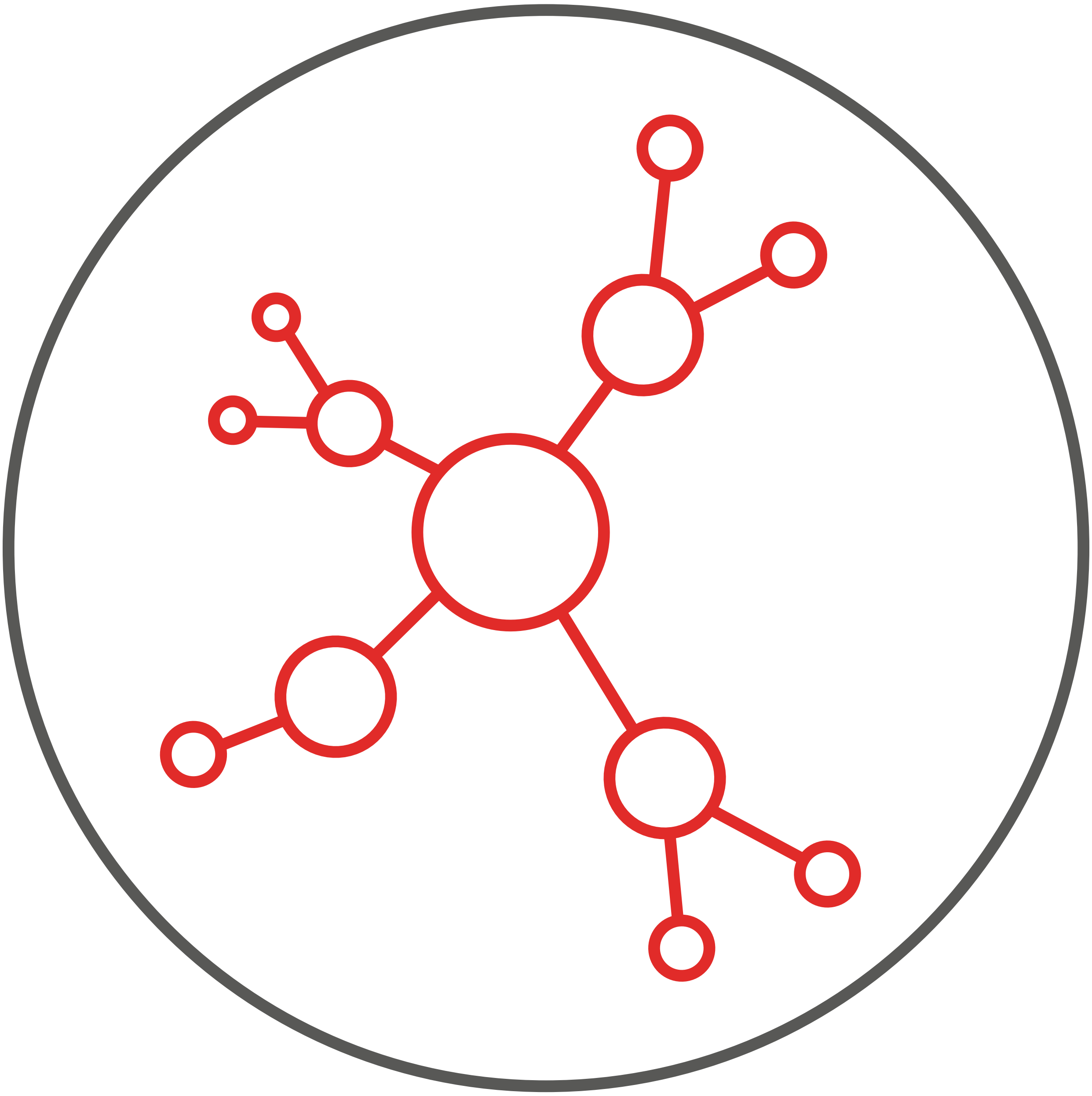

Market Design

Market Design:
Innovation Landscape

- Increasing time granularity in electricity markets
- Increasing space granularity in electricity markets
- Innovative ancillary services
- Re-designing capacity markets
- Regional markets
- Time-of-use tariffs
- Market integration of distributed energy resources
- Net billing schemes

IRENA
International Renewable Energy Agency

INCREASING TIME GRANULARITY IN ELECTRICITY MARKETS

INNOVATION LANDSCAPE BRIEF

IRENA
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1 BENEFITS

Increasing time granularity in electricity markets

Short term:

Improved flexibility in operations through price signals

Long term:

Optimised investments in flexible generation capacity (through granular price signals)

Enable higher shares of VRE in the power system

3 SNAPSHOT

- Shorter market time units are explored in California (United States), Brazil, Germany and other European markets.
- Shorter lead times are proposed in Australia, the Nordic power market in Europe (reduced to 15 minutes), Austria, Belgium and Germany (reduced to 5 minutes).

2 KEY ENABLING FACTORS

- Advanced computational power and optimisation modelling software
- Efficient price formation in well-functioning markets

HOW TO INCREASE TIME GRANULARITY?

The value of flexibility can be internalised in the market price by reducing:
• the market time units (the duration of dispatch)
• the time span between trading gate closure and physical real-time delivery of power (the lead time).

INCREASING TIME GRANULARITY IN ELECTRICITY MARKETS

The better **prices reflect the system conditions** closer to real time, the better **the flexibility** incentives for the system.

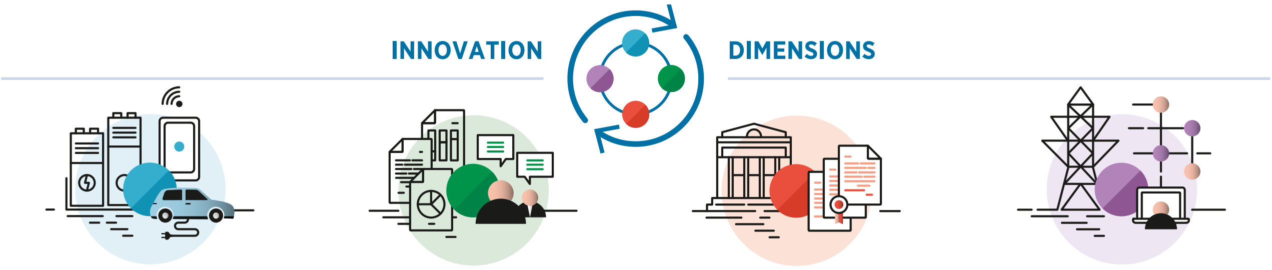
ABOUT THIS BRIEF

This brief forms part of the IRENA project "Innovation landscape for a renewable-powered future", which maps the relevant innovations, identifies the synergies and formulates solutions for integrating high shares of variable renewable energy (VRE) into power systems.

The synthesis report, *Innovation landscape for a renewable-powered future: Solutions to integrate variable renewables* (IRENA, 2019), illustrates the need for synergies between different innovations to create actual flexibility solutions for power systems. Solutions to drive the uptake of solar and wind power span four broad dimensions of innovation: enabling technologies, business models, market design and system operation.

Along with the synthesis report, the project includes a series of innovation landscape briefs, each covering one of 30 key innovations identified across those four dimensions. The 30 innovations are listed in the figure below.

INNOVATION DIMENSIONS



● ENABLING TECHNOLOGIES

1 Utility-scale batteries
2 Behind-the-meter batteries

3 Electric-vehicle smart charging
4 Renewable power-to-heat
5 Renewable power-to-hydrogen

6 Internet of things
7 Artificial intelligence and big data
8 Blockchain

9 Renewable mini-grids
10 Supergrids

11 Flexibility in conventional power plants

● BUSINESS MODELS

12 Aggregators
13 Peer-to-peer electricity trading
14 Energy-as-a-service

15 Community-ownership models
16 Pay-as-you-go models

● MARKET DESIGN

17 Increasing time granularity in electricity markets
18 Increasing space granularity in electricity markets
19 Innovative ancillary services
20 Re-designing capacity markets
21 Regional markets

22 Time-of-use tariffs
23 Market integration of distributed energy resources
24 Net billing schemes

● SYSTEM OPERATION

25 Future role of distribution system operators
26 Co-operation between transmission and distribution system operators

27 Advanced forecasting of variable renewable power generation
28 Innovative operation of pumped hydropower storage

29 Virtual power lines
30 Dynamic line rating

This innovation landscape brief applies to liberalised, open electricity markets, where vertical integrated utilities have been unbundled and there is competition in electricity generation. It examines increasing time granularity in electricity markets with a well-functioning spot market as a key market design innovation that addresses the variability and the uncertainty of the VRE share in the grid. The brief focuses on the reduction of the duration of dispatch interval (pricing shorter market time units[1], shorter clearing and financial settlement periods) and the reduction of the time span between the trading gate closure and physical, real-time delivery of power,[2] etc. Increasing time granularity helps better manage the uncertainty in matching power demand and supply in a system with a high share of VRE through electricity prices that better reflect the system conditions in real time.

The brief is structured as follows:

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[1] "Market time units" are also referred to as "dispatch time interval", "products" or "contracts", depending on the taxonomy used (e.g., 15-minute product).

[2] The time span between the market gate closure and the physical delivery is also referred to as "lead time".

I. DESCRIPTION

Increasing shares of wind and solar generation result in growing volumes of intraday trading need, which in turn increases the need to adjust production schedules and commercial positions to the most recently updated VRE forecast and market conditions. This requires that market time frames – both the granularity of market time units and gate closure times – and financial settlement periods are adjusted to fully exploit the flexibility of existing generators in the system when needed. To enhance the operation of a system with high shares of VRE, the dispatch/scheduling time interval, the pricing of market time units, financial settlement periods, and the time span between gate closure and real time delivery of power should be reduced. The use of shorter market time units would help to internalise the value of flexibility in the market price. The more reflective the prices are of the short-term market conditions, the better the price signals sent to generators, which can quickly alter their output by the system when needed. The following parameters should be shorten in order to increase time granularity in electricity markets (IRENA, 2017)[3]:

- **Market time unit:** Wholesale electricity market products – contracts or a market time unit, depending on the taxonomy applied – refer to the dispatch period for which physical delivery of electricity is traded on a market. For example, an hourly product refers to 60 minutes of a physical electricity delivery. Similarly, a quarter-hourly product equals 15 minutes of a physical delivery of electricity in a given market. Across the European spot (day-ahead and intraday) markets, the vast majority of products traded are hourly products, but more and more products with a lower time granularity are being introduced, such as half-hourly products traded in continuous markets (as opposed to auctions) in France, Germany, the United Kingdom, Luxembourg and Switzerland or quarter-hourly products traded for continuous trading in intraday markets in Austria, Belgium, Germany, Hungary, Luxembourg, the Netherlands, Slovenia and Switzerland (ACER, 2018a). Brazil is testing dispatch intervals of 30 minutes, and California is transitioning from hourly products to quarter-hourly product.

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[3] For a detailed analysis of this topic please refer to: IRENA (2017), *Adapting market design to high shares of variable renewable energy.* International Renewable Energy Agency, Abu Dhabi

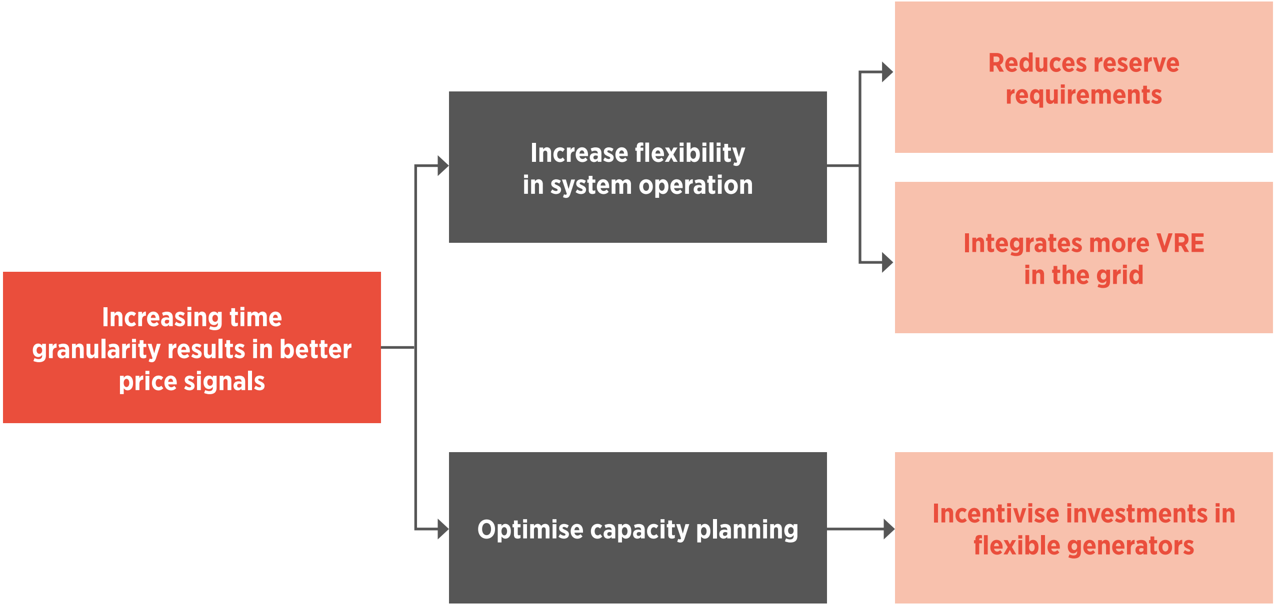
- **Gate closure:** Gate closure is the moment up to which market agents can either submit or modify their own bid or ask orders on the markets. After that point in time, the final binding schedule is determined for all participants. The timing of the last gate closure represents the dividing line between the market and the pure system operation. Setting a gate closure closer to real time helps market agents adjust their positions, with increased certainty about forecasted generation enabling them to minimise imbalances. This also benefits transmission system operators (TSOs), who need to procure and activate fewer reserves for balancing the system.

- **Financial settlement period:** The financial settlement period is a time interval during which financial transactions are being settled for energy being bid in the market. The settlement process ensures that market generators are paid for the energy provided in the market (AEMO, 2019). Generally, the settlement period and the dispatch interval are the same. However, in some markets, the settlement period is different from the dispatch period, which is defined as the time interval during which the agent's bids are received and the dispatch instructions are sent by the system operator. For instance, in Australia, the dispatch interval is 5 minutes, but the settlement period is 30 minutes. Therefore, the seller is not paid based on the price of power in 5-minute intervals but for the average price of a 30-minute block period (meaning 6 dispatch intervals) (AEMC, 2017a). An equal length of settlement period and dispatch interval can help increase the market participation of various players by providing accurate price signals to market participants.

II. CONTRIBUTION TO POWER SECTOR TRANSFORMATION

The changes in market design in terms of the time granularity of settlement periods, market time units and bringing gate closure times closer to real time delivery in the short-term wholesale market are expected to better remunerate the flexible behaviour of existing generators. Consequently, increasing time granularity is likely to promote investments in flexible assets leading to better grid integration of renewable energy sources. Similarly, it also leads to price signals that can better direct investments towards renewable generation that brings the highest value to the system. The contributions of increased time granularity to the power sector transformation are shown in Figure 1.

Figure 1: Key contributions of increased time granularity in electricity markets



Increasing flexibility in system operation

As the amount of VRE generation is uncertain and difficult to accurately predict ahead of real-time delivery, the system operator may need to procure balancing services through the ancillary service market. A gate closure time that is closer to physical delivery allows market players to incorporate the updated forecast of power demand and variable power generation, leading to more accurate scheduling of power generators. Also, shorter dispatch intervals or market time units lead to increased system flexibility as they allow more frequent scheduling of the whole system, leading to the use of the flexibility available from demand loads and generators. Also, increasing the time granularity of traded products leads to better and more opportunities for market participants to adjust their commercial positions closer to real-time physical delivery of electricity, thus increasing the value obtained from trading electricity and reducing their costs for imbalance settlements, where penalties are paid in case of deviations from schedules.

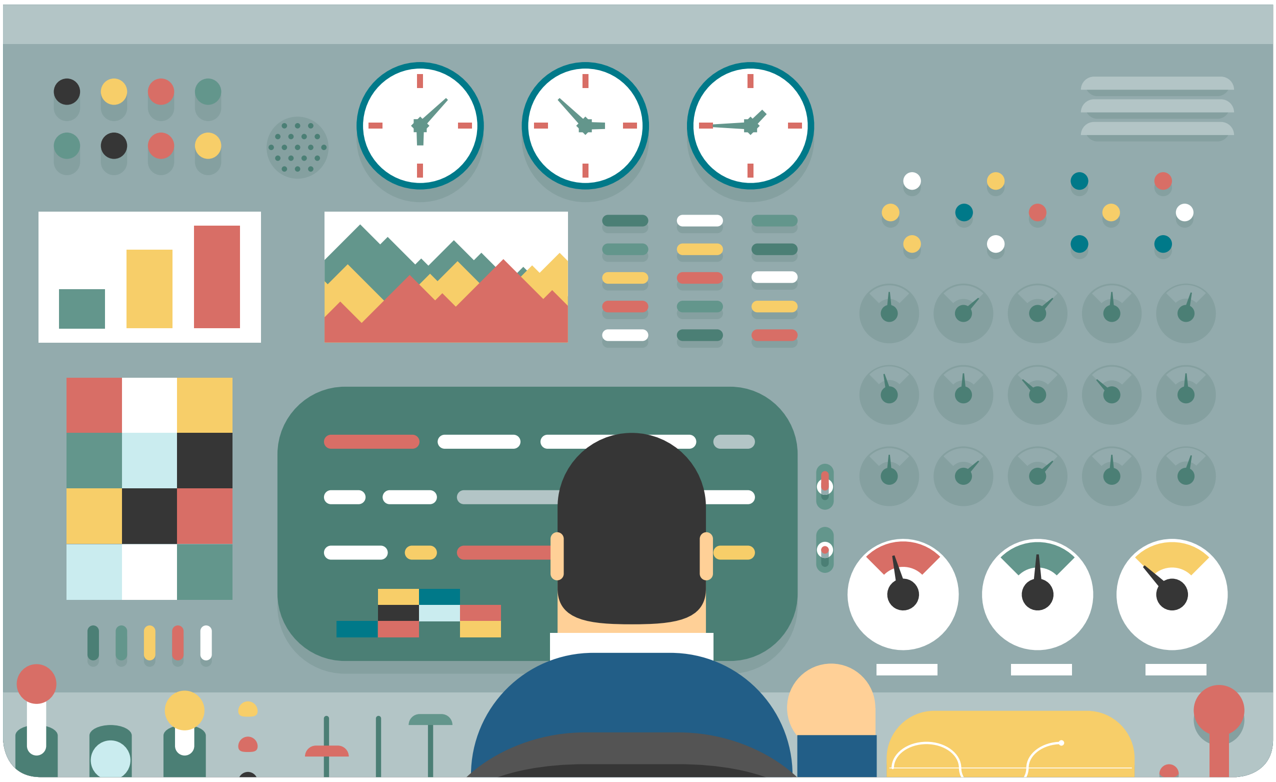
Increased time granularity in power markets, both with regard to market time units and closer-to-real-time gate closure times, helps system operators to forecast real-time operations with better accuracy. This helps avoid issuing re-dispatch instructions (which generally lead to increased power costs) to handle real-time mismatches in demand and supply.

Shorter market time units result in more time-granular wholesale prices, which can be transmitted in retail prices as dynamic time-of-use tariffs, unlocking demand-side flexibility through demand response.

With shorter dispatch periods, system operators need to maintain a lower quantity of reserves. This allows the power generating resources to follow the actual load more closely and the power generation schedule to be changed more frequently. Also, better scheduling of generators due to the reduced lead time between gate closure and real-time operation is expected to reduce the need of procurement of ancillary services and system reserves.

Optimise capacity investment planning

Increased time granularity in electricity markets sends better pricing signals to both power generators and suppliers without generating units, leading to efficient bidding and operational schedules. With flexibility services valued on short-term markets, investments in more flexible generation capacity are also incentivised. With deployment in utility-scale storage or aggregating distributed storage, new generation gas peak plants and rapid demand response are encouraged (AEMC, 2017). Therefore, a future flexible system would be able to cost-effectively integrate high shares of VRE.



III. KEY FACTORS TO ENABLE DEPLOYMENT

Information and communication technologies

Advanced computational power, optimisation modelling software, advanced weather forecasting tools, as well as automation of various processes and information exchange related to scheduling of power plants are key enablers for increasing time granularity in power markets. For example, higher computational power is needed due to the increased volume of information that needs to be processed. Both system and market operators would therefore require more computational power and/or advanced modelling software to run the model at an increased time granularity. Moreover, software for the specific needs of the system and market operators needs to be developed.

Regulatory measures for efficient price formation in wholesale electricity markets

One measure that could help form a price that reflects the conditions in the system, and therefore send the right price signals to participants, would be to remove price caps that are set administratively. Such a measure would allow free price formation in the wholesale electricity markets, including the occurrence of negative prices and price spikes. Negative prices occur in wholesale electricity markets during times of highly inflexible power generation and low demand, while price spikes occur when the system faces very high demand and relatively low generation.

For example, Nord Pool – the power exchange that operates the electricity market in several European countries, including Denmark – introduced negative pricing in 2009. Negative pricing has facilitated wind power integration in Denmark by motivating wind turbines to dispatch down when wind power is in excess, given that offshore turbines do not receive feed-in tariffs when wholesale power prices are negative. In addition, negative pricing is an obvious bonus for flexible storage options, such as Norwegian pumped storage hydropower (PSH) and Danish combined heat and power (CHP), which are effectively paid to consume (and store) electricity and then sell (and inject) it when power prices are positive, or use it for district heating (IEEFA, 2018).

At the European level, the Agency for the Cooperation of Energy Regulators (ACER) adopted Decision No. 05/2017 on 14 November 2017 harmonising the thresholds for the clearing prices for the pan-European single intraday coupling with the minimum at EUR −9 999/MWh and the maximum at EUR 9 999/MWh, which de facto allows for very high negative prices, as well as important price spikes (ACER, 2018b; ACER, 2017).

IV. CURRENT CONTEXT AND EXAMPLES OF LEADING INITIATIVES

Shorter market time units

California

Increasing the penetration of VREs without making changes to market rules and policies has resulted in significant strains on real-time power markets. With an aim to improve grid reliability and efficiency of the day-ahead market, the California Independent System Operator (CAISO) has proposed several changes in the day-ahead market. One of the proposed changes is to reduce the granularity of traded products from 1 hour to 15 minutes[4] (CAISO, 2018). This is in line with FERC Order No. 764, under which granularity in real-time markets was reduced to 15 minutes (for VREs) to remove barriers to the integration of VREs. The reduction in scheduling intervals would allow power-generating resources to more closely follow the load curve as forecasted by CAISO. CAISO may also be able to reduce procurement from real-time markets, especially during morning and evening ramping times as the day-ahead market would be able to commit sufficient resources with sufficient ramping capability.

Germany

The high variability of renewable energy production already requires flexible conventional power plants and other flexibility options to cover fluctuating residual loads (energy not covered by renewables). Increasing shares of wind and solar energy in the power system not only reduce the need for conventional generation capacity, but also influence the required structure of the conventional power plant fleet. In a power system with a share of variable renewables of 40 %, such as in Germany, less conventional base load capacity and more peaking capacity is needed due to increased flexibility requirements (EPE, BMWi and GIZ, 2017).

Germany recently reformed its electricity market system to facilitate flexibility. Some of the measures adopted were related to wholesale price formation and time granularity in the market. For example, in 2011, Germany reduced the dispatch interval to 15 minutes from 1 hour for the intraday market to enable the valuation of flexibility (IEEFA, 2018). Based on the success of 15-minute contracts on the intraday market, EPEX launched an additional 15-minute auction at 3 p.m. one day before the delivery date (in the intraday market) in December 2014 (EPEX, 2014a), (EPEX, 2014b). This helps fine-tune the portfolios after the hourly day-ahead market and facilitate trading for intra-hour variations in power production and consumption. Moreover, free price formation in the wholesale market is allowed (i.e., no price caps, including negative prices).

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[4] Other changes proposed include combining integrated forward market (IFM) and residual unit commitment (RUC), and procuring imbalance reserves that will have a must-offer obligation to submit economic bids for the real-time market.

Single intraday coupling in Europe

Prior to the implementation of the pan-European single intraday coupling via the commercial XBID (cross-border intraday) project on 12 June 2018, several national intraday markets had sub-hourly products, such as 30-minute products, traded in continuous intraday markets in France, Germany, the United Kingdom, Luxembourg and Switzerland. In addition, 15-minute products were traded in continuous markets in Austria, Belgium, Germany, Hungary, Luxembourg, the Netherlands, Slovenia and Switzerland. In Germany and Luxembourg, 15-minute products were also auctioned (as opposed to continuously traded). Moreover, now that the first phase of the XBID project is active, the XBID system supports a wide range of products, including 15-minute and 30-minute products, which are available for specific market areas (XBID, 2018).

Brazil

The design of the wholesale power market in Brazil is heavily influenced by the presence of abundant hydropower. Because Brazil was never a capacity-constrained country (due to the fact that is a hydropower-based system), there was no need for an ancillary service market. Historically, the spot prices in Brazil were calculated for each week for three tiers of loads: peak, shoulder and valley. A computer-aided economic dispatch was performed for these loads for each week, though the system operator had some flexibility to conduct real-time dispatch.

In February 2018, the Brazilian Ministry of Mines and Energy proposed a law for the modernisation and expansion of the free market for electricity. This was in response to recent short-term flexibility needs in the system driven by increasing solar and wind shares, and hydro's changing role in system expansion given the socio-environmental constraints of building new large hydro reservoirs. Also because of these constraints, wind is becoming a relevant source in the Brazilian energy matrix (already 8 % of the electricity mix) (EPE, BMWi and GIZ, 2017). Therefore, a full redesign of the wholesale power market's design aims to create a new energy market (including ancillary service market), a capacity market and a market for clean certificates. Brazil is now introducing hourly prices in power markets (Batlle et al., 2018). It also aims to introduce dispatch intervals of 30 minutes. The half-hourly dispatch and hourly pricing are currently being tested, and Brazil expects to fully introduce them at the beginning of 2020. The law also aims to increase the granularity of wholesale market price formation to increase short-term flexibility.

Gate closure times closer to real-time delivery of electricity

Australia

Perth Energy[5] proposed reducing the gate closure time to no more than 30 minutes from the current 2 hours (Economic Regulation Authority, 2017). Increased participation in the wholesale electricity market combined with growth in the energy sector have made market conditions more dynamic. Using data from between 14 January 2017 and 16 March 2017, Perth Energy showed that there is significant volatility in load forecast[6] in the last two hours. It was further argued that with the reduced gate closure time, market participants would be more confident about the load forecast, leading to better power generation planning and cost reductions. Per Perth Energy's analysis, the inability of generators to respond to price signals (which was due to the low predictability of load) cost consumers around AUD 8.9 million between 14 January 2017 and 16 March 2017. A shorter gate closure time would ensure the reduction of the share of inflexible power generators in the power mix and the increase of responsive power generator use.

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[5] Perth Energy is one of the largest business energy providers in Western Australia.

[6] The document talks about variation in load forecast and price signals. The significant variation in demand may be due to the increasing penetration of solar rooftop systems.

Nordic market in Europe

With the increasing share of wind power in northern Europe, there is an increasing need to balance energy. To optimise investments in balancing resources, therefore, power market rules must change to engage all the balancing resources available. Of the many issues being identified, one was a longer gate closure period. The current gate closure periods of 60 minutes in the intra-day market and 45 minutes in the balancing market restrict the use of commercial power trade to cover the variations in power generation and demand. In its report "Building an efficient Nordic power market", Fortum Energy suggested reducing the gate closure of Nord Pool to 15 minutes in both intraday and balancing markets. It argued that a 15-minute gate closure would help improve the use of commercial resources and reduce the number of occasions when the fast TSO reserves are activated (Fortum, 2016).

In 2016, Nord Pool, Elering (the Estonian TSO) and Fingrid (the Finnish TSO) launched a pilot with a 30 minute gate closure time in the intraday market on the Estonian-Finnish border, replacing the previous 60-minute gate closure. Based on positive feedback from market participants, this pilot was implemented as an interim solution until the XBID project commenced (Baltic Electricity Market Forum, 2016).

Single intraday coupling in Europe

ACER adopted Decision No. 04/2018 on 24 April 2018 harmonising the gate opening (at 3 p.m. on D 1) and closing times (60 minutes) for the pan-European intraday market. As such, the gate closing time on the Estonian-Finnish border (i.e., 30 minutes before physical delivery) "should not be considered as an exception, but rather as a preferred solution", as ACER mentions, because it maximises opportunities for market participants to adjust their balances close to real time while also providing time for TSOs and market participants to schedule and balance processes in relation to network and operational security. Moreover, in other national markets across Europe, such as in Austria, Belgium and Germany/Luxembourg (in certain TSO areas only), the local intraday gate closure time (as opposed to the single intraday gate closure time) is 5 minutes before the beginning of physical delivery (ACER, 2018b).

Shorter financial settlement period

Australia

During its inception in the 1990s, the National Electricity Market (NEM) adopted a 5-minute dispatch period, which is considered the shortest possible timeframe practicable. However, it adopted a 30-minute settlement period based on the limitation in metering and data processing (AEMC, 2017b). Currently, the generators bid to supply electricity for 5-minute block periods because the physical electricity system matches the demand and supply for every 5 minutes. However, the financial settlement for generators is based on average prices over a 30 minute block period.

With the increasing penetration of VREs, the role of flexible technologies[7] in handling the intermittencies in power generation from VREs is expected to increase. However, the mismatch in dispatch and settlement periods has led to many inefficiencies in the operation and generation mix. Inefficient price signals have also impeded the entry of flexible sources, such as fast-response generation or demand-side response in power markets.

In the past few years, the difference between 5 minute dispatch prices and 30 minute settlement prices has increased and is expected to further rise. By matching the physical electricity system and financial settlement period, the Australian Energy Market Commission (AEMC) expects that investment in fast response and flexible technologies will increase. The change in this rule is expected to help power generators to take more efficient decisions, which would ultimately lead to lower power prices for consumers. The 5-minute financial settlement rule is also expected to reward customers who can respond to peak demand for short intervals only.

In this context, in 2017 the AEMC introduced a rule to change the financial settlement from 30 to 5 minutes. The rule is expected to apply as of 1 July 2021. Once the rule is implemented, the price in the market will align with the physical electricity system, which matches demand and supply every 5 minutes. With this change, the AEMC expects that in the long run, efficient price signals to the market will lead to lower wholesale electricity costs.

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[7] Hydro, gas peaking, diesel generators and coal-fired generators (to some extent) provide supply-side flexibility. Increasing adoption of solar, battery and other technologies has enabled demand-side participation by consumers.

V. IMPLEMENTATION REQUIREMENTS: CHECKLIST

TECHNICAL REQUIREMENTS	**Hardware:** • Flexible generators in the system
	Software: • Advanced weather forecasting tools • Higher computational power and better system modelling tools required for marginal price determination • Automation of various processes and information exchange related to the scheduling of power plants
REGULATORY REQUIREMENTS	**Wholesale market:** • A liberalised wholesale electricity market with unbundling across the electricity value chain • Clear and consistent rules in the market • Surveillance of the market to ensure market manipulation does not occur • Regular monitoring of the impact of increasing time granularity on the power costs for consumers and publication of the results for broader public awareness • Adapting the market design to the needs of market participants, system operators and consumers
STAKEHOLDER ROLES AND RESPONSIBILITIES	**Regulators, market and system operators:** • Regulators designing and enforcing required changes in market rules • Market operators implementing necessary regulatory changes on their platforms • Market operators and TSOs to perform pilots and conduct studies to assess the time granularity required in the market design

ABBREVIATIONS

ACER	Agency for the Cooperation of Energy Regulators
AEMC	Australian Energy Market Commission
CAISO	California Independent System Operator
CHP	Combined heat and power
IFM	Integrated forward market
NEM	National Electricity Market
PSH	Pumped storage hydropower
RUC	Residual unit commitment
TSO	Transmission system operator
VRE	Variable renewable energy
XBID	Cross-border intraday

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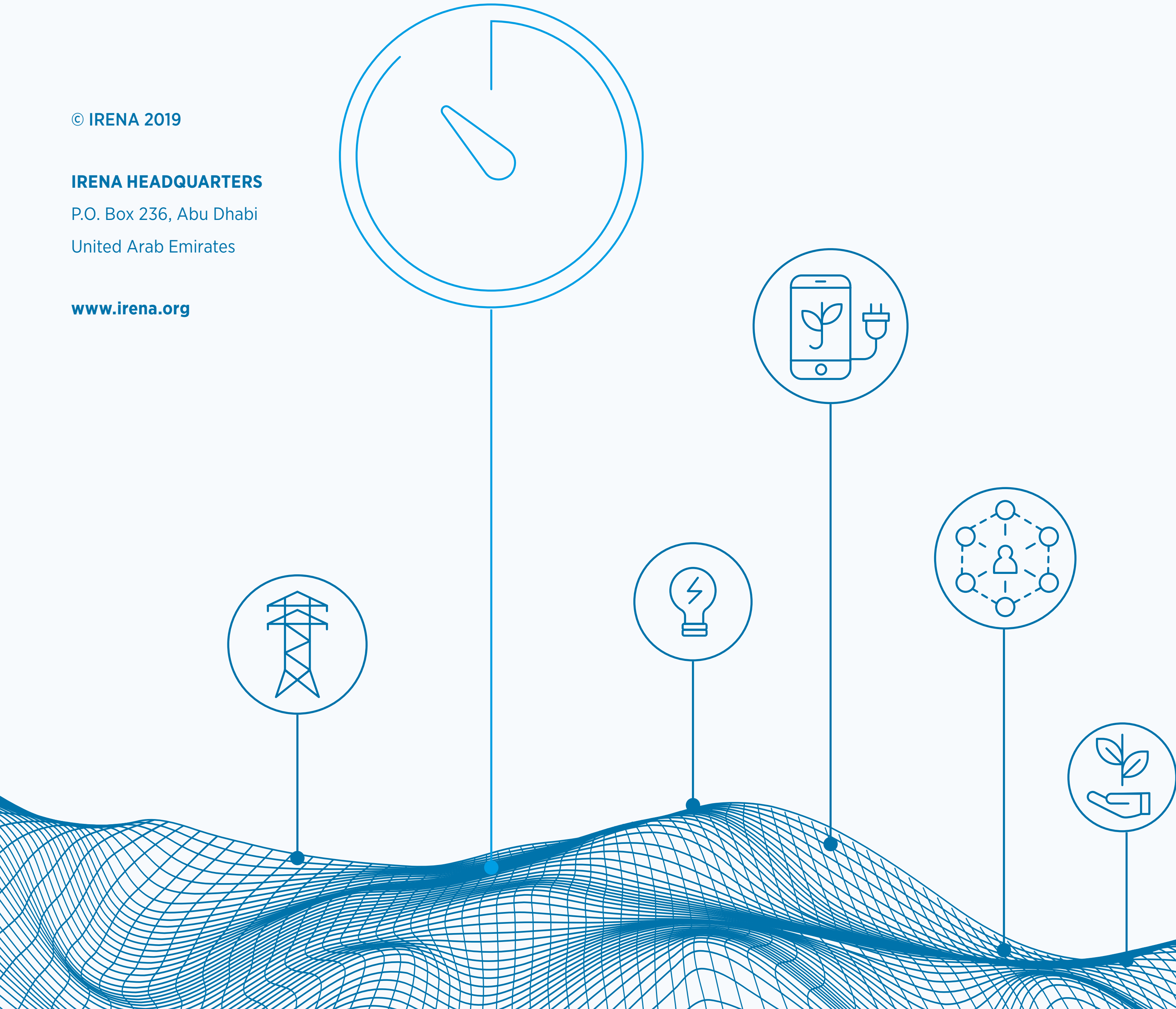

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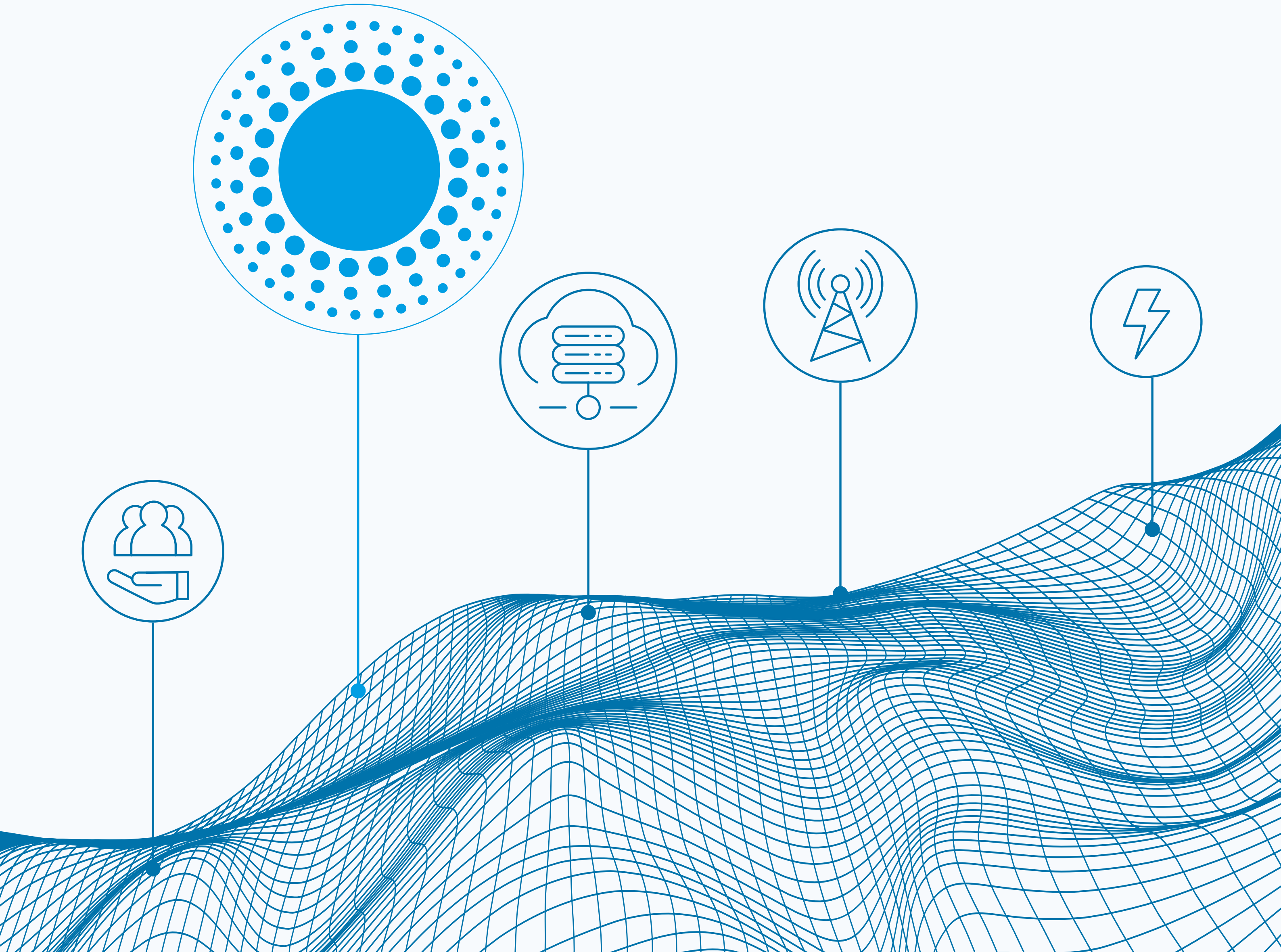
INCREASING SPACE GRANULARITY IN ELECTRICITY MARKETS

INNOVATION LANDSCAPE BRIEF



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INCREASING SPACE GRANULARITY IN ELECTRICITY MARKETS

Zonal and nodal pricing reflectgridcongestions.
Increasing space granularity in electricity markets can help **reduce re-dispatch costs** and **drive investments** where most needed.

