual costs of providing network services in different areas, ensuring fairness and accuracy in the charging system. • Proposals also include new connection standards requiring DERs to provide detailed information about their proposed connections, helping determine associated network costs and ensuring that DERs pay their fair share
		Flexible grid connection regime	• The UK offers flexible connection options for Distributed Energy Resources (DERs), allowing them to connect to the grid without the traditional, often costly and time-consuming, firm connection agreement. • Demand Side Response (DSR) or Aggregated Flexibility Option enables DERs to participate in demand response programs and offer grid services like frequency response and voltage regulation in exchange for payments, ideal for DERs that can provide flexibility, such as battery storage and electric vehicles. • Ofgem recognizes that accommodating more DERs isn't only about network reinforcement but also about efficient utilization of existing grid capacity, including the re-design of network tariffs to incentivize usage during times of spare capacity. • There are moves to implement new grid connections and access regimes to prevent network peaks and make more efficient use of existing grid capacity, with redesigned network tariffs encouraging users to utilize networks where there is more spare capacity.
		Local markets for flexibility services	• DNO Flexibility Marketplaces in the UK are local markets allowing DERs to provide various grid services to the local distribution grid. • Larger DNOs are exploring their evolution into DSOs to utilize DER services for their operational needs and to coordinate DER flexibility services for the TSO. • Examples of Flexibility Marketplaces are: Western Power Distribution (WPD)'s Flexible Power, UK Power Networks (UKPN)'s Power Potential and Northern Powergrid's OpenLV.

			• These marketplaces are valuable for enabling DERs to participate in and contribute to grid balancing services, monetizing their flexibility, and promoting their integration into the grid.
	TSO-DSO coordination	TSO-DSO coordination models (total TSO, total DSO, hybrid DSO)	• Open Networks Project launched by the Energy Networks Association (ENA) in 2016, aiming to reform the operation of local distribution and national transmission networks for customer benefit. • Total TSO Model: The Electricity System Operator (ESO) is key, with DSOs informing ESO of requirements (ii) Hybrid DSO Model: Coordinated procurement and dispatch between DSO and ESO for administering networks and flexible resources (iii) Total DSO Model: DSO as an impartial market intermediary offering location-based services to the National Grid (iv) Price-driven Flexibility: Reform of electricity network access and forward-looking charges by OFGEM promote customer participation (v) Flexibility Coordinators under Hybrid DSO: Third-party entities operate as market intermediaries for DERs offering services to the ESO and/ or DSO. • After extensive consultations and assessments, the 'Total DSO' model was concluded to yield the highest net benefits to system operation up to 2030, with Hybrid DSO as a close second. • UKPN and WPD endorse the 'Total DSO model' as the most efficient for whole-system outcomes in high DER penetration scenarios.
	Wholesale/retail-DERs coordination	Market design	• UK's electricity system operator (ESO) recognizes the importance of utilizing the flexibility of DERs due to the growing need for flexibility services in the UK to accommodate VRE and DERs. • In 2019, the 'Distributed Resource Desk' was installed in the ESO's control room, marking the UK's initial step towards exploring the role of DERs as flexibility service providers. • DERs can participate in the Balancing Mechanism, Capacity Market, or Firm Frequency Response market, receiving payments for providing ancillary services to the grid. • Ofgem has proposed reforms to simplify licensing and data management requirements and clarify the roles and responsibilities of market participants. • Some DERs may lack the required communication systems or responsiveness to changes in the grid for participation in ancillary service markets. ESO proposes new technologies like advanced metering systems and distributed control systems to enhance the visibility and control of DERs on the grid, addressing technical barriers.
		Aggregation	• The UK is exploring DERs aggregation to integrate more renewables into the grid, improve reliability, and reduce carbon emissions. • Private companies like KiWi Power and Limejump aggregate DERs and sell services to grid operators or suppliers for a fee. • Despite active promotion, aggregators face regulatory, technical, and market barriers in the UK electricity market. 2019 reforms by National Grid allowed flexibility providers access to Great Britain's core flexibility market under "Virtual Lead Party," enabling aggregators to participate without a supplier's license and to stack revenue from multiple services. • Post reforms, the entry of VPPs in the market has been significant with BNEF (2020) tracking 32 VPPs representing an aggregated capacity of 6 GW.

