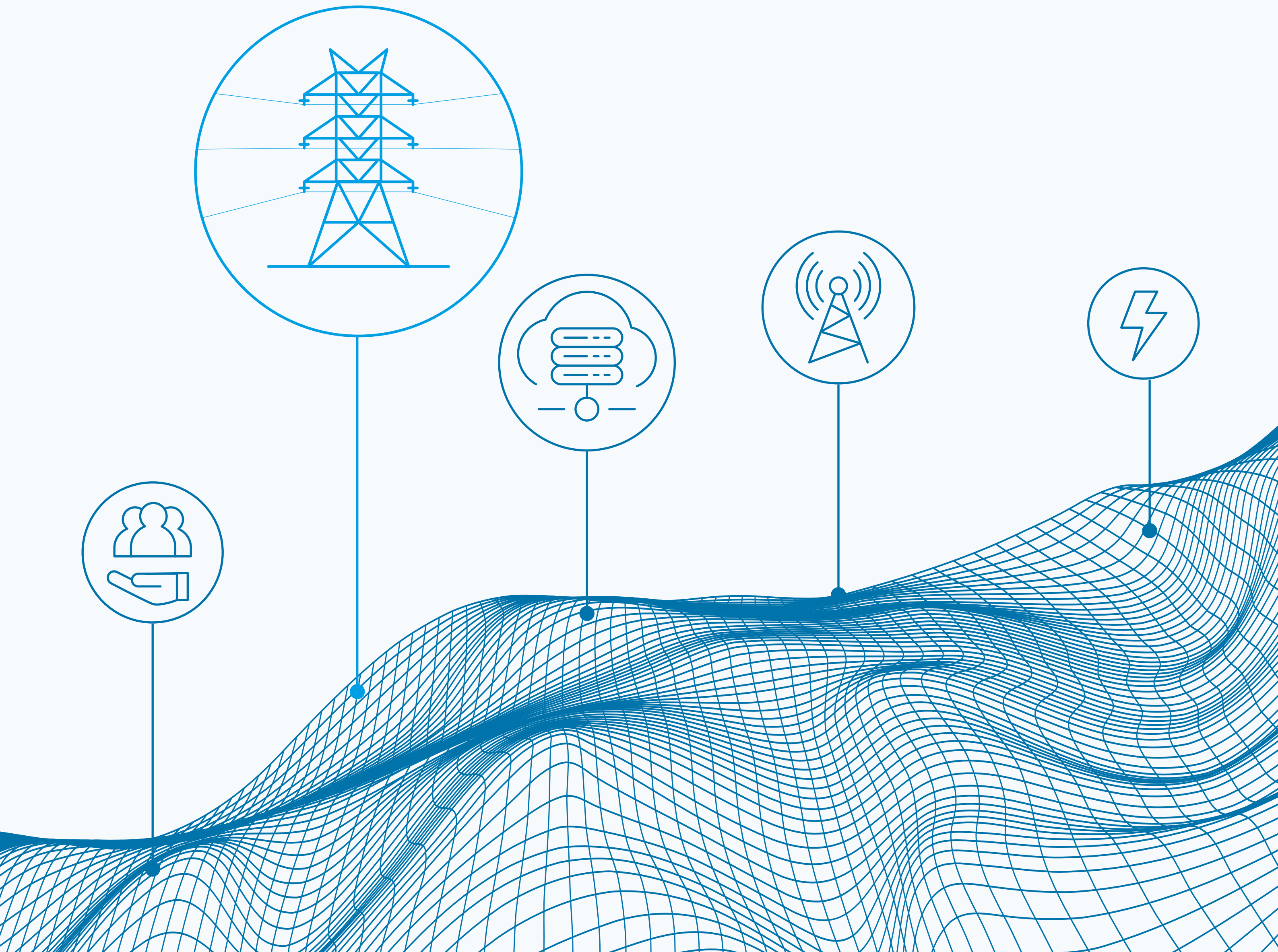
IRENA

International Renewable Energy Agency

SUPERGRIDS

INNOVATION LANDSCAPE BRIEF



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DISCLAIMER

1 BENEFITS

Direct current (DC) power lines show substantially lower power losses than alternating current (AC) lines. Power flow is also more controllable in DC systems, allowing more flexible operation. Supergrids can:

- Transmit renewable energy from resource-rich areas to relatively distant demand centres
- Boost the flexibility and reliability of local grids
- Connect two onshore points using offshore HVDC links (bootstraps)

2 KEY ENABLING FACTORS

- Addressing political and regulatory challenges
- Addressing technical challenges related to network protection

3 SNAPSHOT

- Xilingol League–Taizhou in China is the world's highest-voltage (± 800 kV) and highest-capacity (10 GW) DC line in operation
- One of the world's longest HVDC lines is being constructed in India, with a length of 1 830 km
- In Germany, HelWin1 is a 130 km HVDC line that can transmit up to 576 MW of offshore wind energy from the North Sea to more than 700 000 consumers

WHAT ARE SUPERGRIDS?

