White Paper

Global energy interconnection

Executive summary

Global energy interconnection (GEI) represents the ultimate evolution of the trend towards greater interconnection of power systems. It embodies high-level integration of the flow of energy, flow of information and flow of business as an intelligent, automated and networked-based system for ensuring energy security on a universal scale.

Fueled by global economic growth, world energy consumption rose from 5,4 billion tons of coal equivalent in 1965 to 18,5 billion tons in 2014. Fossil energy accounted for more than 85% of the total. The world's energy consumption will maintain a growing trend in the future, as it is difficult to reverse the long-established patterns of intensive energy consumption.

Seeking a solution to these trends, the implementation of GEI would integrate a large-scale deployment of clean energy led by variable renewables with a Smart Grid incorporating high levels of interoperability and supported by a ultra-high voltage (UHV) grid backbone including extensive interconnections across countries, continents, technical domains, hierarchies and equipment life cycle phases.

Though such levels of deployment are highly ambitious, the technologies themselves are largely available or are currently in the pipeline. The technical difficulties for large-scale, transcontinental or global energy interconnection, on the other hand, will come from the unprecedented degree of system integration that will be required. To help surmount this challenge, consensus-based International Standards and Specifications will form an indispensable basis on which to build concrete solutions. Standards, specifically those at the systems level, will facilitate procurement and national and international acceptance and will play a stabilizing role by pursuing research activities on which real market opportunities are built.

This White Paper examines the readiness of potential markets for GEI, identifies the technical and economic trends in related technologies and evaluates at a high level the impact on energy, environment, technologies and policies.

Taking the large-scale concepts connected with GEI to actual realization will require significant efforts in standardization – e.g. development of initiatives to enable multi-system interoperability. Thus this White Paper aims to highlight the concept of GEI and begin laying the foundations for identifying and addressing the standardization needs for large-scale, transcontinental and global energy interconnection.

Acknowledgments

This White Paper has been prepared by the Global Energy Interconnection project team, in the IEC Market Strategy Board (MSB), with major contributions from the project partner, the International Energy Agency (IEA) and the project leader, State Grid Corporation of China (SGCC). The project team met three times – in January 2016 (Beijing, China), March 2016 (Beijing, China) and June 2016 (Paris, France). The project team is listed below:

Dr. Yinbiao Shu, SGCC, IEC Vice President, MSB Convenor, Project Director

Dr. Luis Munuera, IEA, Project Partner

Dr. Jun Yu, SGCC, Project Manager

Dr. Jianbin Fan, SGCC

Dr. Caihao Liang, CEPRI

Dr. Geng Dan, Climate Parliament of China

Dr. Wei Wang, SGCC

Dr. Xing Lu (Ms.), State Grid Energy Research Institute (of China)

Mr. Richard Schomberg, EDF

Dr. Dongil Lee, KEPCO

Dr. Jae Young Yoon, KERI

Dr. Chan-Ki Kim, KEPCO

Dr. Ho-Keun Kim, KEPCO

Dr. Stefan Engelhardt, SAP SE

Dr. Alexander Rentschler, Siemens AG

Mr. Shinichi Suganuma, TEPCO

Mr. Chengwei Dai, China Datang Corporation

Mr. Yan Qin, China Datang Corporation

Dr. Hao Hu, SGCC

Mr. Peter Lanctot, IEC, MSB Secretary

谢谢观看！

Table of contents

List of abbreviations

Technical and scientific terms

AC	alternating current
AC	advisory committee (of the IEC)
AIN	asset intelligence network
BI	business intelligence
BOS	balance of system
CBA	cost-benefit analysis
COP	conference of the parties
CRM	customer relationship management
CSC	current source converter
CSP	concentrated solar power
DC	direct current
DMS	document management system
DNI	direct normal irradiance
EAM	environmental assessment and management
EDI	electronic data interchange
EES	electrical energy storage
EPC	engineering, procurement and construction (company)
ERP	enterprise resource planning
FACTS	flexible AC transmission system
FCF	frequency converter facility
FMEA	failure mode and effects analysis
FTU	field terminal unit
GDP	gross domestic product
GEI	global energy interconnection
GHG	greenhouse gas
GIS	geographical information system
HES	head-end system
HTS	high-temperature superconducting

HVAC	high-voltage alternating current
HVDC	high-voltage direct current
HWACT	half-wavelength AC transmission
ICT	information and communication technology
IEA-OES	Ocean Energy Systems Technology Collaboration Programme of the IEA
IoT	Internet of Things
IT	information technology
LCC	line-commutated converter
LCOE	levelized cost of energy
MDM	meter data management
MTDC	multi-terminal direct current
OEM	original equipment manufacturer
OLTP	online transaction processing
OT	operational technology
PMU	phaser measurement unit
PV	photovoltaic
RE	renewable energy
SC	subcommittee (of the IEC)
SCADA/EMS	supervisory control and data acquisition/energy management system
SDO	standards developing organization
STE	solar thermal energy
SyC	systems committee (of the IEC)
TC	technical committee (of the IEC)
TSO	transmission system operator
UHV	ultra-high voltage
UHVAC	ultra-high-voltag alternating current
UHVDC	ultra-high-voltage direct current
VSC	voltage source converter
WAMS	wide area monitoring system

Organizations, institutions and companies

ASEAN	Association of Southeast Asian Nations
ASG	Asian Super Grid
ATSOI	Association of the Transmission System Operators of Ireland
BALTSO	Baltic Transmission System Operators
CEPRI	China Electric Power Research Institute
CIGRE	International council on large electric systems
COP21	21st Conference of the Parties, 2015 United Nations Climate Change Conference
CSPG	China Southern Power Grid
EDF	Electricité de France
ENTSO-E	European Network of Transmission System Operators for Electricity
EPRI	Electric Power Research Institute
ERCOT	Electric Reliability Council of Texas
ETSO	European Transmission System Operators
EU	European Union
HAPUA	Heads of ASEAN Power Utilities/Authorities
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IPCC	Intergovernmental Panel on Climate Change
IPS/UPS	Integrated Power System/Unified Power System
ISO	International Organization for Standardization
KEPCO	Korea Electric Power Corporation
KERI	Korea Electrotechnology Research Institute
MSB	Market Strategy Board
NEC	National Electrotechnical Committee
NERC	Northern American Electric Reliability Corporation
NGET	National Grid Electricity Transmission
OECD	Organisation for Economic Co-operation and Development
SAPP	Southern African Power Pool
SE4ALL	United Nations Sustainable Energy for All initiative
SGCC	State Grid Corporation of China

SMB	Standardization Management Board (of the IEC)
TEPCO	Tokyo Electric Power Company
TüV	technischer Überwachungsverein (technical inspection association)
UCTE	Union for the Coordination of the Transmission of Electricity
UKTSOA	United Kingdom Transmission System Operators Association
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change

Glossary

asset intelligence network
AIN

cloud-based hub that facilitates collaborative asset management and allows companies take full advantage of the Internet of Things (IoT)

back-to-back system

two independent neighbouring systems with different and incompatible electrical parameters (frequency/voltage level/short-circuit power level) that are connected via a DC link

NOTE High-voltage direct current (HVDC) transmission systems connect two separate high voltage AC systems via a DC link. The basic principle of operation of an HVDC system is based on the conversion of AC to DC and vice-versa by means of converter valves, which are the heart of a converter station.

balance of system
BOS

quantity encompassing all components of a photovoltaic system other than the photovoltaic panels

NOTE This includes wiring, switches, a mounting system, one or many solar inverters, a battery bank and battery charger.

conference of the parties
COP

governing body of an international convention

NOTE The most well-known United Nations conference of the parties involves countries that have ratified the UN Framework Convention on Climate Change (UNFCCC) adopted in 1992 at the Earth Summit in Rio de Janeiro, Brazil. The 2015 United Nations Climate Change Conference, or COP21, was held in Paris, France, from 30 November to 12 December 2015. The conference was the 21st such event to take place since the signing of the UNFCCC, hence COP21.

exajoule
EJ

unit of energy equal to one quintillion (10^{18}) joules

NOTE In describing national or global energy budgets, it is common practice to use large-scale units based upon the joule: 1 EJ = 10^{18} J. A joule is the SI unit of work or energy equal to the work done by a force of one newton when its point of application moves one metre in the direction of action of the force, equivalent to one 3 600th of a watt-hour.