WHY INCREASE SPACE GRANULARITY?

High shares of VRE deployment, in particular wind, might constrain transmission networks.

1 BENEFITS

Increasing space granularity in electricity markets

Short term:

Avoid costly re-dispatch and incentivise demand response in areas with high prices

Long term:

Optimise network and generation capacity investments through price signals

Incentivise investments in VRE generation in areas with high prices

Incentivise investments in the grid between areas with high price differences

2 KEY ENABLING FACTORS

- Advanced computational power and optimisation modelling software
- Clear and transparent pricing methodology

3 SNAPSHOT

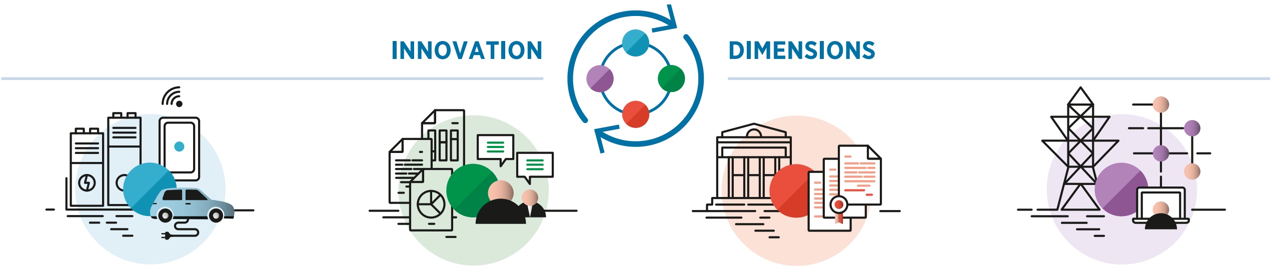
- In the US, ERCOT (Texas) has more than 4 000 pricing nodes, while NYISO (Ney York) has 11 zones. This encourages investments in areas with the highest demand and reduces consumption.
- In Europe, some countries divide their national transmission system into more bidding zones: Denmark (2), Italy (6), Norway (5) and Sweden (4).

ABOUT THIS BRIEF

This brief forms part of the IRENA project "Innovation landscape for a renewable-powered future", which maps the relevant innovations, identifies the synergies and formulates solutions for integrating high shares of variable renewable energy (VRE) into power systems.

The synthesis report, *Innovation landscape for a renewable-powered future: Solutions to integrate variable renewables* (IRENA, 2019), illustrates the need for synergies between different innovations to create actual flexibility solutions for power systems. Solutions to drive the uptake of solar and wind power span four broad dimensions of innovation: enabling technologies, business models, market design and system operation.

Along with the synthesis report, the project includes a series of innovation landscape briefs, each covering one of 30 key innovations identified across those four dimensions. The 30 innovations are listed in the figure below.



● ENABLING TECHNOLOGIES

1 Utility-scale batteries
2 Behind-the-meter batteries

3 Electric-vehicle smart charging
4 Renewable power-to-heat
5 Renewable power-to-hydrogen

6 Internet of things
7 Artificial intelligence and big data
8 Blockchain

9 Renewable mini-grids
10 Supergrids

11 Flexibility in conventional power plants

● BUSINESS MODELS

12 Aggregators
13 Peer-to-peer electricity trading
14 Energy-as-a-service

15 Community-ownership models
16 Pay-as-you-go models

● MARKET DESIGN

17 Increasing time granularity in electricity markets
18 Increasing space granularity in electricity markets
19 Innovative ancillary services
20 Re-designing capacity markets
21 Regional markets

22 Time-of-use tariffs
23 Market integration of distributed energy resources
24 Net billing schemes

● SYSTEM OPERATION

25 Future role of distribution system operators
26 Co-operation between transmission and distribution system operators

27 Advanced forecasting of variable renewable power generation
28 Innovative operation of pumped hydropower storage

29 Virtual power lines
30 Dynamic line rating

This innovation landscape brief applies to liberalised, open electricity markets, where vertical integrated utilities have been unbundled and there is competition in electricity generation. It examines a key market design innovation of increasing space granularity in electricity markets (using nodal or zonal pricing), which addresses the variability and uncertainty of VRE share in the grid. As the share of VRE increases in the overall energy mix, congestion in the transmission network is likely to increase as well. Electricity price formation at different points of the transmission system reflecting congestion can help to reduce the re-dispatch need and can incentivise transmission grid investments in right locations.

The brief is structured as follows:

I Description

II Contribution to power sector transformation

III Key factors to enable deployment

IV Current status and examples of ongoing initiatives

V Implementation requirements: Checklist

I. DESCRIPTION

As the share of VRE increases in the energy mix, it may lead to an increasingly constrained transmission system. Price formation at a granular spatial level can reflect this condition and send the necessary price signals in order to avoid or reduce costly re-dispatch, incentivise demand response, and encourage generation capacity investment in the right location of the network.

When referring to space granularity in electricity markets, there are two fundamentally different market designs, as described below (IRENA, 2017).

- Nodal pricing: Nodal pricing refers to prices paid for electricity consumed or generated at a given transmission node. Under this option, transmission constraints are explicitly observed while determining the optimal dispatch of the system and deriving the locational marginal prices. Nodal pricing better depicts the technical and economic effects of the network on the price of electricity as it implicitly includes the impact of grid losses and transmission congestion (IRENA, 2017). For example, several independent system operators (ISOs) in the United States use nodal prices from which are derived the locational marginal price (LMP).

- Zonal pricing: A pricing zone is defined as the largest geographical area within which market participants are able to trade energy without capacity allocation, i.e., an area where grid congestion is assumed to be low. These zones are defined by the regulator and/or the transmission system operator (TSO) and hence the price differentials between the zones reflect the grid congestion between the zones. Such bidding zones represent, for example, the cornerstone of the pan-European electricity market, whereby electricity is traded across bidding zones, based on available transmission capacities calculated by TSOs, while the electricity traded within a bidding zone is considered unrestricted by transmission capacity. While in most cases a bidding zone corresponds to national borders, there are countries that divide their power system into more zones. Italy, for example, has divided the national transmission system into six geographical bidding zones (GME, n.a).

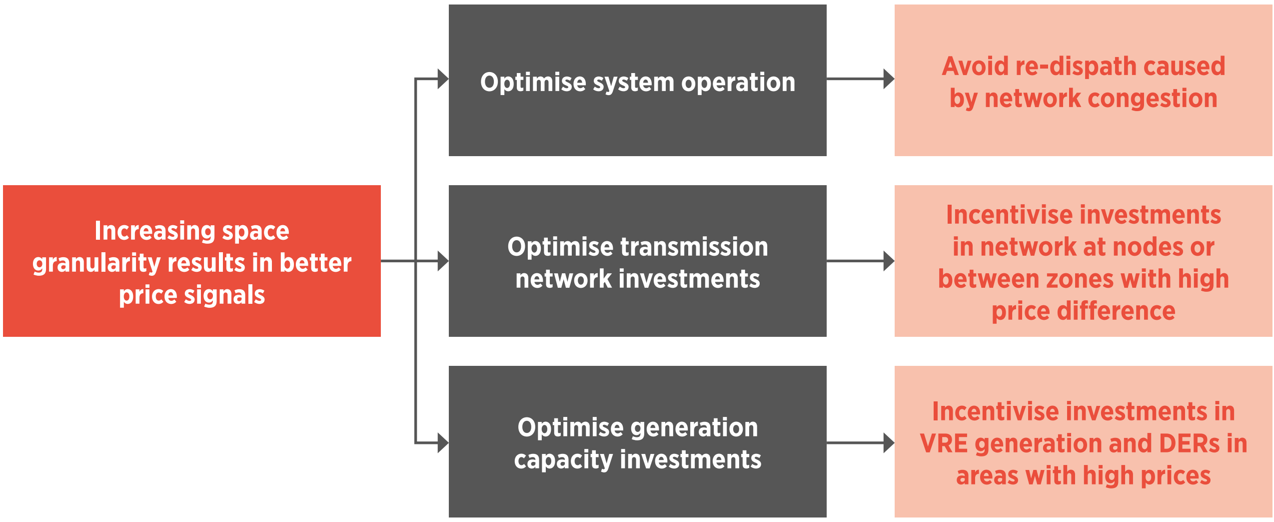
With increasing penetration of VRE, transmission networks are expected to become more congested between areas with relatively high renewable generation units and demand centres. Increased space granularity in electricity markets can help provide better market signals to the system operator and generators, incentivising investments in high-priced zones. "Several issues are to be taken into account when estimating the benefits of these two approaches: the efficiency of the resulting price signals (both in the short and long term), the computational burden and implementation costs, the hedging complexity and the impact on the liquidity of long-term markets and geographical consumer discrimination (IRENA, 2017).

While nodal pricing may be more challenging to implement, it is deemed to be more efficient than zonal pricing because the spatial granularity is lower and reflects better transmission system constraints. However, in cases in which only specific transmission network lines are congested, zonal pricing might be efficient. Also, larger bidding zones are believed to increase liquidity and competition, and zonal prices represent a more stable signal for investors and tend to be less discriminatory for consumers (IRENA, 2017).

II. CONTRIBUTION TO POWER SECTOR TRANSFORMATION

Increasing space granularity by implementing either nodal or zonal pricing would result in price signals that could direct investments towards assets located where the transmission system would benefit the most and, therefore, relieve system constraints in a cost-efficient manner. Furthermore, such price signals can better direct investments towards renewable generation assets in locations with high prices, thereby reducing the overall costs of electricity for consumers. Contributions of increased space granularity in the electricity market to the power sector transformation are depicted in Figure 1.

Figure 1: Key contributions of increased space granularity



Optimise system operation

Both zonal and nodal electricity pricing are used to reflect network congestion. While nodal pricing reflects highly congested nodes, for zonal pricing congestion is reflected in the price difference between two neighbouring zones (i.e., the cross-zonal price differential is an indicator of the congestion at a given border between two zones). Therefore, increasing the space granularity in electricity markets either via nodal or zonal pricing helps locate congestion in the transmission system, which can be accordingly considered by TSOs in their operational procedures to avoid costly re dispatch after the market is cleared.

Moreover, on the demand side of the market, having more granular markets from a geographic point of view could shift peak demand, provided the necessary incentives are in place, such as time-of-use tariffs with locational signals incorporated. Demand-side response would therefore help reduce the network congestion in a particular area.

Optimise transmission network investments

Nodal and zonal pricing also act as drivers to identify grid reinforcement opportunities where these are needed the most. Areas (zones or nodes) with low electricity prices indicate abundant supply and relatively lower demand, whereas areas with high prices indicate relatively high demand and scarce supply. More transmission capacity between such areas would lead to price convergence. This is particularly relevant for integrating VRE into the grid either by a) deploying VRE in areas where there is relatively high demand and low supply or by b) expanding the transmission network so that the VRE is supplied to the areas where demand is higher than in the area where the generation units are located. Such grid reinforcements between zones or nodes would avoid curtailments of abundant VRE generation in areas with high solar and wind potential and relatively low demand.

Optimise generation capacity investments

Zonal and nodal prices can also incentivise investments in generation assets and demand-side response in areas with higher prices, where demand is relatively higher than other areas. On the supply side, this could either result in investments in utility-scale renewable power plants or the deployment of distributed energy resources (DERs) such as solar rooftop installations, combined heat and power plants, electricity storage units, etc. Therefore, electricity could be provided from local sources during peak hours.

III. KEY FACTORS TO ENABLE DEPLOYMENT

Advanced computational power and optimisation modelling software

Increased space granularity and introduction of zonal or nodal pricing in electricity markets requires introducing a detailed network representation in dispatch modelling. While system and market operators should have state-of-the-art hardware and software, including optimisation modelling tools with high computational power, they also need access to a highly skilled workforce capable of modelling and operating the power system.

Clear and transparent pricing methodology

As electricity markets become more complex and their processes become more automated, regulators need to ensure there are clear and transparent methodologies for price formation, regardless of the chosen market design. A clear and transparent methodology builds confidence among market participants. Moreover, combatting insider trading and market manipulation via regulatory oversight strengthens the trust of market participants.

Nodal pricing in California is calculated based on the economic theory that matches the demand and supply of power. Mathematically, it is computed with an objective function to minimise the total system costs subjected to match demand and supply, adhering to all operational constraints. This computation is done at each node of the transmission network (CAISO, 2005).

IV. CURRENT STATUS AND EXAMPLES OF LEADING INITIATIVES

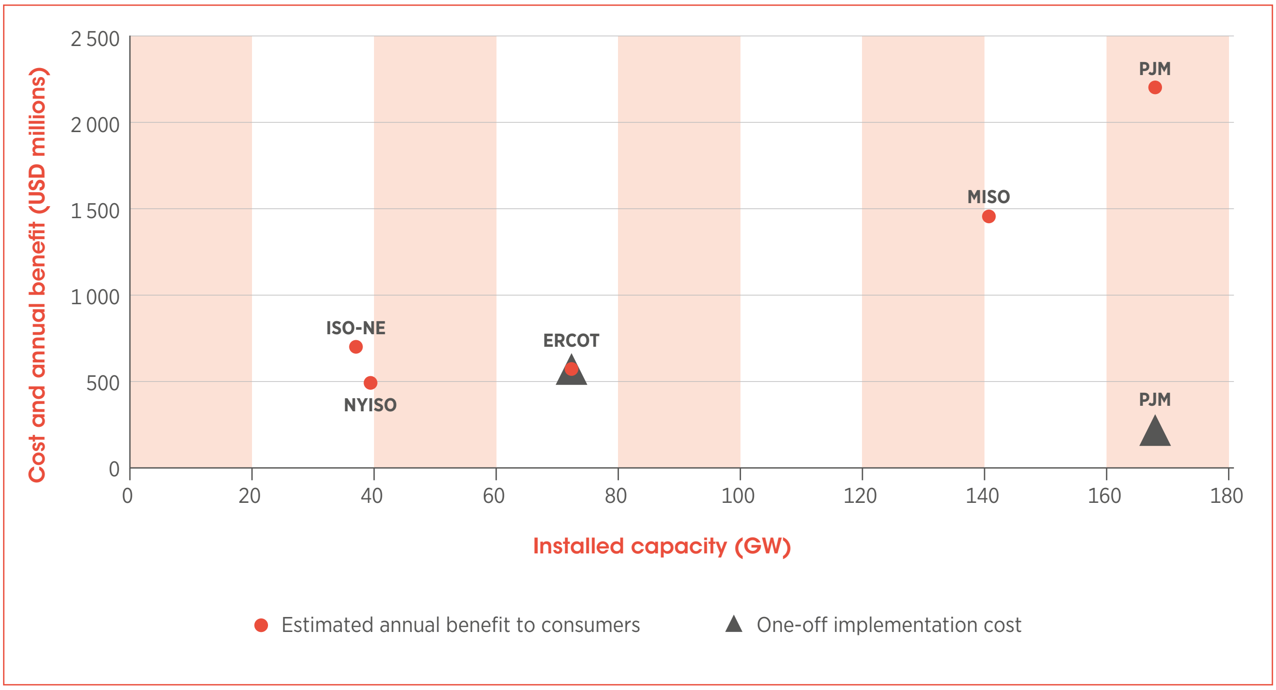
Locational pricing in the United States

Distributed energy resources (DERs) are expected to transform New York's power system. The New York Independent System Operator (NYISO) aims to reform the power market to enable higher participation of DERs, which are mainly renewable energy sources, in the power grid. Currently, NYISO provides real-time prices at the zonal level (updated every five minutes). Zonal pricing however may not necessarily reflect sub-zonal conditions. To enable higher DER participation and to provide more economically efficient DER benefits, NYISO will provide more granular pricing (NYISO, 2017a). The granular pricing data is expected to encourage investments at the most economically efficient transmission location (NYISO, 2017b). NYISO, as part of its Distributed Energy Resources Roadmap for New York's Wholesale Electricity Markets, is planning to provide real-time prices on nodal locations calculated for every five minute block. Currently, NYISO is piloting the roadmap at a few nodes at selected locations (NYISO, 2017b).

Investment in transitioning to a nodal pricing system has been recovered within one year of operation by different Independent System Operators (ISOs) in the United States, as illustrated in Figure 2.

Another important example of nodal pricing implemented in the United States is the ERCOT (Electric Reliability Council of Texas) system. In 2003, ERCOT transitioned from a wholesale electric market with four large zones to a marketplace made up of more than 4 000 nodes. This undertaking, called the Nodal Project, improved the efficiency of the grid by increasing the amount of specific information for different locations throughout the state (Choose Energy, 2015). As Figure 2 illustrates, the one-off implementation cost for the Nodal Project in ERCOT equals the annual benefit to consumers.

Figure 2: Costs and benefits of nodal pricing



ISO-NE: Independent System Operator New England; NYISO: New York Independent System Operator; ERCOT: Electric Reliability Council of Texas; MISO: Midcontinent Independent System Operator; PJM: Pennsylvania New Jersey Maryland Interconnection

Note: GW = Gigawatts

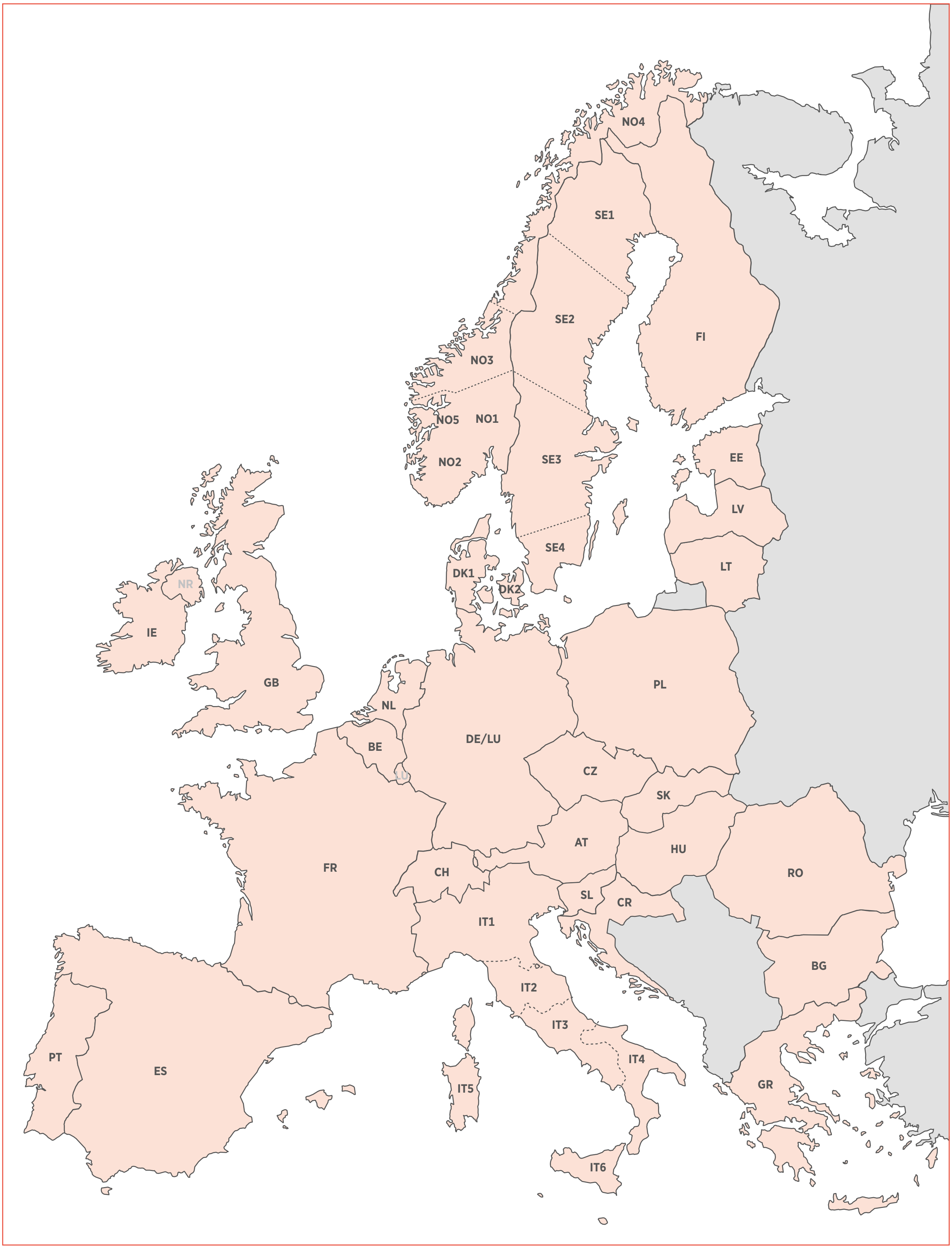
Source: Neuhoff and Boyd (2011)

Zonal pricing in the European markets

Bidding zones represent the cornerstone of the pan-European electricity market. Electricity is traded across bidding zones based on available transmission capacities calculated by TSOs, while the electricity traded within a bidding zone is considered unrestricted and unlimited by transmission capacity. While in most cases a bidding zone corresponds to national borders, some countries have divided their national transmission systems into more bidding zones, including Denmark (two bidding zones), Italy (six geographical bidding zones), Norway (five bidding zones) and Sweden (four bidding zones). Moreover, until 1 October 2018, Austria, Luxembourg and Germany were grouped into a single bidding zone. Following the decision of the Agency for the Cooperation of Energy Regulators (ACER) No. 06/2016 from 17 November 2016, the bidding zones were split into two and a bidding zone border between Germany/Luxembourg and Austria was introduced. Figure 3 illustrates the bidding zone configuration in European wholesale market.

According to ACER, in 2017, the cross-zonal transmission capacity made available for trading on the market was significantly below the “benchmark capacity”, i.e., the maximum capacity that could be made available to the market while preserving operational security. On average only 49 % of the benchmark capacity in high-voltage alternating current interconnectors was made available to the market in 2017, which was probably the result of congestion not being properly addressed by the existing bidding zone configuration. Therefore, the relatively low level of available cross-zonal capacity is an indication that structural congestion is located within bidding zones, rather than between bidding zones, in most of continental Europe. Moreover, congestion at bidding zone borders is mostly linked to intra-zonal network lines, rather than to interconnectors. For example, in 2017, congestion was caused within the Central-West Europe (CWE) region 86 % of the time by internal lines and 14 % of the time by interconnectors. Within CWE, over 50 % of these occurrences related to network elements located inside Germany (ACER, 2018).

Figure 3: Bidding zone configuration in European wholesale markets



Source: Adapted from ENTSO-E (2018)

Disclaimer: Boundaries and names shown on this map do not imply any official endorsement or acceptance by IRENA.

V. IMPLEMENTATION REQUIREMENTS: CHECKLIST

TECHNICAL REQUIREMENTS

Software:
- Higher computational power and better system modelling tools
- Automation of various processes and information exchange related to both market and system operation

REGULATORY REQUIREMENTS

Wholesale market:
- A liberalised wholesale electricity market with unbundling across the entire value chain
- A defined level of granularity for the implementation of locational marginal pricing or for zonal market design based on technical and socio-economic criteria (*e.g.*, welfare maximisation, transmission system reliability, etc.)
- A detailed load flow studies for the identification of key nodes for the implementation of nodal pricing or bidding zone configurations
- The development of a transparent pricing methodology
- Surveillance of the market to ensure market manipulation does not occur
- Regular monitoring of the impact of increasing the geographical granularity on power costs for consumers and publication of the results for broader public awareness

STAKEHOLDER ROLES AND RESPONSIBILITIES

Regulators:
- Design the rules, in consultation with interested stakeholders (market operators, market participants, system operators, etc.)
- Enforce the rules, monitor the market outcomes regularly and adapt the market design, whenever necessary

Market operators and system operators:
- Perform pilots and conduct studies with the regulators and interested stakeholders to assess the space granularity required in the market design

ABBREVIATIONS

ACER	Agency for the Cooperation of Energy Regulators
CWE	Central-West Europe
DER	Distributed energy resource
ERCOT	Electric Reliability Council of Texas
ISO	Independent system operator
LMP	Locational marginal price
NYISO	New York Independent System Operator
TSO	Transmission system operator
VRE	Variable renewable energy

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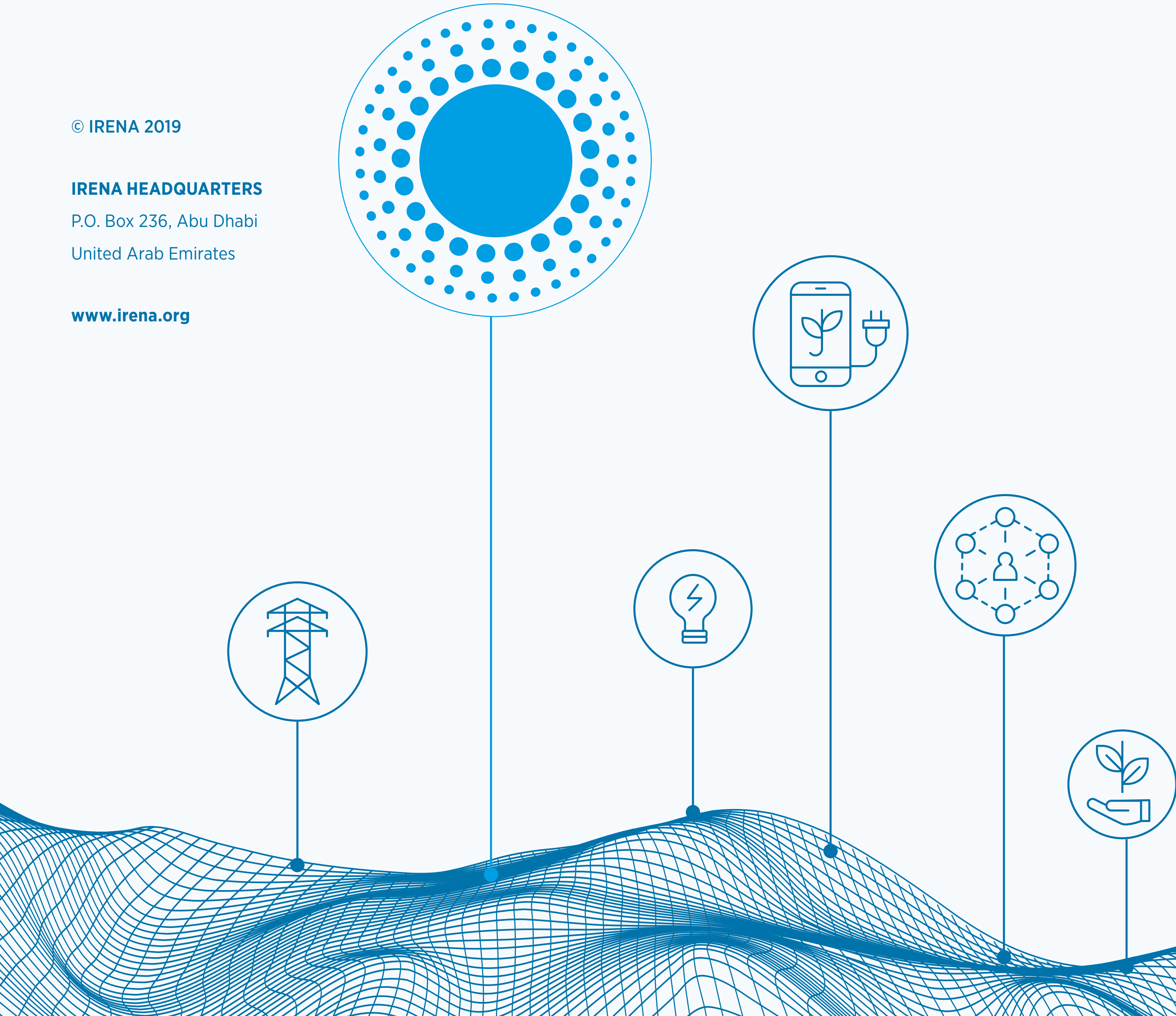

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INNOVATIVE ANCILLARY SERVICES

INNOVATION LANDSCAPE BRIEF

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1 NEW ANCILLARY SERVICE PRODUCTS AND MARKET PARTICIPANTS

New products

- Ramping products
- Fast response frequency reserve

New market participants

- Wind turbines providing inertial response
- Solar PV and batteries providing voltage support
- Distributed energy resources providing frequency and voltage control

→ **Increased flexibility for VRE integration**

2 KEY ENABLING FACTORS

- Defining performance-based products
- Separating capacity and energy products, and contracting periods
- Separating upwards and downwards balancing products

3 SNAPSHOT

- Batteries can provide ancillary services in Australia, Belgium, Germany, Netherlands, UK and USA
- Wind power generators can provide balancing services in nine European countries
- A US system operator uses separated ramping products to help the system meet ramping needs
- The exchange of balancing services across borders in Europe is increasing
- Local flexibility markets emerge in Germany and UK, where ancillary services are procured by the DSOs

WHAT ARE ANCILLARY SERVICES?

Ancillary services are vital to support power system operation. There are two types: frequency and non-frequency services (voltage control, black start).
Innovative ancillary services can address the variability and uncertainty of the VRE.

INNOVATIVE ANCILLARY SERVICES

Ancillary services need to be adapted to increase system flexibility.
The ancillary service market should be open to all participants.

ABOUT THIS BRIEF

This brief forms part of the IRENA project "Innovation landscape for a renewable-powered future", which maps the relevant innovations, identifies the synergies and formulates solutions for integrating high shares of variable renewable energy (VRE) into power systems.

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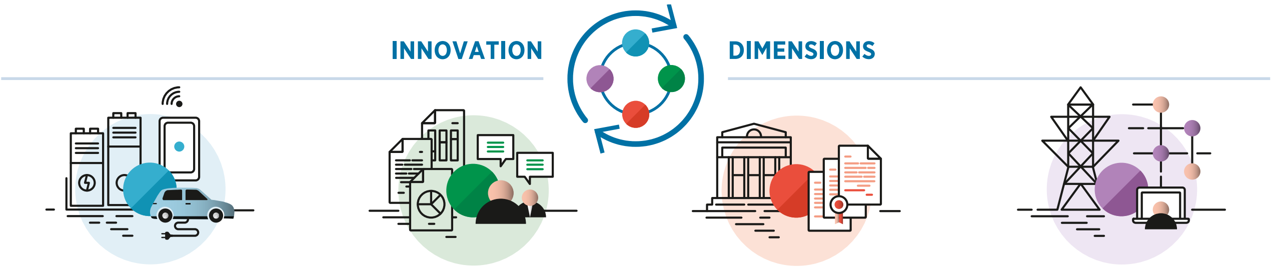

● **ENABLING TECHNOLOGIES**

1 Utility-scale batteries
2 Behind-the-meter batteries

3 Electric-vehicle smart charging
4 Renewable power-to-heat
5 Renewable power-to-hydrogen

6 Internet of things
7 Artificial intelligence and big data
8 Blockchain

9 Renewable mini-grids
10 Supergrids

11 Flexibility in conventional power plants

● **BUSINESS MODELS**

12 Aggregators
13 Peer-to-peer electricity trading
14 Energy-as-a-service

15 Community-ownership models
16 Pay-as-you-go models

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● **SYSTEM OPERATION**

25 Future role of distribution system operators
26 Co-operation between transmission and distribution system operators

27 Advanced forecasting of variable renewable power generation
28 Innovative operation of pumped hydropower storage

29 Virtual power lines
30 Dynamic line rating

This innovation landscape brief examines innovations in ancillary services – a key market design innovation that addresses the variability and uncertainty of the VRE share in the grid. Ancillary services need to be adapted to increase system flexibility by remunerating new services needed in a high-variability scenario. Moreover, in addition to being open to conventional generation units, the ancillary service market should be open to new participants, such as large-scale renewable generators and battery storage, and to providers of distributed energy resources (DERs), including demand response, small-scale battery storage, and distributed VRE generation.

The brief is structured as follows:

I Description

II Contribution to power sector transformation

III Key factors to enable deployment

IV Current status and examples of ongoing initiatives

V Implementation requirements: Checklist

I. DESCRIPTION

The increased deployment of VRE generation sources introduces variability and uncertainty into power system operation. To address these issues, transmission system operators (TSOs) and distribution system operators (DSOs) procure system services: the deployment of flexible on-demand generation, storage or demand-side response to help maintain grid reliability and security. This brief discusses how the design of ancillary service markets can evolve to help system operators integrate VRE by addressing the introduced variability and uncertainty. To ensure a reliable and stable system, the power supply must meet demand at all times to maintain the nominal grid characteristics in terms of frequency and voltage.

"Ancillary services" are services necessary for the operation of a transmission or distribution system. Typical ancillary services are procured by TSOs and can be clustered into frequency ancillary services (balancing of the system[1]) and non-frequency ancillary services (voltage control and black-start capability). Conventionally, TSOs have utilised power from generating resources, storage resources (such as pumped hydro storage or capacitors) or reactive power control equipment (such as synchronous or static compensators or capacitor banks) to obtain ancillary services (Singh & Papalexopoulos, 1999). These strategies help system operators maintain grid frequency and voltage at desired levels while provisioning some generation capacity as reserves for contingency events (Stoft, 2002).

To address the variability and uncertainty of increasing VRE in the grid, ancillary services need to be adapted to increase system flexibility, incentivise fast response and ramping ability, and remunerate each of the services accordingly. Moreover, the definitions and measurement schemes of some conventional ancillary services do not provide a proper basis for evaluating the performance of different resources. As a consequence, some resources may not receive the right incentives to provide flexibility, thus limiting the flexibility available to system operators. To address variability and uncertainty in the grid, there is a need to redesign the existing ancillary service products and create new ones. For instance, Pennsylvania Jersey Maryland (PJM) Interconnection, an independent regional transmission operator in the United States, has developed different frequency regulation products for slower conventional resources and for faster battery storage resources.

Moreover, in addition to being open to conventional generation units, the ancillary service market should be open to new participants, such as large-scale renewable generators and battery storage, and to providers of DERs, including demand response, small-scale battery storage and distributed VRE generation.

Table 1 briefly describes traditional and new ancillary services, as well as new players allowed to provide these services. The innovative ancillary services are highlighted.