Supergrids are high-capacity power transmission lines using either high-voltage direct current **(HVDC, above 500 kV)** or ultra-high-voltage direct current **(UHVDC, above 800 kV)** power lines.

SUPERGRIDS

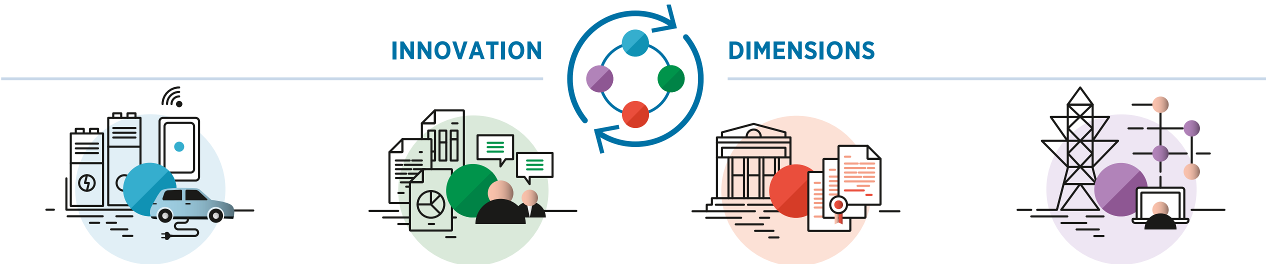
By enabling **high volumes of electricity** to flow across **long distances**, supergrids enhance **cross-border integration** and help to connect **resource-rich areas** with renewable energy potential to **major electricity demand centres**.

ABOUT THIS BRIEF

This brief is 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 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

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SYSTEM OPERATION

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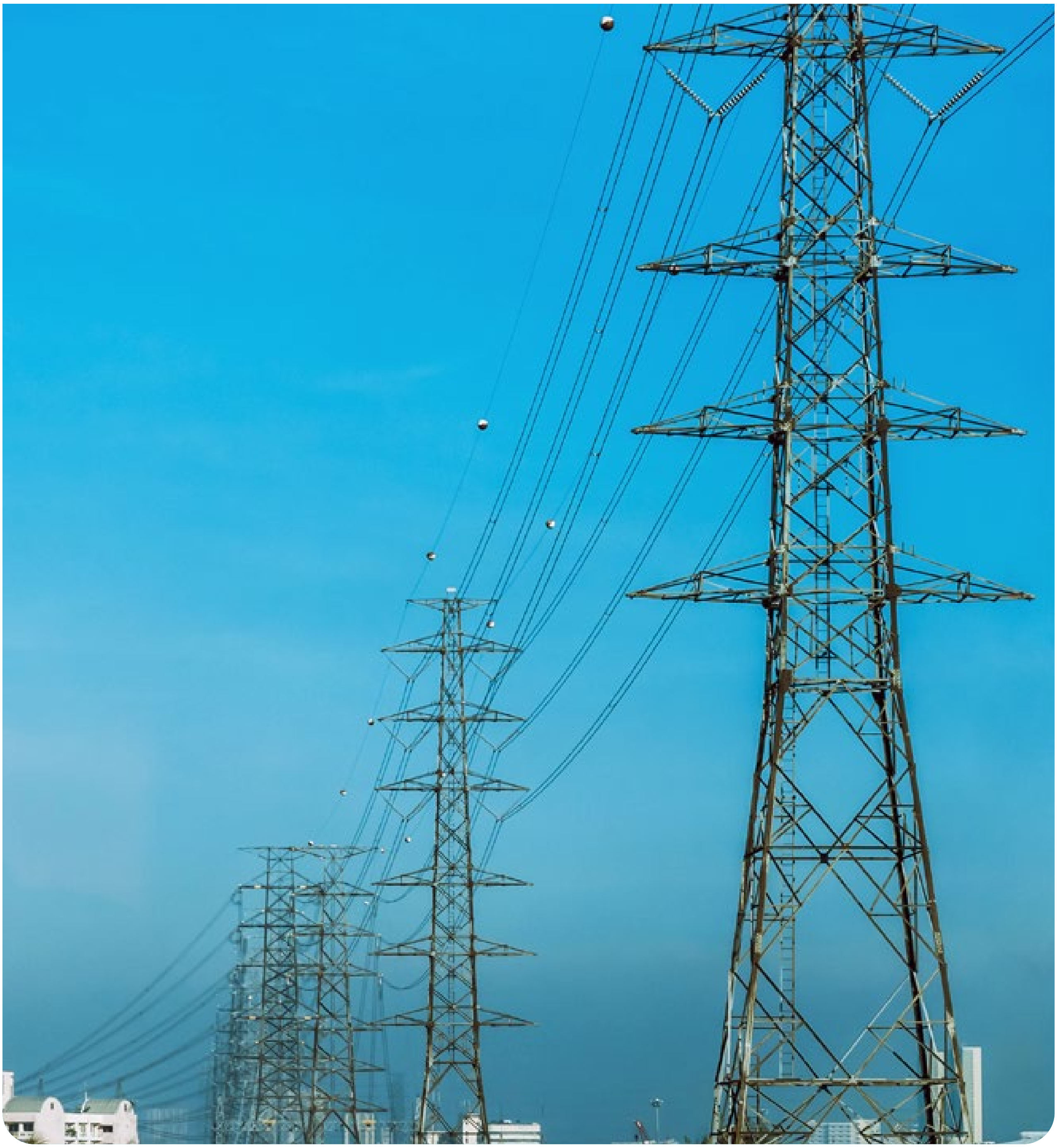
26 Co-operation between transmission and distribution system operators