frequency converter facility
FCF

facility where an electronic or electromechanical device converts alternating current of one frequency to alternating current of another frequency

global energy intensity

amount of energy used to produce a unit of gross domestic product (GDP) at market exchange rates

levelized cost of energy
LCOE

measure of a power source which attempts to compare different methods of electricity generation on a comparable basis

solar thermal energy
STE

form of energy and technology for harnessing solar energy to generate thermal energy or electrical energy

terawatt
TW

unit of power equal to one trillion (10^{12}) watts

TüV
technischer Überwachungsverein (technical inspection association)

German organization that works to validate the safety of products of all kinds to protect humans and the environment against hazards

UHV
ultra-high voltage

voltage above 800 kV

Section 1

Introduction

Achieving a sustainable, secure and affordable supply of energy has traditionally been the goal of both national and international energy policies. At the centre of achieving sustainability in the energy system lies the challenge of climate change, a factor recently brought to the fore by the Paris accords. The rise of electricity as the key energy carrier due to its high quality and versatility has determined its current role as a central vehicle for decarbonizing the supply of energy. Dramatic cost reductions in renewable energy (RE), particularly wind and solar, have made extensive deployment of such energies attractive on a global scale, with emphasis being placed on how to integrate these resources widely. Reducing reliance on fossil fuels by substituting low carbon electricity for the input of energy end-uses that rely on them (e.g. through electric vehicles in transport or electrification of industrial processes), will only increase overall demand for electricity. At the same time, large portions of the global population remain without access to electricity. Following a logical progression in power systems, as generation and demand continue to evolve in response to these trends, power grids will become more and more interconnected at the transnational and regional levels. This is reflected in the recent introduction of the concept of global energy interconnection (GEI).

GEI would represent the ultimate stage in the evolution of power grids towards greater levels of interconnectivity: a global energy network of intercontinental and cross-border backbone networks of high and ultra-high voltage (UHV), as well as smart power grids (transmission and distribution networks) in all interconnected countries at various voltage levels. A GEI could connect the power grids of all continents and take advantage of the diversity of different time zones and seasons, thus supporting a balanced coordination of power supply for all interconnected countries.

As one of the international organizations participating in the United Nations Sustainable Energy for All initiative (SE4ALL), the IEC and its International Standards play a major role in meeting fundamental energy challenges. IEC's purpose in issuing this White Paper is to highlight the concept of GEI and begin laying the foundations for identifying and addressing the standardization needs of large-scale, transcontinental and global energy interconnection.

The main objectives of this White Paper are as follows:

- To provide a high-level assessment of the potential worldwide needs, benefits and conditions of GEI
- To examine the readiness of potential markets for the technologies that would underpin GEI
- To identify technical and economic trends in related technologies
- To evaluate at a high level the impact on energy, environment, technologies, policies and relevant Standards
- To provide an outline of how standardization could be conducted from a high level and recommendations for different stakeholders to participate in the standardization work

1.1 Scope

This White Paper begins by assessing worldwide industrial, commercial application needs and energy resource allocation, development and utilization, as well as the potential benefits in light of the GEI concept, by collecting relevant data from international organizations. Several global transmission schemes are discussed and analyzed by scenario comparison.

The White Paper then examines the readiness of potential markets for GEI. Based on the current status of equipment and technologies from transmission system operators (TSOs) and suppliers, it identifies the technical and business trends (i.e. economic aspects) and challenges in related areas, including clean energy, UHV, Smart Grid, energy storage and grid control. The White Paper also addresses the environmental impact aspects of the concept, including carbon emission reduction, footprint of transmission lines, etc.

Finally the White Paper discusses how GEI will influence present energy system standards and highlights the need for new standardization.

Section 2
A vision for GEI

2.1 Global energy challenges

Global primary energy supply has grown ten-fold in the last 100 years, and more than doubled in the last 40 years. But for the first time in 2006, developing countries (i.e. those not members of the Organisation for Economic Co-operation and Development (OECD)) accounted for a larger share of energy use than developed economies; in 2013 the ratio was 61:39. The shifting of the traditional centres of energy demand to China, India and South Asia are reflected in global trends: China has accounted for the largest increase in primary energy demand and CO2 emission over the last decade, and yet the added pace of RE deployment and drastic improvements in energy intensity have reduced its annual growth in CO2 emissions to levels not seen before 2004, with recent signs of decoupling. India alone has been responsible for almost 10% of the increase in global energy demand since 2000, while Indonesia has seen the largest growth in coal use globally. A combination of emissions caps, a reduction in economic activity, and rapid growth in renewables has drastically altered the energy landscape in Europe. Developments in unconventional oil and gas technology and exploitation are dramatically changing energy prospects in the US and its status as an energy importer. Moreover clean energy added more capacity for the first time in 2014 than all other power generation sources combined.

In spite of these developments, anthropogenic energy-related global CO2 emissions reached a record 31,6 gigatons CO2 (GtCO2) in 2012, warming reached a 1 °C increase above pre-industrial levels, and 1,3 billion people remain without access to clean energy around the world.

The challenges facing the world in terms of providing secure, affordable and clean energy are greater than they have ever been, framed against an array of pressures at an unprecedented scale and a landscape of rapid technological change.

2.1.1 Energy security

Fueled by global economic growth, world energy consumption rose from 5,4 billion tons of standard coal in 1965 to 18,5 billion tons in 2014. Fossil energy accounted for more than 85% of the total. The world's energy consumption will maintain a growing trend in the future, as it is difficult to reverse the long-established pattern of intensive energy consumption.

Energy security can be understood as "the uninterrupted availability of energy sources at an affordable price". Energy security has many dimensions: long-term energy security mainly involves timely investments to supply energy in line with economic developments and sustainable environmental needs. Short-term energy security focuses on the ability of the energy system to react promptly to sudden changes within the supply-demand.

Concern related to physical unavailability of supply is more prevalent in energy markets in which networks and systems must be kept in constant balance, such as electricity and, to some extent, natural gas. This is particularly the case in instances where capacity constraints exist or where prices cannot function as an adjustment mechanism to balance supply and demand in the short term.

The world has plentiful energy resources, including those from fossil energies. In the long term, however, fossil-based energies are exhaustible and are heavily location-constrained. Geopolitics, the changeable economic outlook, the prevailing investment climate and a rapidly shifting technology landscape mean that the circumstances surrounding exploitation of fossil fuels are ever changing. At the same time, the world's RE resources are vast (see Figure 2-1) and, if the full technical potential of such resources is captured, would meet the world's energy needs many times over.

2.1.2 Climate change

The Intergovernmental Panel on Climate Change (IPCC) has concluded that, in the absence of fully committed and urgent action, climate change will have severe and irreversible impacts across the world. Avoiding dangerous climate change and its environmental consequences will require sustained and important reductions in greenhouse gas (GHG) emissions.

Energy production and use account for two-thirds of global GHG emissions generated by human activity. Therefore, transforming the energy sector is essential for addressing the climate challenge. Despite efforts to decarbonize the world's energy system, the past 30 years have seen little change in the share of fossil fuels in global energy supply, which totalled around 81% in 2013. Meanwhile, coal power accounted for the highest contribution to the energy mix in the past 40 years.

Since the Industrial Revolution, annual CO2 emissions from fuel combustion have dramatically increased from nearly zero to over 32 GtCO2 in 2013, and yet since the early 1900s, the carbon intensity of the energy supply (the amount of emissions per unit of energy going into the system) has barely changed (see Figure 2-2). Between 1990 and 2013, a stable carbon intensity of supply combined with an increase in population (35%) and in per capita GDP (60%), leading to a dramatic increase in global CO2 emissions of nearly 60%. The atmospheric concentration of these gases has increased steadily to 445 parts per million carbon-dioxide equivalent (ppm CO2-eq) in 2014.