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[1] Supply may vary with unexpected increases or decreases in power supply.

Table 1 Types of ancillary service and associated products

Ancillary service	Product	Description	Typical response time
Frequency regulation	**Primary regulation**	The automatic local regulation provided by generating unit speed regulators. This level of regulation sustains frequency levels, preventing large deviations from the scheduled value.	Sub-seconds to seconds
		Innovations: • Fast frequency response is a new product designed to remunerate the provision of fast response[1]. Batteries are great providers of such services, creating the possibility of additional revenue streams for battery operators/owners. • Wind turbines can provide inertial response through power electronic converters. • Photovoltaic (PV) installations, direct current systems and batteries can also provide synthetic inertial response if the inverter is programmed to do so. However, as inverters are not stuck with characteristics of large spinning masses and have more options to provide system stability, this might not be the best use of them. • If regulation allows, DERs can provide this service.	
	Secondary regulation	The automatic regional regulation provided by automatic generation control (AGC), which sends signals from the control centre to certain generators to re-establish the nominal frequency value and restore the primary reserve capacity.	5–15 minutes
		• If regulation allows, DERs can provide this service.	
	Tertiary regulation	The manual regional regulation provided by generating units and controlled by the system operator.	>15 minutes
Non-frequency regulation	**Voltage support**	The injection of reactive power to maintain system voltage within a prescribed range.	Seconds
		Innovations: • Voltage control through reactive power provided by resources connected to the power system through inverters, such as solar photovoltaic and battery storage. • If regulation allows, DERs can provide this service.	
	Black start	The ability to restart a grid after a blackout.	Minutes
	Innovations: • Ramping products	Fast ramping resources that can respond to large net load variations in a short time. This product properly remunerates the fast ramping capability of generators and incentivises flexibility.	Minutes

▨ **Innovations in ancillary services**

Note: *The nomenclature and the definitions of different types of ancillary service used in this table are not standardised and can vary significantly from country to country. Historically, the nomenclature and definitions have been based on the services provided by energy resources for reliable grid operations. However, different types of ancillary service are increasingly being categorised as specialised products, catering to specific grid requirements. For example, "Commission Regulation (EU) 2017/1485 of 2 August 2017 establishing a guideline on electricity transmission system operation" specifies how TSOs across the European Union should manage their network, taking into account that the power system is integrating more renewables and that markets are increasingly interconnected (European Commission, 2017a).*

[1] *Sometimes, the inertial response of wind turbines is also classified under the category of fast frequency response.*

(Based on: Banshwara et al., 2017; Batlle, 2013; Kirby, 2004)

Trading ancillary services with neighbouring TSOs within a regional market is also key to increasing the overall flexibility of the transmission system and reducing balancing costs. Several stakeholders in the European Union (EU), including the Agency for the Cooperation of Energy Regulators (ACER), national regulatory authorities, and TSOs within the European Network of Transmission System Operators for Electricity (ENTSO-E), have developed a set of rules on the operation of balancing markets, which entered into force via "Commission Regulation (EU) 2017/2195 of 23 November 2017 establishing a guideline on electricity balancing".

The European balancing guideline sets down rules on the operation of balancing markets throughout the EU, referring to those markets that TSOs use to procure balancing services (either balancing energy or balancing capacity[2]) to keep the system balanced in real time. This regulation provides opportunities for cross-border trading within such balancing markets (European Commission, 2017b). As such, this framework enables a greater cross-border availability of resources for balancing the system and, in turn, lowers costs for procuring these services. (See also Innovation Landscape Brief: Regional Markets. [IRENA, 2019b])

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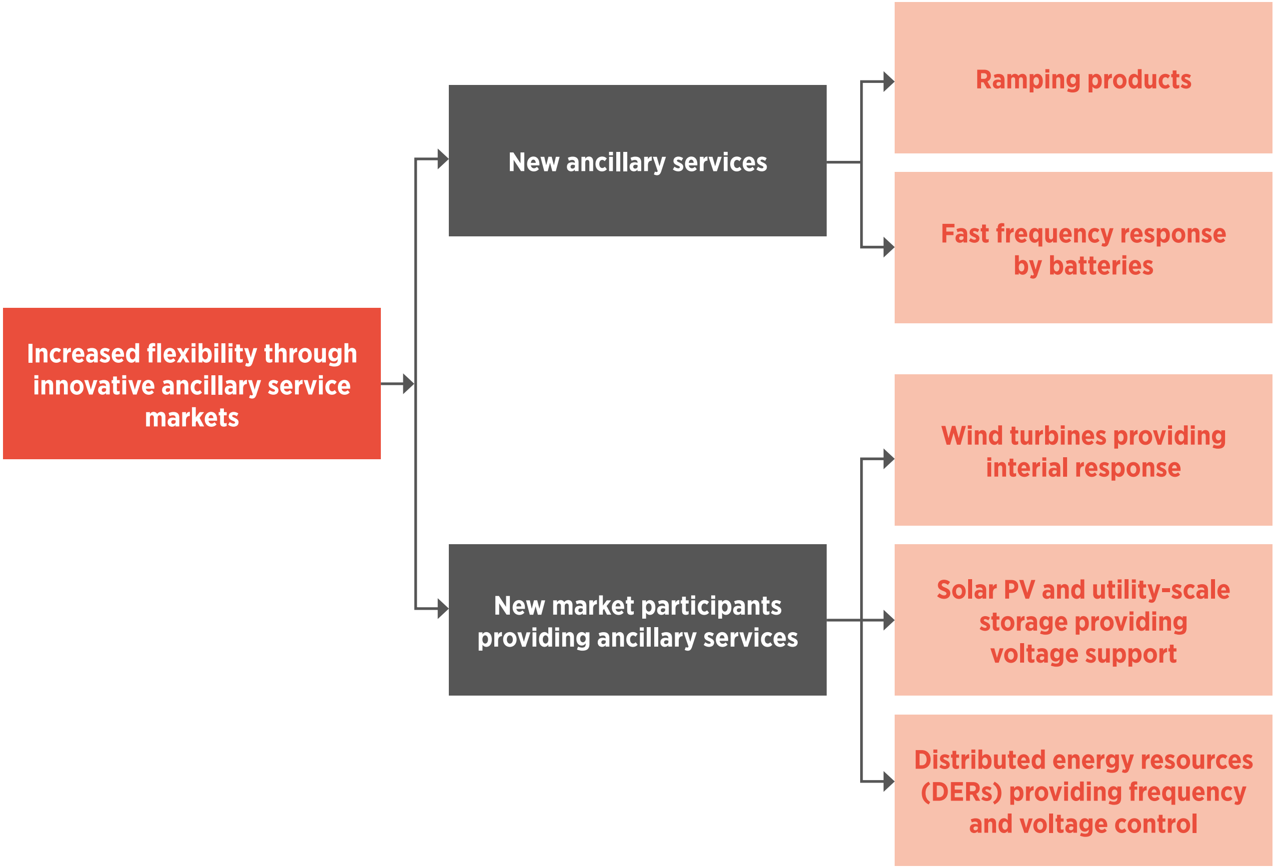
[2] Commission Regulation (EU) 2017/2195 defines "balancing energy" as the energy used by TSOs to perform balancing and provided by a balancing service provider; "balancing capacity" is defined as the volume of reserve capacity that a balancing service provider has agreed to hold and in respect to which the balancing service provider has agreed to submit bids for a corresponding volume of balancing energy to the TSO for the duration of the contract (European Commission, 2017b).

II. CONTRIBUTION TO POWER SECTOR TRANSFORMATION

To increase system flexibility and integrate a high share of VRE, while keeping the system in balance, several innovative products are being developed in different markets. One set of innovative ancillary services addresses flexibility issues, remunerating those services related to rapid ramping requirements, frequency regulation, and so on. Another set of innovative ancillary products allows new market participants to offer such services: wind turbines can be utilised to provide inertial response, solar photovoltaic (PV) can offer reactive power support, and other DERs can help increase market liquidity across different trading time frames and reduce ancillary service procurement costs.

Figure 1: Innovations in ancillary services and examples



New ancillary services

Ramping products

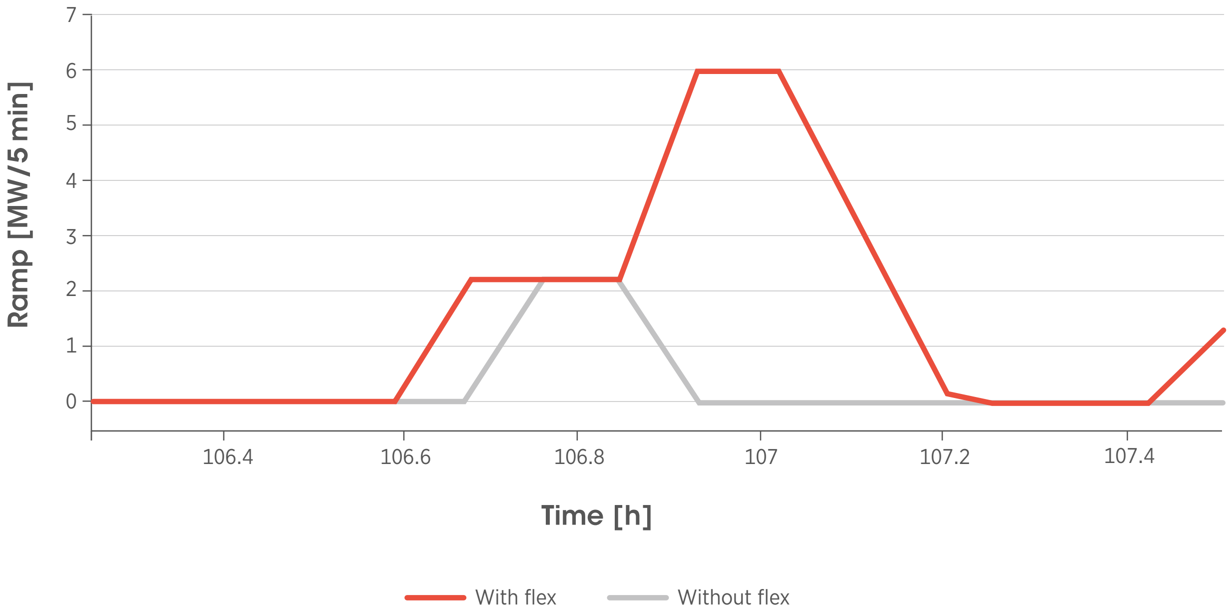
With an increase in the VRE share, the net load[3] curve becomes increasingly volatile (Kirby & Milligan, 2008). Conventional generation, with a controllable generation profile, is expected to be increasingly displaced by low marginal cost VRE generators and is instead expected to be used to provide back-up power.

System operators would need reserves that can provide fast ramping capabilities to address such net load volatility. Conventionally, net load ramping requirements have been served by conventional generators. In most markets, such ramping by conventional generators is not identified as a separate ancillary service and is only compensated based on the marginal cost of electricity production. When such ramping is procured through energy markets, steep ramping requirements can lead to increased prices in the energy market, thereby distorting the market for participants who are not providing ramping services (Ela *et al*., 2012).

To address this issue, a separate ramping or flexibility product is created as part of the balancing market to serve the net load ramping requirements. For example, California Independent System Operator (CAISO) in the United States was among the first independent system operators in North America to implement a separate flexibility ramping product. In November 2016, CAISO implemented Flexible Ramp Up and Flexible Ramp Down Uncertainty Awards, which are ancillary service market products to procure ramp-up and ramp-down capability for 15 minute (min) and 5 min time intervals. The product is procured in terms of megawatts (MW) of ramping required in a 5 min duration, and any resource capable of fulfilling the ramping requirement can participate. Market participants do not provide bids for this product but are instead compensated according to their lost opportunity cost of providing other services in the ancillary service market. The price for providing ramp-up service is capped at USD 247 per megawatt-hour (/MWh), while the price for providing ramp-down service is capped at USD 152/MWh (CAISO, 2018).

Furthermore, when such ramping products are traded in the ancillary service market, the availability of fast ramping capacity increases, which in turn reduces the price spikes associated with ramping shortfall (Krad, Ibanez & Ela, 2015a). This is depicted in Figure 2.

Figure 2: Available ramping capacity with and without flexibility reserve products



Source: IRENA (2017), adapted from Krad, Ibanez & Ela (2015a)

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[3] "Net load" is the difference between the load and the electricity production from variable renewable generation.

Fast frequency response provided by batteries

Grid frequency must be kept in the system within a prescribed range for secure system operations. In cases of sudden variation in demand and supply in the system, grid frequency can suddenly go out of range, thus affecting the reliability and security of the system. Conventionally, quick restoration of frequency within a few seconds to minutes has been enabled by increased output by conventional generators through autonomous governor control. However, with increased VRE penetration, autonomous response offered by the remaining conventional generators may not be sufficient to address frequency drops. Batteries are well suited to providing balancing services and fast frequency response because of their short response times.

The fall in costs of battery storage technologies has led to their increased deployment by system operators as well as generators for various purposes. Battery storage technology has a sub-second response capability that makes it suitable for use by system operators as a rapid response frequency reserve. A separate ancillary service market product can be created to procure such services from battery storage systems. For instance, National Grid in the United Kingdom has added a new product to contract with battery storage providers for fast frequency reserve services. In 2016, National Grid conducted an enhanced frequency response (EFR) tender under which it contracted eight battery storage facilities for four years to provide sub-second rapid response frequency reserves (KPMG, 2016).

Similarly, Australia's energy market operator contracted Tesla's 100 MW/129 MWh lithium-ion battery in South Australia. The battery, known as Hornsdale Power Reserve, provides accurate response to the frequency control and ancillary services market at a lower rate than conventional sources of energy. In its first four months of operation, the price of frequency ancillary services was reduced by 90 % (Gabbatiss, 2018; Vorrath & Parkinson, 2018).

In Japan, as opposed to the TSO procuring the ancillary service directly, some utilities require that large solar PV projects control their feed-in of electricity by using battery storage to meet grid frequency requirements. For example, the 38 MW Tomakomai solar PV project includes a 20 MW lithium-ion battery, one of the world's biggest at the time of construction in 2017. The sole application of the battery is to meet the frequency requirements of the local energy utility, Hokkaido Electric Power Company.

New market participants providing ancillary services

Wind turbines providing inertial response

"Inertial response" refers to the ability of synchronous generators to speed up or speed down to overcome immediate frequency disturbances. Inertial response has been traditionally provided by large thermal generators and large hydropower plants. Although such frequency disturbances can be addressed using fast frequency response services, inertial response can provide faster response times and more reliable response because it is an inherent feature of generators.

VRE technologies have been exempted from balancing responsibilities in many countries. However, some VRE technologies can offer balancing services. Wind turbines connected to the power system through a power electronic converter can provide inertial response (also known as synthetic inertia) during frequency disturbances. During a frequency surge, the power electronic controller can apply a retarding torque on the turbine to reduce generation, whereas during frequency drops (Ela et al., 2012), the controller can utilise the kinetic energy of the turbine to increase power output (Morrena, Pierikb & Haana, 2006). This can also be achieved by reducing or increasing the blade angle to decrease or increase the power supply (Miao et al., 2010). For instance, Hydro-Québec TransÉnergie, a TSO in Canada, requested an inertia emulation function in the wind turbines as a part of its 2 000 MW wind energy procurement tender (Brisebois & Aubut, 2011).

Inverters can be programmed to help control frequency as well, and the way that PV plants are operated can be a factor in the ability to provide frequency response. However, a question is whether it is best to use inverters this way. Inverters are not stuck with the characteristics of large spinning masses and have more options to provide system stability (Roselund, 2019).

Obtaining system services from VRE requires various policy measures, such as specific grid codes and upgrades to the system services procurement mechanism (IRENA/IEA/REN21, 2018).

PV power plants and utility-scale storage providing reactive power

Reactive power helps maintain voltages in the network within prescribed limits (Kirby & Hirst, 1997). However, reactive power flowing for long distances in the transmission and distribution grid causes a number of problems, which include inadmissible voltage excursions and increased losses. Therefore, reactive power must be supplied, when needed, from a nearby source. This has conventionally limited market mechanisms for procuring reactive power, as there may be limited alternative sources of reactive power at a given location.

Devices such as solar PV or battery storage, which have a solid-state electronics interface with the power system, can provide reactive power support (Ela *et al*., 2012). Reactive power support from large-scale wind and solar generation connected to the grid via inverters is also important in some jurisdictions – notably, where high-quality primary energetic resources are in areas far from main load centres and connect to main load centres via "weak" networks. Designing proper mechanisms to ensure that these assets contribute to reactive power control is also relevant. Such mechanisms can include:

- adequately designed connection requirements in grid codes, which may slightly increase capital expenditure requirements for generators and thus guide investment decisions

- incentives oriented specifically to the procurement of reactive power as a separate product, which have been less common so far.

Distributed energy resources

DERs, such as rooftop solar systems, behind-the-meter battery storage systems, plug-in electric vehicles, and commercial and industrial loads, can provide ancillary services to system operators through price-based incentives, often referred to as "explicit demand response". By increasing liquidity and competition in the ancillary service markets, DERs can also help lower ancillary service procurement costs. DERs may be allowed to participate independently or through aggregators or retailers, depending on the market design in place.

For instance, in December 2017, the New York Independent System Operator (NYISO) released a concept proposal of market design to enable DERs to participate in wholesale as well as ancillary service markets. Under this proposal, DERs would be treated on a par with other market players and would be able to participate in capacity reserve markets, regulation service markets, and so on, either directly or via aggregators of small-scale DERs (<100 kilowatts) (NYISO, 2017).

Also, DERs can participate in local flexibility markets, if established. Local flexibility markets are platforms that centralise local flexibility offers to allow system operators to reliably and economically relieve physical congestions and bottlenecks from the grid (EPEX SPOT, 2019). Being connected to the distribution grid, DERs are potentially problematic for network stability and reliability in the distribution network. In addition to central utilisation of DER flexibility services in traditional markets, decentralised management of DERs by DSOs could be possible. The interest in this type of management is rising, especially because of upcoming risks for, among other things, over-voltage and congestion with the penetration of distributed generation. DSOs could then procure local system services from DERs to solve issues related to voltage regulation, power quality and distribution network congestion. (See also: Innovation Landscape Brief: Market Integration of distributed energy resources [IRENA, 2019c])

Potential impact on power sector transformation

- In Germany, renewable energy generators, battery storage systems and industrial loads were allowed – alongside conventional generators – to participate in the balancing markets in 2009. In the period from 2009 to 2015, the balancing **market size in gigawatts (GW) decreased by 20 % and ancillary service procurement costs by TSOs decreased by 70 %**. During the same period, **system stability increased and the installed capacity of VRE increased by 200 %**. This experience indicates that allowing new resources to participate in ancillary service markets can help increase system stability while reducing costs (Wang, 2017).

- The deployment of the sub-second EFR by National Grid in the United Kingdom is expected to result in **costs savings of approximately USD 262 million**[4] over four years compared with alternative ways of providing frequency response (KPMG, 2016).

- According to a study by Krad, Ibanez and Ela (2015b), the deployment of flexibility reserve products, such as CAISO's flexibility ramping product (Flexible Ramp Up and Flexible Ramp Down Uncertainty Awards), **can offer value in managing uncertainty introduced by VRE** (i.e. real-time prices that exceed USD 1000/MWh).

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[4] Original figure of GBP 200 million converted to USD using the prevailing exchange rate as per Bloomberg on 24 July 2018 (www.bloomberg.com/quote/GBPUSD:CUR).

III. KEY FACTORS TO ENABLE DEPLOYMENT

Introduction of innovative products and new market participants requires revision of rules on how these services should be procured are also needed (e.g. more frequent contracting periods, local markets, cross-border sharing of reserves).

Defining performance-based products

Conventionally, different energy resources providing frequency regulation services have been compensated at the same remuneration, irrespective of their performance (IRENA, 2017). However, battery storage-based resources can provide much faster regulation service than conventional generators. Therefore, the compensation mechanism must appropriately value the performance characteristics of different resources. This will incentivise greater deployment of battery storage technology in providing ancillary services.

For instance, in 2011 the Federal Electricity Regulatory Commission's Order 755 mandated compensation to resources providing frequency regulation based on their performance (FERC, 2011). Following this order, PJM Interconnection implemented a new product to remunerate resources based on how fast they are able to respond to the system operator signals. The compensation is proportional to the response time, thereby incentivising battery storage systems in providing such services. Two different signals were created – a conventional signal and a fast response signal – so that fast responsive resources such as batteries have an advantage over conventional resources and can be remunerated for this service (PJM Interconnection, 2018).

Separating capacity and energy products, as well as contracting period

In many ancillary service markets, balancing capacity and balancing energy are jointly procured. Balancing capacity gives TSOs the possibility of activating a certain amount of balancing energy in real time. For instance, automatic frequency restoration reserve (FRR) markets in Denmark and Spain and manual and automatic FRR markets in Germany follow this approach (IRENA, 2017). However, only those generators that can offer balancing capacity can offer balancing energy in real time. This method does not reveal the most cost-effective resources in real time. It also restricts the participation of various DERs, including VRE, because such products are procured well in advance and most VRE resources or DERs cannot commit capacity earlier than in real time.

For instance, the Netherlands' automatic and manual FRR markets, as well as Belgium and Denmark's manual FRR market, procure balancing capacity and energy as separate products (IRENA, 2017). For Belgium and the Netherlands, two options are available: capacity and energy in one product or as separate energy products (free bids).

Separating balancing capacity products from balancing energy products can help discover cost-effective resources in real time while allowing VRE resources and other DERs to offer their energy flexibility in such markets. For this, the acquisition of balancing energy has to shift from yearly to monthly, or even daily, procurement. This will increase VRE resources and DER participation in ancillary service markets, thereby increasing system flexibility while leading to increased deployment of such resources.

The US National Renewable Energy Laboratory has conducted studies to analyse the changes required to operate reserve requirements due to the introduction of up to 30 % solar PV and wind energy resources on large portions of the western and eastern interconnections of the US grid. Studies concluded that the reserve requirements should not be static, as they have conventionally been, but instead should change according to the system conditions on a shorter time scale, such as on an hourly basis (EnerNex Corporation, 2011; GE Energy, 2010).

However, in systems where the short-term signals are, for whatever reason (e.g. volatility, lack of credibility), insufficient to incentivise investments in resources capable of providing ancillary services in real time, contracting them in advance can be a way to enable or unlock investments.

Separating upwards and downwards balancing products

In many ancillary service markets, frequency regulation service is procured as a single product that includes both frequency regulation up and frequency regulation down services. For instance, in Denmark, Italy and Spain system operators procure such a unified frequency regulation service under FRR requirements (IRENA, 2017).

Procuring frequency regulation up and down as a single product limits the amount of capacity and the types of resources that can participate in the ancillary service market. For instance, a combined-cycle plant operating at its minimum generation point could provide only regulation up, whereas a wind plant operating at its maximum generation could provide only regulation down. However, neither resource would be able to participate in the ancillary service market, which procures regulation up and down as a single service. Therefore, frequency up and down regulations should be procured as separate products. This will enable VRE resources, as well as DERs, to participate in ancillary service markets, thereby increasing system flexibility and resource deployment. For example, Elia, the Belgium TSO, has defined two asymmetrical products for frequency containment reserves (FCRs, also called R1): “R1- down” and “R1- up”, for which the supplier needs to react to any frequency deviation bigger than 100 mHz (separated for the positive and negative deviations) (Elia, 2018). CAISO implemented Flexible Ramp Up and Flexible Ramp Down Uncertainty Awards.

IV. CURRENT STATUS AND EXAMPLES OF ONGOING INITIATIVES

Some of the key indicators of an innovative ancillary service market are described in the table below. Case studies of innovative ancillary services follow.

Table 2 Innovative ancillary service market: Key indicators

Key indicator	Examples
VREs are able to participate in the existing ancillary service markets	• Wind power generators are allowed to provide balancing services in Belgium, Denmark, Estonia, Finland, the Netherlands, Poland, Spain, Sweden, and the United Kingdom. • In Chile, the first pilot was implemented to enable a PV power plant to provide ancillary service to the utility grid and ensure grid stability.
New ancillary service products have been designed for VRE integration	• In the United Kingdom, a new product was introduced for battery storage: enhanced frequency response. • Ramping products introduced in the United States. • EirGrid, the Irish TSO, has defined several additional system service products to cope with wind energy fluctuations. • PJM Interconnection, a system operator in the United States, has developed different frequency regulation products for slower conventional resources and for faster battery storage ones.
Battery storage can participate in ancillary service markets	• Australia, Belgium, Germany, the Netherlands, the United Kingdom, and the United States.
Reforms are made to ongoing ancillary service market or balancing market	• The EU-wide development and implementation of network codes for balancing markets and system operation, including the procurement of ancillary services by TSOs (applicable in all EU member states). • In Denmark, wind turbine operators now face charges for incorrect forecasts, the same way as conventional generators. • In the United Kingdom, recent reforms have increased charges in general for incorrect forecasts and rewarded generators and suppliers that can plug these gaps.

Examples of new ancillary services

National Grid's enhanced frequency response tender (United Kingdom)

National Grid, the TSO in the United Kingdom, has the obligation to maintain system frequency within ±1% of the target value of 50 hertz. The rising share of renewables and declining share of conventional generators in the energy mix in the recent years had led to decreased system inertia and an increase in frequency volatility. This resulted in the need for faster frequency response than the existing options could provide.

Until August 2016, National Grid was procuring fast frequency response, which was its fastest tool, with a primary response time of 30 seconds (s) and a secondary response time of 60 s. Then National Grid introduced an enhanced frequency response (EFR) to provide sub-second rapid response frequency reserves. The tender to procure EFR contracted eight battery storage facilities for four years at prices between USD 9.21/MW/h and USD 15.74/MW/h.[5] The tender was oversubscribed by seven times, with 1.2 GW of battery capacity being unsuccessful in the tender, which indicated a large interest and appetite by battery storage developers to provide these services (KPMG, 2016).

Midcontinent Independent System Operator's ramping product (United States)

To prevent pricing spikes in the energy market, Midcontinent Independent System Operator (MISO) in the United States has implemented a separate ramping product to help the system meet ramping needs. The product is procured on a day-ahead as well as a real-time basis. Resources can provide ramp up, ramp down or both, and the output in MW they can attain within 10 min counts towards the ramp up or ramp down. All dispatchable resources can participate in offering this product, which is procured by MISO across its territory and does not vary by location or zone within MISO's territory. The resources providing ramping services are compensated for the lost opportunity cost, calculated from the clearing price of other products in the market (NYISO, 2018).

New York Independent System Operator's proposed flexibility ramping product (United States)

After the successful implementation of the flexibility ramping product by CAISO and MISO, the NYISO proposed a similar flexible ramping product in its 2018 master plan. The NYISO expects that the product would be procured in both day-ahead and real-time markets. Moreover, the ramping requirement is expected to be specified in terms of the MW of response a resource can provide in a given time interval. The resources providing the ramping service are expected to be compensated at the lost opportunity cost of a resource participating in the energy market (NYISO, 2018).

Pan-European guidelines on electricity balancing and electricity transmission system operation (European Union)

As part of the EU's so-called third legislative energy package, Regulation (EC) No 714/2009 sets out the rules governing access to the network for cross-border exchanges in electricity, with a view to ensuring the proper functioning of the EU's internal market in electricity (Council of the European Union, 2009). This package created ENTSO-E, which together with the Agency for the Cooperation of Energy Regulators (ACER), develops the European network codes and guidelines (i.e. the rules for the operation of the electricity sector), which are then adopted by the European Commission. Within this framework, several network codes have been adopted, including "Commission Regulation (EU) 2017/1485 of 2 August 2017 establishing a guideline on electricity transmission system operation" and "Commission Regulation (EU) 2017/2195 of 23 November 2017 establishing a guideline on electricity balancing" (European Commission, 2017a, 2017b). The former lays down detailed guidelines on operational planning for ancillary services, as well as load-frequency control and reserve rules, including operational agreements, frequency quality, load-frequency control structure, operation of load-frequency control, FCRs, FRRs, replacement reserves, exchange and sharing of reserves, time control process, co-operation with DSOs, and transparency of information. The balancing capacity products can be defined as follows:

- **Frequency containment reserves (FCR)**: Active power reserves available to contain system frequency after the occurrence of an imbalance.

- **Frequency restoration reserves (FRR)**: Active power reserves available to restore system frequency to the nominal frequency and, for a synchronous area consisting of more than one load-frequency control area, to restore power balance to the scheduled value. A distinction is made between automatic FRRs and manual FRRs.

- **Replacement reserves**: Active power reserves available to restore or support the required level of FRRs to be prepared for additional system imbalances, including generation reserves.

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[5] Original figure of GBP 7/MW/h and GBP 11.97/MW/h converted to USD using the prevailing exchange rate as per Bloomberg as on 26 July 2018 (www.bloomberg.com/quote/GBPUSD:CUR).

Local flexibility markets

Piclo flexibility market (United Kingdom)

Open Utility is developing an online marketplace, called Piclo Flex, to enable DSOs to access location-specific flexible resources. These local flexibility markets will play a critical role in balancing local smart grids and facilitating the rollout of distributed generation, storage and electric vehicles. It acts as a marketplace for DSOs to procure services from DERs that can provide flexibility at times when the network is becoming more congested. This market is open to aggregators, suppliers, battery operators, electric vehicle charge points, industrial consumers or any other flexibility provider.

Piclo Flex allows network operators to see what is available in their regions; they can then plan how to meet their needs accordingly. It also allows them to provide greater transparency to flexibility providers seeking to determine the opportunities for additional revenues. DSOs can hold auctions to procure services in flexible capacity from a range of providers that have uploaded their capabilities to the platform.

A smart and flexible network could reduce the United Kingdom's emissions from electricity generation, but only if the DSOs can quickly and easily access flexible assets on the grid. Open Utility's resource optimisation algorithms, delivered via an intuitive online service, lower the barriers to entry and manage the deployment of localised flexibility in a highly efficient and scalable way.

Flexibility platform for congestion management (Germany)

The grid operators Avacon Netz, EWE NETZ and TenneT, and the European power exchange EPEX SPOT, have developed a clear and transparent market mechanism for flexibility providers that want to participate in market-based congestion management. By introducing local order books, flexibility offers based on network topological information will be recorded. These offers can then be accessed by system operators, who can use them to avoid grid congestions. EPEX SPOT acts as a neutral intermediary between system operators and flexibility providers.

In Germany, there is growing input from wind power plants in the north, while the main consumption areas are in the south. As a result, grid congestion at all voltage levels is increasingly occurring. This has caused substantial expenditure on grid-stabilising measures, such as feed-in management and redispatch. The transmission grid is particularly concerned by this, but congestion is also increasingly occurring at the distribution grid level.

This flexibility platform is demonstrating that a voluntary market-based instrument can prevent forecasted grid congestion by enabling better matching of generation and consumption, while taking into account local flexibility assets. In addition to other providers of local flexibilities, the automobile manufacturer Audi is participating in this flexibility market with its power-to-gas plant in Werlte, Lower Saxony.

Ancillary services trading across borders

Pan-European pilot projects for trading ancillary services across borders (European Union)

As of 2017, several European projects that aim to increase the exchange of balancing services across borders had been initiated and had started to show results. For example, the International Frequency Containment Reserve co-operation is a common market for the procurement and exchange of balancing capacity and involves ten TSOs in seven countries: Austria (APG), Belgium (Elia), Denmark (Energinet), France (RTE), Germany (50Hertz, Amprion, TenneT DE, TransnetBW), the Netherlands (TenneT NL) and Switzerland (Swissgrid). As a result of this project, where FCRs are procured through a common merit order list, FCR capacity prices have been steadily decreasing and converging across the participating countries. Other initiatives in Europe aim to net imbalances or exchange balancing energy across TSO scheduling areas, such as the project to exchange energy from automatic FRRs between Austria and Germany. As a result, the overall cross-zonal exchange of balancing energy (including imbalance netting) almost doubled between 2015 and 2017 (ACER/CEER, 2018).

Other pan-European pilot projects for trading ancillary services include:

- **International Grid Control Cooperation**: A regional project operating the imbalance netting process that involves 11 TSOs in eight countries: Austria (APG), Belgium (Elia), Czech Republic (ČEPS), Denmark (Energinet.dk), France (RTE), Germany (50Hertz, Amprion, TenneT DE, TransnetBW), the Netherlands (TenneT NL) and Switzerland (Swissgrid).

- **e-GCC**: A regional project operating the imbalance netting process that involves Czech Republic (ČEPS), Hungary (MAVIR) and Slovakia (SEPS).

- **Imbalance Netting Cooperation**: A regional project operating the imbalance netting process that involves Austria (APG), Croatia (HOPS) and Slovenia (ELES).

- **Platform for the International Coordination of Automated Frequency Restoration and Stable System Operation**: Starting point for the implementation and operation of a platform for automatically activated FRRs, in compliance with the European network codes.

- **Manually Activated Reserves Initiative**: An initiative to design a platform for exchanging balancing energy from manually activated FRRs, launched in 2017 by 19 European TSOs.

- **Trans European Replacement Reserves Exchange**: A project selected by ENTSO-E to become the European platform for the exchange of balancing energy from replacement reserves pursuant to the network codes, in which nine TSOs participate: Czech Republic (ČEPS), France (RTE), Italy (Terna), Poland (PSE), Portugal (REN), Romania (Transelectrica), Spain (RED), Switzerland (Swissgrid) and the United Kingdom (National Grid).