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 examines supergrids, an emerging enabling technology that can be used to transport electricity from VRE sources over long distances. Direct current (DC) supergrids have the potential to transmit electricity over longer distances and with lower losses than alternating current (AC) systems. Coupling renewable energy generation and power load centres across long distances with supergrids enables remotely located renewable generation to be integrated in the system, bringing it closer to the demand more efficiently.

The brief is structured as follows:



I. DESCRIPTION

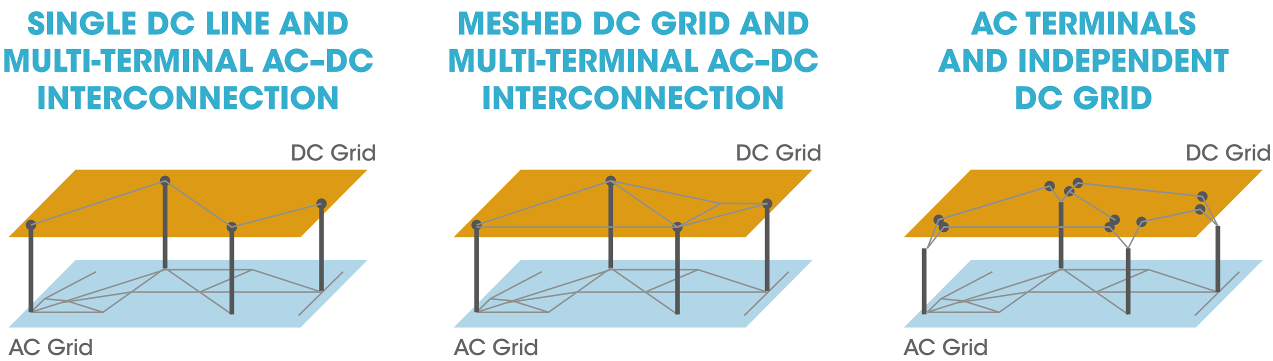
Areas rich in renewable resources, with high solar irradiation levels or wind speeds, are frequently remote from major electricity demand centres, such as cities or industrial hubs. Similarly, geographies with high solar irradiation, such as those in African deserts, may be optimal for deploying solar power generation technologies, but may not have high energy demand locally. Therefore, great potential exists to increase the share of renewables in power consumption by transporting VRE from remote but resource-rich locations to demand centres through supergrids.

A supergrid is a large transmission network that makes it possible to trade high volumes of electricity across great distances. Supergrids are high-voltage DC (HVDC) transmission power lines (with rated voltage greater than or equal to 500 kilovolts [kV]) or ultra-high-voltage DC (UHVDC) power lines (greater than or equal to 800 kV). DC technology is more promising for supergrids than AC technology for several reasons. The transmission of power over long distances using AC technology is challenging, as AC systems require reactive power support. Moreover, line losses are significantly higher for AC lines, between 30% and 40% higher in comparison with DC technology (Siemens, n.d.). Additionally, HVDC systems have greater controllability than AC grids, allowing power flow control and increased flexibility in system operation.