The global energy system is thus at a crossroads in the race against climate change. The recent UN Climate summit delivered an unprecedented response to this challenge. Countries from around

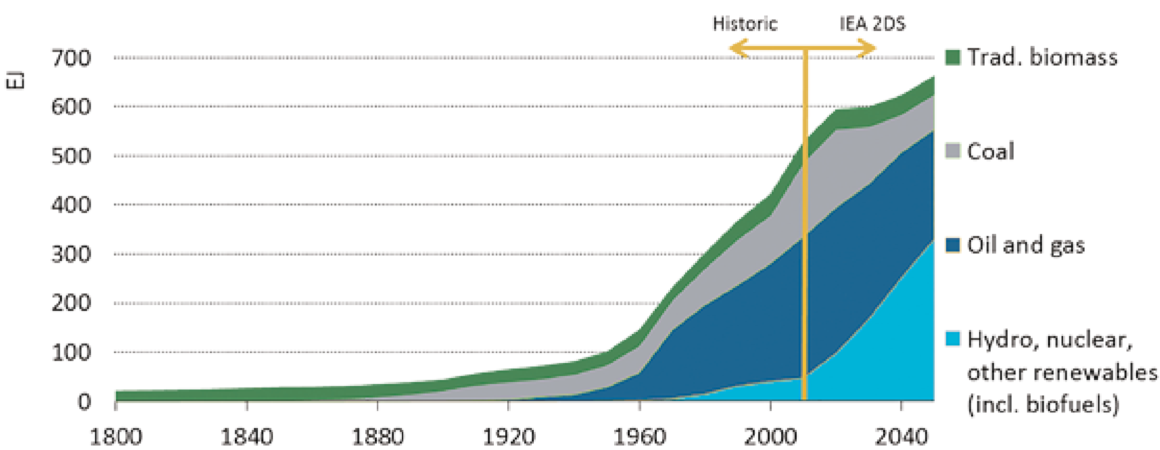


Figure 2-1 | Primary energy supply by source, historic 1800-2013, and IEA 2-degree scenario 2013-2050 (IEA)

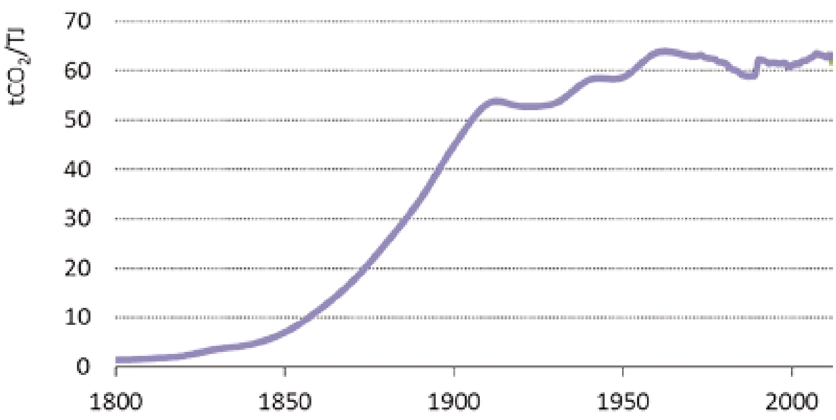


Figure 2-2 | Carbon intensity of global energy supply, 1800-2013 (IEA)

the world gathered in Paris for the 21st Conference of the Parties (COP21) to negotiate an international agreement and set a direction for combating climate change within the next decade and beyond – one that aims to reach global peaking of GHG emissions as soon as possible, with an ambition to limit the global average temperature rise to well below 2 °C and pursue efforts to limit the temperature increase to 1,5 °C. The international commitment to keep the increase in long-term average temperatures to within this target of temperature rise relative to pre-industrial levels will require substantial and sustained reductions in global emissions.

GHG remain in the atmosphere for many years – what matters for climate change is the concentration of GHG that accumulates over a period of time. The world had emitted an estimated 1 970 GtCO2 by 2014. The IPCC estimated that the cumulative amount of CO2 emitted between 1991 and 2100 would have to remain below approximately 3 000 Gt to maintain a 50% chance of keeping global warming below 2 °C. Taking into account estimated non-energy related emissions of GHG, around 880 Gt to 1 180 Gt could be emitted by the energy sector between now and 2100 – around 60% of what was emitted during the last century.

2.1.3 Environmental pollution

An estimated 6,5 million annual deaths are linked to air pollution, a number that will only increase unless the energy sector takes greater action to curb emissions. Premature deaths due to outdoor air pollution are projected to rise from 3 million today to 4,5 million by 2040, concentrated mainly in developing Asia. The IEA estimates that under a clean air scenario, premature deaths from outdoor pollution would decline by 1,7 million in 2040 – a scenario that would only require a 7% increase in total energy investment

2.2 The GEI concept

2.2.1 Why larger-scale interconnection?

The challenge of providing an affordable and secure supply of energy, and one that is sustainable and adequately mitigates the risk of dangerous climate change, requires unprecedented investments in new energy infrastructure and technology, and the large-scale retrofitting of existing energy delivery systems. Crucially, a future energy system that meets these goals will have to dramatically reduce its reliance on fossil fuels, improve the efficiency of supply and increase the share of renewable and clean energy sources. At the crossroads of this challenge is the progressive large-scale interconnection of power systems.

The key renewable resources are to a large degree constrained both in time and space. The best wind and solar resources are often located far from centres of energy demand; sites with the most extensive such resources (e.g. wind in Northern China or solar in the Southwestern US) are often located in remote regions far from the major demand centres. While technological progress in wind and solar photovoltaic (PV) is opening new deployment possibilities in less favourable resource areas, transmission expansion is often the only possible way to utilize most attractive resources. Hydropower, the largest clean energy power source today, is constrained by the geographic location of suitable natural resources, and the same is true for less deployed renewable technologies such as geothermal, wave or tidal power.

In the case of wind and solar, the output of such energies fluctuates depending on wind speed and solar irradiation at any given moment. Transmission interconnection is proving to be a valuable flexibility tool for facilitating the integration of variable renewable resources, as it allows the smoothing of generation profiles.

Similarly, hourly patterns of energy demand vary greatly from country to country, depending on time zones, behaviours or the structure of an economy. Demand patterns exhibit considerable variability due to differences in overall economic structure as well as in the spread of air conditioning and electric heating in various regions.

Interconnection allows for balancing of electricity demands across larger areas: linking winter peak demand regions with summer peak demand regions and separate regions in different time zones yields large benefits by smoothing daily peak/valley and seasonal loads. Similarly, there is a regional disparity between renewable production patterns and resource endowment. As a result, a strong transmission interconnection can increase the flexibility of the power system and achieve measurable savings in peak capacity needs.

The trend towards extensive interconnection has been present in many countries. While continental-scale interconnected and frequency-harmonized systems have existed for decades, large-scale long-distance power flows have been limited (often focussing on connection of distant hydro resources), and interconnections have primarily served system security purposes. Interconnecting regions and continents on a much larger scale can bring significant benefits to any sustainable energy scenario. Within this context, achieving interconnection on a global scale could become a possible solution to many energy challenges.

2.2.2 What is GEI?

GEI would constitute the ultimate stage of a natural progression of power grids towards ever-greater interconnection: a globally interconnected power system, supported by Smart Grid infrastructure, and making optimal use of UHV technology to transmit power over great distances. Such large-scale power grids would form the backbone for the extensive deployment of clean energy, allowing for an appropriate allocation of power generation plants where resources are best.

Scenarios that would benefit from higher levels of interconnection and GEI would also contemplate much higher electricity demand than that of today, with greatly increased levels of electrification of industrial processes that have traditionally relied on fossil fuels, transport – particularly private transportation – and increased demand for electric heating, cooling and appliance energy use in the residential and commercial sectors.