			• UK regulation has evolved to allow DER aggregation in various markets, enabling service providers to pursue multi-use applications to maximize revenue for their resources.
		Retail tariffs design	• Current UK retail tariffs may not sufficiently encourage investments in Distributed Energy Resources (DERs) like rooftop solar, energy storage, and electric vehicles. • The UK has limited experience with dynamic real-time pricing and critical peak pricing, partly due to the lack of smart meters. Retailers, assigned the responsibility to implement smart meters, lack incentives to deploy them, resulting in low penetration. • The adoption of time-of-use tariffs has been slow, and many customers are either unaware of the benefits or find them too complex to understand and manage. • There are ongoing efforts from utilities, suppliers, and regulators to update tariffs to incentivize consumption during high renewable generation and low demand periods and to adapt to the increase in DER deployment.

Table A3: Germany

Country	Are of coordination	Regulatory instrument	Summary of key points
Germany	DSO-DERs coordination	Cost-reflective network tariffs	• Distributed Energy Resources (DERs) in Germany face several charges related to their connection to the distribution network, intended to cover the costs of maintaining and operating the distribution grid. • It is unclear whether the charges are fully cost-reflective, especially for small-scale DERs like battery energy systems, which can both draw and feed electricity into the grid. • Small-scale DERs, with relatively low impact on the grid, face challenges in justifying the same network usage fees as traditional electricity consumers. • Proposals to make charges more cost-reflective include varying charges based on time of day or season and based on the location of the DER. • Implementing such variations can better align usage charges with actual grid service costs, reflecting the real costs of maintaining and operating the grid in different areas and times. • Proposals suggest fair compensation for DER owners for the value of the services they provide, incentivizing DER deployment and ensuring DER owners contribute equitably to grid maintenance costs.
		Flexible grid connection regime	• In Germany, non-firm or flexible grid connection options like curtailment and dynamic grid connection are available for DERs (Distributed Energy Resources). • Typically used for renewable energy systems like solar PV and wind due to their variable output. DER owners may receive payment for providing this service. • Dynamic grid connection allows DERs to adjust their output in response to grid conditions by observing the voltage and frequency of the grid. • Germany has pioneered the use of smart inverters which convert DC power produced by DERs into AC electricity, equipped with advanced control and communication capabilities. They manage the power output of DERs actively and communicate with the grid, especially crucial for new solar installations over 30 kW, providing grid support services as per the country's grid code. • These non-firm grid connection options are crucial in Germany's evolving energy landscape, allowing DERs to offer grid services and benefiting the owners of the systems by optimizing energy production and consumption.
		Local markets for flexibility services	• In the EU, local markets for flexibility services are in their early stages, despite Article 32 of the European Electricity Directive emphasizing their importance. • Progress varies across Europe, with the UK, Norway, and the Netherlands having some innovative solutions due to initiatives by national regulators, network operators, and market participants, while other places are still evolving. • In Germany, DSOs are mandated to procure flexibility services as part of the country's energy transition to a low-carbon system. Procurement of flexibility services from DERs is integral to this transition, focusing on maintaining grid stability and reliability.