AC grids have prevailed due to AC transformers' ability to change the voltage level. Until recently DC lines could only be used for point-to-point transmission and did not easily form the integrated grid networks that exist today. Over the past few years equipment manufacturers have conducted intensive research and development, into DC breakers and products, making a meshed DC grid now feasible. One such activity is the ongoing EU project PROMOTioN, which seeks to address challenges to the development of meshed HVDC offshore transmission grids (PROMOTioN, 2018).

Supergrid networks are typically built independent of the conventional AC grid and can interact with the existing AC grid at a few or multiple nodes. Figure 1 depicts the common configurations/topologies for HVDC/UHVDC grids and conventional AC grids.

Figure 1: Common configurations of supergrids and AC grids



Source: Ahmed *et al.*, 2011

As Figure 1 depicts, the HVDC/UHVDC grid is built independently of the conventional AC grid and is connected to the AC grid at multiple points along the AC network. The first schematic depicts a single DC line connected to the conventional AC grid at multiple points along the network. In this setup, only a single DC line is present without any DC mesh structure, which makes it a zero-redundancy system. This means that if a technical disruption occurs at any point on the DC line, the entire DC circuit would break. However, such setup can be useful as a component in the hybrid AC–DC grid as a reinforcement to the AC grid. The South West link in Sweden is based on this setup (Ahmed *et al.*, 2011; SVK, n.d.).

The second schematic depicts a meshed DC grid connected to the AC grid at multiple points. This meshed DC grid structure provides greater reliability as compared to the first schematic. In the third schematic, all the nodes are AC nodes and transmission between them is done using DC lines. This setup makes it quite straightforward to incorporate existing HVDC lines in the new DC grid. The link between continental Europe and Scandinavia is an example of this setup (Ahmed *et al.*, 2011).

II. CONTRIBUTION TO POWER SECTOR TRANSFORMATION

Supergrids offer increased energy reliability, higher availability of generation, decreased costs of electricity across regions and, particularly relevant for the integration of VRE, greater system flexibility. In addition to the better integration of VRE resources, supergrids can facilitate the interconnection of multiple control areas and countries as well, leading to several benefits for the power system as a whole – both economic and social. These benefits are described below.

Transmission of renewable energy from resource-rich areas to distant demand centres

VRE generation can be deployed in locations where renewable resources are more abundant and transported to consumption centres. HVDC lines are suited to connect distances of more than 3 000 km (Navigant Research, 2018). Furthermore, HVDC lines might already be cost-effective for distances from 650 km on land and from 50 km in the case of subsea power cables (considering the full life-time of the assets). HVDC subsea cables are particularly relevant for offshore wind power plants, which are being increasingly deployed around the world due to higher wind speeds at sea. Global offshore wind cumulative capacity has reached 23.3 gigawatts (GW) in 2018 (IRENA, 2019b). Europe is home to the world's largest operational offshore wind farm, namely Walney Extension located in the Irish Sea, with a nominal installed capacity of 659 MW (Frangoul, 2019).

Transporting power from such remote offshore areas using conventional AC transmission systems requires reactive power compensation for long-distance transmission, which is difficult to provide in offshore transmission lines (Cole *et al.*, 2011). HVDC-based supergrids can help better integrate VRE from such remote locations across a wider geographic area while minimising line losses and increasing the controllability of the AC–DC network. However, wind turbines produce AC and convertors from AC to DC would be needed to connect the wind turbines to DC transmission lines. This would also incur loses. Assessment on a case-by-case basis would be needed to identify the optimal line technology solution.

Increased flexibility and reliability in local grids

Supergrids can also level out excess power or variability generated in local grids. As deployment of VRE generators increases in the power mix, so the variability and uncertainty introduced by these resources progressively affects local grid balances. For example, wind power generation has a regional character and may lead to large regional power imbalances. Development of supergrids can help reduce such power imbalances, as they can transfer power from regions of excess VRE generation to those with a supply deficit (Vrana, 2013). This helps system operators across nations and regions to have more system flexibility, as they are able to draw power from or feed power into the supergrid network.

Connecting two onshore points using "bootstraps" (offshore HVDC links)

Transmission system operators (TSOs) can face delays and difficulties in connecting two onshore points due to challenges in land acquisition and permits for constructing overhead lines. An alternative to this is connecting the two points using long-distance offshore HVDC links, often referred to as "bootstraps".