V. IMPLEMENTATION REQUIREMENTS: CHECKLIST

TECHNICAL REQUIREMENTS

Hardware:
- Power electronic converters and control devices to enable inertial response by wind turbines
- Inverters enabling PV, battery storage to provide ancillary services

Software:
- Extension of existing software applications or development of dedicated software applications for trading of new products in the ancillary service markets
- Data analytics software to record and analyse ancillary service market transactions

REGULATORY REQUIREMENTS

Retail market:
- Allowing DERs to participate in ancillary service markets

Wholesale market:
- Regulatory mandates for new ancillary service products that can enable better integration of VRE into the system, as well as in recognition of the services VRE generators can provide to the grid

Distribution and transmission system:
- Regional, national, federal or sub-national roadmap for integration of VRE generation into the grid, encompassing role of ancillary service providers and including the design of dedicated ancillary service markets at DSO or TSO level
- Permission for DSOs to procure ancillary services
- Strong co-operation frameworks between DSOs, TSOs and ancillary service providers

STAKEHOLDER ROLES AND RESPONSIBILITIES

TSOs:
- Conducting studies to evaluate development of new ancillary services for better VRE integration
- Conducting pilots for new ancillary service products (including regional projects, where applicable)
- Introducing specific grid codes and upgrading the system services procurement mechanism

DSOs:
- Forecasting ancillary services that could be provided by DERs, based on historical data and advanced weather forecasts
- Securely storing and sharing grid-related data with TSOs and other ancillary service providers, according to applicable data privacy and sharing norms

New ancillary service providers (utility-scale VRE and DERs):
- Participating in ancillary service markets, where established
- Complying with existent regulation and technical requirements of the ancillary service market, including information exchange with DSOs and TSOs (*e.g.* capacity, location, type of DER)

Regulators:
- Defining and mandating new ancillary service products in collaboration with TSOs and DSOs to enable better VRE integrationasts

ABBREVIATIONS

ACER	Agency for the Cooperation of Energy Regulators
CAISO	California Independent System Operator
CEER	Council of European Energy Regulators
DER	distributed energy resource
DSO	distribution system operator
EFR	enhanced frequency response
ENTSO-E	European Network of Transmission System Operators for Electricity
EU	European Union
FCR	frequency containment reserve
FERC	Federal Electricity Regulatory Commission
FRR	frequency restoration reserve
GW	gigawatts
min	minutes
MISO	Midcontinent Independent System Operator
MW	megawatts
MWh	megawatt-hour
NYISO	New York Independent System Operator
PJM	Pennsylvania Jersey Maryland
PV	photovoltaic
s	seconds
TSO	transmission system operator
VRE	variable renewable energy

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INNOVATIVE ANCILLARY SERVICES
INNOVATION LANDSCAPE BRIEF

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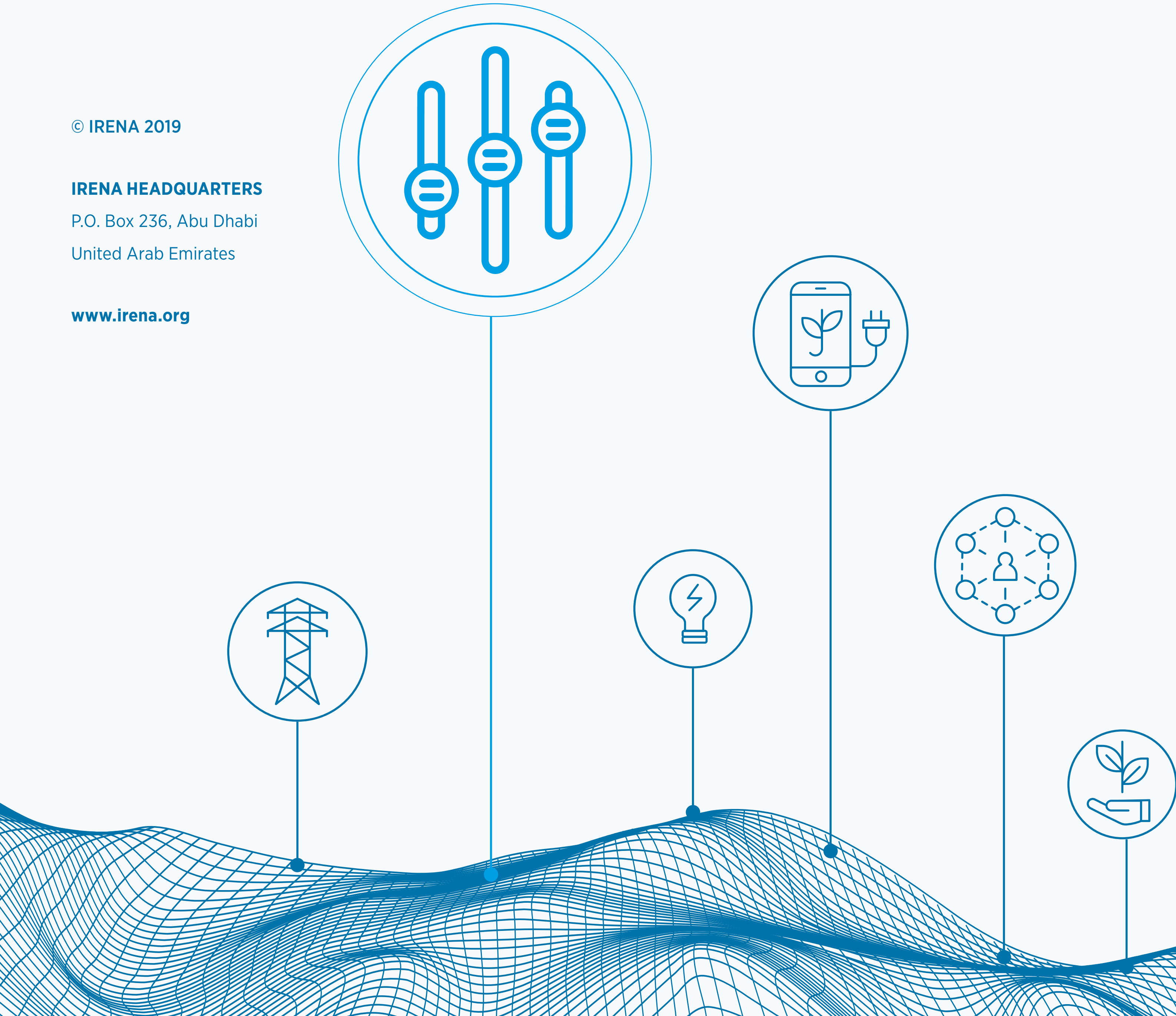

IRENA
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REDESIGNING CAPACITY MARKETS

INNOVATION LANDSCAPE BRIEF

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The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future, and serves as the principal platform for international co-operation, a centre of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity. **www.irena.org**

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1 KEY INNOVATIONS IN CAPACITY MARKETS

Introducing flexibility requirements to ensure new flexible capacity additions

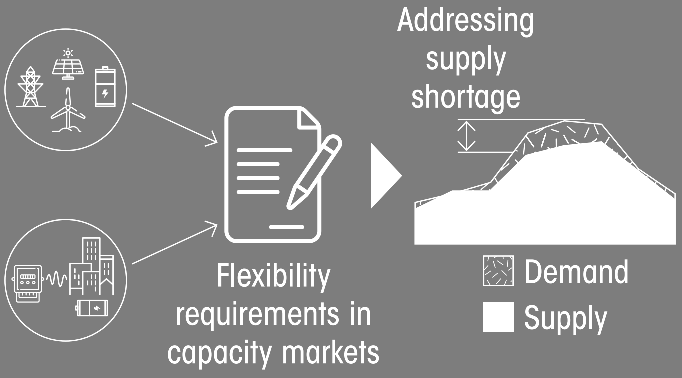
Allowing new participants in the market, such as storage, interconnections, demand response and VRE resources

Supply-side capacity resource:

- VRE resources
- Battery storage
- Interconnectors

Demand-side capacity resources:

- Demand response



Flexibility requirements in capacity markets

Addressing supply shortage

▨ Demand

□ Supply

2 KEY ENABLING FACTORS

Adoption of a clear methodology for defining the capacity credit of VRE resources

Deployment advanced metering infrastructure for demand-side participation

3 SNAPSHOT

- Under the French capacity mechanism, consumers with flexible loads can opt to provide **demand response**.
- In Alberta, Canada, the capacity markets require all participants to submit **the ramping capability**.
- In the single electricity market of Ireland and United Kingdom, **interconnectors, renewable energy sources and demand response are allowed** to participate in capacity markets.

WHAT ARE CAPACITY MARKETS?

Power systems need a mechanism to ensure **generation adequacy** and **security of supply**. Capacity markets serve this purpose.

REDESIGNING CAPACITY MARKETS

Redesigning capacity markets **fosters flexibility**, allows entry by **new participants** and enables the integration of **high shares of VRE**.

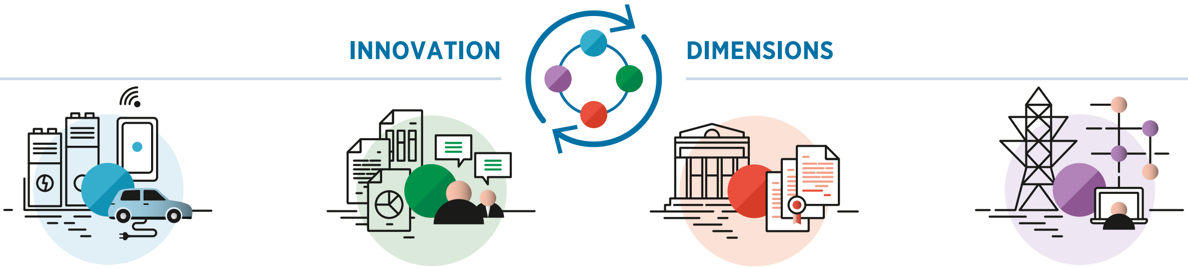
ABOUT THIS BRIEF

This brief forms part of the IRENA project "Innovation landscape for a renewable-powered future", which maps the relevant innovations, identifies the synergies and formulates solutions for integrating high shares of variable renewable energy (VRE) into power systems.

The synthesis report, *Innovation landscape for a renewable-powered future: Solutions to integrate variable renewables* (IRENA, 2019), illustrates the need for synergies between different innovations to create actual flexibility solutions for power systems. Solutions to drive the uptake of solar and wind power span four broad dimensions of innovation: enabling technologies, business models, market design and system operation.

Along with the synthesis report, the project includes a series of innovation landscape briefs, each covering one of 30 key innovations identified across those four dimensions. The 30 innovations are listed in the figure below.

INNOVATION DIMENSIONS



● **ENABLING TECHNOLOGIES**

1 Utility-scale batteries
2 Behind-the-meter batteries
3 Electric-vehicle smart charging
4 Renewable power-to-heat
5 Renewable power-to-hydrogen
6 Internet of things
7 Artificial intelligence and big data
8 Blockchain
9 Renewable mini-grids
10 Supergrids
11 Flexibility in conventional power plants

● **BUSINESS MODELS**

12 Aggregators
13 Peer-to-peer electricity trading
14 Energy-as-a-service
15 Community-ownership models
16 Pay-as-you-go models

● **MARKET DESIGN**

17 Increasing time granularity in electricity markets
18 Increasing space granularity in electricity markets
19 Innovative ancillary services
20 Re-designing capacity markets
21 Regional markets
22 Time-of-use tariffs
23 Market integration of distributed energy resources
24 Net billing schemes

● **SYSTEM OPERATION**

25 Future role of distribution system operators
26 Co-operation between transmission and distribution system operators
27 Advanced forecasting of variable renewable power generation
28 Innovative operation of pumped hydropower storage
29 Virtual power lines
30 Dynamic line rating

This innovation landscape brief provides an overview of innovations in capacity market design features that ensure that the generating resources are adequate to meet demand at all times. Capacity markets are not, in themselves, an innovation. Their comprehensive redesign, however, allows the necessary flexibility for the future system to integrate high shares of solar and wind power. This brief introduces innovations in capacity market requirements, together with new actors that should be allowed to participate in the markets.

The brief is structured as follows:

I Description

II Contribution to power sector transformation

III Key factors to enable deployment

IV Current status and examples of ongoing initiatives

V Implementation requirements: Checklist

I. DESCRIPTION

With increasing installation of renewable generation capacity, in particular wind and solar photovoltaic (PV), power systems require large amounts of flexible resources to provide quick responses to mitigate the additional variability and uncertainty created by the generation of variable renewable energy (VRE). At times, electricity markets prove to be insufficient to compensate flexible resources for their services. Ancillary service markets may cover some of these costs, but in some cases, they cannot attract enough additional investment in flexible resources in the longer term.

Moreover, prices in electricity markets are sometimes considered by market participants to be inadequate to meet medium-term to long-term resource investment needs. The high penetration of VRE displaces conventional baseload generation and depresses prices in the short-term markets (even to negative price levels) due to their zero marginal costs. Renewable energy technologies have decreased the load factors of many conventional baseload plants, which are increasingly used to provide flexible generation when VRE is not available.

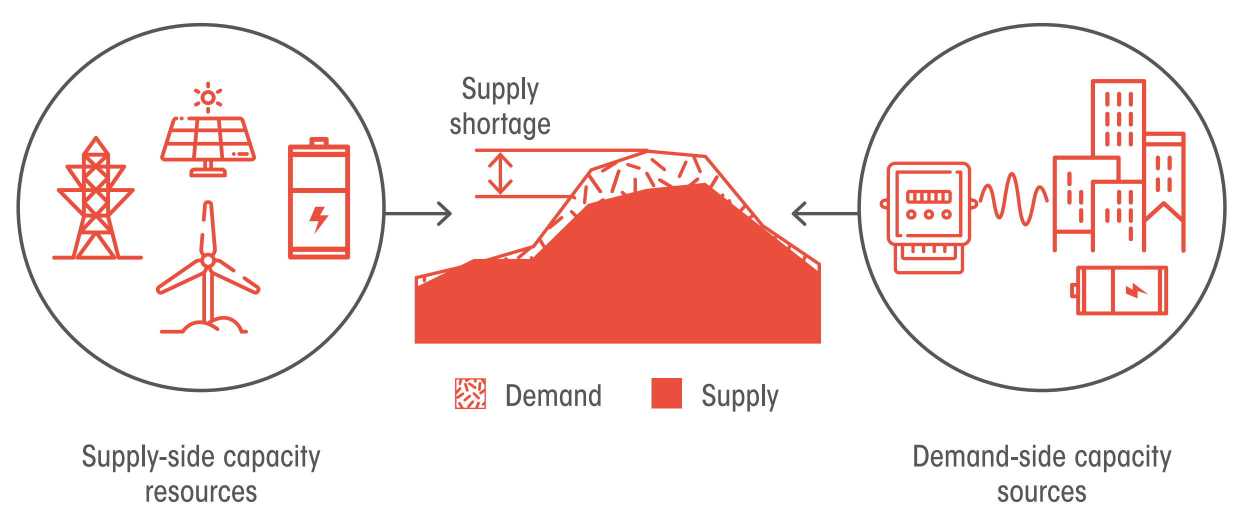
Capacity markets can co-exist alongside the energy-only (electricity) and the ancillary service markets. They are a mechanism to ensure the adequate medium-term and long-term security of supply by remunerating generators for the availability of their resources. The aim is to fill the expected capacity gap in the presence of volatile and unpredictable renewable generation plants. By focusing on the long-term security of supply issues, capacity markets incentivise investments into adequate generation capacity.

While low wholesale electricity prices are good for end-consumers, low prices (even negative prices) hamper medium-term and long-term investments in new generation capacity. To ensure resource adequacy and reliability of supply, several countries and regions have introduced, in addition to the electricity markets, schemes to remunerate market participants for their available capacity via capacity markets. Adding a capacity market in addition to an electricity market is useful in cases in which a resource adequacy issue has been identified.

Under capacity mechanisms, capacity prices are either set in advance administratively or are the result of market-based principles (for example, auctions) and are independent of the cost of the energy produced. Such capacity prices are based on the cost of providing the required capacity whenever needed. These capacity payments are often designed for long periods of time. For example, in the United Kingdom, the capacity market agreement for new generators is 15 years, which incentivises market participants to invest in capacity with a long-term security of supply perspective.

Originally, capacity markets were designed for conventional generation power plants, which have a firm and controllable power output. However, in future power systems that are characterised by a high share of VRE, flexibility is crucial and could be incentivised via capacity mechanisms. Additionally, allowing consumers to adjust their consumption based on price signals would increase demand-side flexibility in the system by shifting consumer demand from peak to off-peak periods. Similarly, other new market participants should be allowed to participate in a capacity adequacy mechanism, based on their firm capacity. Together with demand response, other flexible capacities – such as battery storage technology (when exporting energy to the grid) and interconnections – could contribute to the reliability of the system in times of shortage of su1pply. This is depicted in Figure 1.

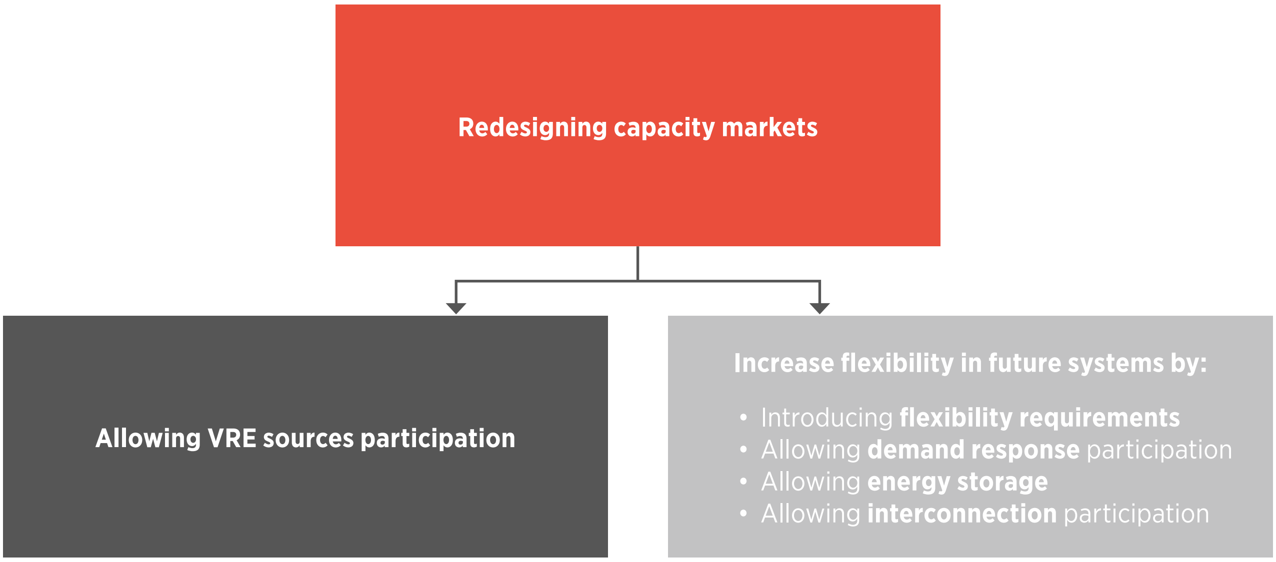
Figure 1: New participants in capacity markets addressing supply shortages



II. CONTRIBUTION TO POWER SECTOR TRANSFORMATION

Introducing flexibility requirements in capacity markets, such as ramping requirements, improves the integration of VRE into the power system. Similarly, allowing new participants in capacity markets, such as energy storage, demand response and cross-border participation (through grid interconnectors), contributes to cost-effective system expansion and a flexible system. Moreover, VRE technologies should increasingly be encouraged or mandated to participate in all markets, including energy-only and capacity markets, and therefore be exposed to the same incentives as any other generation technologies. This would avoid distortions in the market.

Figure 2: Key innovations in capacity markets for a renewable energy-based, flexible system



Incentivising VRE deployment by allowing VRE resources to participate in capacity markets

Conventional power plants have been the main participants in capacity markets due to the predictable and controllable nature of their power output. In some cases, VRE resources, such as wind and solar energy, have also helped to ensure resource adequacy. Generally, however, the contribution of VRE resources to the security of supply is lower per unit of installed capacity than for conventional technologies. Their contribution depends in part on the specific conditions of the power system, such as its location and scarcity conditions (whether it is a capacity-constrained or an energy-constrained system). Yet the integration of VRE into the system is increased by allowing these resources to play a role in capacity markets, with providers being remunerated for their services (IRENA, 2017).

Several countries already have frameworks in place that allow VRE resources to participate in capacity mechanisms. For example, in France, electricity suppliers are required by law to procure capacity guarantees based on consumers' load patterns during peak periods in winter (1 November-31 March). Such capacity adequacy can be provided by thermal generators, renewable energy resources (RES) or demand response if the providers register and obtain the necessary certification. Such certificates of guarantee are then traded in the capacity market (RTE, 2015).

In the United States, the Pennsylvania-Jersey-Maryland (PJM) Interconnection, a regional transmission organisation (RTO), cleared 116 megawatt (MW) solar power plants and 803 MW wind power plants to provide capacity in 2017 and 2018 (FERC, 2015). (See Section IV.)

The European Commission has approved a new capacity mechanism for the single energy market in Ireland and the United Kingdom of Great Britain and Northern Ireland under which RES and demand response can participate alongside conventional generators (European Commission, 2017). A similar mechanism is being proposed in Italy and is awaiting approval from the European Commission (Bonucci, 2018).

Means to increase flexibility in power systems

Introducing flexibility requirement in capacity markets

The role of capacity markets has traditionally been to incentivise investments in new generation capacity. With the increasing penetration of VRE, an efficient means to increase flexibility in power systems is to introduce flexible resource requirements into the existing capacity mechanisms that could incentivise investments in more flexible resources, meaning resources that can ramp up and down quickly.

For example, in January 2017 the government of Alberta (Canada) launched the design and implementation of a capacity market in collaboration with the Alberta Electric System Operator (AESO). The capacity market requires all participating assets to submit the ramp capability. The first auction is planned in 2019 with the first delivery in 2021 (AESO, 2018).

Participation of demand-side response in capacity markets

Demand-side response refers to the ability to reduce energy loads during times of supply scarcity. Under demand response, consumers are incentivised through price signals to reduce their consumption at times of supply deficit. Commercial and industrial consumers account for a large share of the peak demand and can change their consumption patterns with more ease than residential consumers. Demand response has proven to be competitive in the forward capacity markets operated by PJM and the independent system operator (ISO) for the New England region of the United States.

The capacity value of aggregated distributed energy resources (DERs) can also be used to satisfy long-term resource adequacy requirements or to defer other infrastructure investments. Some capacity markets, such as Alberta's capacity market, allow the participation of aggregated DERs, which is further explained in Section IV. Similarly, under the French capacity mechanism, consumers with flexible loads can opt to provide demand response either to electricity suppliers during winter peak times or to system operators whenever needed (RTE, 2015).

PJM introduced the US “reliability pricing model” (RPM) under which demand response resources are treated like generation resources, ensuring the security of supply. Demand response resources are paid to be “available” during expected emergency situations with monthly to yearly commitments (PJM, 2018a).

The Spanish transmission system operator (TSO) Red Eléctrica de España procures an “interruptibility service” in which large consumers reduce their demand through demand response when requested by the TSO. This service covers two capacity products of 5 MW and 40 MW, respectively, that are procured via auctions conducted by the Red Eléctrica de España (Red Eléctrica de España, 2018).

Storage participation in capacity markets

Energy storage resources also participate in capacity markets by committing to discharge energy when requested by system operators to ensure the security of supply. These resources are usually rewarded based on the duration of discharge they provide. They are a great source of flexibility for the system, and their participation in capacity markets provides them with an extra revenue stream, which in turn incentivises their further investments. Many markets already allow storage participation in capacity markets.

The UK’s TSO, the National Grid, plans to procure about 50 GW of capacity in its forthcoming auctions for delivery in 2023. These auctions allow the participation of battery storage systems that provide at least 30 minutes of service. The de-rating factors for battery storage systems were changed in December 2017, making the revenues proportionately greater for systems with a longer duration of discharge (Colthorpe, 2018).

In the United States, the Federal Electricity Regulatory Commission (FERC) recently issued Order No. 841, which allows energy storage systems to participate in capacity markets. It also requires system operators to revise their tariffs and establish rules that recognise the physical and operational characteristics of energy storage systems (Walton, 2018).

Cross-border participation in capacity market via interconnections

Currently, the majority of capacity mechanisms have a national scope. Benefiting from available interconnections, regional capacity markets can play an important role in more efficiently co ordinating investment plans in generation capacity. Opening capacity market mechanisms to capacity providers in neighbouring countries or systems will incentivise investments in domestic and foreign capacity, as well as in interconnections, which will result in reduced system costs for all participating countries.

For example, in Great Britain, interconnectors, de-rated like batteries, have been allowed to participate in capacity market auctions since 2015. Interconnectors are treated like any other market participants such as generators or demand response and must deliver capacity when requested by system operators during stress events or pay penalties for under-delivery. The British model has witnessed participation from interconnectors with Belgium, Ireland and the Netherlands (Tennbakk *et al.*, 2016).

Similarly, in the single electricity market of Ireland and Northern Ireland, interconnectors have been allowed to participate in capacity markets alongside other energy resources such as renewable energy resources, conventional generators and demand response. No international capacity contracts have been witnessed until now (Tennbakk *et al.*, 2016).

III. KEY FACTORS TO ENABLE DEPLOYMENT

Adopting a clear methodology for defining the capacity credit of VRE resources

VRE resources produce a variable and an uncertain energy output. Therefore, the amount of reliable electricity that can be provided by VRE resources must be assessed based on a clear methodology.

For instance, in Colombia, the Colombian Energy Regulator (CREG) has established a metric called ENFICC (Energía Firme para el Cargo por Confiabilidad) that represents the maximum amount of power that a generator can offer as firm capacity in capacity market auctions. It is expressed as a percentage of the plant's total generation capacity (Robinson, Riascos and Harbord, 2012).

Such metrics can be established based on clear methodologies such as calculating the average generation during relevant shortage periods. Alternatively, a threshold percentile-based method may be adopted. For example, the level of wind generation that has occurred at least 85 % of the time (P85) may be considered as the firm energy contribution of wind power (Letson, 2015).

Oversight and advanced metering infrastructure (AMI) for demand-side participation

Demand response and DERs can play an important role in providing flexible capacity reduction to ensure reliability in case of supply shortages. However, if aggregated DERs are relied upon for resource adequacy, the need to ensure that aggregators are genuinely capable of delivering capacity whenever and wherever needed becomes essential for reliability.

Developing the underlying infrastructure is key and includes smart meters, communication networks and data management systems, often referred to as "advanced metering infrastructure" (AMI).

Regional mindset for interconnections participation in adequacy resource mechanism

Important savings can be realised when the security of supply is considered at the regional level, rather than at the individual system level, and when investments in interconnections are incentivised through capacity markets. The functioning of regional markets requires a high level of trust among countries that, in case of supply scarcity, they will share generation capacity according to the established rules rather than giving priority to local demand. This represents a major opportunity to reap benefits from regional integration, instead of installing local generation capacity to meet individual countries' demand (Perez-Arriaga, 2013).

IV. CURRENT CONTEXT AND EXAMPLES OF LEADING INITIATIVES

Alberta capacity market (Canada)

In January 2017, under the government of Alberta's direction, the AESO launched the design and implementation of an Alberta capacity market. This newly designed capacity market aims to achieve resource adequacy at least cost by facilitating broad competition among resources while working effectively and efficiently with the energy and ancillary service market. It also identifies the following assets that are eligible to prequalify: thermal, demand response, external capacity assets (through interconnections), storage, hydro, variable, and aggregated assets. In addition, it requires the minimum size of the assets to be 1 MW, whereas storage assets must demonstrate four hour continuous discharge capability to be able to participate in the market. Additionally, for all participating generating and storage assets, the ramp capability has to be submitted. In effect, this means the capacity market includes some flexibility requirements. The first capacity auction was scheduled for November 2019 with the first delivery of capacity in 2021 (AESO, 2018).

PJM's reliability pricing model (United States)

PJM Interconnection administers a capacity market called the reliability pricing model (RPM) in the US market through which it procures capacity for reliability by including participation of both demand responsive loads and VRE resources. In its 2018 base residual auction, it cleared 116 MW of solar power capacity and 803 MW of wind power capacity (FERC, 2015). Furthermore, for providing demand response services, PJM compensates its end users for reducing their electricity usage upon PJM's request in the event of a supply shortage or threatened reliability of the grid (PJM, 2018b).

French capacity mechanism

The French capacity market began in 2015, and a new demand response scheme within the capacity market was launched in February 2018. Under its new market design, capacity obligations are placed on electricity suppliers based on their customers' consumption profiles during the peak winter months. Both VRE and demand-side resources can participate in the capacity market. Each participating resource is certified for the amount of capacity it offers to suppliers upon request. Each participating resource obtains one certificate for every 0.1 MW of capacity offered in the capacity market. In addition, VRE resources are eligible to obtain historical certificates for the energy provided to system operators in situations of stress and during peaks prior to the introduction of the first capacity mechanism (RTE, 2015).

Calls for the capacity market redesign in Great Britain

In Great Britain, the underlying reason to redesign the existing capacity market mechanism is to encourage investments and the deployment of flexible resources such as batteries. In February 2018, the capacity market auctions witnessed record low prices due to very high participation of the conventional generators, which were seeking additional revenue, while a very small amount of the more flexible battery storage was contracted. The capacity market forward auction for 2022 completed in February 2018 cleared at record low prices of ~USD (US dollar) 10.8/kWh (kilowatt-hour) compared to previous years' market clearing at ~USD 29/kWh.[1] Only 153 MW of battery storage capacity was contracted, even though significant capacity may have pre-qualified (Cuff, 2018).

However, the British capacity market has been on hold since November 2018 given the ruling of the General Court of the European Union that annulled the approval of the capacity mechanisms due to procedural reasons, such as the lack of a detailed formal investigation into the market design prior to its initial approval in 2014. One of the arguments against the design of this capacity market is that it discriminated against technology designed to cut electricity demand during peak times (European Commission, 2019).

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[1] Original figures of GBP (British pounds) 8.4/kWh and GBP 22.5/kWh converted to US dollars based on exchange rates prevailing on 21 August 2018 using quotes provided by Bloomberg (www.bloomberg.com/quote/GBPUSD:CUR).

V. IMPLEMENTATION REQUIREMENTS: CHECKLIST

TECHNICAL REQUIREMENTS	**Hardware:** • Equipment, such as smart meters (required to provide real-time power consumption and production), home gateways (energy boxes), communication networks and smart appliances for energy management, are necessary for enabling the DERs' interaction with the existing grid • Smart grids that enable two-way flow of data and electricity **Software:** • Automation of various processes and information exchange related to scheduling of power plants and demand response
REGULATORY REQUIREMENTS	**Wholesale market:** • Assess the need to establish or redesign capacity mechanisms based on the resource adequacy situation • Define clear methodologies to calculate the amount of firm capacity that each resource can offer • Introduce oversight regulation to ensure that new actors allowed to participate in capacity markets are delivering capacity when and where it is needed • Incentivise the participation of VRE and storage, as well as interconnectors in capacity mechanisms, which can provide flexibility in addition to conventional generators **Retail market:** • Incentivise demand response, especially for commercial and industrial consumers
STAKEHOLDER ROLES AND RESPONSIBILITIES	**Consumers:** • Commit to respond to price signals and offer capacity when the system needs it in moments of scarce generation, *e.g.*, via automation, aggregators, etc. **System operators:** • Define capacity market products according to the flexibility needed in the system • Conduct flexible capacity market auctions if a resource adequacy issue is identified • Provide oversight and forecasts of system adequacy issues and the necessary capacity requirements, including potential shortages • Update stakeholders about changes to the resource adequacy issues in the systems

ABBREVIATIONS

AESO	Alberta Electric System Operator
AMI	Advanced metering infrastructure
CREG	Colombian Energy Regulator
DER	Distributed energy resource
ENFICC	Energía Firme para el Cargo por Confiabilidad
FERC	Federal Electricity Regulatory Commission
ISO	Independent system operator
kWh	Kilowatt-hour
MW	Megawatt
PJM	Pennsylvania-Jersey-Maryland
PV	Photovoltaic
RES	Renewable energy resources
RPM	Reliability pricing model
RTO	Regional transmission organisation
TSO	Transmission system operator
VRE	Variable renewable energy

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REDESIGNING CAPACITY MARKETS

INNOVATION LANDSCAPE BRIEF

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REGIONAL MARKETS

INNOVATION LANDSCAPE BRIEF

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The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future, and serves as the principal platform for international co-operation, a centre of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity. **www.irena.org**

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1 HOW IT WORKS

Regional markets require the harmonisation of market rules for electricity to flow freely in response to market-based price signals. The deeper the integration, the more rules needs to be harmonised. There are different stages of market integration:

Early stage of market integration	Bilateral contracts
Shallow market integration	+ Harmonisation of wholesale market rules
Deep market integration	+ Harmonisation of ancillary service markets, and possibly capacity markets

2 BENEFITS

- Increased flexibility through expanding balancing area
- Advantages of spatial complementarity of VRE generation
- Co-ordinate generation planning
- Reduce system operation cost

3 KEY ENABLING FACTORS

- Physical interconnections with sufficient capacity
- Regional mindset, strong institutional arrangements and governance model
- Robust IT system for market operation

4 SNAPSHOT

➜ The Western Energy Imbalance Market (EIM) in US helped to avoid curtailment of 760 TWh of RE and provide more than USD 565 million since its inception in 2014.

REGIONAL MARKETS

Coupling markets creates a **larger balancing area** with **wider resource diversity.** This facilitates the integration of variable renewables.

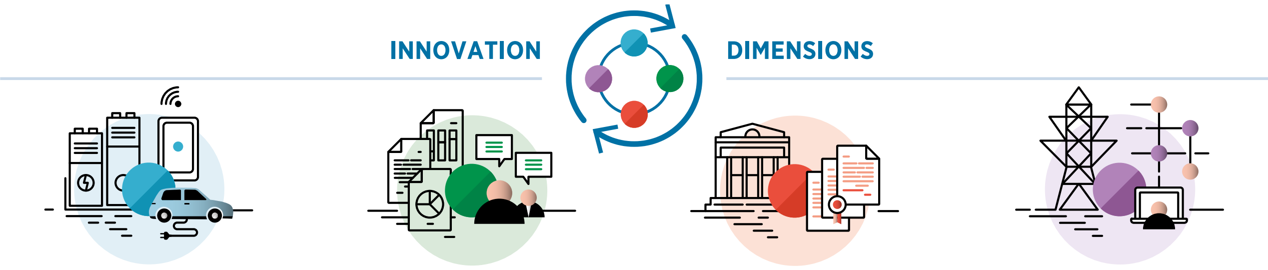
ABOUT THIS BRIEF

This brief forms part of the IRENA project "Innovation landscape for a renewable-powered future", which maps the relevant innovations, identifies the synergies and formulates solutions for integrating high shares of variable renewable energy (VRE) into power systems.

The synthesis report, *Innovation landscape for a renewable-powered future: Solutions to integrate variable renewables* (IRENA, 2019), illustrates the need for synergies between different innovations to create actual flexibility solutions for power systems. Solutions to drive the uptake of solar and wind power span four broad dimensions of innovation: enabling technologies, business models, market design and system operation.

Along with the synthesis report, the project includes a series of innovation landscape briefs, each covering one of 30 key innovations identified across those four dimensions. The 30 innovations are listed in the figure below.

INNOVATION DIMENSIONS



● ENABLING TECHNOLOGIES

1 Utility scale batteries
2 Behind-the-meter batteries

3 Electric-vehicle smart charging
4 Renewable power-to-heat
5 Renewable power-to-hydrogen

6 Internet of Things
7 Artificial intelligence and big data
8 Blockchain

9 Renewable mini-grids
10 Supergrids

11 Flexibility in conventional power plants

● BUSINESS MODELS

12 Aggregators
13 Peer-to-peer electricity trading
14 Energy-as-a-service

15 Community-ownership models
16 Pay-as-you-go models

● MARKET DESIGN

17 Increasing time granularity in electricity markets
18 Increasing space granularity in electricity markets
19 Innovative ancillary services
20 Re-designing capacity markets
21 Regional markets

22 Time-of-use tariffs
23 Market integration of distributed energy resources
24 Net billing schemes

● SYSTEM OPERATION

25 Future role of distribution system operators
26 Co-operation between transmission and distribution system operators

27 Advanced forecasting of variable renewable power generation
28 Innovative operation of pumped hydropower storage

29 Virtual power lines
30 Dynamic line rating

This innovation landscape brief applies to liberalised, open electricity markets, where the vertical integrated utilities are unbundled and there is competition in electricity generation. It provides an overview of regional markets, a market design innovation, that allows electricity to be transported more easily within a larger balancing market area across several control areas. In this way, a wider geographic diversity of resources can be used to balance supply and demand by taking full advantage of weather and resource diversity and differences in load patterns.

The brief is structured as follows:

I Description

II Contribution to power sector transformation

III Key factors to enable deployment

IV Current status and examples of leading initiatives

V Implementation requirements: Checklist

I. DESCRIPTION

A regional market is the outcome of establishing a higher hierarchical level of organisation of several national, sub-national or local systems, so that their original spontaneous interactions become stronger and subject to well-defined, commonly agreed rules (Perez-Arriaga, 2013). In addition to the liberalisation of markets in the broader sense, the last two decades have witnessed a trend towards the creation of regional electricity markets via the integration of existent national markets. Some of the examples include the European Union's (EU's) Internal Electricity Market (IEM), the Central American Electricity Market (Mercado Regional de Electricidad, or MER), the Western Energy Imbalance Market (EIM) in the United States, the Australian National Electricity Market (NEM), the market in the Mekong Delta region in Viet Nam, the West African Power Pool (WAPP) and the South African Power Pool (SAPP).

The establishment of regional markets started long before the takeoff of VRE. Their role has been to enhance the security of supply and reduce costs as liberalised and integrated markets allow relatively free cross-border flows, enhance competition in power generation and supply, and offer more choices for consumers. Regional markets are gaining more importance, as these bring additional benefits to the grid integration of VRE. A well-integrated regional market can create locational and temporal[1] synergies between renewable energy sources and demand patterns across the entire region. Regional markets can also facilitate the investment planning in generation assets by exploring the existing advantages of different geographical locations, provided appropriate co-ordination rules and regulatory frameworks are in place.

The creation of a regional electricity market requires the harmonisation of market rules so electricity can flow freely in response to market-based price signals. There are different levels of regional market integration, as described in Table 1. Deepening the level of market integration requires the harmonisation of different market rules. Figure 1 depicts the relationship between increased market integration levels and the corresponding harmonisation needed for various market design features.

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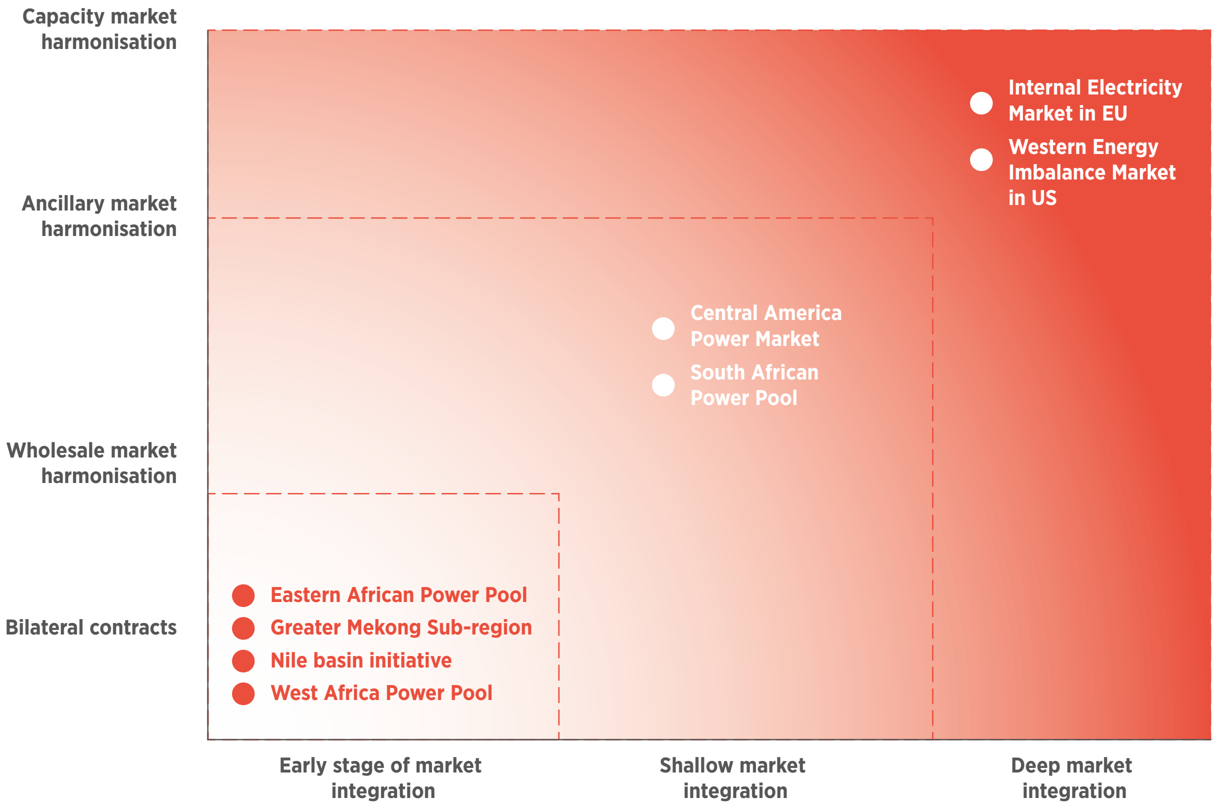
[1] When participating electricity markets are not in the same time zone.