The GEI concept is thus built on three pillars:

- A large-scale deployment of clean energy, particularly variable renewables, coupled with high levels of electrification

- The transmission of power over large distances, which necessitates UHV technology
- Smart Grid solutions leveraging intelligent monitoring and control at all voltage levels (see Figure 2-3)

2.2.3 Potential benefits of GEI

Achieving very high levels of interconnection across large geographical areas affords the creation of platforms for power exchange, with greater balancing of electricity demand and supply and generally increased utilization of power generation assets. On a global scale, this would represent a comprehensive platform for clean energy deployment and access to low carbon electricity and result in potential economic, social and environmental benefits:

- A global network could bring environmental benefits, as it would form the backbone for deployment of RE where such resources are optimal from the power plant perspective

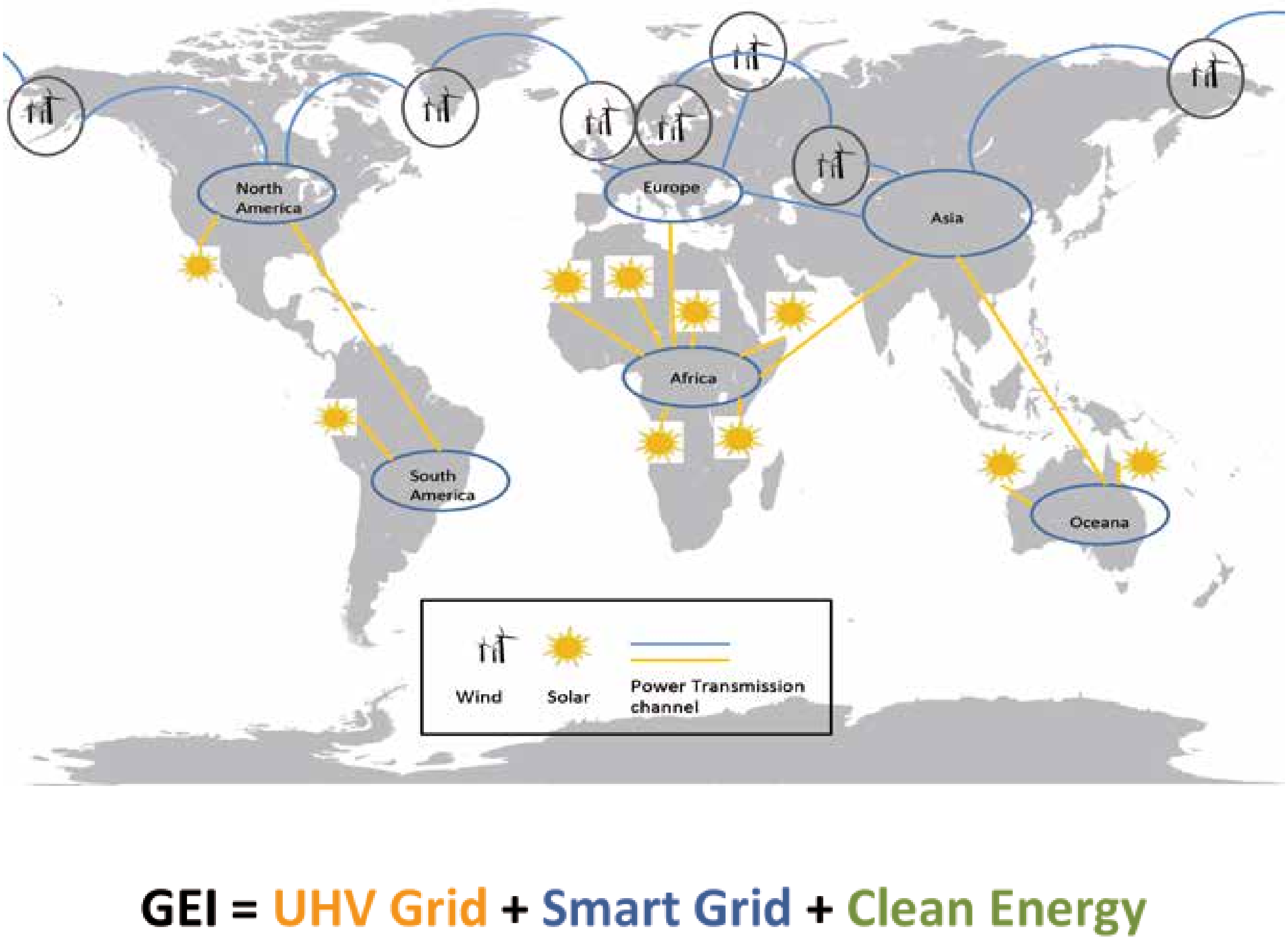


Figure 2-3 | The GEI concept

- While cost trends between now and 2050 cannot be predicted, low carbon scenarios aimed at assessing the lowest cost of decarbonizing the global energy system have identified RE as the key pillar of decarbonization
- The large-scale deployment of transmission grids and low carbon power would bring social benefits to developing countries in the form of energy access to clean power and opportunities for local capacity building and employment

2.2.4 GEI vision

GEI would constitute an organic whole. The development of national grids would be coordinated with increased levels of interconnection in transnational and transcontinental grids. UHV transmission technology and technologies affording smart monitoring and control of electricity grids would form the backbone of such grids, laid out to facilitate connections to wind power bases in northern latitudes and the Arctic, solar energy bases in the equatorial regions as well as major RE bases and main load centres on all continents. An integrated view of concurrent electrification, generation deployment and transmission and distribution capacity, would split the future development of a globally interconnected energy network into three distinct phases at a high level:

- A first phase, in which alignment on the objective of increasing the degree of interconnection to levels much higher than those of today would be progressively reached by governments, system owners and operators, utilities and other stakeholders. During this phase domestic grids would continue to be upgraded and strengthened and national power systems would be progressively decarbonized
- A second phase, in which transnational interconnection would be promoted within each continent and large-scale clean energy bases would be developed (e.g. Northern European wind, Western China wind and solar, Northen Africa solar power)
- A third and final phase, in which more distant energy hubs would begin development of wind power in northern latitudes and the Arctic and solar power around the equator, and transcontinental interconnection would start to emerge

Section 3

Energy trends and market readiness for GEI

3.1 Global energy resources and energy demands

Total world primary energy demand has maintained an almost uninterrupted growth trend, with constant changes in the energy mix (see Figure 3-1). Each major transition from one dominant form of energy to the next has taken, on average, between 20 to 40 years to complete. Until the mid-nineteenth century, traditional biomass was the primary source of energy consumed globally. With the start of the Industrial Revolution, consumption of coal and its derivatives increased substantially as more energy services and end-uses were found for the fuel. A third major shift towards oil and gas occurred towards the middle of the twentieth century, and by the end of the 1970s the world was poised for another major transition. Since then, however, the share of oil demand in primary energy supply has peaked, while natural gas has experienced constant growth. Economic development in China has driven a rebound in coal consumption, albeit a minor one. More importantly, low carbon energy sources (hydro, nuclear and other RE sources) have risen greatly in prominence.

3.1.1 Energy resources

The world has plentiful energy resources, but the size of economic and technical potential varies greatly according to location and technical and economic conditions. Global energy resources primarily include fossil fuels (e.g. coal, oil, and natural gas), nuclear fissile energy (e.g. uranium and potentially thorium) and RE (e.g. hydro, wind, solar, biomass, geothermal or ocean energy).

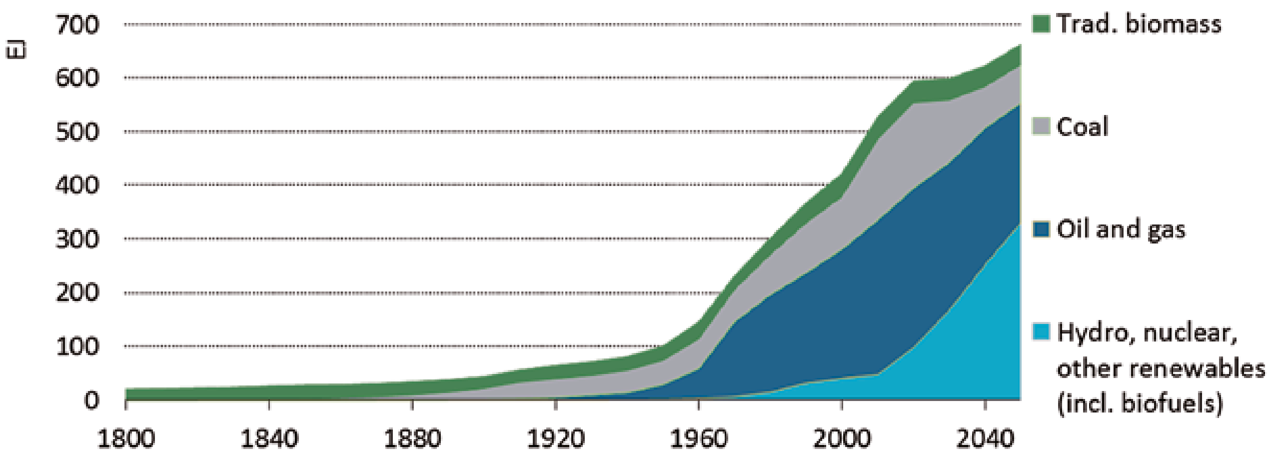


Figure 3-1 | Global primary energy supply mix, 1800-2013 (IEA)

3.1.1.1 Fossil energy and nuclear

The resource base from fossil energies is abundant – but fossil resources are unevenly dispersed and are not inexhaustible (see Figure 3-2). Globally, the remaining technically recoverable oil resources total approximately 6 100 billion barrels, 1 700 billion of which are categorized as "proven" (i.e. having a 90% chance of profitable extraction). At current rates of production, current proven reserves would be exhausted after 52 years while technically recoverable oil resources (a much more uncertain category) would last 185 years. Proven reserves for coal equate to 122 years of current production, while proven reserves of gas would sustain production for 61 years, and uranium reserves would last 120 years at 2012 consumption rates. As new technology develops, the size of the technically recoverable base for an exhaustible energy resource also expands.