For instance, the UK TSO National Grid is considering adding to the existing western offshore HVDC link with an eastern link. This would result in two offshore HVDC links connecting Scotland and England, one on each coast as shown in Figure 2 (Cole *et al.*, 2011; Csanyi, 2014). While the eastern HVDC link is now planned beyond 2021 (SSEN, n.d.), the western HVDC link has been in operation since 2017, delivering up to 2 250 MW of power transfer capability from Scotland to England and Wales.

Strengthening and increasing the capacity of the UK's electricity transmission system are considered as critical requirements for the integration of higher shares of renewables (Western Link Project, n.d.).

Figure 2: Western HVDC link between Hunterston in Scotland and Kelsterton in North Wales

Source: Cole *et al.*, 2011
Disclaimer: Boundaries and names shown on this map do not imply any official endorsement or acceptance by IRENA.

III. KEY FACTORS TO ENABLE DEPLOYMENT

In addition to technical and engineering hurdles, challenges to the deployment of supergrids are mainly linked to political will, international regulatory co-ordination and capital mobilisation.

Political and regulatory challenges

Supergrids are typically transnational and transregional power networks. Therefore, their development requires international political collaboration on grid ownership, rights and revenue allocation, amongst other matters. They also require regulatory cohesion across multiple countries in order to clearly define the roles and responsibilities of the stakeholders in such networks across national boundaries. Balancing power at the distribution, regional, national and international level further requires close co-ordination between system operators across territories, which is deemed complex.

For instance, Desertec was a project proposed in 2003 to integrate solar generators in Northern Africa into the European grid via subsea HVDC cables. The project attracted multiple industrial and financial stakeholders, including China's state grid. However, issues regarding ownership, rights, obligations, revenue allocation and location of electricity usage were repeatedly raised amongst stakeholders. This led to successive downscaling of the initial proposal over the years and, by the end of 2014, almost all stakeholders had withdrawn, with the remaining ones aiming to facilitate project deployment and VRE integration in desert areas (Patterson, 2016).

Technical challenges

The development of HVDC supergrids is faced with technical and engineering challenges related to network protection. Current source converter (CSC), which is a classic HVDC technology, is mostly used for large point-to-point transmissions. It requires fast communication channels between the two stations, and large rotating units – generators or synchronous condensers – to be present on the AC network at both ends of the HVDC transmission. Some of the challenges in using CSC in supergrids relate to speed, selectivity and time delay when responding to DC circuit faults (Barker & Subramanian, 2014). Addressing these challenges would require manufacturers, engineers and system operators to work together.

HVDC based on voltage source converter (VSC) is a newer technology and is less widely used. The continuous development of VSC technology brings more control to the DC systems. The technology has already been trialled in a few multi-terminal DC interconnection pilot projects. It makes it easier to integrate HVDC lines into existing networks, and has the further capability to rapidly control both active and reactive power independently of each other, to keep the voltage and frequency stable. This gives complete flexibility regarding the location of the converters on the AC system, as they do not need to rely on the AC network's capability to keep the voltage and frequency stable. This makes it possible to connect the converters between the DC and the AC system where most convenient.

Table 1 UHVDC technical equipment – current status and future requirements for development

UHVDC technical equipment	Brief description	Current development status	Developments needed
UHVDC circuit breakers	A circuit breaker is an electrical switch to protect electrical circuits from damage caused by excess current. They function by interrupting the current after a fault is detected.	Currently the highest-capacity HVDC circuit breaker of ± 500 kV was developed in 2017 by China (with a breaking current of 26 kA and breaking time of 3 ms). A ± 200 kV HVDC circuit breaker used in the Zhoushan five-terminal flexible DC transmission project in China is the only site application in the world so far.	UHVDC circuit breakers for a higher capacity of ± 800 kV, maximum breaking current greater than 50 kA and breaking time of around 2 ms.
UHVDC cables	Cables specifically designed for carrying DC current while minimising losses.	So far cables for voltages of ± 525 kV have been developed using XLPE. XLPE cables are expected to lead deployment due to their technical superiority over other DC cable technologies.	XLPE DC cables for voltages of ± 800 kV, transmission capacity of 6 GW and working temperatures of 70–90 °C. The technology for overhead lines is already mature; further developments are needed for submarine and underground use.
UHVDC converter valves	Converts UHVAC to UHVDC or vice versa.	A UHVDC flexible converter valve of ± 800 kV/5 GVA has been developed successfully in China. Currently deployed valves have ratings of ± 320 kV/1 GVA and valves of ± 500 kV are about to put into application.	Engineering application of ± 800 kV flexible valves and development of ± 800 kV/10 GVA valves.