Table 1 Different levels of regional market integration

Market integration level	Interconnectivity level	Trading arrangements	Harmonisation rules
Early stage of market integration	Physical interconnection between two countries	Long-term, bilateral, over-the-counter (OTC)[3] power purchase agreements (PPAs)	Simple rules agreed for the operation of the interconnected system
Shallow market integration	Physical interconnection between several neighbouring countries	Long-term PPAs supplemented with short-term wholesale markets	Harmonisation of market rules, grid codes, and transmission tariffs
Deep market integration	Full synchronous operation of a multi-country interconnected system	Well-functioning markets with competition achieved through trading in different timeframes and various markets (OTC vs. power exchanges, capacity vs. power markets, day-ahead vs. intraday markets, etc.)	Regional regulatory agencies, regional market operators and harmonisation of market rules, grid codes, and transmission tariffs

Source: Adapted from ESMAP (2010)

Figure 1: Market integration levels depending on the regional market design



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[2] OTC trading refers to bilateral contracts signed outside an organised market place (*i.e.*, power exchange).

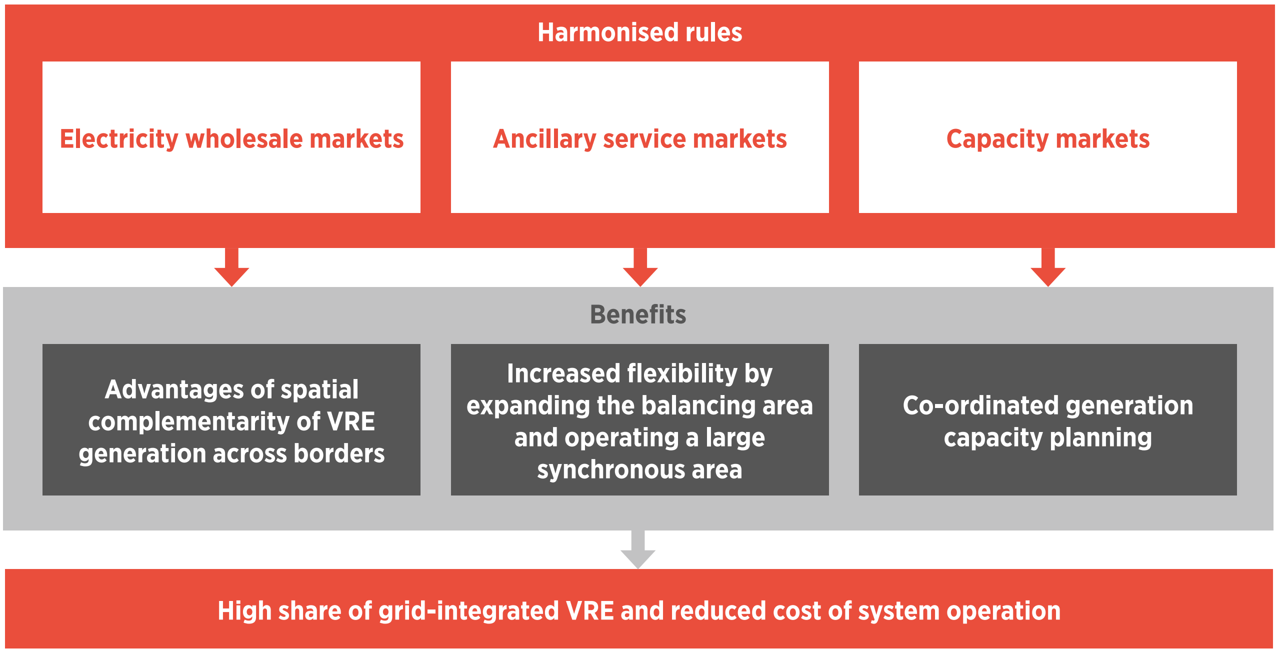
II. CONTRIBUTION TO POWER SECTOR TRANSFORMATION

In general, each jurisdiction lays down its own required standards for power quality and subsequently on the required quantity of reserve, as well as institutional and policy frameworks. A truly integrated regional market implies harmonised rules across different markets, as well as different trading time frames. For example, in the ideal case, a well-functioning and deeply integrated regional market would have harmonised rules across the entire region for the wholesale electricity market, ancillary service market and the capacity market.

Similarly, in the wholesale electricity market as well as the ancillary service market, all time frames (long term and short term) would have the same regulatory framework. A well-functioning regional market would require participating power systems to agree on various regulatory aspects, including time and space granularity, cost sharing and recovery, a strategic road map, and contractual details such as the co-operation between system and market operators, etc. (ENTSO-E, 2018a).

Harmonising rules among different markets improves flexibility in the power systems involved by increasing the trading opportunities for market participants, increasing the balancing area, reducing the balancing costs, taking advantage of complementarities between different renewable energy sources and helping to plan the best-suited generation capacity investment across multiple power systems. Figure 2 shows the key benefits of deeply integrated regional markets.

Figure 2: Benefits of deeply integrated regional markets



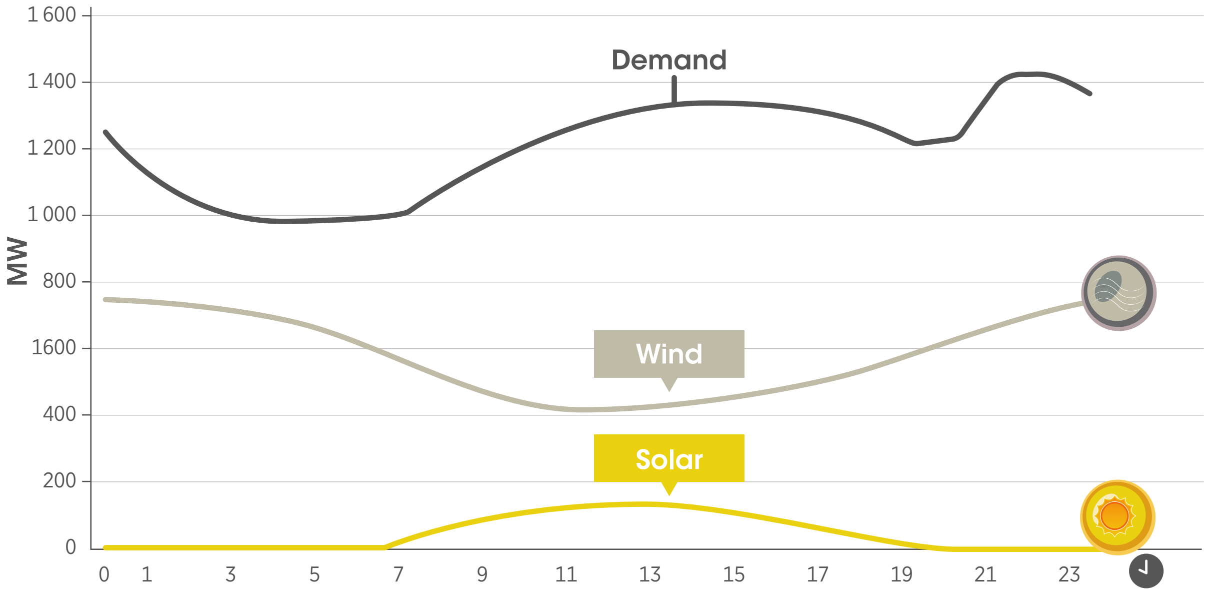
Advantages of the spatial complementarity of VRE generation across borders

Harmonised rules in the wholesale electricity markets, such as harmonised gate opening and closure times and market time units (scheduling intervals) of the day-ahead and intraday markets, allow all market participants in the region to submit their bids and offers within the same trading intervals, therefore increasing their trading opportunities. Considering the available transmission network capacity, supply and demand orders are matched more efficiently from an economic point of view within a wider regional market with different demand patterns, especially when the participating regions are in different time zones. This allows greater integration of wind and solar PV generation, as it reduces the VRE curtailments that are more likely to occur in smaller systems.

Regional markets enable synergies in spatial complementarities of VRE sources. For instance, when the wind does not blow in France, the sun might be shining in Spain. The possibility of importing electricity from Spain in such cases could reduce the need for local flexibility or balancing reserves in France. Better integration of markets allows power systems to take advantage of clean electricity sources beyond the borders of the system, allowing for the co-ordination between different renewable energy resources. (Newbery, Pollitt and Ritz, 2017).

Complementarity patterns have been observed between wind and solar at both daily and seasonal scales. Figure 3 shows the expected daily profile of demand, wind and solar PV generation in Uruguay. It highlights the complementarity between wind generation, which decreases during daytime hours, and solar generation, which increases during the same hours (IRENA, 2016). In regional markets, such complementarity can be even stronger because abundant solar resources are usually distant from abundant wind resources.

Figure 3: Daily complementarity between renewable energy sources in Uruguay



Source: Chaer et al. (2014) and IRENA (2016)

Central American countries have expanded their transmission systems to facilitate the incorporation of large amounts of renewable energy. They have jointly developed a regional transmission line, the Central American Electrical Interconnection System (SIEPAC), to enable international power exchanges (ECA, 2010). The SIEPAC was completed at the end of 2013 and allows for the trade of electricity among Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua and Panama. This facilitates the incorporation of large amounts of renewable energy by capitalising on different VRE resources and demand profiles in different countries. The region's dependence on hydropower has led to concerns about energy security, especially given recent extreme droughts that resulted in electricity shortages. The creation of SIEPAC, along with a higher penetration of renewable power, helped Central American countries to cope with droughts without any rationing of electricity[3] (Lippmann and DiPippo, 2017; IRENA, 2016). SIEPAC also resulted in the establishment of a regional electricity market, a regional system operator and a regional regulator.

Regional markets can help reduce the overall operation costs of power generation because they allow for the more efficient use of existing assets across countries, dispatching the most efficient generators in the region. Generators operate in a more stable point that is closer to their most efficient operation point, which leads to further reductions in operation costs. Such resource sharing and diversification of resources in regional markets lower the risk associated with a shortage of any given fuel, ensure the regional supply at a lower cost, and in some cases, even avoid expensive shortages.

Increased flexibility by expanding the balancing area and operating a large synchronous area

System balancing refers to actions taken by the transmission system operators (TSOs) to ensure that system frequency is maintained within a pre-defined range (Emissions-EUETS, 2009). Supply and/or demand may vary due to unexpected events (*e.g.*, an increase/decrease in power supply from conventional generators, VRE, weather-determined high-power demand, etc.), causing imbalances in the system. In this context, ancillary services are defined as services necessary for the operation of a system (ENTSO-E, n.d.) and can be clustered into frequency ancillary services (balancing), and non-frequency ancillary services (voltage control and black-start capability).

Trading ancillary services with neighbouring TSOs within a regional market is key to increasing the overall flexibility of the transmission system and reducing balancing costs. Large power grids can absorb more fluctuations in power demand and generation compared to smaller grids, leading to more flexibility in the system (Pariente-David, 2014). Regional markets result in a larger underlying power grid, which thereby helps to reduce the reserve requirements. The development of regional markets allows electricity to be transported more easily within a larger balancing area, meaning that more resources are available to be used to balance power supply and demand. Harmonising products and rules in the ancillary service market across different countries allows access to a broad range of services from an expanded balancing area, giving system operators more flexibility, which allows them to ensure the security of supply at a lower cost.

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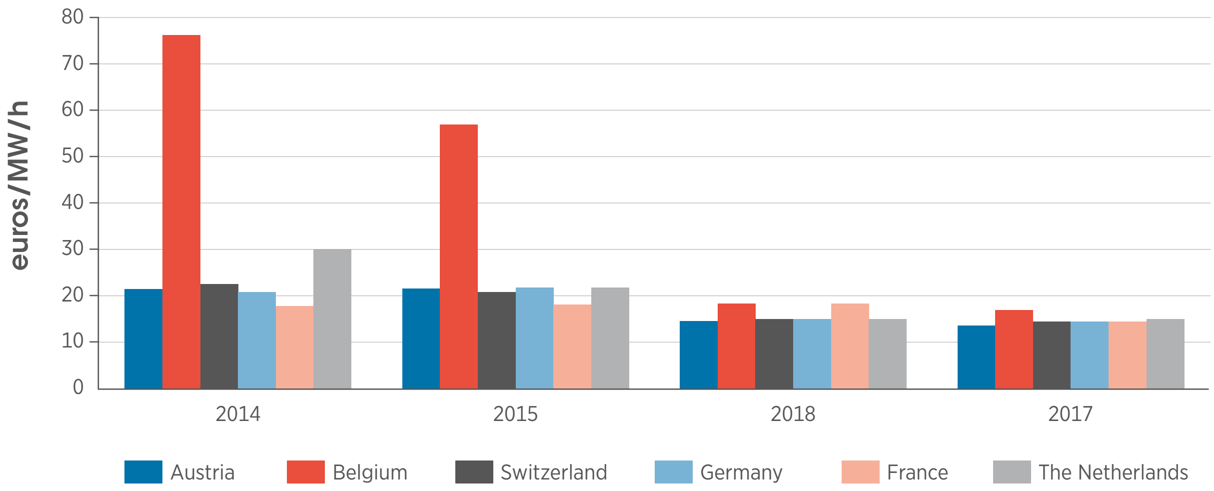
[3] Central America is heavily dependent on hydropower and fossil fuel for power generation (Lippmann and DiPippo, 2017).

A regional balancing reserve market in deeply integrated regions can help reduce the overall power reserve requirements, as reserves are shared across the whole region. Several stakeholders in the EU, including the Agency for the Cooperation of Energy Regulators (ACER), national regulatory authorities, and TSOs within the European Network of Transmission System Operators for Electricity (ENTSO-E), developed a guideline on electricity balancing that entered into force in November 2017 (Commission Regulation, 2017). The European guideline on electricity balancing sets down the rules on the operation of balancing markets throughout the EU, referring to those markets that TSOs use to procure balancing services to keep the system balanced in real time. On top of that, the regulation provides opportunities for cross-border trading within such balancing markets. As such, this framework enables greater cross-border availability of resources for balancing the system and in turn lower costs for procuring these services.

Moreover, ENTSO-E is working on the implementation of an integrated market for balancing services in Europe, which is expected to ensure the security of the power supply while reducing the need for back-up generation (ENTSO-E, n.d.). ENTSO-E conducted a pilot to establish a common market for the procurement of frequency containment reserves (FCRs) based on the TSO-TSO model[4] in the following seven countries and involving the respective TSOs: Austria (APG), Belgium (Elia), Western Denmark (Energinet), France (RTE), Germany (50Hertz, Amprion, TenneT DE, TransnetBW), the Netherlands (TenneT NL), and Switzerland (Swissgrid). The pilot showed that with geographical extension, between 2014 and 2017, balancing capacity prices steadily decreased and converged across the markets involved in the FCR co-operation project, as illustrated in Figure 4.

Figure 4: Average prices of balancing capacity (from FCRs) in the markets involved in the FCR co-operation project



Source: ACER (2018)

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[4] The TSO-TSO model refers to a model for the exchange of balancing services exclusively operated by TSOs, as opposed to a TSO-balancing responsible party (BSP) model, in which a BSP has a contractual relationship with another TSO other than the TSO to which the BSP is connected.

Co-ordinated generation capacity planning

In the absence of well-functioning wholesale electricity markets or where a generation adequacy issue has been identified across a region, regional capacity markets can play an important role in co ordinating the investment plans for generation capacity. The harmonisation of rules in capacity markets across a region sends a clear price signal regarding the investment needs for capacity generation at a regional level, rather than sending several price signals at national or sub-national levels. Co ordinated planning across an entire region has several benefits, including the efficient use of renewable energy resources from areas where these are abundant, as well as the capitalisation on the spatial complementarity of such resources. Capacity-expansion models can take into account the regional integration of the system, the stochastic nature of the VRE and the ability of the system to address intermittency with minimal back-up reserves (Pariente-David, 2014).

Co-ordinated capacity planning among countries helps to lower capital investments to meet future demand. For instance, in the SAPP 2025 plan, 57 gigawatts (GW) of capacity was expected to be added at a cost of USD 89 billion (US dollar), which was USD 48 billion less than the total of the national power development plans to meet the same level of demand (ESMAP, 2010). On the contrary, if capacity markets are introduced at the national level in an unco-ordinated manner across a deeply integrated region with a well-functioning wholesale market, capacity markets could have a negative impact on the regional electricity-only market.

Regional markets can also help improve the financial feasibility of large power generators, which may otherwise not be doable. For instance, the Grand Inga project (a 20 000 MW hydro power project in the Democratic Republic of Congo), which is one of the largest clean energy power generation projects in the SAPP, will only be economically viable under the inter-country transmission capacity (IRENA, 2017). The same applies to large onshore and offshore wind projects, which may only be economically feasible if they serve the demand of a larger system.

Potential impact on power sector transformation

Regional markets bring several advantages, including better economic utilisation of the interconnections between countries and wider welfare benefits for end-customers. Efficient utilisation of the existent interconnection infrastructure helps reduce the short-term costs of integrating VRE into the power grid (Newbery, Pollitt and Ritz, 2017). Examples with potential positive impacts on power sector transformation, including enhanced security of supply, reduced system costs and efficient use of resources, are provided below:

- Across Europe, the successful exchange of balancing services resulted in the utilisation of imbalance netting[5] across borders, which covers more than half of the need for balancing energy in several European markets, including Austria, Germany, Latvia, Germany and the Netherlands. In these countries, **imbalance netting helped to avoid 83 %, 60 %, 55 %, and 51 %, respectively, of the system's balancing energy needs** in 2017. Overall, the potential welfare benefits from efficient imbalance netting and the exchange of balancing energy across European borders is estimated to be **EUR 1.3 billion per year**. In this context, the effective implementation of the harmonised rules set out in the Commission Regulation (EU) 2017/2195 establishing a guideline on electricity balancing would materialise these welfare gains (ACER, 2018), (Commission Regulation, 2017).

- Significant interconnection[6] with neighbouring countries (Germany, Norway and Sweden) allowed Denmark to integrate around **53 % of wind power** without significant curtailments in 2017 (IEEFA, 2018). Over the years, wind power generation has been curtailed only twice: for six to eight hours in 2008 and 2010, curtailing 200–300 megawatts (MW), due to an outage in one of the interconnectors (Danish Energy Agency, 2015). The excess wind power is traded with neighbouring countries, for example by using it to charge pumped hydro storage facilities (IEEFA, 2018).

- The Western Energy Imbalance Market (EIM) has helped to **avoid curtailment of almost 720 TWh of renewable energy** since its inception, thereby **avoiding the emission of 306 112 equivalent tonnes of carbon dioxide** (CO_2) (CAISO, 2018). The EIM has provided **USD 400 million in gross benefits** to market participants since its launch in November 2014 (Larson, 2018).

- The World Bank has estimated that the economic benefits of regional trade in the Western African Power Pool (WAPP) would reach **USD 5–8 billion per year** due to reduced operation costs while making power generation more sustainable by displacing baseload oil-fired power generation with cleaner sources of electricity such as natural gas, solar and hydropower (The World Bank, 2018).

- Exports of power to the United Kingdom from Ireland (via sub-sea interconnection) helped **reduce power curtailment by approximately 50 %** in 2013 (IEEFA, 2018). By 2017, Ireland's cross-border interconnections reached 7 % of total installed generation, compared to the EU target of 10 % by 2020 (although Ireland is expected to increase the interconnection to 18 % by 2020) (European Commission, 2017).

- The economic benefits of fully integrating the European market could be as high as **EUR 40 billion per year by 2030 in a high renewable energy scenario** (Newbery, Pollitt and Ritz, 2017).

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[5] Imbalance netting refers to the process agreed among TSOs of two or more load-frequent control areas which avoids the simultaneous activation of frequency restoration reserves in opposite directions.

[6] Denmark has cross-border connection equivalent to 51 % of its total power generation capacity with target to increase the interconnection capacity to 59 % by 2022 (European Commission, 2017).

III. KEY FACTORS TO ENABLE DEPLOYMENT

Physical interconnections with sufficient capacity made available to the market

The underlying requirement for functioning regional markets (regardless of the market integration level) is the availability of sufficient transmission capacity among the participating countries. As mentioned, Denmark has low curtailment levels of VRE thanks to the interconnector capacity with neighbouring countries, which is nearly equal to the peak load of 6.5 GW. The EU target is for cross-border interconnections to reach 10 % of total installed generation by 2020 (European Commission, 2017). In its Ten Year Network Development Plan, ENTSO-E is proposing investments in transmission projects worth EUR 114 billion by 2030 that would result in annual savings of up to EUR 5 billion in generation costs (ENTSO-E, 2018b).

In addition to the construction of new interconnections, another aspect that enables the integration of regional markets is a sufficient level of transmission capacity made available to the market by the TSOs. For example, in the European wholesale markets, in 2017, the cross-zonal capacity made available for trading remained significantly below an estimated “benchmark capacity”, *i.e.*, the maximum capacity that could be made available to the market while preserving operational security.

Regional mindset, strong institutional arrangements and governance model

Perhaps the most challenging issue in the design and implementation of a regional market is the shift from a “national/system mind-set” of institutions and consumers towards a “regional mind-set” with the prime objective of maximising the social welfare of the entire region while ensuring that each system participating in the regional market is better off within the regional market integration. Successful regional integration requires political buy-in along with strong institutional arrangements and a governance model to address any future issues that may lead to distrust among participating entities.

For instance, important savings are to be made when the security of supply is considered at the regional level rather than at the individual country level. This requires a high level of trust among countries that, in case of supply scarcity, neighbouring countries will share generation capacity according to established rules rather than giving priority to a single country’s local demand. This represents a major challenge if every country installs local generation capacity to meet its demand without benefiting from the wider regional generation capacity, therefore reducing the potential welfare benefits derived from regional integration (Perez-Arriaga, 2013).

Regional planning of resources helps optimise capital investments in the generation and transmission network. Along with a strong governance model, formal endorsement from heads of participating countries or regions may increase trust and help with future investments, as has been done in WAPP (ESMAP, 2010). Participating countries need to strictly adhere to the regional framework to reap the benefits of the integrated regional market.

For the successful implementation of a well-functioning regional market and to create trust, the regulator is required to oversee and sanction activities of market participants that would violate the set of rules agreed regionally. The regulator would need to take proactive measures to prevent predatory pricing and other forms of unruly market conduct. Cross-border agreements among institutions (dealing with power sector-related issues on the national and regional levels) are essential for sustainable regional market operations (Oseni and Pollitt, 2016). Some form of regulatory oversight has made Nord Pool and MER successful power pools (Oseni and Pollitt, 2016).

For deeply integrated markets, an appropriate institutional arrangement is necessary to facilitate the co-operation and co-ordination required to align national regulatory frameworks. This institution must work in close co-ordination with relevant national-level entities and with electricity regulators and TSOs. The European regional market offers a good example: the Agency for the Cooperation of Energy Regulators (ACER) defines the guidelines for transnational electricity networks and markets, while national regulators set the rules for system operations in electricity markets within their jurisdictions. ENTSO-E, the European TSO representative body, further develops the frameworks, *i.e.*, the grid codes, ensuring overall alignment, which are then approved and implemented by the TSOs. Similarly, in the Central American Power Market, the CRIE (the Regional Commission for Electricity Interconnection) is the regulatory body for the regional market. The CRIE's board of commissioners is composed of one commissioner from each of the six countries.

Robust information technology for market and transmission system operation

Regional market operators are expected to handle orders from all participating countries, which need to be processed in a transparent manner and for which a robust information-technology (IT) system is essential. For example, the cross-border intraday (XBID) project in Europe has created an integrated platform based on the shared order book (SOB) concept of trading modules, the Capacity Management Module (CMM) and the Shipping Module (SM). The platform allows multiple exchanges across participating regions to trade power continuously on a centralised platform (Nord Pool, 2018).

With the increasing penetration of VRE, increasing the granularity of power markets in terms of time and space can help integrate more VRE into the grid. As the granularity increases, the operation of power markets becomes increasingly complex, especially within a wider regional market. Similarly, the number of bid and ask orders, as well as the number of transactions (contracts) is also expected to increase significantly once the power markets merge at a regional level. Calculation of the available cross-zonal capacity requires an extensive alignment, and the calculation process involves more parties compared to the process within one single market area (Nord Pool, 2018). Hence, market and system operators should have state-of-the-art IT systems that can provide higher computational power at a low cost.

As the market becomes more complex and automated, market operators need to ensure a clear and transparent methodology to price the power at different times and across different locations. Clear and transparent methodologies also help create confidence among market participants, especially those with long-term investments across the value chain (*e.g.*, in generation assets).

IV. CURRENT STATUS AND EXAMPLES OF LEADING INITIATIVES

Some of the key indicators of selected regional electricity markets have been captured in the Table 2.

Table 2 Leading initiatives of regional markets and key indicators

Regional market	Participating countries/systems	Year of establishment
Central America Power Market[1]	**6 countries:** Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua and Panama	2013
European Union[2]	**23 countries (day-ahead market):** Austria, Belgium, the Czech Republic, Germany, Denmark, Estonia, Finland, France, Great Britain, Hungary, Italy, Lithuania, Latvia, Luxembourg, the Netherlands, Norway, Poland, Portugal, Romania, Spain, Slovenia, Slovakia and Sweden	1990s (NordPool was created)
	14 countries (intraday market): Austria, Belgium, Denmark, Estonia, Finland, France, Germany, Latvia, Lithuania, Norway, the Netherlands, Portugal, Spain and Sweden	2018 (XBID Project – intraday market)
Eastern Africa Power Pool[3]	**10 countries:** Burundi, the Democratic Republic of Congo (DRC), Egypt, Ethiopia, Kenya, Rwanda, Tanzania, Libya, Uganda and Sudan	2005
Greater Mekong Sub-region[4]	**6 countries:** Kingdom of Cambodia, Guangxi Zhuang Autonomous Region and Yunnan Province of the People's, Republic of China (PRC), Lao People's Democratic Republic (Lao PDR), Union of Myanmar, Kingdom of Thailand and the Socialist Republic of Viet Nam	1995
South African Power Pool (SAPP)[5]	**12 countries:** Angola, Democratic Republic of Congo (DRC), Tanzania, Malawi, Zambia, Zimbabwe, Mozambique, Swaziland, South Africa, Lesotho, Namibia, Botswana	1995
Western Energy Imbalance Market (EIM), United States[7]	**8 active members:** Idaho Power Company, Powerex, Portland General Electric, Puget Sound Energy, Arizona Public Service, NV Energy, PacifiCorp, CAISO and Balancing Authority of Northern California/SMUD	2014

Sources:
1. Navarrete (2016)
2. ENTSO-E (2018c)
3. The Eastern Africa Power Pool (2016); Olingo (2018)
4. Asian Development Bank (2016)
5. SAPP (2016)
6. Westerneim (2019)

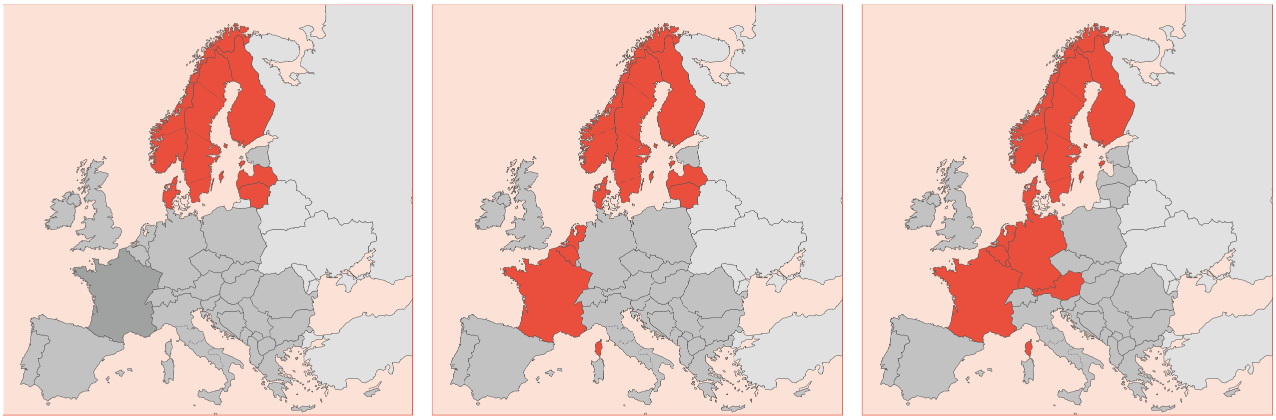
Total capacity	% penetration of VRE	Impact on VRE grid integration	Level of integration
16.5 GW (2016)	From 3 % in to 8.7 % in 2016	Increased the power generation from renewables, displacing generation from fossil fuel based plants	Shallow market integration
995 GW (2017)	14.7 % (2017)	Significant interconnection between Germany, Sweden and Norway allows Denmark to integrate ~49 % of wind power without significant curtailments Spatial complementarities between VRE in different countries and larger balancing area	Deep market integration
60.7 GW (2015)	n.a.	The Kenya and Ethiopia electricity transmission interconnector is expected to be completed by mid-2019, concluding the first phase of the region's power pool project	Early stage of market integration
118.9 GW (2012)	3 %	New interconnections expected to improve gird integration of renewables: • A North West pole connecting the PRC, Myanmar, and Thailand to replace coal and gas-fired power generation in the PRC and Thailand by hydro power from Myanmar (about 26 000 MW) • An East West pole to connect Thailand, northern Lao PDR, and northern Viet Nam to substitute Lao hydro for thermal generation (about 4 500 MW) • A Southern pole to connect southern Lao PDR to central Viet Nam, and to a lesser extent, Cambodia and southern Viet Nam to strengthen supply in these regions and to displace coal and possibly some gas-fired plants	Early stage of market integration
62 GW	n.a	A large hydro power project in the Democratic Republic of Congo (Grand Inga project: 20 000 MW) is economically viable only with interconnections (Lippmann and DiPippo, 2017)(IRENA, 2016)	Shallow market integration
		The EIM has avoided curtailment of 757 862 GWh since its inception (2014–2018), avoiding 324 284 eq. tonnes of CO_2 and has netted USD 564.88 million in gross benefits (2014–2018) for market participants	Deep market integration

Internal day-ahead market for electricity in the EU

In the EU, regional market integration is already well advanced in several aspects and further pan-European harmonisation of rules is ongoing (ACER, 2018). Significant progress has been made especially towards the implementation of single day-ahead coupling (SDAC) via the Commission Regulation (EU) 2015/1222 of 24 July 2015 establishing a guideline on capacity allocation and congestion management (CACM), which sets the rules for co-ordinated European day-ahead and intraday markets (Commission Regulation, 2015).

The day-ahead market timeframe foresees a single day-ahead market coupling that enables cross-zonal transmission capacity to be used efficiently from an economic point of view. In 2018, day-ahead market coupling was implemented on 30 out of 42 EU borders (excluding the four borders with Switzerland), covering 23 European countries: Austria, Belgium, the Czech Republic, Denmark, Estonia, Finland, France, Germany, Great Britain, Hungary, Italy, Latvia, Lithuania, Luxembourg, the Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain and Sweden. The gradual integration of the European day-ahead market coupling is depicted in the figure below.

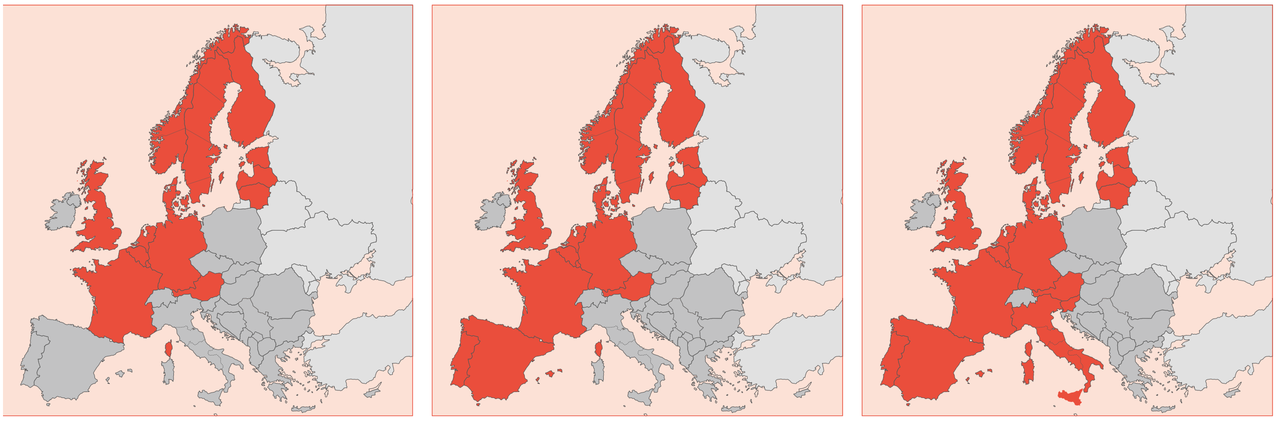
Figure 5: Gradual integration of the European regional wholesale market (day-ahead timeframe)



1990s – NORD POOL

2006

2011



FEBRUARY 2014

MAY 2014

FEBRUARY 2015

Source: ENTSO-E (n.d.)

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Internal intraday market for electricity in the EU

An important step towards further integration of European wholesale markets across Europe was taken on 12 June 2018 with the go-live of the XBID project establishing a single intraday coupling (SIDC), which is one of the key elements of market design envisaged in the CACM Regulation. TSOs of 11 countries and 4 power exchanges (EPEX SPOT, GME, Nord Pool and OMIE) jointly started the XBID project, initially covering 14 countries.[7] A second go-live with further countries is foreseen in 2019, the objective being to extend the mechanism for XBID trading to all Europe and, potentially, interconnected countries.

The project is expected to increase liquidity in the intraday markets, as bid and ask orders that were not met in local markets can now be matched within the larger integrated regional market. This project is also expected to increase market efficiency since the cross-border transmission capacity allocation and energy matching process is being carried out (implicitly) at same time. The increased market liquidity and efficiency is expected to facilitate the integration of renewable energy into the energy market and therefore a better absorption of this energy into the grid. As it becomes challenging for market participants to be in balance after the closing of the day-ahead market, trading interest in the intraday market is increasing. Being balanced on the network closer to physical delivery time is beneficial both for market participants and for the power systems, among others by reducing the need of balancing reserves and the associated costs (NordPool, 2018).

Internal balancing market for electricity in the EU

Commission Regulation (EU) 2017/2195 of 23 November 2017 establishing a guideline on electricity balancing will play a crucial role in the further integration of the internal energy market across Europe (Commission Regulation, 2017). ENTSO-E conducted various cross-border electricity balancing pilot projects with the purpose of testing the feasibility of the European target model (*i.e.*, envisaged design for balancing markets), its intermediate steps, as well as evaluating the associated implementation impact and with the purpose to report on the experience gained.

For example, the **Frequency Containment Reserves (FCR) Cooperation** is a common market for the procurement and exchange of balancing capacity, which involves ten TSOs in seven countries: Austria (APG), Belgium (Elia), Germany (50Hertz, Amprion, TenneT DE, TransnetBW), Western Denmark (Energinet), France (RTE), the Netherlands (TenneT NL) and Switzerland (Swissgrid). As a result of this project, where FCR are procured through a common merit order list, FCR capacity prices have been steadily decreasing and converging across the participating countries.

The **Trans European Replacement Reserves Exchange (TERRE)** is the project selected by ENTSO-E to become the European platform for the exchange of balancing energy from Replacement Reserves pursuant to the guideline on electricity balancing, in which nine TSOs participate: France (RTE), Great Britain (National Grid), Italy (Terna), Portugal (REN), Spain (RED), Switzerland (SwissGrid), Czech Republic (ČEPS), Poland (PSE) and Romania (Transelectrica).

Other initiatives in Europe aim to net imbalances or exchange balancing energy across TSOs' scheduling areas, such as the project to exchange energy from aFRR (automatically activated frequency restoration reserves) between Austria and Germany. As a result, the overall cross-zonal exchange of balancing energy (including imbalance netting) almost doubled between 2015 and 2017 (ACER, 2018).