Distribution of these fossil fuels is extremely unbalanced on a global basis: 95% of coal is distributed in Europe, the Eurasian continent, Asia-Pacific, and North America; 80% of oil is distributed in the Middle East, and in North, South, and Central America; and Europe, the Eurasian continent, and the Middle East are home to over 70% of natural gas reserves.

While the resource base is ample, much of the fossil fuel reserves – including an important share which is already part of the resource accounting of national and international oil companies – will have to remain unexploited if the CO2 budgets are not to be exceeded. Figure 3-3 shows the maximum amount of current reserves that can be consumed in order to limit the planet to a certain temperature increase with a 50% probability, highlighting that consuming all current listed reserves would far exceed the threshold for a 3 °C increase.

3.1.1.2 Renewable energy (RE)

In total, the sun offers a considerable amount of power: about 885 million terawatt hours (TWh) reach the earth's surface in a year, that is 6 200 times the commercial primary energy consumed by humankind in 2008 and 4 200 times the energy that the world population would consume in 2035 according to the IEA Current Policies Scenario (see Figure 3-4). World wind resources, while various orders of magnitude smaller, have been demonstrated to exceed global electricity demand, and ample potential exists in most regions of

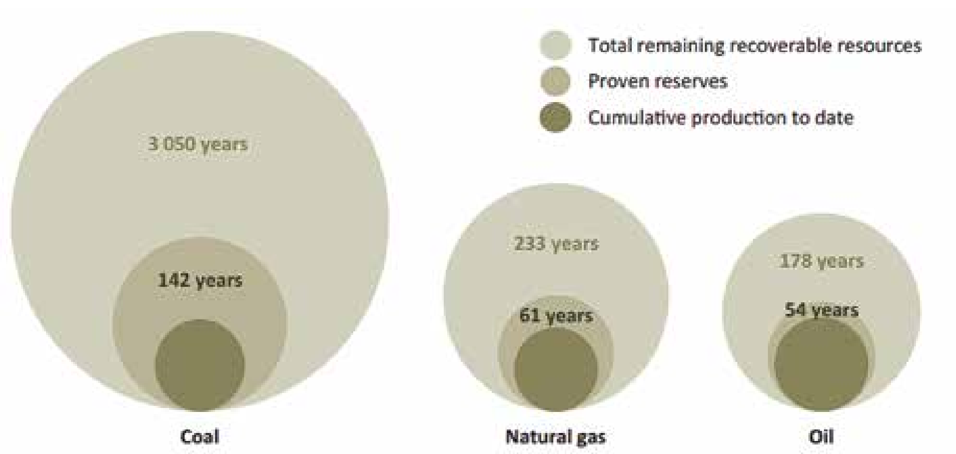


Figure 3-2 | Fossil fuel reserves time line

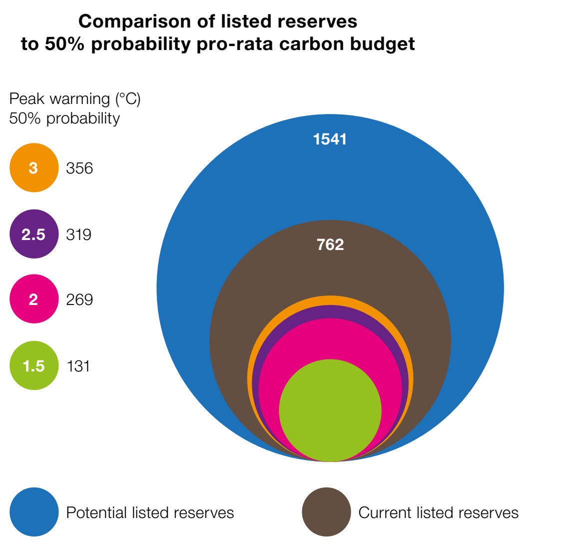


Figure 3-3 | 50% probability of reserves

the world to enable significant wind and hydro development. Using the standard IEA method of deriving primary energy equivalence (where electricity supply, in TWh, is translated directly to primary energy, in EJ), the IPCC 2007 estimate of onshore wind energy potential is 180 EJ/yr (50 000 TWh/yr), two and a half times greater than global electricity demand in 2014. The IEA has estimated global hydropower potential at more than 16 400 TWh/year, enough to cover two-thirds of global electricity demand.

Clean energy resources, however, are distributed very unevenly (see Figure 3-5). Hydro resources are distributed primarily in the drainage basins of Asia, South America, North America and Central Africa. Wind resources are distributed mainly in

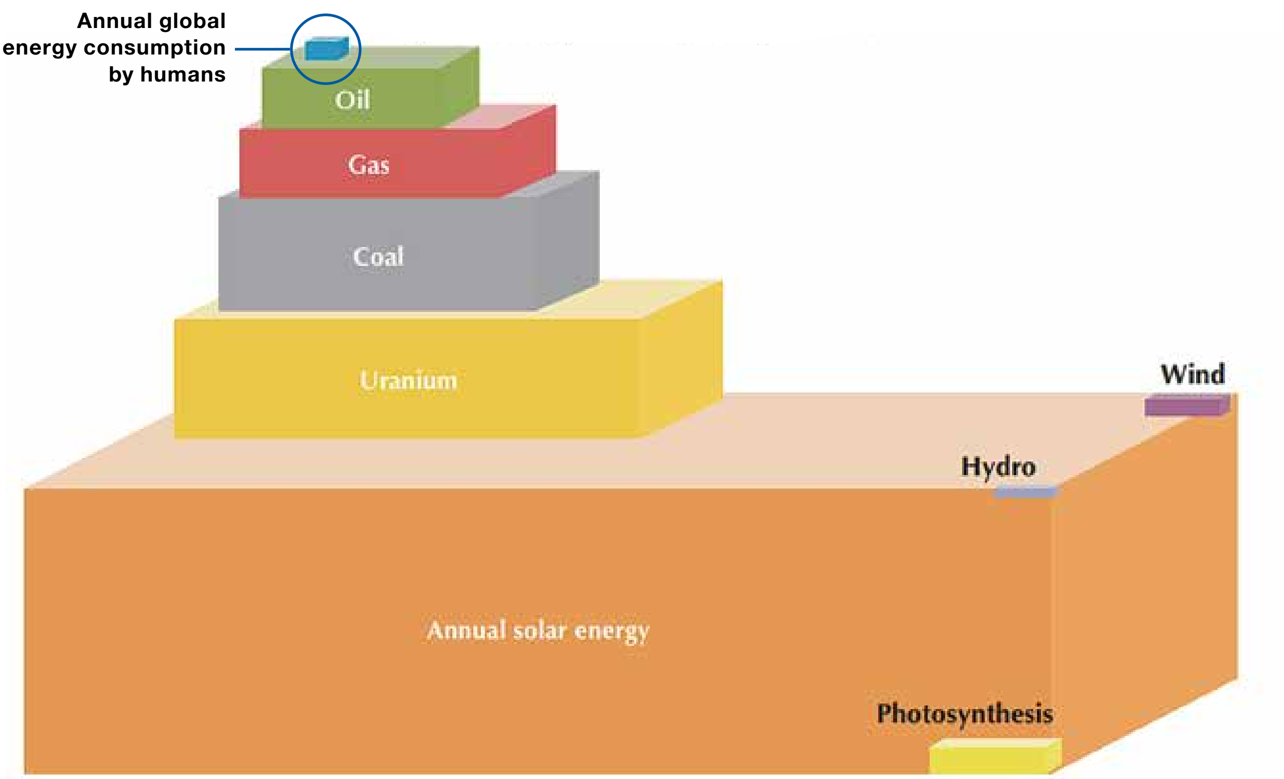


Figure 3-4 | Annual global energy consumption by humans set against known resources (IEA 2012)

the Arctic, Central and Northern Asia, Northern Europe, Central North America, and East Africa. To a lesser extent, quality wind resources are also found in the near-shore regions of each continent. The highest quality solar energy resources are found primarily in North Africa, East Africa, the Middle East, Oceania, Central and South America and other regions near the equator. Additionally, areas of arid climate, such as the Gobi, Rajasthan and other deserts, are also endowed with quality solar resources. As previously highlighted, when concentrated in sparsely populated areas several hundreds to thousands of kilometres away from load centres, exploitation of RE on very large scales requires the ability to shift significant volumes of power over large distances, which would enable the development of power generation capacities where resources are of the highest quality.