Notes: GVA = gigavolt ampere; kA = kiloamp; kV = kilovolt; UHVAC = ultra-high-voltage alternating current; **XLPE** = cross-linked polyethylene.

Development of any HVDC or UHVDC grid configuration requires the development of key electrical and power electronics equipment. These include converter valves, converter transformers, arresters, ultra-high-capacity switchgears, instrument transformers, bushing, DC circuit breakers, and UHVDC cables. Although such equipment has been sufficiently developed, many engineering breakthroughs still needed to be adapted to accommodate higher voltages and transmission capacities. Table 1 provides a brief description of some of the essential items of equipment on a UHVDC grid, outlining their current development status and the future requirements for their development.

Hybrid AC–DC transmission lines

Hybrid AC–DC lines act as a facilitator for increased deployment of DC lines. They use the same electricity pylon (electricity tower) to carry both AC and DC cables. Existing pylons can be upgraded at minimal cost to also enable their support of DC cables. This would decrease the cost of developing supergrid networks and ease access to existing AC nodes.

For instance, Germany's Ultranet is a hybrid line that is due to open in 2023 and will carry DC wind power from Osterath, North Rhine-Westphalia, to Philippsburg, Baden-Württemberg, an area whose industry has a requirement for electricity (Federal Ministry for Economic Affairs and Energy, 2019).

IV. CURRENT STATUS AND EXAMPLES OF ONGOING INITIATIVES

Currently, China is a front-runner in the development of high-capacity UHVDC transmission. Its domestic system comprises 35 000 kilometres (km) of HVDC transmission lines and 500 billion kWh of annual transmission by quantity (Xu, 2016).

Europe is leading the development of offshore UHVDC transmission lines, driven by its existing offshore wind projects.

Recent trends related to supergrids are presented in Table 2, followed by case studies on key projects and initiatives conducted around the world.

Table 2 Current supergrid context and trends

Description	Key facts
Supergrid investment	USD 8.3 billion in 2016, rising to USD 10.2 billion by the end of 2025.[1]
Geographies where supergrids are deployed or planned	Europe, India–Bangladesh–Nepal–Bhutan, North Asia (China–Japan–Russian Federation–Republic of Korea–Mongolia), United States, Africa.
Average costs for developing UHVDC transmission lines	Average costs for developing DC 500 kV transmission lines: approximately USD 570 000/km.[2]
Highest-voltage UHVDC line currently in operation	Xilingol League–Taizhou, China (± 800 kV).[3]
Highest-capacity UHVDC line currently in operation	Xilingol League–Taizhou, China (10 GW).[3]
Highest-voltage UHVDC line under construction	Changji–Guquan, China (± 1 100 kV).
Highest-capacity UHVDC line under construction	Changji–Guquan, China (12 GW).
European supergrid projects labelled as an EU "electricity highway"	1. The EuroAsia Interconnector connecting the national electricity grids of Israel, Cyprus and Crete–Attica, Greece, through a 1 518 km subsea HVDC cable of 2 000 MW. [4] 2. The EuroAfrica Interconnector, a 2 000 MW electricity interconnector between Egypt, Cyprus, Crete–Attica, Greece, via a 1 707 km subsea HVDC cable. [5]

Sources: [1]Hansen (2019); [2]EIA (2018); [3]SGCC (2017); [4]EuroAsia interconnector (2018); [5]EuroAfrica interconnector (2018).

UHVDC projects in India

Power Grid Corporation of India Limited, a transmission network operator in India, has teamed up with ABB to build an 800 kV UHVDC network from Raipur in Central India to Pugalur in South India. Once constructed, this transmission line is poised to be among the world's longest, at 1 830 km. The project will transmit wind power from South India to the demand centres in the north during times of excess wind generation and will transmit thermal power from Northern India to the south when wind generation is low. It is expected to serve about 80 million people (T&D World, 2017).

Power Grid Corporation of India and ABB are also working to deliver the world's first multi-terminal UHVDC transmission link. The 800 kV North-East Agra UHVDC link will transmit clean hydroelectric power from India's northeast region to the city of Agra, a distance of 1 728 km. The supergrid will supply 90 million people (Navigant research, 2018; ABB, 2019).

HVDC HelWin1 project in Germany

As part of the German Energiewende, the HVDC HelWin1 was built to integrate offshore wind power within the German grid. It is a 130 km long, 250 kV HVDC transmission line owned and operated by TenneT to transmit power from the Nordsee Ost and Meerwind Süd/Ost wind parks. It can transmit up to 576 megawatt hours of clean energy to over 700 000 consumers (Offshorewind. biz, 2015).