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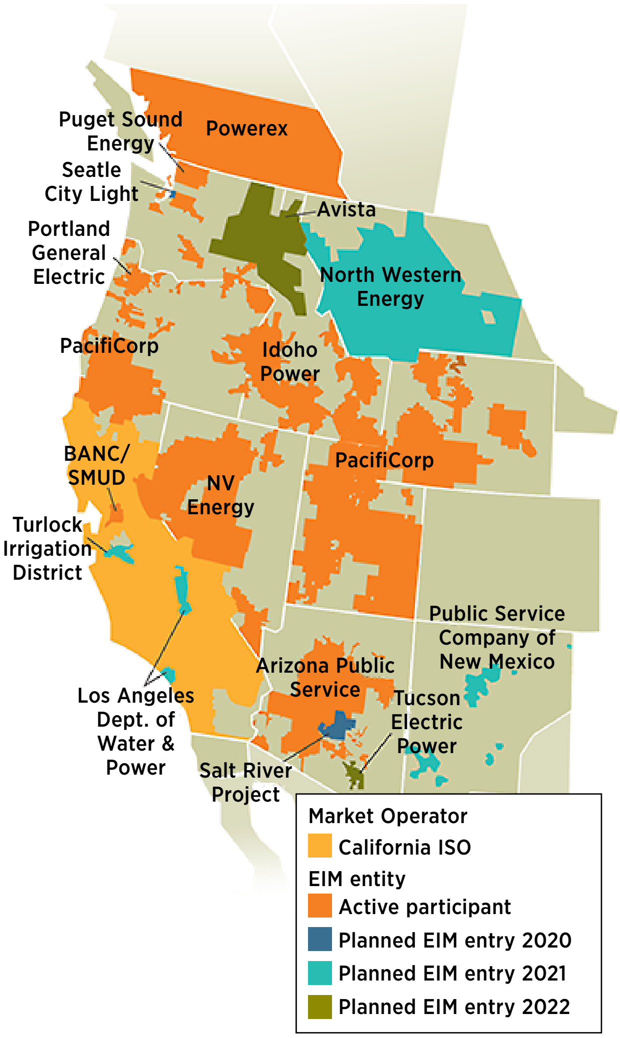
[7] Austria, Belgium, Denmark, Estonia, Finland, France, Germany, Latvia, Lithuania, Norway, the Netherlands, Portugal, Spain and Sweden.

Western Energy Imbalance Market (EIM), United States

In November 2014, the California independent system operator (CAISO) and PacifiCorp launched the Western Energy Imbalance Market (EIM) (PacifiCorp, 2019). The EIM is a "real time" market involving eight western states that trades the difference between the day-ahead forecast of power and the actual amount of energy needed to meet demand in each hour.

Figure 6: Western EIM active and pending participants



Source: Westerneim (2019)

Disclaimer: Boundaries and names shown on this map do not imply any official endorsement or acceptance by IRENA.

Currently, there are nine active members[8] of this EIM with other five members[9] to join by 2021 (Westerneim, 2019). The Western EIM aimed to balance the power demand for every five minutes with the lowest cost energy available across the combined grid. The EIM leverages the flexible backup resources and demand across the combined grid. Apart from reducing the cost of power,[10] the Western EIM also improves the grid integration of renewable energy (Westerneim, 2019).

Western EIM also manages congestion on transmission lines to maintain grid reliability and makes excess renewable energy available at a low cost to participating utilities rather than forcing generating assets offline. The EIM has helped to avoid curtailment of almost 760 TWh since its inception (2014–2018), avoiding 324 284 eq. tonnes of CO_2 emission (CAISO, 2019) as Table 3 details.

CAISO's Western EIM showed benefits to the eight market participants of more than USD 62 million during the fourth quarter of 2018. That brought the total gross benefits attributable to the real-time western energy market to nearly USD 565 million since it began operation in 2014 (CAISO, 2019).

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[8] Idaho Power Company, Powerex, Portland General Electric, Puget Sound Energy, Arizona Public Service, NV Energy, PacifiCorp, CAISO and Balancing Authority of Northern California/SMUD.

[9] Los Angeles Department of Power & Water, Salt River Project, Seattle City Light, Public Service Company of New Mexico, and NorthWestern Energy.

[10] Western EIM has helped save USD 401 million since its inception in the second quarter of 2018 in power costs (CAISO, 2018).

Table 3 Maximising green energy, minimising greenhouse gases

Year	Curtailment avoided (MWh)	CO_2 emissions avoided (metric tonnes)
2015	31 082	13 220
2016	328 238	140 486
2017	161 097	68 951
2018	237 445	101 627
Total	**757 862**	**324 284**

Note: CAISO calculates CO_2 emissions reductions attributable to the EIM from avoided renewable energy curtailments based on a default emission rate of 0.428 metric tonnes CO_2/MWh.
Source: CAISO (2019)

Through increased co-ordination and optimisation, utilities like Western EMI can realise cost benefits and reduce carbon emissions. Sharing resources across a larger geographic area, even if it is only in real-time, continues to have the positive effect of reducing greenhouse gas emissions by using renewable generation that otherwise would have been turned off. Use of this energy to meet demand across the EIM footprint is likely replacing less clean energy sources. The quantified benefits from avoided curtailments of renewable generation from 2015 to date reached 324 284 metric tonnes of CO_2, roughly the equivalent of avoiding the emissions from 68 179 passenger cars driven for one year.

V. IMPLEMENTATION REQUIREMENTS: CHECKLIST

TECHNICAL REQUIREMENTS	**Hardware:** • Physical interconnection capacity among countries/systems in the region • Sufficient capacity made available by system operators to the market **Software:** • Robust IT system and higher computational power required to process bids from market participants across the entire region • Automation of various processes and information exchange related to scheduling of power plants
REGULATORY REQUIREMENTS	**Wholesale market and system operation:** • Strong institutional arrangements and a regulatory framework for cross-border co-ordination among various stakeholders (TSOs, market operators, regulators, etc.) • Co-ordination of scheduling and dispatch across different trading timeframes • Regional grid code to achieve co-ordinated operations and investment planning • For deeply integrated markets, a harmonised market design (*e.g.*, same gate opening and closure time, same scheduling intervals and products), while considering the specificities of participating countries • Effective, efficient and timely implementation of all legal provisions among participating countries • Clear, transparent and consistent pricing methodology • Surveillance of the market to ensure market manipulation does not occur
STAKEHOLDER ROLES AND RESPONSIBILITIES	• Establishment of regional regulatory agencies and market operators • Regional mindset and trust of policy makers, regulators, TSOs, market participants, etc.

ABBREVIATIONS

ACER	Agency for the Cooperation of Energy Regulators
aFRR	Automatically activated frequency restoration reserves
BSP	Balancing responsible party
CACM	Capacity allocation and congestion management
CAISO	California independent system operator
CMM	Capacity Management Module
CO_2	Carbon dioxide
CRIE	Regional Commission for Electricity Interconnection
EIM	Energy Imbalance Market
ENTSO-E	European Network of Transmission System Operators for Electricity
EU	European Union
EUR	Euro
FCR	Frequency containment reserves
GW	Gigawatt
GWh	Gigawatt-hour
IEEFA	Institute for Energy Economics and Financial Analysis
IEM	Internal Electricity Market
IRENA	International Renewable Energy Agency
IT	Information technology
MER	Mercado Regional de Electricidad
MRC	Multi-Regional Coupling
MW	Megawatt
NEM	National Electricity Market
OTC	Over-the-counter
PPA	Power purchase agreement
SADC	Single day-ahead coupling
SAPP	South African Power Pool
SIDC	Single intraday coupling
SIEPAC	Central American Electrical Interconnection System
SM	Shipping Module
SOB	Shared order book
TERRE	Trans European Replacement Reserves Exchange
TSO	Transmission system operator
TWh	Terawatt-hour
USD	US dollar
VRE	Variable renewable energy
WAPP	West African Power Pool
XBID	Cross-border intraday

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REGIONAL MARKETS
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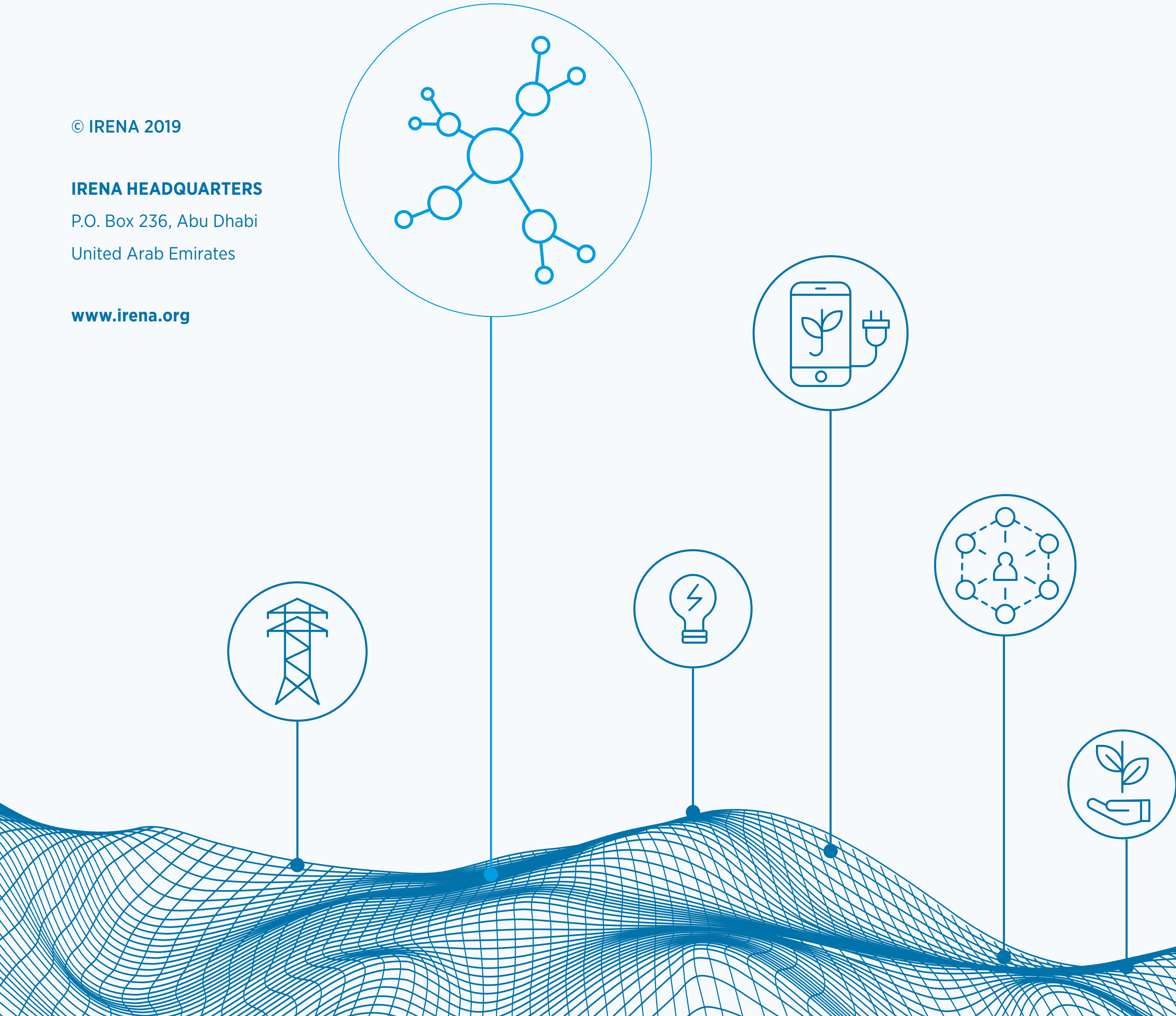

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TIME-OF-USE TARIFFS

INNOVATION LANDSCAPE BRIEF

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The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future, and serves as the principal platform for international co-operation, a centre of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity. **www.irena.org**

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TIME-OF-USE TARIFFS

Demand-side flexibility is key for a renewable-powered future.
Tariffs that change with time of use enable **demand response**.

WHAT ARE THEY?

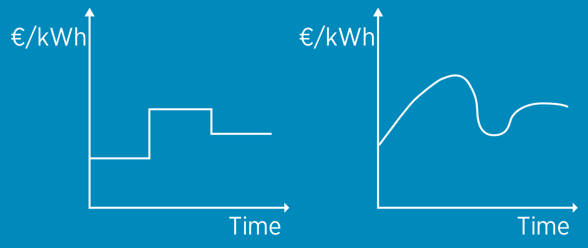
Time-varying tariffs incentivise load adjustment, either manual or automated.
This allows customers to save on energy expenses while benefitting the system.

1 HOW THEY WORK

Tariffs send customers **price signals** that reflect **system conditions**.

Static (determined in advanced)

Dynamic (determined in real time based on actual system conditions)



2 BENEFITS FOR THE SYSTEM

- Unlock demand response
- Reduce peak load and investments in grid infrastructure

3 KEY ENABLING FACTORS

- Advanced metering infrastructure
- Digital technologies for automation
- Dynamic pricing, linking retail and wholesale markets

4 SNAPSHOT

- ➜ US saved over 5 % on retail electricity sales due to demand response, by implementing time-of-use tariffs in 2015
- ➜ Nordic market could achieve 15–20 GW of demand-side flexibility
- ➜ Implemented in at least 17 EU countries (including, Finland, France, Germany, Sweden)

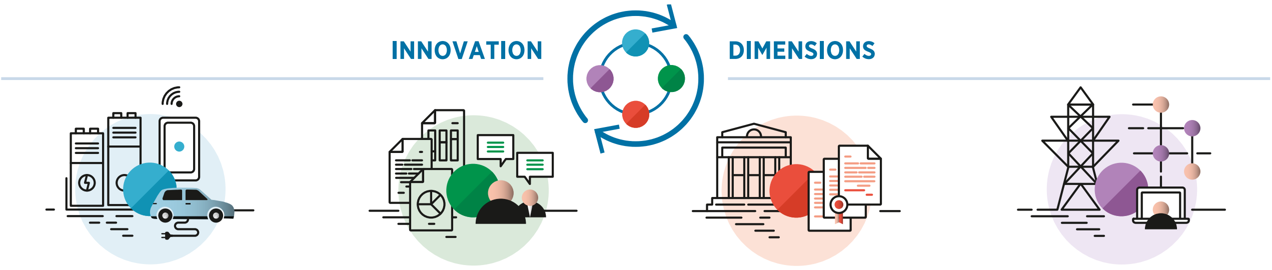
ABOUT THIS BRIEF

This brief forms part of the IRENA project "Innovation landscape for a renewable-powered future", which maps the relevant innovations, identifies the synergies and formulates solutions for integrating high shares of variable renewable energy (VRE) into power systems.

The synthesis report, *Innovation landscape for a renewable-powered future: Solutions to integrate variable renewables* (IRENA, 2019), illustrates the need for synergies between different innovations to create actual solutions. Solutions to drive the uptake of solar and wind power span four broad dimensions of innovation: enabling technologies, business models, market design and system operation.

Along with the synthesis report, the project includes a series of briefs, each covering one of 30 key innovations identified across those four dimensions. The 30 innovations are listed in the figure below.

INNOVATION DIMENSIONS



● **ENABLING TECHNOLOGIES**

1 Utility-scale batteries
2 Behind-the-meter batteries

3 Electric-vehicle smart charging
4 Renewable power-to-heat
5 Renewable power-to-hydrogen

6 Internet of things
7 Artificial intelligence and big data
8 Blockchain

9 Renewable mini-grids
10 Supergrids

11 Flexibility in conventional power plants

● **BUSINESS MODELS**

12 Aggregators
13 Peer-to-peer electricity trading
14 Energy-as-a-service

15 Community-ownership models
16 Pay-as-you-go models

● **MARKET DESIGN**

17 Increasing time granularity in electricity markets
18 Increasing space granularity in electricity markets
19 Innovative ancillary services
20 Re-designing capacity markets
21 Regional markets

22 Time-of-use tariffs
23 Market integration of distributed energy resources
24 Net billing schemes

● **SYSTEM OPERATION**

25 Future role of distribution system operators
26 Co-operation between transmission and distribution system operators

27 Advanced forecasting of variable renewable power generation
28 Innovative operation of pumped hydropower storage

29 Virtual power lines
30 Dynamic line rating

This brief provides an overview of a key innovation in market design: time-of-use (ToU) tariffs, also referred to as a mechanism for implicit demand response.

With a ToU tariff scheme, customers can adjust their electricity consumption voluntarily (either through automation or manually) to reduce their energy expenses. As the name indicates, the price signals are time-varying, determined based on the power system balance or on short-term wholesale market price signals.

Significantly, ToU tariffs unlocks demand-side flexibility and can thereby help to increase the penetration of renewable energy. Examples show how various countries and regions have adopted ToU tariffs and illustrate the impact of these tariffs on the power system.the electricity system, such as aggregators.

The brief is structured as follows:

I. DESCRIPTION

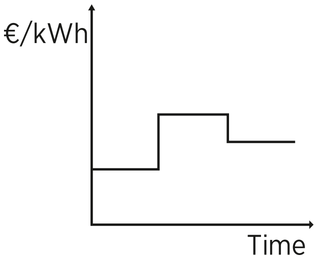
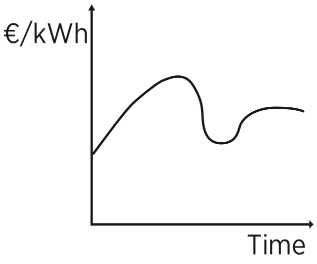
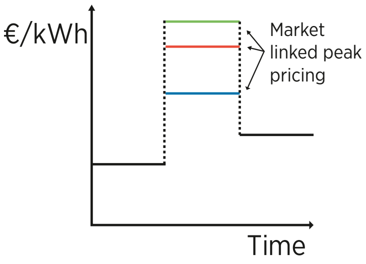
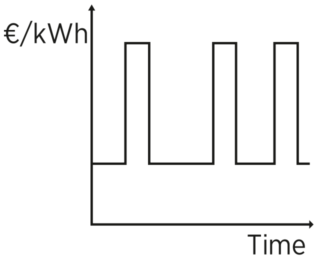
Demand response refers to the possibility of changing energy loads during specific time intervals by exposing consumers to the correct cost-reflective price signals. The US Federal Energy Regulatory Commission (FERC) defines demand response as "changes in the electric usage by demand-side resources from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when the system reliability is jeopardised" (FERC, 2017).

Demand response can be achieved through ToU tariffs, based on consumers' reaction to price signals (also referred to as implicit demand response) or through incentive-driven demand response, by trading committed and dispatchable flexibility on energy markets (also referred to as explicit demand response) (SEDC, 2016).

This brief is focused on ToU tariffs, also called price-based demand response programs. ToU tariffs enable customers to adjust their electricity consumption voluntarily (either through automation or manually) to reduce energy expenses. As the name indicates, the price signals are time-varying, determined based on the power system balance or on short-term wholesale market price signals (such as day-ahead or intraday price signals).

Time-based tariff structures can be static (e.g., tariffs determined in advance) or dynamic (e.g., tariffs determined in "real time" based on the actual system conditions). Dynamic tariff structures include real-time pricing, variable peak pricing and critical peak pricing /critical peak rebates. Time-based rate programmes require advanced metering infrastructure (AMI). The table below gives an overview of time-based demand response pricing options.

Table 1 Forms of time-of-use tariffs

Type of tariffs	Nature of pricing	Illustrative graphical representation	Features
Static ToU pricing	**Static**		This typically applies to usage over large time blocks of several hours, where the price for each time block is determined in advance and remains constant. It can use simple day and night pricing to broadly reflect on-peak and off-peak hours, or the day can be split into smaller segments, allowing several slack periods. Seasonality can also be taken into account.
Real time pricing	**Dynamic**		Prices are determined close to real-time consumption of electricity and are based on wholesale electricity prices. Electricity prices are calculated based on at least hourly metering of consumption, or with even higher granularity (e.g., 15 minutes). Such tariffs are mostly composed of the wholesale price of electricity plus a supplier margin.
Variable peak pricing	**Combination of static and dynamic**		A hybrid of static and dynamic pricing, where the different periods for pricing are defined in advance, but the price established for the on-peak period varies by market conditions.
Critical peak pricing	**Combination of static and dynamic**		A rate in which electricity prices increase substantially for a few days in a year, typically during times the wholesale prices are the highest. E.g., French Tempo tariff is a contract with a fixed price all year except for a maximum of 22 days with very high prices. Customer are notified of

Source: Adopted from smartgrid.gov (n.d.) and EURELECTRIC (2017)

When there are constraints on the electricity network, it makes sense to introduce location-based tariff structures. Location-based tariffs reflect the cost associated with congestion in electrical networks (e.g., nodal pricing), incentivising the consumers and prosumers (i.e., participants who can both buy and sell electricity) to reduce electricity consumption from the grid or to inject electricity into the grid based on network congestion. As such, ToU tariffs can be applied to the supply of electricity or to the use of the electricity network, or both.

II. CONTRIBUTION TO POWER SECTOR TRANSFORMATION

ToU tariffs do not impose a firm commitment on consumers. Consumers are free to decide how and when to react to price signals and to adjust consumption during specific time intervals. With consumers' higher responsiveness to price signals, the whole power system, as well as consumers themselves, can benefit.

Providing power system flexibility – Key for integrating variable renewable energy generation

Demand response has the potential to become one of the most cost-effective flexibility sources in a power system, key to enabling the integration of a high share of VRE generation. ToU tariff programmes can shift demand towards periods when renewable energy generation is abundant and decrease consumption when there are generation constraints in the system.

ToU therefore has the potential to substantially reduce the curtailment of VRE resources and improve the system's reliability and predictability. With real-time pricing, even shorter-term variations in renewable energy output can be balanced with demand.

Automation processes using smart appliances based on pre-set criteria according to consumers' preferences can increase the responsiveness of consumers to price signals. This can improve the predictability and reliability of demand response. In the case of dynamic ToU tariffs, automation is key to enabling consumers to react to price changes on short notice and to reaping the benefits of such a mechanism. Consumers can also use energy storage systems, integrated with smart meters, to automatically charge and discharge, depending on price variations. As an example, by applying dynamic prices in combination with smart charging of electric vehicles (EVs), EVs could alter their charging patterns to flatten the peak demand, fill the load valleys and support real-time balancing of the grids (Eid et al., 2016).

Reducing investments in grid reinforcement and peak capacity

The increasing responsiveness of customers to tariffs allows system operators to save investments in generation reserve capacities by shifting consumption to the off-peak time interval or lower price time intervals. By reducing peak demand, network upgraded investments can also be reduced, resulting in lower final tariffs.

Also, by providing information about grid conditions through location-based pricing, market participants know the time and location of system congestion and can react quickly based on the prices (IRENA, 2017). By optimising the distributed energy resource (DER) participation in the local grid – incentivising a prosumer to supply a specific demand to decongest a line – or by simply reducing demand in a specific location, investments in the grid may be reduced.

Potential impact on power sector transformation

The increased adoption of demand response programmes is expected to result in better network management, with consumers being conscious about their electricity consumption during high price time periods.

- In a pilot conducted in Gotland, Sweden, customers participated in a programme that used price signals. During the initial stage of the programme, **23 %** of total electricity consumption was experienced during the five most expensive hours. This **fell to 19 % and 20 % in the first and second year of the programme**, respectively (World Economic Forum and Bain & Company, 2017).

- According to an estimate provided by the American Council for an Energy-Efficient Economy (ACEEE), in the US during 2015, about **200 billion kWh** of electricity, or more than **5 %** of retail electricity sales, were **saved due to demand response programmes**. For each 1 % reduction in retail electricity sales for the retailers, on a median basis, a reduction in the peak demand of about 0.66 % was found to be achievable (ACEEE, 2017).

- A feasible potential of about **8 GW** of **demand side flexibility** is available in Sweden if ToU tariffs are implemented (The Nordic Council of Ministers, 2017).

- In a meta-study of several modelling exercises to determine the potential for demand flexibility in the Nordic market, the Nordic Council of Ministers estimate a **1520 GW potential for demand side flexibility** resources if, amongst others, real-time pricing and metering, information and communication technology (ICT) infrastructure and aggregator services are encouraged (The Nordic Council of Ministers, 2017).

III. KEY FACTORS TO ENABLE DEPLOYMENT

Deployment of advanced metering infrastructure

Advanced metering to track the consumption of individual consumers is a prerequisite for market-based pricing schemes. Smart meters that record the consumption at an hourly, half-hourly or quarter-hourly basis are required at each of the consumption connection points.

Advanced metering infrastructure (AMI) integrates smart meters, communications networks and data management systems to enable two-way communication between suppliers and customers. AMI also enables the collection and storage of customer consumption profiles on an hourly or sub-hourly basis. This allows retailers to implement refined rate structures that can better cover the costs of energy production and supply.

AMI can also integrate additional technologies, such as web-based portals that enable customers to analyse their hourly electricity usage, compare their usage to other local consumers and gather information about the options to manage their electricity consumption better. Such data could also be used by customers when requesting a new (or better) offer from other suppliers in the markets when switching contracts.

Adoption of smart appliances and automation control

Automation control using smart appliances based on pre-set criteria according to consumers' preferences can increase the responsiveness of consumers to price signals. Dedicated software can allow customers to set price preferences, using automation control, for operating the connected appliances. In addition, customers participating in price-based demand response programmes may allow the operators to make small adjustments to their energy consumption during critical periods in exchange for a payment or rebate from the retailer.

One example of automation control is electric heating at lowest daily prices. This can be done with relatively simple automation: the customer has hourly pricing based on the day-ahead price. An algorithm can determine how many hours the water boiler (storing electrical heating) needs to be turned on during one day based on previous data and outdoor temperature (for example, seven hours). Then, the algorithm creates a calendar that determines on which hours the heaters is turned on or off (for example, choosing the seven cheapest hours). This calendar is then sent daily to the smart meter, which has a relay that is connected to the heater/boiler and controls it.

This example requires very little communication between the customer and the supplier (calendar updated daily), and the algorithm can be relatively simple. The main requirements are that the smart meter is equipped with the relay, the heater/boiler is connected to the relay and there is an interface that can be used to send the calendars. If this interface is open and standardised, customers can contract with any chosen market party to give consent to control the relay to provide customers with the control service needed to benefit from implicit demand response.

Consumer engagement and communication

Because ToU tariffs do not require a firm commitment by consumers, who are left to decide how and when to react to the price signals given, consumer engagement is often a challenge. For example, a 2015 study in a selection of European Union countries showed the main underlying barriers to dynamic pricing in electricity supply tariffs to household consumers are a lack of awareness of consumer benefits, followed by insufficient savings to be made (as perceived by consumers) and the lack of policy framework in support of dynamic pricing (ACER/CEER,2016).

Some consumers may be satisfied with business as usual, even though they could save money within demand response programmes. For industrial loads where the cost savings can be substantial, higher responsiveness to demand response programmes might be easier realised.

For domestic consumers, effective demand response might be easier achieved with automation control that enables their loads to respond automatically to price signals, without their active participation via manual response.

However, the focus should be on finding the customers that can benefit the most (by reducing their electricity bill and providing benefits to the system). These are domestic customers with loads that are large enough and controllable enough, namely electric heating, cooling and ventilation loads, as well as EVs, if available. For example, Finland has an estimated 1 800 MW of domestic heating loads that could relatively easily participate in demand response.[1]

Defining the methodology for formulating dynamic prices

Dynamic tariffs, in particular real-time pricing, are more difficult to implement, as they require continuous exchange of information between actors in the retail market, the wholesale market and system operators. Dynamic prices can be derived using various methods, such as indexing with a weighted average of current and past wholesale prices, using advanced statistical techniques, and so forth.

For example, the Finnish system is an interesting case study because the whole value chain from wholesale market to the individual smart meter is unbroken, in the sense that suppliers pass the wholesale market price directly on to consumers. Therefore, one day after physical delivery, suppliers get the measured hourly consumption data of each of their customers (smart metering point). Consequently, the retail supplier can define dynamic pricing as spot-price plus a margin.

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[1] *Based on discussions during the IRENA Innovation Week, September 2018.*

IV. CURRENT STATUS AND EXAMPLES OF LEADING INITIATIVES

Some of the key indicators about ToU tariffs have been captured in the table below, followed by case studies on country-specific adoption of ToU tariffs.

Table 2 ToU tariffs: Key indicators

Key parameters	Description
Countries where ToU tariffs are applied	17 European countries (including Sweden, Germany, Finland, France, Germany), USA, India
Types of ToU adopted	**Static ToU tariffs:** Day/night ToU differentiation (this is very common in Europe; e.g., in Italy, all low-voltage consumers are mandatorily exposed to ToU pricing if they do not choose a supplier in the liberalised market). **Dynamic real-time pricing:** Estonia, Romania, Spain Sweden and the UK applied such tariffs (e.g., between 25 % and 50 % of all households in Estonia and Spain incur their supply charges based on hourly pricing). **Other dynamic pricing methods:** These apply in Denmark, Norway and Sweden, where electricity consumers incur spot-market-based pricing through the monthly average wholesale price. **Critical peak pricing:** This is applied to a smaller extent in the UK, Lithuania, Portugal, Romania and France (ACER, 2016).
Services provided	• Implicit demand response (participation of consumers in the energy transition). • Consumers benefits, such as electricity bill savings. • Cost-reflective tariffs benefiting suppliers • Increased competition among suppliers in the retail market, as a driver for innovative business models.

Finnish dynamic pricing structure

In Finland, consumers have the option of choosing a dynamic pricing tariff structure for electricity. Retail suppliers offer dynamic pricing to consumers who chose to do so in the liberalised market (as opposed to regulated markets). The price is determined based on the Nord Pool spot price for the price area of Finland. The customer, who chooses a dynamic price tariff structure, pays the hourly price, retailer’s premium and a monthly fixed fee to the retailer with which they opted to enter into a contract.

By the end of 2017, approximately 9 % (about 340 000) of customers had opted for this tariff structure (Energy Authority, Finland, 2018; EURELECTRIC, 2017). The customer can check electricity prices for each hour of the succeeding day from the chosen retailer's website. The published prices are based on the spot market timetable. Therefore, the prices for the next day (24 hours), starting from midnight, are finalised at around 2 p.m. of D-1 (day ahead). The price that the customer pays for a particular time slot depends on the time of consumption. This customer requires hourly metering, which is the case for all consumers in Finland. Customers can see their hourly consumption one day after delivery on their local distribution system operator's (DSO's) web portal or application.

Apart from the above pricing structure, some retailers offer price-optimised heating hours, depending on weather conditions and actual heating capacity. This enables the current heating system to operate efficiently and helps to save up to 15 % on heating expenses (EURELECTRIC, 2017).

New market design in the European Union

While there is significant variation in the penetration of ToU tariffs among electricity consumers in the European Union, the new draft Electricity Directive and Electricity Regulation (being part of the Clean Energy for All Europeans legislative package) sets new rules for consumers throughout the union. For example, via the new market design rules, every consumer in the European Union would be able to offer demand response and to receive remuneration, directly or through aggregators. Dynamic electricity price contracts reflecting the changing prices on the day-ahead or intraday markets would allow consumers to respond to price signals and actively manage their consumption. As such, consumers would be able to freely choose and change suppliers or aggregators, while also being entitled to a dynamic price contract. Additionally, the new framework foresees the entitlement of every consumer to request a smart meter equipped with a minimum set of functionalities, and it improves pre-existing rules on the consumers' ability to share their data with suppliers and service providers by clarifying the role of the parties responsible for data management and by setting a common European data format (EU Commission, 2016).

Real-time pricing in Illinois (U.S.) – Consolidated Edison (Con Ed)

In a demand response programme in Illinois, launched by Con Ed, a utility operating in the United States, consumers were given the opportunity to participate in an hourly pricing programme in which electricity prices were reflective of the electricity load (i.e., prices were low during the low demand period and prices were high during the high demand hours). An example of demand shifting by consumers includes pre-cooling the house in early morning hours, when prices are lower, and setting the cooling systems to an idle mode when prices are higher. The programme has allowed consumers to save about 15 % on their electricity bills (USD 15 million from 2007 to 2016) (Energy News Network, 2016).

Reducing renewable energy curtailment – Reverse demand-response programme in Arizona (U.S.)

The Arizona Public Service Company (APS), a utility in the United States, experiences demand peaks in summer due to increased space cooling use. However, with more moderate temperatures during the remaining nine months of the year, the utility has excess renewable energy that is often curtailed. The electricity prices during some time intervals in the daytime turn negative on account of solar generation exceeding demand.

APS recently proposed a new programme that aims to reduce the need to curtail solar energy during the periods of negative pricing. Instead of curtailing renewable production, APS will pay customers to use energy to keep the renewables online and smooth the load curve. This is similar to load shifting. However, since it is less predictable in terms of the on-peak/off-peak price arbitrage (due to the intermittency of the renewables), the APS programme will be specific to the dispatchable non-essential loads. For example, EVs with smart charging could off-take the free or negatively priced energy when the reverse demand response is activated, and smart appliances (e.g., dishwashers, washing machines, dryers, etc.) could be set to run during these times as well.

V. IMPLEMENTATION REQUIREMENTS: CHECKLIST

TECHNICAL REQUIREMENTS

Hardware:

- Advanced metering infrastructure (AMI) to enable two-way communication between the demand response participants and the system operators. AMI will also enable the collection and storage of the customer consumption profile on an hourly or sub-hourly basis.

Software:

- Energy management systems that can respond to electricity price signals and automatically adjust consumption according to the customer's preferences, such as during peak price periods.

Communication protocols:

- Agree to and develop common interoperable standards (at both the physical and ICT layers) to increase the co-ordination between the consumer, demand response aggregators and system operators.

REGULATORY REQUIREMENTS

Wholesale market:

- Allow easier and equal access to the wholesale market to all kinds of flexibility service providers.
- Reveal the value of flexibility by a more granular market time representation.

Distribution system:

- Incentivise distribution system operators and/or consumers to adopt smart metering solutions, including innovative ICT infrastructure financing models.

Retail market:

- Regulators should define a standardised methodology for computing dynamic prices that can be adopted by retailers.
- Functioning retail markets could provide innovative products and pricing models for various customer needs. For example, in Finland innovative products are being introduced, and customers can opt to choose the product and pricing method best suited to their needs (such as hourly dynamic pricing, retailers buying excess solar photovoltaic generation as a marketbased solution, ToU tariffs, etc.).
- Regulation should set clear roles and responsibilities for market parties. Long-term foreseeable regulation is needed.
- Liberalised markets, as opposed to regulated markets, could facilitate the market entry

STAKEHOLDER ROLES AND RESPONSIBILITIES

Consumers:

- Engage in demand response programmes.
- Change to suppliers/retailers offering ToU tariffs.

Retailers:

- Customers should be adequately informed about the opportunities and risks of dynamic pricing contracts. As these contracts become more commonplace, consumers' awareness and learning will further increase with their participation or the participation of someone they know.
- Involve the customer in the design of the tariff. The involvement of customers in the design phase, such as through public consultations, could improve the acceptance of the dynamic pricing scheme as consumer preferences could be taken into consideration.

State institutions/Regulators:

- Conduct cost-benefit analyses assessing to what extent demand response would bring social welfare benefits before investing in costly enabling infrastructure.
- Provide incentive-based policy frameworks for the deployment of innovative technologies in the distribution network.
- Understand customer behaviour and create awareness of the possibility of using load management.
- Encourage pilot programmes and disseminate the results publicly.