3.1.2 Energy demand

Over the last several decades, global energy consumption has grown at a much slower rate than GDP, primarily because of structural changes in the economy, energy efficiency improvements and fuel switching. Global energy intensity – defined as the amount of energy used to produce a unit of GDP at market exchange rates – fell by 32% between 1971 and 2012. Despite this partial decoupling of energy demand and economic growth, which has been particularly evident in the OECD, the two remain closely tied (see Figure 3-6).

Figure 3-5 | Allocation of world clean energy

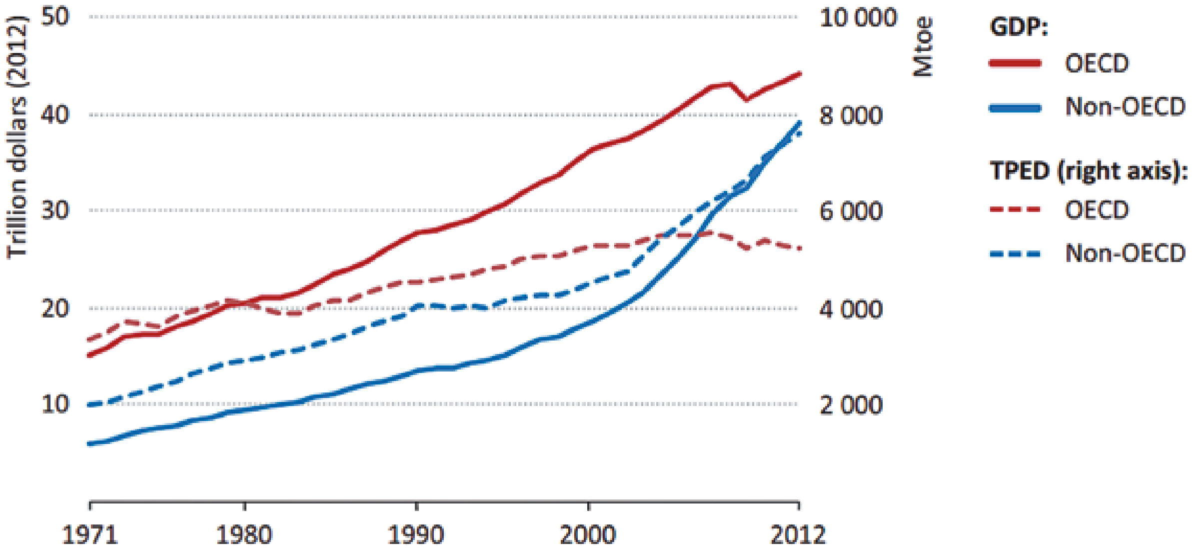


Figure 3-6 | Total volume and growth rate of global primary energy demand

The average rate of improvement, however, was much lower in 2000-2011 than in 1980-2000 (and energy intensity actually increased in 2009 and 2010) due to a shift in the balance of global economic activity to developing countries in Asia which have relatively high energy intensities. Projections are highly sensitive to assumptions about the rates and patterns of GDP growth.

The world's population will continue to grow from 6,92 billion in the same period to a projected 9,55 billion, while 1,3 billion people do not currently have access to clean energy. Rising energy demand across all energy carriers, particularly from new growth areas such as Africa, South Asia or Latin America, will be a mainstay of future energy systems.

3.1.2.1 Global energy demand

Primary energy demand worldwide is expected to continue growing, albeit at a steadily lower rate.

Electricity is already at the core of the global energy system and is projected to play an increasing role. Almost 40% of global primary energy is currently used to generate electricity, yet electricity covers on average only 17% of all global final energy needs. Among all final energy carriers, per capita growth of electricity has been the strongest, more than doubling from 1 263 kilowatt hours per capita (kWh/cap) in 1974 to 2 933 kWh/cap in 2011. This trend is expected to continue to 2050. Generation from wind and solar technologies has grown annually at double-digit rates over the last ten years, but fossil fuels account for over 75% of net new electricity generation during the same time period.

Crucially, the electrification of new energy end-uses and sectors is expected to compensate for the decline in electricity intensity of OECD countries. Electrification of transport particularly private mobility, and heating and cooling, and maximizing the use of electricity in industrial processes, are driving electricity demand upwards in mainstream energy scenarios.

3.1.2.2 Regional electricity demand

Growth in electricity demand has been uneven across regions, in part reflecting the global economic recession or a shift away from increasing industrial development to a more service-oriented economy. Electricity system reliability has been questioned due to ageing infrastructure, while also being put to the test by deployment of renewables and increased intense weather patterns.

The share of developed economies in Europe and America in total global electricity demand will decline substantially, in contrast to a significantly higher share for Asia, Africa, and South America. In 1990, non-OECD countries accounted for only 35% of the world's total electricity. More recently, driven by the fast-growing electricity consumption among emerging economies, non-OECD countries accounted for 51% of total global consumption in 2010, a figure that rose to 53% in 2013.

3.2 Trends in cost reduction of key technologies for GEI

While renewable technologies are becoming increasingly competitive on a cost basis in a rising number of regions and circumstances, public support remains necessary to facilitate their implementation in the vast majority of countries. Power generation from renewables grew by a record 128 gigawatts (GW) in 2014, accounting for nearly half of all new plants. Around 69% of all investment in new capacity went to RE sources. Over half of all power sector investments were accounted for by variable renewable generation technologies, namely wind and solar PV, with 14% of investments going towards hydro. Of the anticipated annual output of all capacity that came online in 2015, and assuming current load factors, new wind and solar plants would represent a fifth.

Costs for RE, particularly for solar PV and wind power, have fallen greatly over the last two decades. Technological progress, improved mechanisms and conditions for financing new projects, expansion to markets with good resources, and the consolidation of markets and build-up of local capacities have combined to reduce the cost per unit energy from renewable power sources, with further decreases forecast (see Figure 3-7).

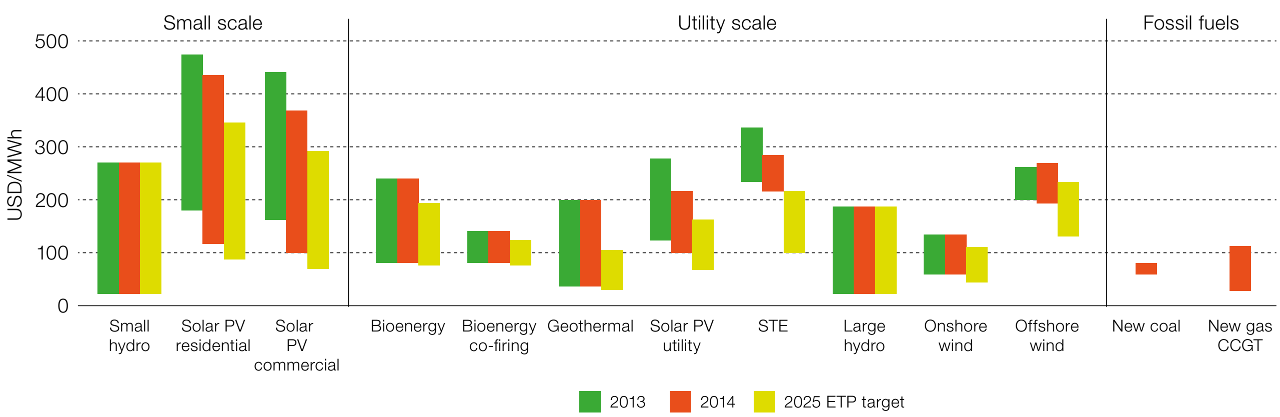


Figure 3-7 | Levelized cost of power generation in 2013, 2014 and 2025 target (IEA)

3.2.1 Market trends for wind power generation

The cost per kWh of wind power depends on various factors, including wind resources, investment costs, operation and maintenance costs, finance costs, as well as the ability of the conversion technology to turn wind output into electricity, generally measured as a capacity factor. Larger hub heights with larger swept areas result in higher capacity factors and a greater amount of electricity generated, all else being equal.