HVDC projects connecting United Kingdom

Viking Link is a proposed offshore and onshore HVDC link between Great Britain and Denmark. The 770 km long transmission line is expected to enable effective use of renewable energy and increase security of energy supply for both countries. The project is expected to be operational by 2022 (Viking Link, n.d.).

IceLink is an early-stage project aiming to connect Iceland and the UK, planned to be around 1 000 km long and to operate at 800–1 100 kV. The project is expected to be operational in 2027, and it will supply power to approximately 1.6 million homes (Navigant research, 2018).

EU-Horizon 2020 PROMOTioN project – Progress on Meshed HVDC Offshore Transmission Networks

PROMOTioN is an ongoing project with 35 partners across the European Union, including major HVDC and wind turbine manufacturers, TSOs linked to the North Sea, offshore wind developers, leading academia and consulting companies. It uses the North Sea as an example and aims to demonstrate the technological maturity of critical supergrid components, such as DC circuit breakers and DC protection schemes. It uses multi-vendor methods to become a "plug-and-play" solution and provide recommendations for standardisation to improve both technology and vendor interoperability. Additionally, it aims to analyse member state, EU and international (UNCLOS) laws, regulations and methodologies for cost-benefit analysis on the development of transnational transmission infrastructure. It will identify hurdles on the path to implementing a meshed offshore HVDC network. The overall results of the project are due to be available in 2020 (PROMOTioN, 2018).

Global Energy Interconnection

Global Energy Interconnection (GEI) is a proposed transnational, transregional and transcontinental UHVDC smart grid that will be primarily utilised for transmitting clean energy. The GEI has been proposed by the Global Energy Interconnection Development and Cooperation Organization (GEIDCO), a non-governmental and non-profit international organisation whose members comprise global energy firms, utilities, associations and institutions. GEIDCO's roadmap envisages: i) forming a consensus and developing, delivering and consuming clean energy mainly via various intracontinental interconnected UHVDC grids by 2030; ii) developing large-scale wind and solar energy bases worldwide, with a globally interconnected energy network by 2040; and iii) establishing a global energy interconnection, with well-organised operational mechanisms and a global system operation centre by 2050 (Liu, 2015).

Asia Supergrid

Asia Supergrid is a concept to develop an international supergrid in Asia connecting major countries. It was first proposed in 2011 at the Renewable Energy Institute by Masayoshi Son, its founder and chairman. A study group was formed to conduct research on international supergrids and to provide recommendations for developing the Asia Supergrid. The group released an interim report in April 2017, which studied the evolution of grid interconnections across Europe to derive key lessons. The report found that Europe had a high complementarity of generation sources amongst different nations, which can be beneficial to an interconnected grid. Further, due to its geographical extent, Europe had significant differences in demand and supply patterns between countries, which ensured that the interconnected network would never witness high demand from all regions simultaneously. These learnings were then applied to the context of five Northeast Asian countries, comprising China, Japan, South Korea, Mongolia and Russia (Asia International Grid Connection Study Group, 2017).

North American Supergrid

North American Supergrid is a proposed HVDC transmission network covering 48 states of the United States. The network is intended to be largely underground and is aimed at transporting renewable energy to demand centres. It is foreseen to make renewable energy cheaper than conventional energy and is also expected to provide electromagnetic pulse (EMP) and geomagnetic disturbance (GMD) protection, which can protect the transmission system from natural disasters and which is unavailable in current AC-based overhead transmission lines (cleanandsecuregrid.org, n.d.).

V. IMPLEMENTATION REQUIREMENTS: CHECKLIST

TECHNICAL REQUIREMENTS	**Hardware:** • DC breakers, DC protection systems, HVDC cables, DC switchgears, AC–DC interconnection systems etc
POLICIES NEEDED	• Multinational policies to develop transnational supergrids addressing clarity on ownership rights, stakeholder roles, responsibilities, obligations and financing aspects, methodologies for cost–benefit analysis.
REGULATORY REQUIREMENTS	**Wholesale market:** • International exchange of power using supergrid networks.
STAKEHOLDER ROLES AND RESPONSIBILITIES	**National governments:** • Collaboration between national governments for the formulation of common policy frameworks and agreements for the development of transnational supergrids, ownership rights and operation etc.
	System operators: • Consider the DC connections in the operation of the system.