			• DSOs in Germany procure flexibility from DERs using various methods, including organizing local flexibility markets, partnering with aggregators like energy service companies, or working directly with specific DER owners or third-party aggregators. • Despite the initiation of local markets for procuring flexibility in Germany, several challenges and barriers need addressing. Close collaboration among policymakers, regulators, and stakeholders is crucial to understand the issues and develop effective solutions for creating fair and transparent markets for DER flexibility.
	TSO-DSO coordination	TSO-DSO coordination models (total TSO, total DSO, hybrid DSO)	• In Germany, TSOs and DSOs work in tandem; TSOs manage the overall grid balance, while DSOs manage the distribution grid and connection of DERs, ensuring grid stability and reliability. • A recast of the Electricity Regulation in the EU mandates new roles for DSOs, including the establishment of an EU DSO entity to streamline operations, plan distribution networks, facilitate renewables integration, and support developments in data management and cybersecurity. • Recent data suggests a transition towards more transactive grids in Germany and Europe, with DSOs managing active consumers and considering non-wire alternatives for network investments. • Various coordination models are being explored in Germany, including the ‘integrated grid’ model focusing on closer collaboration for integrating renewables and DERs, and the ‘platform model’, where a third party coordinates between TSOs and DSOs. • Distribution utilities in Europe are exhibiting increasing sophistication with growing investments in networking, automation, and monitoring due to innovations from companies like General Electric and Siemens. • The models for coordinating TSOs and DSOs in Germany are expected to continue evolving, with close coordination between TSOs and DSOs being critical for managing high levels of renewable energy and DERs and ensuring grid stability and reliability.
	Wholesale/retail-DERs coordination	Market design	• DERs in Germany can participate in the electricity market, offering services like frequency regulation or voltage support through various market mechanisms, such as frequency containment reserve (FCR) and primary control reserve (PCR) auctions managed by TSOs. • DERs can provide services directly, either individually via aggregators or VPPs, or by participating in balancing groups to help provide ancillary services and receive compensation. • A lack of clear, standardized rules and well-defined technical requirements creates uncertainties and can result in high transaction costs for DERs, potentially discouraging market participation. • Germany has implemented changes to market rules, such as allowing demand response providers to offer services directly to TSOs and creating a new market segment, the ‘regulation energy market’ specifically for smaller resources like DERs to provide frequency regulation services.
		Aggregation	• Two models of aggregation identified by regulatory authorities in the European single electricity market are demand-side aggregation and distributed generation aggregation, focusing primarily on balancing markets, the day-ahead market, and the intra-day market. • Despite progressive frameworks, regulatory barriers, stringent technical requirements, reporting obligations, and market design primarily favoring large, centralized power plants still pose challenges for DER aggregators in participating in the market on equal terms.

			• DER aggregators face difficulties in accessing crucial operational data on grid conditions, weather patterns, and energy prices, impacting the effectiveness of their VPPs. • Germany is implementing measures to accommodate DER aggregators better, such as amending regulatory barriers, creating specific market segments for DERs, and providing clearer price signals, aiming for a more open, flexible, and competitive electricity market receptive to increasing DERs and their aggregators.
		Retail tariffs design	• Traditionally aimed to recover costs related to grid construction and operation, and energy generation, and they don't reflect the full value of DERs' benefits to the grid like reducing infrastructure needs and greenhouse gas emissions. • Mostly based on a flat-rate system, not varying with the time of day or energy demand levels, which doesn't allow an efficient response from DERs to grid conditions and leads to inefficient investments and operations. • Existing tariffs include charges for grid maintenance and operation but often don't acknowledge the benefits DERs bring, such as increased grid stability, creating disincentives for DERs. • Lack of real-time pricing information in many tariffs prevents DERs from adapting to energy supply and demand changes and maximizing the value of the energy they produce. Germany is exploring ToU tariffs to provide better price signals and incentivize operations during high demand.

Table A4: California

Country	Are of coordination	Regulatory instrument	Summary of key points
California	DSO-DERs coordination	Cost-reflective network tariffs	• DERs, like rooftop solar panels and small-scale wind turbines, connect to the grid mostly through the Net Energy Metering (NEM) Program in California. • It employs a tiered rate structure comprising fixed (covering grid maintenance costs) and variable charges, based on energy drawn from or fed into the grid. • DERs face other fees like interconnection fees, standby charges, and demand charges to cover the costs of maintaining and upgrading the grid. • There are initiatives to ensure charges for DERs accurately reflect the costs of maintaining and upgrading the electricity distribution network. • Proposals have been made for capacity-based pricing to incentivize DER owners to reduce their capacity requirements, lessening the need for infrastructure upgrades. • California Public Utilities Commission has proposed adopting an avoided cost methodology for DER compensation, reflecting cost savings provided by DERs by reducing the need for expensive infrastructure upgrades. • Overall, the charges that DERs pay to access the electricity distribution network in California are generally designed to be cost-reflective, intending to cover the costs associated with maintaining and upgrading the grid infrastructure.
		Flexible grid connection regime	• California provides non-firm or flexible grid connection options designed to allow DER owners and operators more effective management of their energy resources and responsiveness to grid conditions. • Some utilities offer curtailment programs where DERs can curtail energy production upon request in exchange for compensation or incentives, aiding in distribution system stability during high demand or stress periods. • Pacific Gas & Electric Offers a 'smart' interconnection option enabling developers to receive real-time information about the grid's capacity and stability and adjust their energy production accordingly to maintain grid stability. Like the flexible DER interconnection program, participation might yield reduced interconnection costs or other incentives.
		Local markets for flexibility services	• The state enforces policies and regulations, incentivizing and mandating DSOs to procure flexibility from DERs to fulfill the state's clean energy goals. • California Public Utilities Commission's (CPUC) Distribution Resource Plans (DRP) mandates DSOs to formulate plans to incorporate DERs into their distribution systems and procure the requisite flexibility from these resources to remedy grid constraints. • The process requires DSOs to pinpoint grid constraints and assess potential DER solutions, establishing procurement targets for each type of resource.