3.2.1.1 Onshore wind power generation

Onshore wind power is a mature technology with a global supply chain. Onshore technology has gradually evolved to maximize the electricity produced for every megawatt installed. Turbines have increased in height, with larger swept areas and often greater generating capacities. The result has been an increase in investment costs, but also a reduction in costs on a per unit energy basis due to the greater capacity factors achieved (see Figure 3-8). New turbines with a greater swept area per megawatt have unlocked low- and medium-wind sites that previously were not viable to develop.

The trend responds to three factors. In some countries, such as Denmark and Germany, the relatively high penetration of wind power has reduced the availability of high quality wind sites. The reduction of incentives in some countries has squeezed profit margins for wind developers, adding pressure to maximize generation per megawatt (MW) installed. Finally, the trend away from uncompetitive feed-in tariff schemes and towards auctions and competitive tenders has increased competition.

An estimated 65% to 80% of the costs of wind power are accounted for by turbines. Costs associated with construction, grid connection and soft costs can also impact cost reduction trends. While competition, local production and market potential are major indicators of country-level turbine pricing, the drivers for other system costs are more complex. Table 3-1 shows the expected cost reductions in wind power out to 2020 in selected regions.

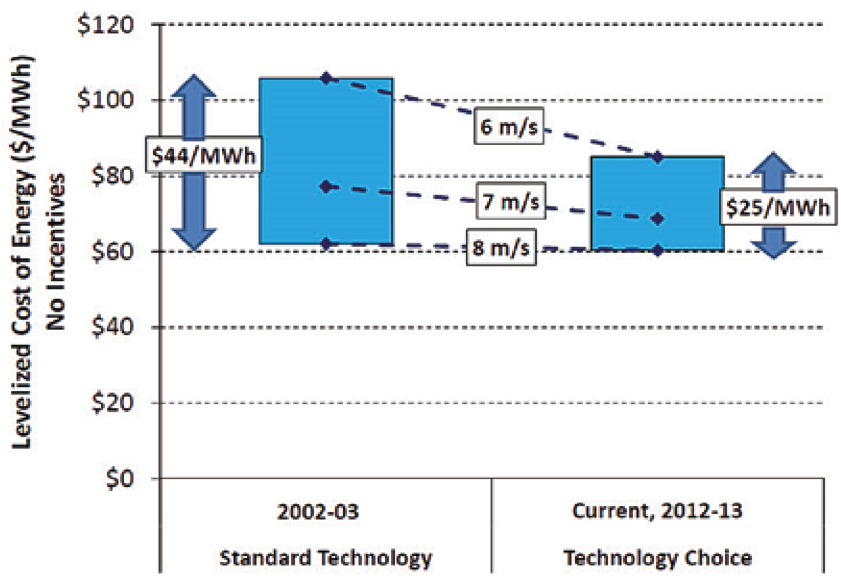
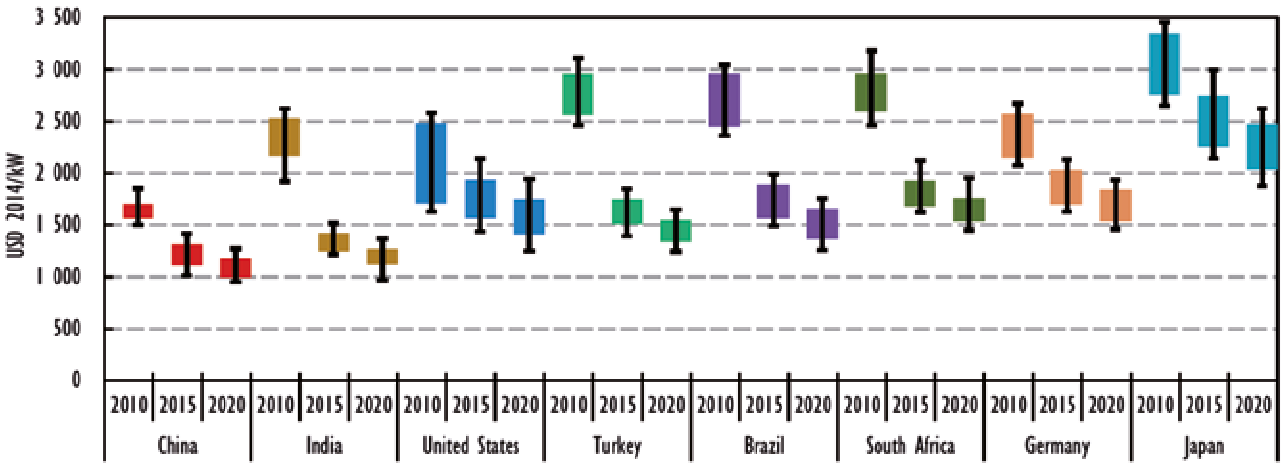


Figure 3-8 | Change trend of wind power cost under different wind [1])

Table 3-1 | Total investment costs per kW for onshore wind in selected countries (IEA)



Globally, at the beginning of 2015, typical levelized cost of energy (LCOE) figures ranged from USD 60/MWh to USD 140/MWh. In the majority of countries having some deployment experience, LCOEs for onshore wind projects stand at USD 70-80/MWh. The lowest LCOEs are estimated in various large sites in Brazil and the US, where capacity factors can be close to 50% and developers were able to obtain low interest rates.

In 2014, LCOEs in China amounted to USD 64-84/MWh. In India, wind projects in general are marked by high financing costs and low capacity factors ranging from 17% to 23%, which results in relatively higher LCOEs even though systems costs are slightly higher than in China. In Germany, projects have LCOEs as low as USD 65/MWh in good sites, while typical costs range from USD 75-100/MWh.

3.2.1.2 Offshore wind power generation

The commissioning of large-scale projects in Europe and the commercialization of turbines with larger power capacity and higher rotor diameters have marked the trend in the offshore wind market over the last few years. The offshore wind supply chain has continued to evolve with further standardization efforts. The latest tender results in Denmark and the UK for projects expected to be commissioned within the period 2017-2020, and a large project pipeline in Germany, show the potential for a significant cost decrease over the medium term. Still, grid connection delays and the need for a long-term stable market and regulatory environment continue to constitute ongoing challenges to deployment.

Current system costs range from USD 4 000/kW to USD 5 250/kW. This cost range includes both onshore and offshore electrical infrastructure required to commission a project. Total investment costs are highly variable and project-specific. However, it is important to highlight the dynamics behind these costs. Going forward, offshore wind investment costs are expected to decrease with the deployment of larger power plants, increased competition among turbine manufacturers and providers of other supply chain elements, the standardization of some foundation structures, and more efficient operations and management (see Figure 3-9).

Turbines have the largest cost reduction potential, as they still account for the majority of investment

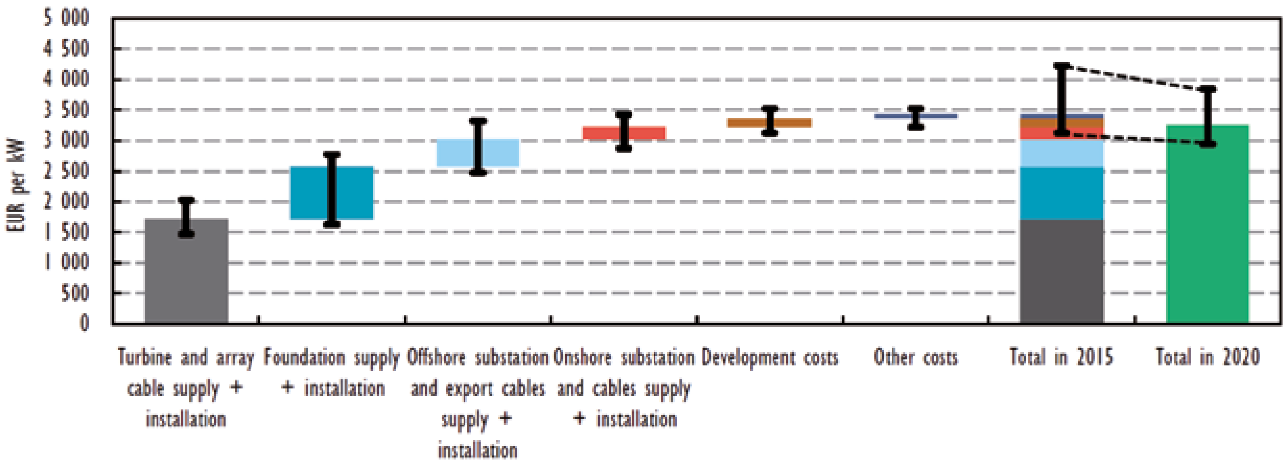


Figure 3-9 | European offshore wind farm investment cost components and trend (IEA)

costs, and increasing competition among offshore turbine manufacturers should reduce prices over the medium term. In addition, the increasing generator capacity of turbines is expected to lower construction costs significantly, as fewer foundations and array cables will be required. Floating offshore wind installations may offer innovative solutions in the years to come, including the use of vertical-axis turbines, a design that has been outpaced on shore but may have some advantages on floating platforms.