ABBREVIATIONS

AC	alternating current
CCS	current source convertor
DC	direct current
GEI	Global Energy Interconnection
GEIDCO	Global Energy Interconnection Development and Cooperation Organization
GVA	gigavolt ampere
GW	gigawatt
HVAC	high-voltage alternating current
HVDC	high-voltage direct current
kA	kiloamp
km	kilometre
kV	kilovolt
ms	millisecond
MW	megawatt
TSO	transmission system operator
UHVAC	ultra-high-voltage alternating current
UHVDC	ultra-high-voltage direct current
VRE	variable renewable energy
VSC	voltage source convertor
XLPE	cross-linked polyethylene

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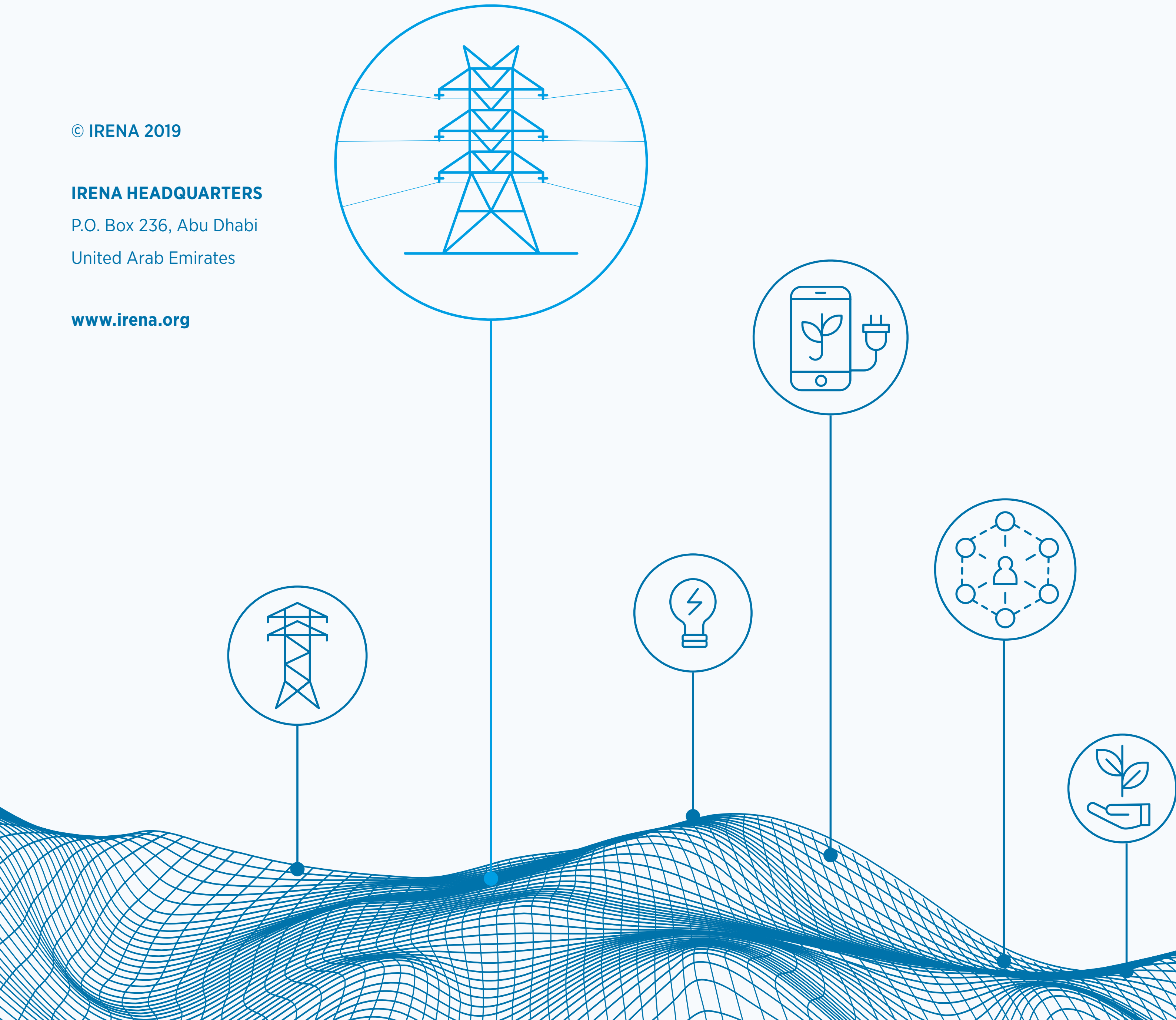
SUPERGRIDS
INNOVATION LANDSCAPE BRIEF



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