			• Distribution utilities are required to identify grid constraints like voltage fluctuations or capacity limitations and define the DER flexibility needed to address such constraints, including specifying types, amounts, durations, and frequencies of required flexibility. • They solicit proposals from DER providers offering the necessary flexibility, evaluate these proposals, and enter into contracts with the providers that best meet their needs.
	TSO-DSO coordination	TSO-DSO coordination models (total TSO, total DSO, hybrid DSO)	• Transmission and distribution utilities, CAISO, and regulators in California recognize the need for enhanced coordination between transmission and distribution operations to integrate DERs into the state's rapidly decarbonizing energy mix. • Several models have been proposed to coordinate actions of TSOs and DSOs concerning DERs in California. • The Distribution System Platform (DSP) Model proposes a centralized platform providing real-time data and communication channels between DSOs and DER providers, requiring significant investment in technology and infrastructure. • The Integrated Distribution System Operator (IDSO) Model suggests the creation of a single entity managing both the distribution grid and connected DERs, requiring alterations to the regulatory framework and new governance structures.
	Wholesale/retail-DERs coordination	Market design	• FERC Order 2222, implemented in September 2020, opens organized wholesale markets to DERs, allowing them to compete on equal footing with centralized resources. This order is a game changer, mandating grid operators to revise tariffs and establish DERs as a category of market participant by 2021. • It not only acknowledges the pivotal role of DERs in future grids but also ensures their participation in wholesale markets, fostering competition, innovation, and cost reduction for customers. • The Distributed Energy Resource Provider (DERP) program by CAISO allows aggregators of DERs, like third-party providers or utilities, to participate in its market. • Participating DERs, which include distributed generation resources, energy storage systems, and demand response programs, can be compensated similarly to traditional power plants. • To participate, aggregators need to register with CAISO and fulfil certain requirements, such as proving ownership or control of the DERs and demonstrating the ability to provide required grid services. • Participating DERs can offer various grid services including energy, capacity, and ancillary services, and are compensated based on the market clearing price, determined through competitive bidding. • This compensation provides an additional revenue stream for DER owners and supports the reliability and stability of the grid.
		Aggregation	• DER aggregators are pivotal in California's electricity market, with their significance likely to escalate as the utilization of DERs amplifies. • Companies like OhmConnect, Stem, and Enel X are notable DER aggregators, forming VPPs to offer grid services such as frequency regulation, peak shaving, and demand response. • The CPUC has proposed facilitating measures, like offering real-time grid data and market prices and conditions data, to ease the participation of DER aggregators in the market.

			• Proposals for market design alterations, such as the introduction of 'fast-start' products, are being considered to enable quick provision of ancillary services by DER aggregators in response to grid events. • Technical assistance is being provided by CPUC and other organizations to help aggregators overcome challenges related to DER aggregation like software, hardware, and data management.
		Retail tariffs design	• A rising per centage of Californian consumers opt for electricity from municipal alternative suppliers or CCAs. • CCAs, which are over 19 in number, serve over 11 million customers across 200 regions, focusing on local energy needs, economic growth, and decarbonization efforts. They procure generation but don't operate Transmission & Distribution (T&D) infrastructure or serve as the direct retailer to customers. • A tiered rate structure and a NEM program exist to incentivize reduced energy consumption and investment in Distributed Energy Resources (DERs). • The tiered structure and NEM program have limitations, such as not reflecting the true cost of electricity and the true value of DERs to the grid, leading to mismatches and underinvestment in DERs. • California is exploring alternative rate structures like ToU rates and evaluating methods to aptly value the benefits of DERs to the grid. • These efforts aim to align incentives and needs more efficiently and boost investment and deployment of DERs.