ABBREVIATIONS

ACEEE	American Council for an Energy-Efficient Economy
AMI	Advanced metering infrastructure
APS	Arizona Public Service Company
BtM	Behind-the-meter
ConEd	Consolidated Edison
D-1	Day ahead
DER	Distributed energy resource
DSO	Distribution system operator
EV	Electric vehicle
GW	Gigawatts
ICT	Information and communication technology
IoT	Internet of Things
kWh	Kilowatt-hours
P2P	Peer-to-peer
ToU	Time-of-use
TSO	Transmission system operator
VRE	Variable renewable energy

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MARKET INTEGRATION OF DISTRIBUTED ENERGY RESOURCES

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The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future, and serves as the principal platform for international co-operation, a centre of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity. **www.irena.org**

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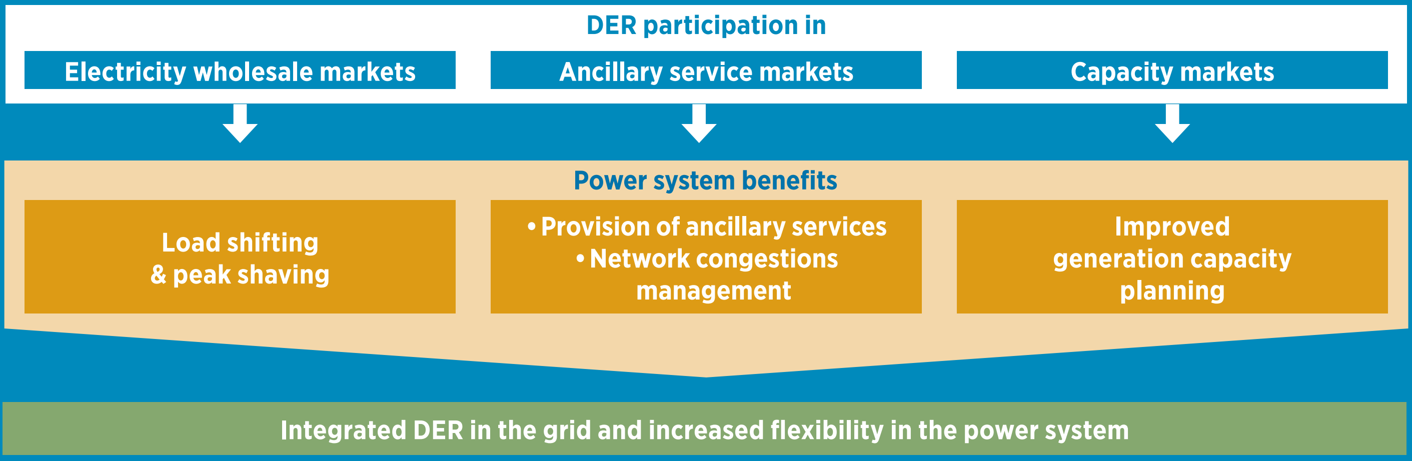
1 HOW IT WORKS



DER participation in

Electricity wholesale markets

Ancillary service markets

Capacity markets

Power system benefits

Load shifting & peak shaving

- Provision of ancillary services
- Network congestions management

Improved generation capacity planning

Integrated DER in the grid and increased flexibility in the power system

2 KEY ENABLING FACTORS

- Aggregators enable DER to bundle and behave like a traditional power plant in the market
- DSO becomes market facilitator or market maker for DERs
- Enhanced co-ordination between DSO and TSO
- Advanced metering infrastructure

3 SNAPSHOT

➜ In EU, DERs can offer 100 GW of demand response potential.

➜ New York's ISO (NYISO) is planning to enable DER participation in Day-Ahead Demand Response Program and Demand Side Ancillary Services Program.

➜ By 2050, DERs would supply 30–45 % of Australia's electricity needs

WHAT ARE DERs?

Distributed energy resources (DERs) are small and medium-sized power sources connected to the distribution network, that can potentially provide services to the power system

MARKET INTEGRATION OF DERs

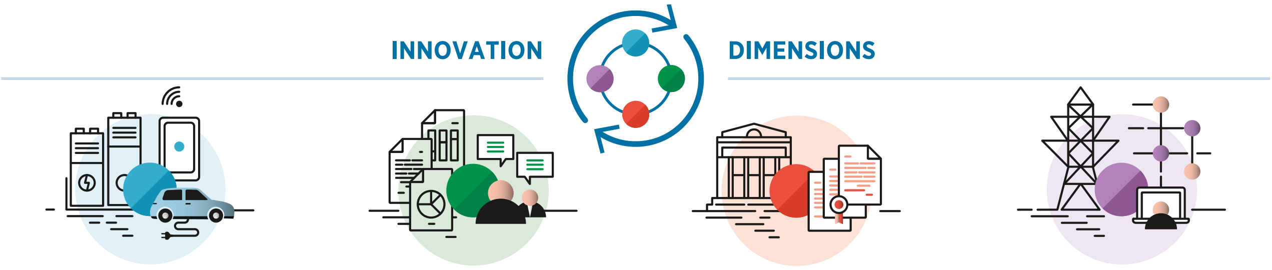
Participation in wholesale and ancillary service markets exposes DERs to **market prices** and enable **demand-side flexibility**

ABOUT THIS BRIEF

This innovation landscape brief is part of the project "Innovation landscape for a renewable-powered future", which maps innovations, identifies synergies and formulates solutions for integrating high shares of variable renewable energy (VRE) into power systems.

A synthesis report, *Innovation landscape for a renewable-powered future: Solutions to integrate variable renewables* (IRENA, 2019a), details the need for synergies between different innovations to create actual flexibility solutions for power systems. Solutions to drive the uptake of solar and wind power span four broad dimensions of innovation: enabling technologies, business models, market design and system operation.

Along with the synthesis report, the project includes a series of innovation landscape briefs, each covering one of 30 key innovations identified across those four dimensions. The 30 innovations are listed in the figure below.



● ENABLING TECHNOLOGIES

1 Utility-scale batteries
2 Behind-the-meter batteries

3 Electric-vehicle smart charging
4 Renewable power-to-heat
5 Renewable power-to-hydrogen

6 Internet of things
7 Artificial intelligence and big data
8 Blockchain

9 Renewable mini-grids
10 Supergrids

11 Flexibility in conventional power plants

● BUSINESS MODELS

12 Aggregators
13 Peer-to-peer electricity trading
14 Energy-as-a-service

15 Community-ownership models
16 Pay-as-you-go models

● MARKET DESIGN

17 Increasing time granularity in electricity markets
18 Increasing space granularity in electricity markets
19 Innovative ancillary services
20 Re-designing capacity markets
21 Regional markets

22 Time-of-use tariffs
23 Market integration of distributed energy resources
24 Net billing schemes

● SYSTEM OPERATION

25 Future role of distribution system operators
26 Co-operation between transmission and distribution system operators

27 Advanced forecasting of variable renewable power generation
28 Innovative operation of pumped hydropower storage

29 Virtual power lines
30 Dynamic line rating

This innovation landscape brief provides an overview of a market design innovation that allows distributed energy resources (DERs) to provide grid services, by participating in wholesale and ancillary service markets and being exposed to market prices (also referred to as explicit or incentive-driven demand response, as opposed to implicit or price-based demand response in which end-consumers react to price signals). The objective of the market integration of DERs is to achieve better integration of these resources into the grid and to use them to increase grid flexibility.

The brief is structured as follows:

I Description

II Contribution to power sector transformation

III Key factors to enable deployment

IV Current status and examples of leading initiatives

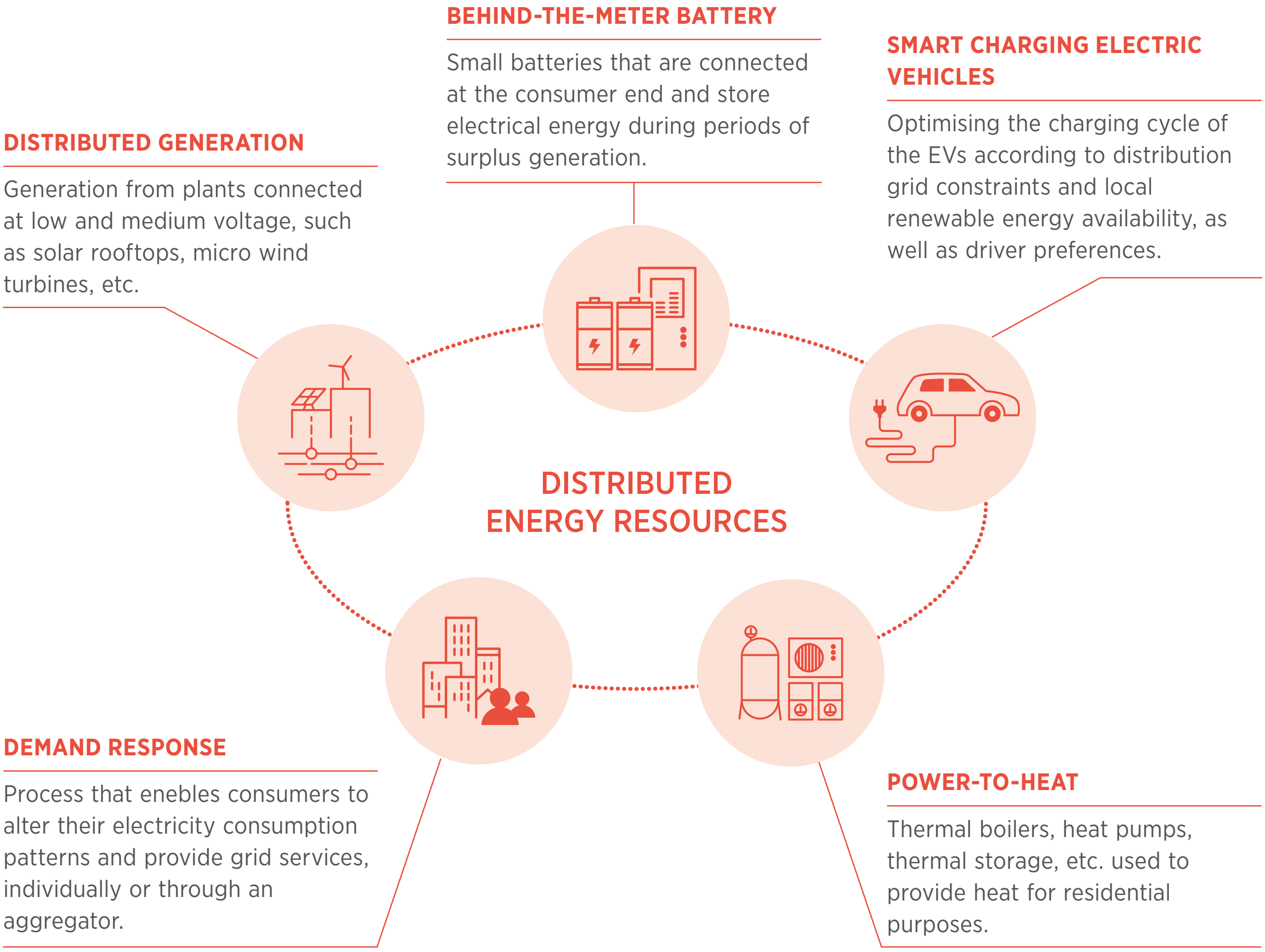
V Implementation requirements: Checklist

I. DESCRIPTION

Distributed energy resources (DERs) are small or medium-sized resources that can potentially provide services to the power system, directly connected to the distribution network or near the end-user (European Commission, 2015). DERs include distributed generation, behind-the-meter batteries and controllable loads that can be used for demand response, *e.g.* household appliances, smart charging electric vehicles (EVs), power-to-heat (heat pumps, electric boilers, enabled by smart meters and data services) (ARENA, 2018).

The following figure shows the different types of DERs.

Figure 1: Types of distributed energy resources



BEHIND-THE-METER BATTERY

Small batteries that are connected at the consumer end and store electrical energy during periods of surplus generation.

SMART CHARGING ELECTRIC VEHICLES

Optimising the charging cycle of the EVs according to distribution grid constraints and local renewable energy availability, as well as driver preferences.

DISTRIBUTED GENERATION

Generation from plants connected at low and medium voltage, such as solar rooftops, micro wind turbines, etc.

DEMAND RESPONSE

Process that enebles consumers to alter their electricity consumption patterns and provide grid services, individually or through an aggregator.

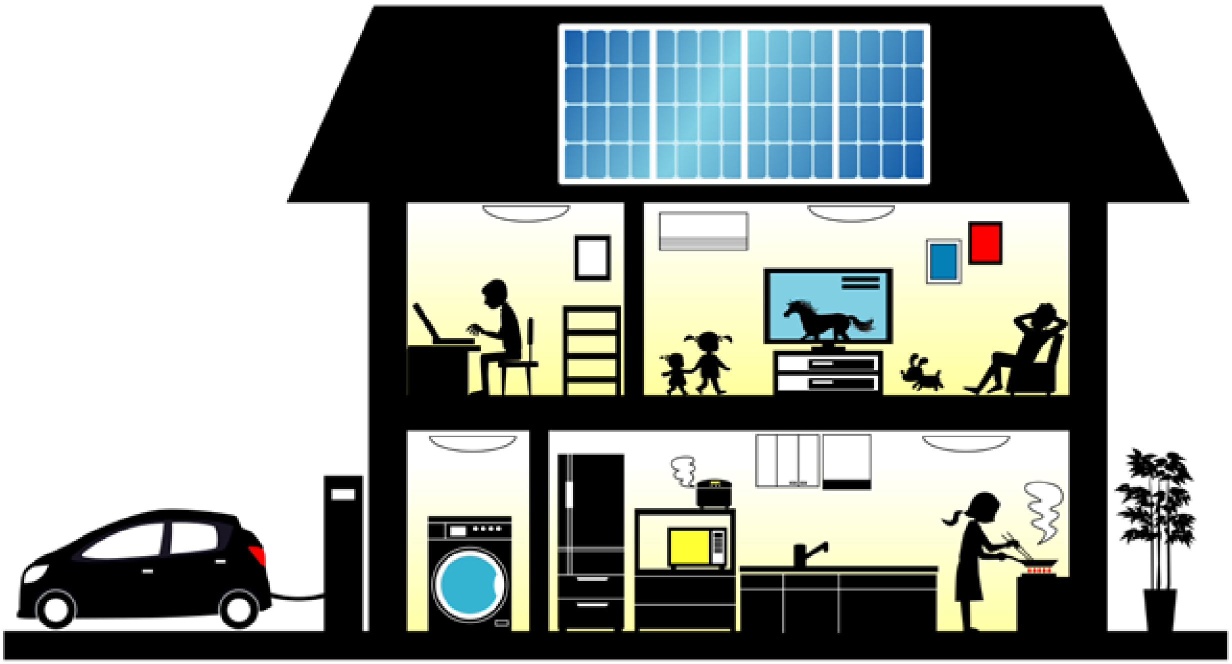
POWER-TO-HEAT

Thermal boilers, heat pumps, thermal storage, etc. used to provide heat for residential purposes.

The deployment of rooftop solar photovoltaic (PV) systems has increased significantly in recent years. Distributed storage has gained momentum as well. For example, behind-the-meter storage business models allow consumers to store the electricity generated by rooftop solar PV power plants and consume it later when needed or sell it (inject it) to the grid. Increased deployment of distributed generation, such as rooftop solar PV, illustrates the emergence of a decentralisation trend versus the traditionally centralised power system. This brings challenges to the system, as well as new opportunitites. Microlevel monitoring and control is needed to ensure optimal system operation and the integration of these resources into the system.

Taking a "connect and forget" approach to DERs would harm the system and result in a missed opportunity in the long term, given the increased deployment of wind and solar power plants connected at the distribution level. However, these resources can be integrated into the grid and provide flexibility services if the enabling policy and regulatory framework is in place.

A key innovation to achieve this is to enable distributed resources to participate in established markets, such as wholesale electricity markets, ancillary service markets and capacity markets (if applicable), so that DERs are exposed to market price signals. This can be done either via aggregators (either an electricity supplier or an independent service provider) or by decreasing the minimum capacity requirement for participating in such markets. For example, DERs should be allowed to participate in wholesale electricity markets (day-ahead and the intraday timeframes) in the same way that supply-side large generators bid in these markets. Exposing DERs to market price signals would in turn increase the demand-side flexibility of the system (also known as explicit demand response, as opposed to the implicit demand response approach used by setting time-of-use tariffs).[1,2]



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[1] There are two types of demand response: implicit demand response and explicit demand response. In implicit demand response, consumers are exposed to time-of-use electricity prices or time-of-use network prices. In explicit demand response mechanisms, DERs are exposed directly to market prices (Ma, Billanes and Jørgensen, 2017).

[2] For implicit demand response, please refer to Innovation landscape brief: Time-of-use tariff (IRENA, 2019c).

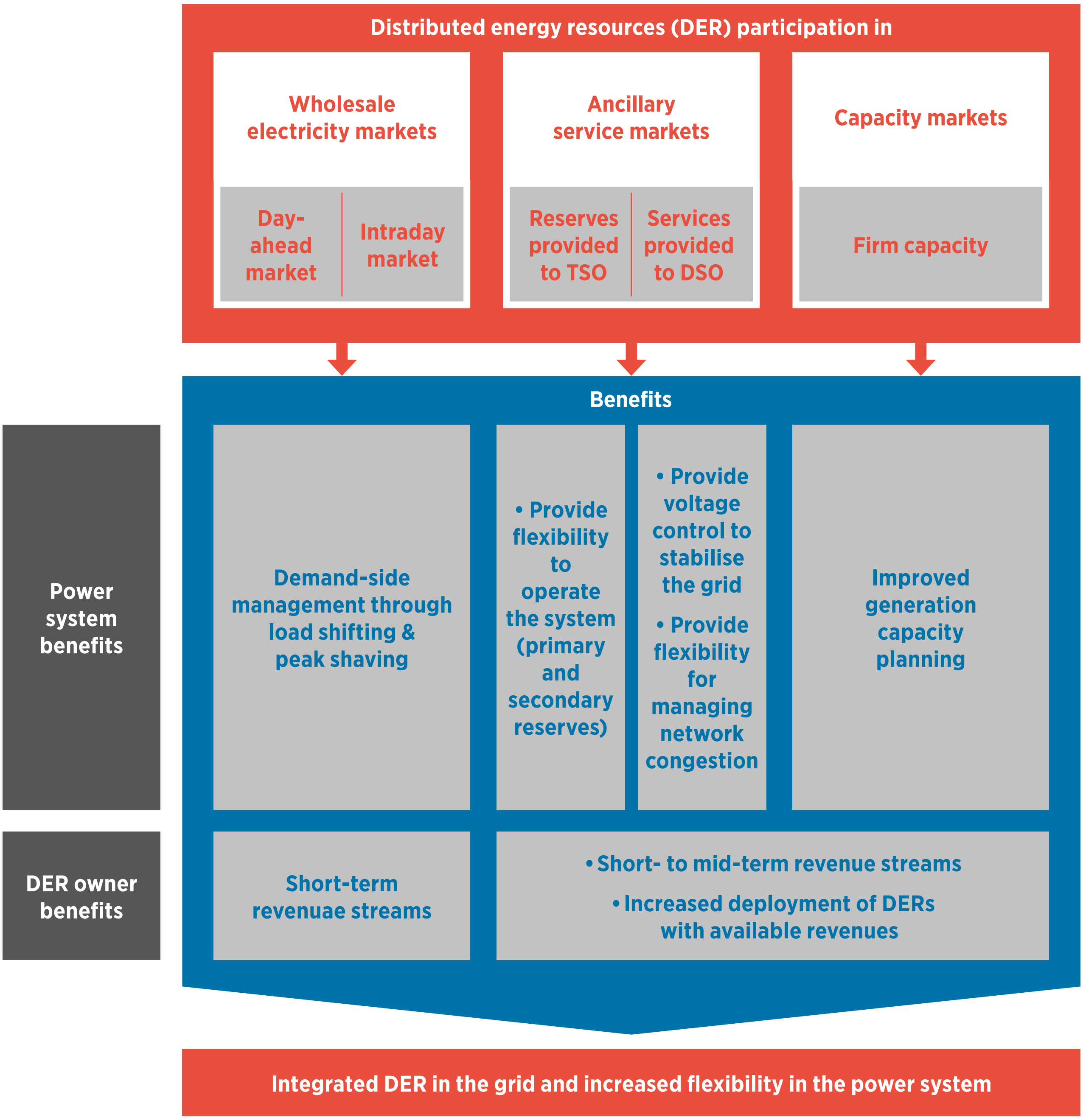
II. CONTRIBUTION TO POWER SECTOR TRANSFORMATION

The participation of DERs in wholesale electricity markets, ancillary service markets and/or capacity markets could offer many benefits to a high number of market participants. It could facilitate the integration of distributed renewable energy generation through the management of available resources and therefore better operation of the grid. It could also incentivise DERs to offer their flexibility, facilitating in turn the integration of distributed renewable energy generators into the system and providing benefits to the entire power system (European Commission, 2015). Moreover, DER participation would increase revenue streams for the asset owners and incentivise further deployment of such resources. While these revenue streams may be more volatile in short-term wholesale electricity markets, they tend to be more stable when entering medium- to long-term markets by providing reserves to transmission system operators (TSOs) or when participating in capacity markets.

While a single DER can offer limited services to the grid, aggregating a relatively large number of DERs can lead to the creation of a single, large and predictable entity (*i.e.*, like dispatchable fossil fuel generation). Bundled DERs can provide services for a longer duration, as opposed to single DERs that might not comply with TSOs' requirements. Aggregation can be achieved by co-ordinating the operation of bundled DERs using information and communication technology (ICT) devices (*i.e.*, create a virtual power plant, VPP) and algorithms (*i.e.*, artificial intelligence) to improve the forecast of renewable generation and electricity demand (see Innovation landscape brief: Aggregators [IRENA, 2019b]).

As shown in the figure below, DERs could participate across different markets and offer various services that would increase flexibility in power systems and facilitate the integration of DERs into the grid. For example, in the US market in December 2017, the New York Independent System Operator (NYISO) released a concept proposal of market design changes to enable the participation of DERs in wholesale, as well as ancillary service, markets. According to this proposal, DERs will be treated on par with other market players and will be able to participate in capacity reserve markets and regulation service markets either directly or via aggregators of small-scale DERs (<100 kW) (NYISO, 2017a).

Figure 2: Benefits of market integration of distributed energy resources



Distributed energy resources' participation in wholesale electricity markets

DER participation in wholesale electricity markets allows consumers who have the capacity to also produce electricity (*i.e.*, prosumers, which are actors that both consume and produce electricity) to respond to market price signals and alter their consumption or generation patterns. Prosumers would have two options for using the flexibility provided by their DERs: either they could sell it in the market (directly or via aggregators) or they could optimise their local consumption. While the first option enables stacking revenues from all the services provided in the market, the second option would help reduce final electricity bills. Both options unlock demand-side flexibility in the system through load shifting and peak shaving.

The participation of a significant amount of DERs in the wholesale electricity markets would also increase competitiveness in this market, lowering the volatility of the prices by reducing price spikes and reducing the occurrence of negative prices. For example, when large-scale wind generation produces less energy than forecasted, distributed generators connected to storage devices could bid into the wholesale market. This would reduce stress on the system and would be reflected in the wholesale electricity market, for example by avoiding or reducing price spikes. Similarly, when wind or solar generation surpasses demand, negative prices are sometimes observed. Owners or operators of generation assets connected to batteries could use these price signals to charge their batteries and sell (inject) this electricity at a later point, when prices are positive. DERs could therefore contribute to a more competitive, well-functioning market.

Table 1: Potential services provided by DERs in wholesale markets

Type of market	Trading time frame	Capacity/ Energy trade	Notification time before real time	DERs suited for market need	Examples
Wholesale electricity market	Intraday market	Energy	Usually 24 hours to a few minutes	Aggregated loads and generation	**Europe:** Nord Pool's intraday market (Nordic region) opened to demand response. The French Block Exchange Notification of Demand Response (NEBEF) mechanism allows trading of demand response as well. **US:** Some wholesale markets allow demand response trading, such as Pennsylvania-New Jersey-Maryland (PJM) Interconnection.
	Day-ahead market	Energy	Usually several days to a few hours		

Distributed energy resources' participation in ancillary service markets:

Providing flexibility to transmission system operators (TSOs)

Ancillary service markets are in place to manage demand and generation variations in the transmission network and to provide other transmission network-related services to allow for grid stability and security when assets are called upon by the TSO. DERs should be granted access to the ancillary services market (IRENA, 2017).

TSOs can procure ancillary services from DERs, which have been previously bundled by aggregators, such as primary and secondary reserves. Primary reserves involve response given in milliseconds and providing the service for up to seconds (<30 s). They refer to frequency control services that need to be provided by fast response resources with rapid ramping, such as storage batteries. Secondary reserves are provided in minutes and help stabilise the system by providing power over a longer period of time (compared to primary reserves).

Aggregating DERs to participate in ancillary services markets would allow TSOs access to a larger set of resources, which can provide more flexible, rapid responding services to the grid that last for a few hours (as opposed to one DER). At the same time, DERs get correspondingly remunerated for these services.

DERs can also support the TSO in network congestion management. For example, customers contracted with Voltalis, a French aggregator, receive Bluepod, a free box installed in their homes, which reduces their electric heating device operation in short time intervals whenever Voltalis receives a signal from the TSO. The dispatch signal is used primarily for electricity supply shortage in Brittany (a poorly interconnected French region) or when the network is congested. During these events, customers with Bluepod have their heating automatically controlled, but Bluepod gives them the option to and assume full control over their heating devices. While Voltalis is able to trade the aggregated flexibility in different ancillary services markets, customers observe a reduction of their normal electricity bills due to limited interruptions in electricity consumption for heating (Eid *et al.*, 2016).

Table 2: Potential services provided by DERs to TSOs in ancillary service market

Type of market	Service traded	Capacity/ Energy trade	Response time	Duration of service provision	DERs suited for market need	Examples[3]
Ancillary service market	Primary reserves	Capacity	<30 seconds	Up to 15 minutes (depending on the service)	**Direct control:** Aggrgated EVs, commercial and residential loads, electrical heating, storage systems	**UK:** Demand response with dynamically controlled refrigerators. **US:** EVs and stationary batteries for frequency regulation in PJM.
	Secondary reserves	Capacity	<15 minutes	From 15 minutes up to a couple of hours	**Direct control:** Aggregated EVs, residential continuous loads, electrical heating, storage systems	
	Transmission congestion management	Energy	13 minutes – 2 hours	Several hours	Aggregated EVs, energy storage and combined heat and power (CHP) units	**France:** Volatis, an aggregator, supports the TSO when the network is congested.

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[3] Source: Eid *et al.* (2016).

Providing flexibility to distribution system operators (DSOs)

Because they are connected to the distribution grid, DERs are potentially problematic for the stability and reliability of the distribution network. The management of DERs could be decentralised by the DSOs. There is an increasing interest in decentralised management of DERs due to expected associated risks for over-voltage, under-voltage and grid congestion caused by the penetration of distributed generation. Such management methods can be supported with the roll-out of smart meters and distributed automation and control.

DSOs can procure local system flexibility services from DERs to solve issues related to voltage regulation, power quality and distribution network congestion. DERs such as PV installations, energy storage devices and plug-in EVs can enable peak shaving during intervals of high demand by discharging and serving local demand. This could reduce the net load on the network and thereby reduce network congestion. By optimally managing DERs across the distribution network, either directly or through third parties (*e.g.*, via aggregators), DSOs could not only avoid congestion, but also defer costly grid reinforcement investments.

For example, battery storage systems deployed by end-consumers could store excess energy from renewable sources, such as solar PV, or be charged for using electricity from the grid when it is relatively cheap. This energy could then be discharged during peak time intervals to fulfil demand.

Aggregating DERs to provide power can also be used to manage grid congestion and avoid grid reinforcement investments. For example, the UK Power Networks, a distribution network operator in the United Kingdom, announced its plan to create London's first virtual power plant (VPP), comprising solar panels and a fleet of batteries across 40 homes in London. A trial of this concept was conducted in February 2018 wherein a fleet of 45 batteries was used to fulfil peak demand. The project is expected to provide an alternative to the traditional approach of increasing network capacity to meet peak demand (Hill, 2018).

Table 3: Potential services provided by DERs to DSOs in ancillary service market

Type of market	Service traded	Capacity/ Energy trade	Response time	DERs suited for market need	Examples[4]
Ancillary service market	Voltage control	Capacity	<1 minute	**Direct control:** Aggregted EVs, residential loads, energy storage systems	
	Distribution congestion management	Energy	<15 minutes	Aggregated EVs, energy storage and CHP units	**UK:** A DSO is using an aggregator to fulfil peak demand without increasing network capacity.

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[4] Source: Eid *et al.* (2016).

Distributed energy resources' participation in capacity markets: Improved generation capacity planning

Some capacity markets have opened up to the participation of aggregated DERs. The capacity value of aggregated DERs can be used to satisfy a utility's long-term resource adequacy requirements or to defer other infrastructure investments. DERs can also bid in as a resource in capacity markets, where they exist. For example, demand response has proven to be consistently competitive as a capacity resource in the capacity markets operated by PJM and ISO-New England. Demand response refers to the possibility of reducing electricity loads during times of supply scarcity or when system security is in jeopardy. In France, demand response has been allowed to participate in the capacity market (Le Réseau de Transport d'Électricité, 2018). Moreover, Alberta's capacity market allows DER participation, including demand response and distributed generation.

DERs may have different capabilities than traditional generators. This underlines the importance of developing the compensation mechanism for DERs, so that smaller DERs are incentivised to provide capacity services. PJM, a regional transmission organisation (RTO) in the United States, has a capacity market called the "Reliability Pricing Model" under which demand-response resources are treated like generation resources to ensure security of supply. Demand-response providers are paid to ensure resource availability during expected emergency conditions (PJM, 2018). PJM awarded 20 megawatts (MW) in its capacity market to a residential solar and storage provider. For providing 20 MW of power, 24 hours per day for a single year period, the company will be paid USD 912 million for the entire year (Weaver, 2019).

DERs help improve the economic efficiency of overall systems by reducing the need to call on high-cost peaking generating stations (NYISO, 2017a). In the long term, DERs can also help reduce overall investment in networks.

Table 4: Potential services provided by DERs to DSOs in ancillary service market

Type of market	Service	Capacity/ Energy trade	Contract signed	Response time and duration of service provision	DERs suited for market need	Examples[5]
Capacity market	Generation capacity planning	Capacity	Up to several years ahead	Response in minutes, lasting for several hours	Aggregated loads and generation	**US and France:** demand response participates in capacity markets. **Alberta (Canda):** DERs participate in capacity markets.

Potential impact on power sector transformation

For example, an assessment of power systems in Australia, performed by CSIRO and Energy Networks Australia, indicated that increasing the penetration of DERs would lead to the following impacts by 2050 (CSIRO and Energy Network Australia, 2017):

- DERs would supply 30–45 % of Australia's electricity needs.
- The electricity sector would achieve zero net emissions.
- Network operators would pay DER customers over USD 2.5 billion per annum for grid support services.
- Network charges in final electricity bills would be 30 % lower.
- Network infrastructure investment would be reduced by USD 16 billion if DERs were carefully planned.
- Total system costs would be reduced by USD 101 billion.

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[5] Source: Eid *et al.* (2016).

III. KEY FACTORS TO ENABLE DEPLOYMENT

Expanding the role of distribution system operators

To take advantage of the emerging penetration of DERs, DSOs would need to adjust their current role and transform their operation procedures (see Innovation landscape brief: Future role of distribution system operators [IRENA, 2019c]). For DSOs to consider DER flexibility as a real and effective alternative to grid investments, the regulatory framework should be adapted, introducing new incentives for DERs and enabling DSOs to interact with DERs to procure flexibility services from them. Such measures should aim at developing the mechanisms that encourage DSOs to take up this new role, as well as developing technical specifications and amending grid codes for the provision of such services.

Neutrality and transparency should govern any interaction between DSOs and network users. DSOs must maintain the role of a market facilitator or market maker, but not of a market actor. This means they should not build, manage or operate DERs on their own, like flexible assets. DSOs should be responsible for creating markets and setting the rules for market access. As such, there should be a clear split between the roles of regulated and non-regulated entities (*e.g.*, retail suppliers). Furthermore, regulation should incentivise the DSOs on total expenditures, rather than separately on CAPEX and OPEX.[6] This would in turn incentivise the DSO to better optimise the CAPEX and OPEX mix, and thus leverage the flexibility gained from DER to reduce CAPEX needs (European Commission, 2015).

Enhanced co-ordination between distribution system operators and transmission system operators

DERs can provide grid services to manage local grids. As the penetration of DERs increases, the role of DSOs is expected to become more important. Improved co-ordination between DSOs and TSOs can optimise investments in network enhancement. An institutional arrangement together with the definition of the right protocols for this co-ordination will become necessary. Such co-ordination is expected to benefit from increased DER participation in the power systems via their participation in power markets.

Aggregators, a key enabler of distributed energy resource participation in the market

To create a sizeable quantity of the flexible DERs' capacity to participate in electricity markets, aggregation of these resources should be allowed. Aggregated DERs can behave like traditional power plants – with standard attributes such as minimum/maximum capacity and ramp-up and ramp-down criteria – and can participate in markets by selling electricity or ancillary services. Many DERs can provide the fast response needed for some ancillary services, but they cannot provide the service for the duration needed. Aggregating DERs into a VPP with a fast response enables the provision of services for a long duration. A clear regulatory framework should be designed to allow fair competition among all market participants, including aggregators, whose role could be accomplished either by local electricity retailers or independent third-party aggregators.

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[6] Total expenditure (TOTEX) = capital expenditure (CAPEX) + operating expenditure (OPEX).

Allowing both electricity retailers and independent aggregators to compete in the market is key to providing cost-effective consumer services. Some countries with demand-response programmes have also allowed the aggregated load to participate in such schemes (*e.g.*, France, Belgium, Switzerland, Great Britain, Australia, etc.). In Western Australia, allowing independent demand-response aggregation has led to 12 % of the peak demand being met through dispatchable loads (SEDC, 2017).

Deployment of advanced metering infrastructure and communication protocols

Smart meters, network remote control and digitalisation, Internet of Things (IoT), broadband communication infrastructure, and smart charging stations for EVs are all fundamental enablers to services associated with DERs. Smart meters will allow real-time communication between system operators and the connected DERs. Network remote control and digitalisation will help improve low voltage network efficiency, since the data gathered can be used to detect outages and better forecast demand. Aggregators, retailers and utilities should be able to communicate with smart appliances and smart meters. Two-way communication network devices would become absolutely essential.

Grid modernisation plays an equally important role. This includes the transformation of the power grid to a platform that can detect, accommodate and control decentralised production and consumption assets, so that power flow in multiple directions can be measured and controlled to ensure the security and reliability of the active distribution network.

To integrate DERs effectively into system operations, communication protocols must be defined for different types of resources. In the case of independent aggregation, communication protocols are needed between system operators and aggregators, using the existing communication system. This ensures that the system operator is able to secure data without the addition of any special communication equipment. Moreover, rules and protocols must be defined to ensure the security of data, while protecting equipment from potential cyberattacks.

Better generation forecasting

A high level of forecasting accuracy of renewable energy generation may help better manage the impact of distributed generation on the grid. Smaller participants may lack the tools or experience that larger renewable players have. Having good weather datasets improves the forecasts of distributed generation. Forecasts for distributed solar PV, for example, can be integrated with load forecasting to obtain net-load forecasts, thus increasing the visibility of the demand-side variations.

IV. CURRENT STATUS AND EXAMPLES OF LEADING INITIATIVES

DERs are being increasingly deployed globally. Some of the key indicators are captured in Table 5.

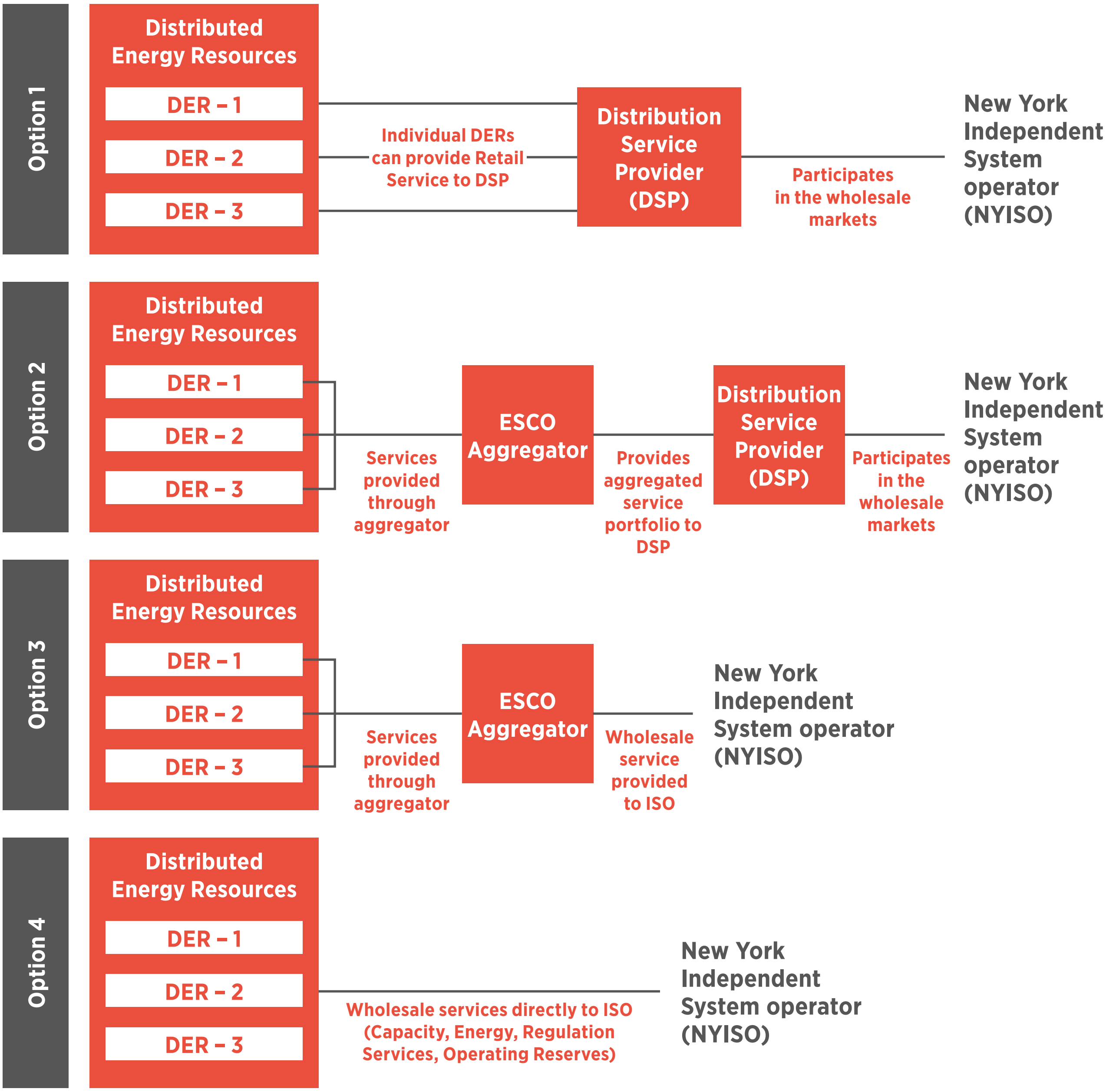
Table 5 Key indicators for DERs deployment in selected regions

Country/Region	Installed capacity of distributed energy resources
Australia	• Small-scale renewable capacity: 7 198 MW (until June 2018) (Clean Energy Regulator, 2018) • EV: 7 340 cars (IEA, 2018) ► 30–45 % of demand is expected to be met by DERs by 2050 (CSIRO and Energy Network Australia, 2017)
United States	• Small-scale renewable capacity: 20 125 MW (small-scale solar PV capacity – until February 2019) (US Energy Information Administration, 2018) • EV: 762 060 cars (IEA, 2018)
China	• Small-scale renewable capacity: 31 600 MW (distributed solar by June 2018) (Yuan, Hong, and Zhang, 2018) • EV: 1 227 770 cars (IEA, 2018)
European Union	• Demand response: 21 GW (Jiménez, 2017) • EV: 537 340 cars (IEA, 2018)

Integrating distributed energy resources into wholesale electricity markets: New York's Reforming the Energy Vision strategy

NYISO's December 2017 concept proposal (NYISO, 2017b) outlined a market design that would enable DER participation (NYISO, 2017a). The proposal called for developing market enhancements over the next three to five years that would permit DER participation in NYISO's energy, ancillary services and capacity markets. Under this new design, NYISO aims to replace the existing Day-Ahead Demand Response Program (DADRP) and the Demand Side Ancillary Services Program (DSASP) with a dispatchable DER programme. DERs would be treated on a par with other wholesale market resources by fully integrating them with the energy and ancillary services markets. The participation of DERs would be allowed either directly or via aggregators of small-scale DERs (<100 kilowatts [kW]). Figure 3 shows the various options available to DER participants to provide services in wholesale power markets.

Figure 3: NYISO integrating distributed energy resources in ancillary service markets



ESCO = energy service company; **Based on:** NYISO (2017b).

Integrating distributed energy resources in Europe

There is an increasing awareness among European policy makers that demand response is becoming a critical resource to manage the grid at a reasonable cost. This is evident from the fact that there is a thorough inclusion of demand response in the European Commission's legislative package on the new electricity market design within the Clean Energy Package. As such, the revised Electricity Regulation, which will enter into force on 1 January 2020, opens up electricity wholesale markets to renewables, energy storage and demand response (European Commission, 2019). Explicit demand response contributes around 15 GW out of a total 21 GW of demand-response capacity in Europe (Jiménez, 2017). Until now, the European countries with the most conducive frameworks for explicit demand response were Belgium, Finland, France, Ireland, the United Kingdom and Switzerland. Belgium, France, the United Kingdom and Switzerland have already enabled the participation of demand response either individually or via aggregators, while countries such as Slovenia and Poland have opened their power markets to individual demand response only (SEDC, 2017).

V. IMPLEMENTATION REQUIREMENTS: CHECKLIST

TECHNICAL REQUIREMENTS

Hardware:

- Widespread adoption of distributed generation sources and energy storage technologies.
- Equipment, such as smart meters (required to provide real-time power consumption and production data), home gateways (*e.g.*, energy boxes) and smart appliances for energy management.
- Smart grids enabling two-way flow of data and electricity.

Software:

- Aggregation and generation forecasting software: real-time communication between the aggregator and the smart meters, smart appliances and the energy storage systems.
- Distribution system management software ensuring reliability and safe operations.

Communication protocol:

- Common interoperable protocol to increase co ordination between DER assets, aggregators and system operators.

POLICIES NEEDED

Strategic policies could include:

- Supportive policies encouraging the decentralisation of power systems and better utilisation of existing infrastructure.
- Policies focusing on creating functioning markets (wholesale electricity, ancillary services and/or capacity markets), deploying innovative technologies and reducing grid costs.

REQUIREMENTS REGULATORY

Electricity wholesale market:

- Allow aggregation of DERs to enable their participation in the markets or reduce the minimum bid sizes to allow DERs to participate.
- Reduce the time before trading gate closure to better capture the short-term forecast of DERs.

Ancillary service market:

- Make ancillary service product requirements and local system service product requirements technology neutral.
- Introduce shorter procurement times that facilitate DERs’ participation.

Transmission and distribution system:

- Define geographic markets, *i.e.*, geographic segmentation into local zones, where DERs can provide balancing and flexibility services to meet local needs.
- Incentivise network operators to upgrade their network infrastructure to facilitate wider DER adoption, or to use DERs to manage grid congestion.

STAKEHOLDER ROLES AND RESPONSIBILITIES

Policy makers and regulators:

- Define a vision for DER deployment: DER implementation roadmap, planning and optimising the location of DERs, etc.
- Develop pilot programmes to work as test beds and disseminate the results.
- Establish innovation centres within research institutions, government and industry to further promote innovation in the operation of DERs.

Distribution system operators and transmission system operators:

- Change the role of DSOs to act as market facilitators for DERs or as buyers of local flexibility.
- Strengthen TSO-DSO co-operation so information flows in both directions, thereby enabling DERs to provide services to the TSO by increasing the visibility of available flexibility at the DSO level to the benefit of the TSO.

Consumers:

- Engage consumers beyond the retail market (*e.g.*, reacting to prices in wholesale markets and changing consumption patterns accordingly).
- Encourage consumers to become prosumers by owning DER assets (*e.g.*, behind-the-meter storage, solar PV plants, EVs, etc.).

ABBREVIATIONS

CAPEX	Capital expenditure
CHP	Combined heat and power
DADRP	Day-Ahead Demand Response Program
DER	Distributed energy resource
DSASP	Demand Side Ancillary Services Program
DSM	Demand-side management
DSO	Distribution system operator
ESCO	Energy service company
EV	Electric vehicle
ICT	Information and communication technology
IoT	Internet of Things
ISO	Independent system operator
kW	Kilowatt
MW	Megawatt
NYISO	New York Independent System Operator
OPEX	Operating expenditure
PJM	Pennsylvania-New Jersey-Maryland
PV	Photovoltaic
REV	Reforming the Energy Vision
RTO	Regional transmission operator
TOTEX	Total expenditure
TSO	Transmission system operator
VPP	Virtual power plant
VRE	Variable renewable energy

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MARKET INTEGRATION OF DISTRIBUTED ENERGY RESOURCES

INNOVATION LANDSCAPE BRIEF

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NET BILLING SCHEMES

INNOVATION LANDSCAPE BRIEF

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About IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future, and serves as the principal platform for international co-operation, a centre of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity. **www.irena.org**

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1 BENEFITS

Increase system flexibility by engaging prosumers, by incentivizing:

- self-consumption and injecting electricity in the grid when prices are high
- withdrawing electricity from the grid when prices are low

2 KEY ENABLING FACTORS

- Injected energy valued according to system needs
- Mechanisms to recover network costs
- Advanced metering infrastructure
- Prosumer awareness, empowerment and engagement

3 SNAPSHOT

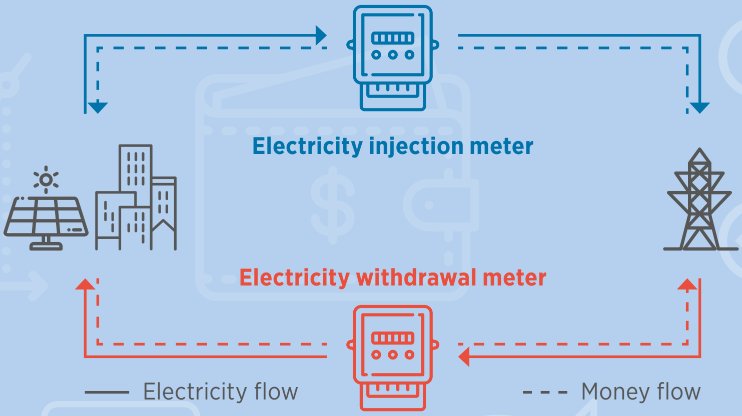
Net billing schemes are used in e.g. Indonesia, Italy, Mexico, Portugal and the USA (NY and AZ).

In New York, a formula was set to compensate the injection of renewable electricity from prosumers, combining the wholesale price with other elements of distributed generation that benefit the grid:

- avoided carbon emissions
- cost savings to other customers
- savings from avoiding capital investments

WHAT IS NET BILLING?

Net billing is a way to **charge but also compensate** prosumers based on the actual market value of electricity, balancing what they consume against what they inject into the grid.



NET BILLING SCHEMES

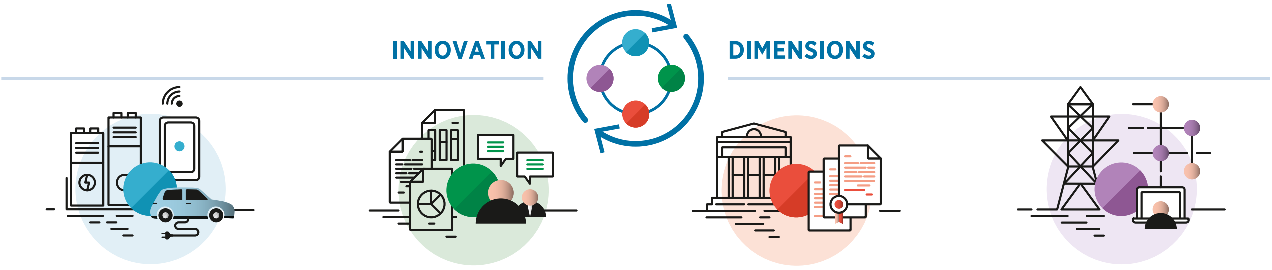
Incentivise prosumers to better interact with the grid.

ABOUT THIS BRIEF

This brief forms part of the IRENA project "Innovation landscape for a renewable-powered future", which maps the relevant innovations, identifies the synergies and formulates solutions for integrating high shares of variable renewable energy (VRE) into power systems.

The synthesis report, *Innovation landscape for a renewable-powered future: Solutions to integrate variable renewables* (IRENA, 2019a), illustrates the need for synergies between different innovations to create actual solutions. Solutions to drive the uptake of solar and wind power span four broad dimensions of innovation: enabling technologies, business models, market design and system operation.

Along with the synthesis report, the project includes a series of innovation landscape briefs, each covering one of 30 key innovations identified across those four dimensions. The 30 innovations are listed in the figure below.



● ENABLING TECHNOLOGIES

1 Utility-scale batteries
2 Behind-the-meter batteries
3 Electric-vehicle smart charging
4 Renewable power-to-heat
5 Renewable power-to-hydrogen
6 Internet of things
7 Artificial intelligence and big data
8 Blockchain
9 Renewable mini-grids
10 Supergrids
11 Flexibility in conventional power plants

● BUSINESS MODELS

12 Aggregators
13 Peer-to-peer electricity trading
14 Energy-as-a-service
15 Community-ownership models
16 Pay-as-you-go models

● MARKET DESIGN

17 Increasing time granularity in electricity markets
18 Increasing space granularity in electricity markets
19 Innovative ancillary services
20 Re-designing capacity markets
21 Regional markets
22 Time-of-use tariffs
23 Market integration of distributed energy resources
24 Net billing schemes

● SYSTEM OPERATION

25 Future role of distribution system operators
26 Co-operation between transmission and distribution system operators
27 Advanced forecasting of variable renewable power generation
28 Innovative operation of pumped hydropower storage
29 Virtual power lines
30 Dynamic line rating

This brief provides an overview of net billing mechanisms, a market design feature that incentivises prosumers (*i.e.* actors that both consume and produce electricity) to better interact with the grid. This works by introducing a method to calculate the compensation of excess renewable energy injected into the grid by distributed renewable generation assets. Net billing is an alternative mechanism addressing the limitations of net metering schemes (or net energy metering) and feed-in tariff compensation mechanisms, which are largely applicable to prosumers. Further, this brief describes the key benefits of the net billing mechanism for integrating distributed generation into the grid and increasing system flexibility.

The brief is structured as follows:

I. DESCRIPTION

The installed capacity of distributed renewable generation, especially from rooftop solar photovoltaic (PV) power plants, has increased at a rapid pace thanks to a significant decline in the cost of solar power technology over the past few years. Further, many countries across the globe have introduced schemes, such as net energy metering (NEM) and feed-in tariff (FiT) schemes, to compensate consumers for injecting excess renewable electricity into the grid, leading to a significant growth in rooftop solar capacity additions.

Under the NEM mechanism, the consumer is charged for the net electricity consumption from the grid after netting off the electricity injected by the consumer into the grid. This bidirectional flow of energy is measured through bidirectional meters, also called net meters, which keep account of the net flow of electricity. Since electricity consumption is set off against the electricity injected into the grid, prosumers typically get compensated for the injected electricity at the retail electricity tariff. In contrast, under FiT schemes, electricity generation and consumption from the grid are separated through the installation of two separate meters and are accounted for differently. While energy consumed from the grid is priced at the retail electricity tariff, the excess energy injected into the grid is compensated at a predetermined tariff notified by the regulator, also called the “feed-in tariff”. FiTs can be higher than retail electricity tariffs so that they incentivise consumers to install distributed renewable generation capacity. For example, FiTs higher than the retail electricity tariffs were witnessed in Germany, which led to increased adoption of rooftop solar PV. Subsequently, the FiTs were gradually decreased.

While these schemes have been widely accepted by prosumers, the compensation mechanisms defined under these schemes are not reflective of the cost of electricity at the moment of injection into the grid and might distort the market if the quantity injected were significant. For example, injection of excess renewable electricity into the grid is more valuable for the system during peak load hours than during off-peak hours. Similarly, oversupply of renewable electricity into the grid during time intervals of low demand could lead to curtailment of the power plant or to the formation of negative electricity prices in wholesale markets. Further, retail tariffs include other costs, such as grid access costs, supply costs and balancing costs, which are not subtracted from the compensation made to consumers under NEM. In addition, NEM mechanism allows prosumers to use the grid as a virtual storage system for free by injecting or drawing electricity at any time for the same price, which reduces consumers’ sensitivity to volatile electricity prices and hence undermines efforts to further develop demand-side response (CEER, 2016) (IRENA/IEA/REN21, 2018).

While NEM and FiTs have helped jump-start the development of distributed generation by providing an economic incentive, they must evolve into more mature compensation mechanisms that capture the true value of renewable electricity at the time of injection into the grid. As such, a compensation at wholesale electricity market price (*e.g.* when trading day-ahead platforms are established and liquid) might reflect more accurately the value of electricity injected into the grid.

Net billing is a market-based compensation mechanism, as prosumer compensation is based on the actual market value of the kilowatt-hours (kWh) consumed or injected into the grid. The invoice issued by the retail supplier to the consumer is based on the value of withdrawn electricity after subtracting the value of the injected energy (Energy Community, 2018). Figure 1 depicts the flow of electricity payments and electricity flow in a net billing scheme, which illustrates that two meters are needed. Table 1 contains different methods used to value the injected energy.

Figure 1: Schematic electricity flows and payments in a net billing scheme

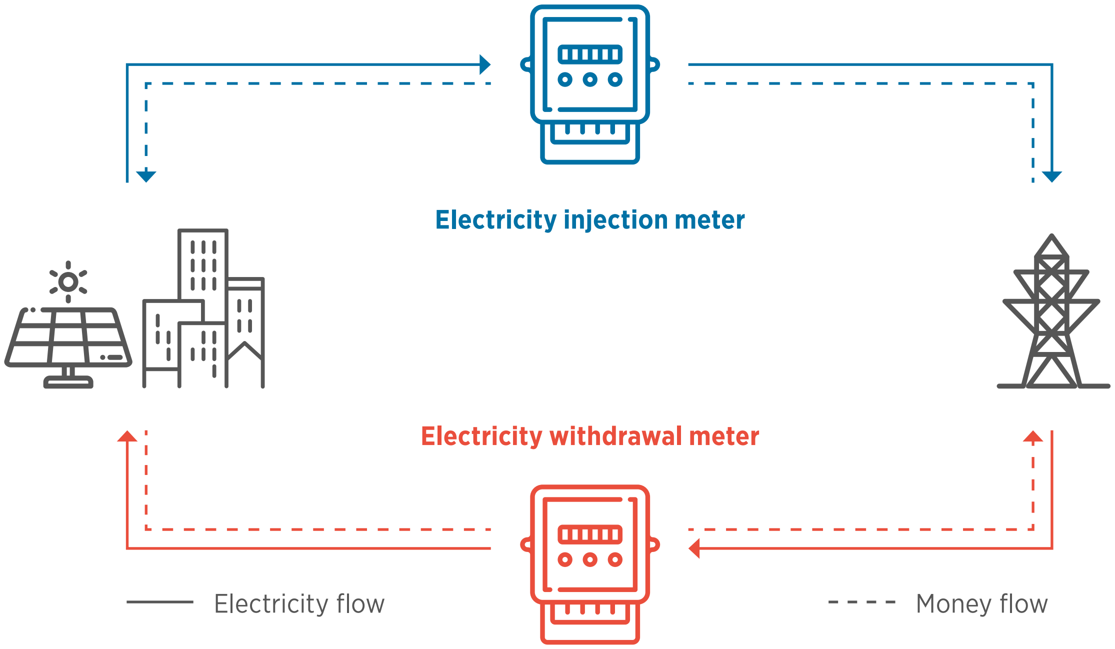


Table 1 Methods for determining the compensation tariff for excess electricity injected under net billing schemes

Method	Description		Example
Time-of-use tariffs	**Static**	Tariffs determined in advance and based on historical power system balance.	Mexico
	Dynamic	Tariffs determined in real time and based on actual power system balance or linked to wholesale market electricity prices .	Finland
Location-varying tariffs	Tariffs based on grid congestion at different nodes, including among other environmental factors.		New York (United States), Mexico
Tariffs based on the avoided cost of electricity	Tariffs based on the marginal cost of electricity procurement that was avoided by retailers/system operators because of the injection of one unit of renewable electricity into the grid		Arizona (United States)

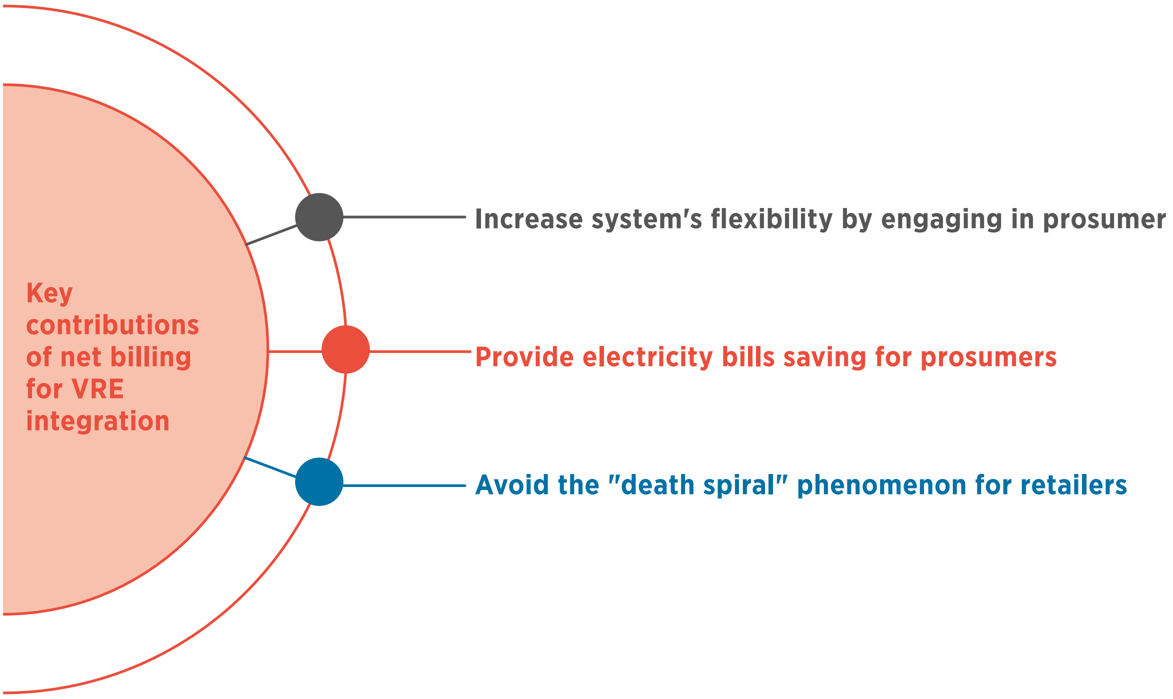
Variants of compensation tariffs for injected renewable electricity under net billing schemes shown in Table 1 can incentivise prosumers to inject energy when the compensation tariffs for injection are higher and to maximise self-consumption or to store electricity when these tariffs are lower. To take full advantage of net billing for the power system, the method for defining the tariffs should be dynamic, so that the prosumers would be able to respond to differentiated rates for the surplus electricity, according to the real-time system conditions.

Another innovative approach to net billing is the net billing advanced arrangement, which would be applicable even if generation and consumption were located in different places (also known as ''virtual net billing''). In addition, net billing could be applied in multi-apartment buildings, where the net credits for production on one site could be split between several consumers, which could facilitate the integration of community-owned generation projects into the system.

II. CONTRIBUTION TO POWER SECTOR TRANSFORMATION

A compensation mechanism that appropriately values the injected distributed renewable energy according to a sound methodology can help maximise the value of such generation for all stakeholders, such as system operators, utilities, distributed renewable energy generation owners and even those who do not own such systems (Zinaman *et al.*, 2017). Under the net billing scheme, if the compensation for the injected renewable electricity is based on time or location-varying tariffs, consumers can – by responding to price signals – help support the grid. Figure 2 below depicts the ways in which the net billing mechanism can contribute to increased flexibility in the system, while maximising self-consumption by the prosumers.

Figure 2: Contribution of net billing schemes to enhanced grid integration of renewable electricity



Increase system's flexibility by engaging the prosumer

Net billing schemes incentivise prosumers to interact with the grid in a way that maximises the benefit of self-consumption and distributed generation the most for the system.

Well-designed net billing schemes can increase the injection of renewable electricity into the grid when the compensation tariffs are high, if such tariffs are reflecting scarcity in the system. In the same way, they can maximise self-consumption or store the generated electricity in behind-the-meter batteries when the compensation tariffs are low, given that the tariffs reflect abundant VRE generation in the system and lower demand. By responding to time-varying compensation tariffs, prosumers can either shift their demand or deploy battery storage systems to maximise their revenue streams from their distributed renewable generation. Such incentives lead to more flexibility in the system, encouraging prosumers to inject electricity in the grid when the system needs it, and consume electricity from the grid when there is abundant renewable generation in the system and low demand. This would further facilitate the integration of distributed renewable generation into the grid. Moreover, when locational signals are incorporated in addition to time-of-use tariffs, prosumers can contribute to reducing network congestion and potentially deferring or minimising network investments (IRENA, 2017) (see Innovation landscape brief: Time-of-use tariffs [IRENA, 2019b]).

Provide electricity bill savings for prosumers

Prosumers can save on energy charges in the final electricity bill. Self-consumption of locally generated renewable electricity replaces costlier electricity withdrawn from the grid, thus resulting in savings on energy-related charges payable to electricity retailers in the final electricity bill.

Demand charges are generally based on the highest electricity usage requirement (peak demand in terms of kilowatts [kW]) for the consumer within a specified period (usually ranging from 15 minutes to 3 months), depending on the applicable tariff designs. When the demand charges are based on peak demand, the savings can be significant for commercial and industrial consumers, but limited for household consumers. Locally generated renewable electricity can serve some of the consumer's peak loads, thus helping reduce peak demand and, consequently, the demand charges. If the consumer's consumption pattern and renewable generation do not match well, either consumption can be shifted to coincide with the hours when renewable generation is the highest or battery storage technologies may be deployed to add flexibility.

Avoid the "death spiral" phenomenon for retailers

Under schemes such as NEM and FiT, prosumers are incentivised to produce electricity at a level that may not be optimal for the electricity system overall, sometimes being overcompensated for the renewable electricity fed into the grid. This may lead to oversupply of distributed renewable electricity into the grid, based on distorted price signals, further leading to grid integration challenges, while resulting in revenue losses for retailers and utilities. As a consequence, to maintain their revenue base, retailers may increase tariffs, which results in increased self-consumption and exacerbates the situation further. Higher rates also increase the economic incentives to become a self-consumer, creating a vicious circle (IRENA, 2017). In other words, the oversupply of distributed generation injected into the grid may increase retail tariffs, which consequently makes the grid more expensive for consumers who depend exclusively on the grid for their consumption, while making self-generation of electricity economically attractive for more consumers. The interdependence of such factors is often referred to as the "death spiral" or "death valley" for retailers.

The risk for "death spiral" to occur is lower when net billing mechanism is in place, preventing distributed renewable generation being unduly overcompensated. For instance, in the United States, rapid growth in rooftop solar installations under the NEM framework has led some utilities to modify their NEM policies and move towards net-billing-based mechanisms. Some of the examples from Nevada, Arizona, and New York are explained in the following sections.

III. KEY FACTORS TO ENABLE DEPLOYMENT

To enable the adoption of net billing schemes, a method must be developed to send the right price signals to prosumers. Appropriate mechanisms to recover network costs need to be in place. Enabling infrastructure, such as advanced metering, is required to accelerate the adoption and functioning of net billing schemes, as is consumer awareness, empowerment and engagement.

Method for valuing the electricity supplied by distributed generation according to system needs

The concept of net billing is based on assigning a high value to electricity injection from distributed renewable sources into the grid when this is most needed, while keeping the system in balance. Such valuation can therefore vary with time, location, grid characteristics or supply and demand situation, among other factors. In addition to benefitting the individual consumer, the method needs to maximise the benefits of distributed generation for the system.

For example, the New York Public Service Commission approved the first phase of the Value of Distributed Energy Resources Order, which contains a transparent method that values the injection of renewable energy from distributed renewable installations owned by commercial, industrial, non-profit and governmental entities, and is based on:

- **Locational marginal price** – the price for adding 1 kWh of electricity from a distributed energy resource (DER) into the grid, including the wholesale price of electricity, transmission congestion charges and line losses.

- **Avoided distribution infrastructure costs** – the price payable to distributed renewable generators for meeting demand and reducing stress on the distribution grid.

- **External value** – a price element corresponding to the positive externality of the environmental and health costs avoided through the replacement of polluting generation sources with renewable sources (Roselund, 2017).

California's Distributed Energy Resources Roadmap and Texas utility ERCOT's Distributed Resource Energy and Ancillary Markets Task Force include or consider locational marginal prices as part of the net billing methodology.

Appropriate mechanisms to recover network costs

Volumetric tariffs are charged on the consumption of every additional unit of electricity, whereas capacity tariffs are linked to either the installed capacity or the peak load. In many countries, fixed network costs are primarily recovered through volumetric tariffs. This is, for example, the case in most European countries (European Commission, 2015). However, increased self-consumption leads to lower revenues for distribution system operators, which may not be sufficient to recover their fixed network costs, especially when the number of self-consumption points is significant.

With a transparent method, fixed costs related to network assets could be recovered through either volumetric tariffs, capacity charges or a combination of both methods. For instance, consumers installing renewable systems may be charged a flat fee based on the installed capacity and other fixed costs incurred by distribution system operators. Such a method was applied in the Flanders region of Belgium in 2015. A grid fee of approximately EUR 70/kW was introduced for solar PV systems for self-consumption with capacity up to 10 peak kilowatts (European Commission, 2015).

Deployment of advanced metering infrastructure

Advanced metering infrastructure (AMI) integrates smart meters, communication networks and data management systems to enable a two-way communication between system operators and consumers.

Net billing requires either two separate meters or one meter with two registers to measure and distinguish the quantity of the electricity injected from the one consumed, which are valued at different rates. In the case of dynamic time-of-use tariffs, AMI is required to enable a two-way communication on prices between retailers, system operators and prosumers. Further, the design of location-varying tariffs requires system operators to monitor and understand the consumption profile at different distribution nodes. To enable this, smart meters that record the consumption on an hourly or sub-hourly basis (*e.g.* half-hourly or quarter-hourly) are required at each of the consumption points.

Prosumer awareness, empowerment and engagement via automation

Consumers installing distributed renewable systems under a net billing regime need appropriate information and supporting technologies, such as energy management systems, to be able to respond to time- or location-varying price signals. Prosumer awareness about their impact on the network, prosumer empowerment to engage with the system and, therefore, their engagement are key challenges that need to be addressed to enable effective implementation of net billing schemes.

Automated inverter control for solar PV systems, along with software applications, may enable consumers to respond appropriately to price signals without the active and manual participation of individual consumers. To achieve this, pilot programmes can be initiated to demonstrate the benefits that consumers can reap if they participate in net billing schemes.

IV. CURRENT STATUS AND EXAMPLES OF ONGOING INITIATIVES

Net billing schemes are being increasingly adopted globally, and some of the regulatory developments are captured in Table 2.

Table 2 Examples of net billing frameworks across the globe

Country	Net billing framework details
Indonesia	As per net metering regulations in Indonesia, electricity injected into the grid by prosumers will be settled at a maximum of 85 % or 100 % of the local generation cost, depending on whether the local generation cost is higher or lower than the national average generation cost (Tongsopit *et al.*, 2017)
Italy	The Italian net billing scheme calculates the value of the excess electricity fed into the grid at wholesale price, and this value can be either used as a credit for subsequent consumption periods or paid back to the consumer (European Commission, 2015).
Mexico	Under the revised net metering regulations in Mexico, renewable energy fed back into the grid will be settled according to hourly time-of-use tariffs (Jimenez, 2016).
Portugal	As per recent Portuguese self-consumption regulations, excess injection of electricity into the grid will be settled at 90 % of the average Iberian spot price; 10 % is deducted to cover the grid integration costs of renewable electricity (European Commission, 2015).
United States (Arizona)	In December 2016, the Arizona Corporation Commission voted to replace net metering with net billing under which the renewable energy injected into the grid would be compensated on the “avoided cost rate”, to be calculated by the commission for each utility (DSIRE, 2017).
United States (New York)	In March 2017, the New York Public Service Commission approved the first phase of the Value of Distributed Energy Resources Order, which sets a formula to compensate the injection of renewable electricity from installations owned by commercial, industrial, non-profit and government entities, combining the wholesale price of energy with the distinct elements of DER that benefit the grid: avoided carbon emissions, cost savings to other customers and utilities, and other savings from avoiding expensive capital investments (Roselund, 2017).

V. IMPLEMENTATION REQUIREMENTS: CHECKLIST

TECHNICAL REQUIREMENTS

Hardware:

- AMI, including equipment such as smart meters and smart inverters, which are required for price-based demand management
- Behind-the-meter battery systems or vehicle-to-home charging for electric vehicles for added value and increased revenue streams for consumers

Software:

- Communication software for real-time communication between renewable energy generation systems, inverters and batteries
- Energy management software for consumer energy cost optimisation, including energy management systems that can respond to electricity price signals and automatically adjust consumption according to the customer's preferences and/or system needs

REGULATORY REQUIREMENTS

Retail market:

- Supportive regulations encouraging the decentralisation of power systems, liberalisation of retail markets and better utilisation of the existing infrastructure
- Appropriate valuation method for renewable electricity injected into the grid that is based on system needs, wholesale prices, location, positive externalities (*e.g.* health and environmental benefits), etc.

Distribution and transmission system:

- Recovery of network costs through suitable network tariff design applicable for prosumers installing distributed generation assets

STAKEHOLDER ROLES AND RESPONSIBILITIES

Consumers:

- Become prosumers by owning DER assets (*e.g.* behind-the-meter storage, solar PV plants, electric vehicles, etc.)
- Take the role of active participants in the market and make informed decisions about reducing system costs and electricity bills, while maximising the revenue streams from DERs

Policy makers and regulators:

- Provide incentive-based policy frameworks for the deployment of AMI
- Ensure that consumers are well informed about rights and responsibilities, including impact on the network; empower consumers to take an active role as prosumers and engage with the power system
- Encourage pilot programmes demonstrating the benefits of net billing mechanisms for consumers and the system, and disseminate the results publicly

ABBREVIATIONS

AMI	advanced metering infrastructure
CEER	Council of European Energy Regulators
DER	distributed energy resource
FiT	feed-in tariff
kW	kilowatt
kWh	kilowatt-hour
NEM	net energy metering
PV	photovoltaic
VRE	variable renewable energy

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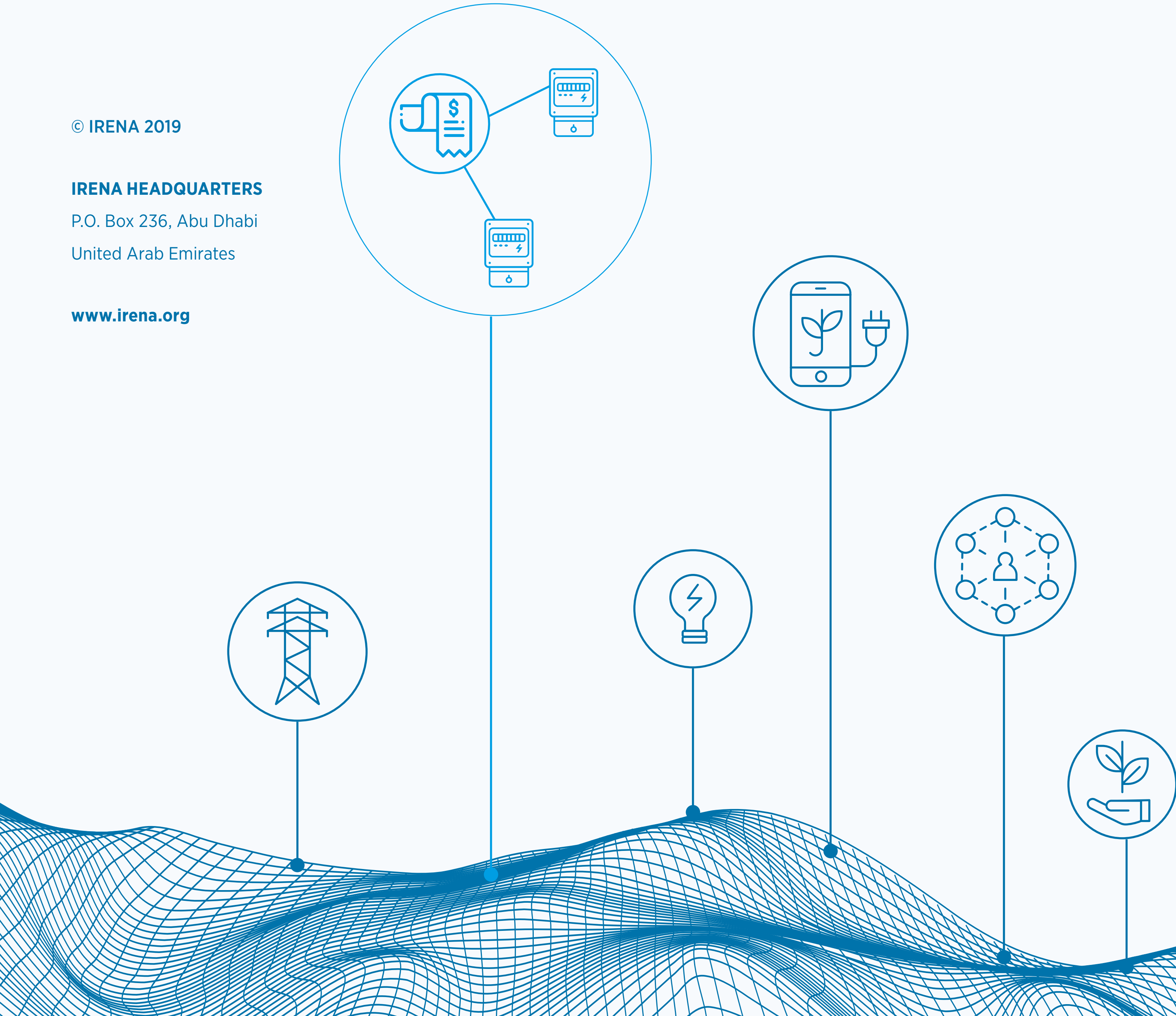
NET BILLING SCHEMES
INNOVATION LANDSCAPE BRIEF



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