3.2.2 Market trends for solar power generation

3.2.2.1 Solar PV

By the end of 2014, the global total solar PV capacity reached 177 GW, with about 40 GW of capacity added in 2014 itself (see Figure 3-10). From 2008 to 2012, solar PV module prices were divided by five, and solar PV system prices divided by three in mature markets such as Italy due to sustained technology improvement and great economies of scale. In 2013 and 2014, module prices declined by 15%-18% annually in markets such as Japan and Germany, however, they remained largely stable in China, with several months of higher prices. In early 2015, average module prices stood at USD 0,60-0,70 per watt, and differentials between markets have narrowed, though China still occupies the lower end of the price range. Increased domestic demand has been an important driver for stabilizing module prices in China, the source of almost half of global module shipments in 2014.

Technology improvement has been and will continue to act as an important driver for sustained investment cost reductions in solar PV systems (see Figure 3-11). Technology evolution will likely be marked by three broad trends:

- Incremental progress towards higher conversion efficiency, which would allow for smaller module sizes
- Lower materials usage
- Streamlined and more innovative manufacturing processes

Still, given uncertainty in trying to predict technology trends as well as separating the effects from industrial competition, some debate

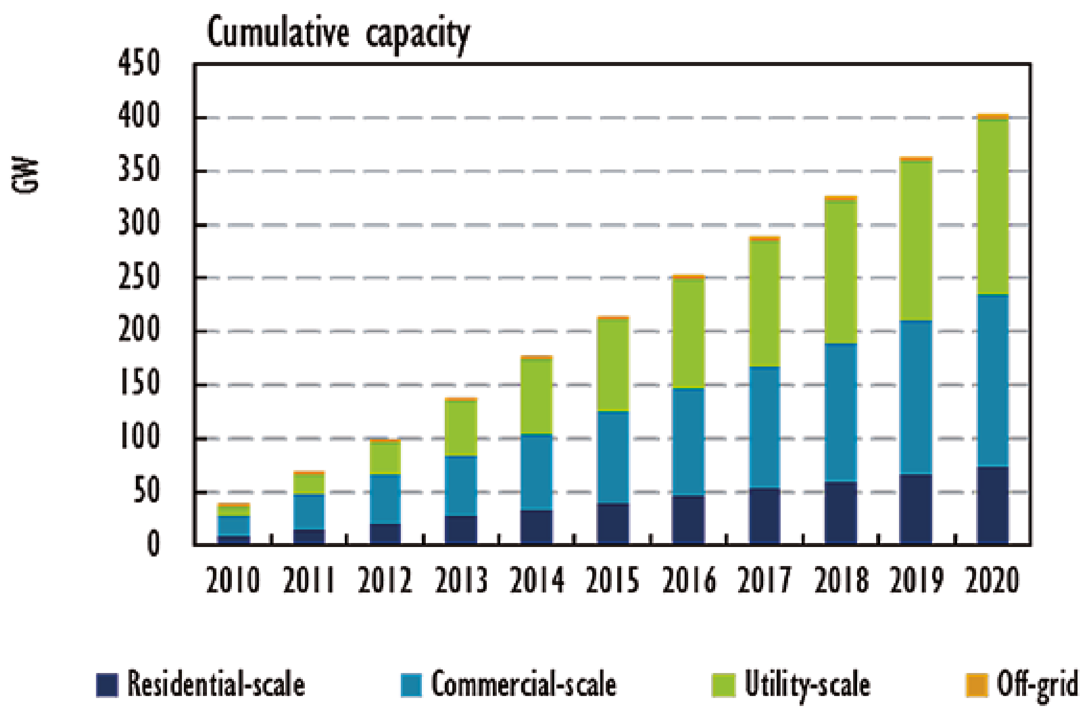


Figure 3-10 | Global total solar PV capacity and trend, by sector (IEA)

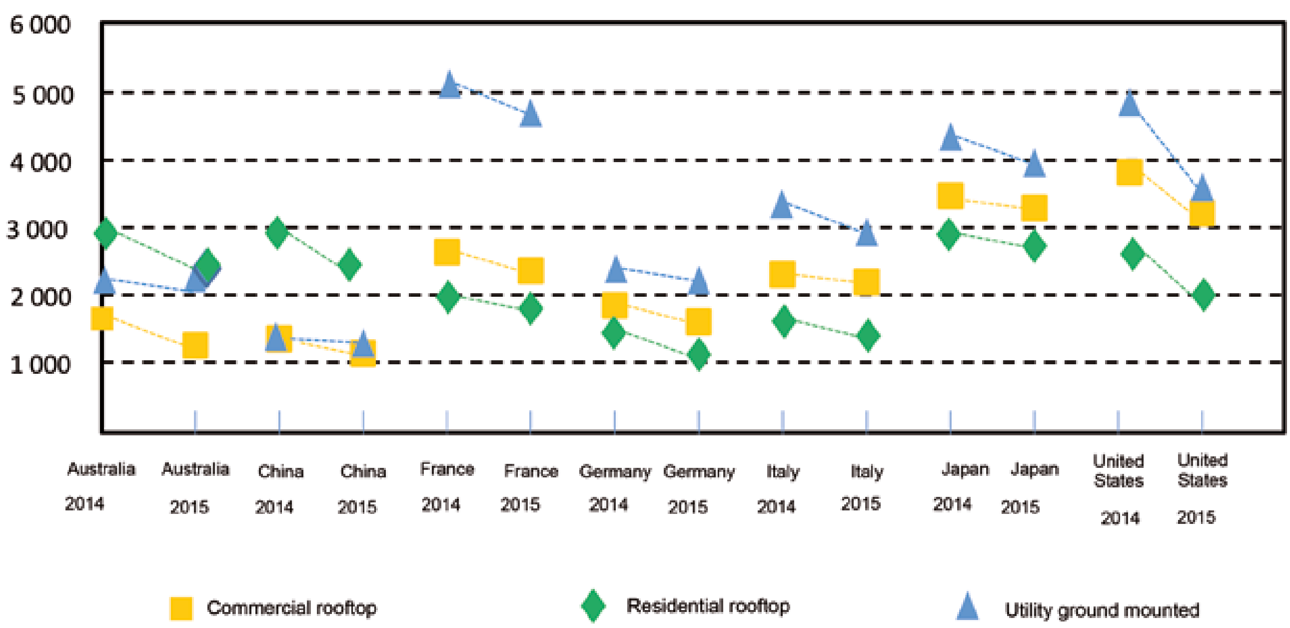


Figure 3-11 | System cost trend for PV technologies (IEA)

has emerged over the trajectory of the PV module learning curve going forward.

Even as module price decreases have somewhat slowed, balance of system (BOS) costs have experienced an accelerated decrease. In 2015, typical utility-scale solar PV prices were estimated to be as low as USD 1 300/kW in China and Germany. Commercial-scale solar PV prices were at USD 1 150/kW in China and USD 1 300 in Australia. Meanwhile, the lowest residential-scale systems still remained at levels of USD 2 000/kW and higher. In general, most new utility-scale projects in the world can currently be developed at investment costs of between USD 1 000-2 000/kW, depending on the market.

Going forward, solar PV investment costs are likely to decline due to a combination of continued global learning in module production and local improvements in soft costs. Average crystalline module prices are expected to reach around USD 0,50/W in real terms by 2020 (see Figure 3-12).

Beyond installed costs, the LCOE for PV systems depends greatly on the solar resource. Globally, LCOEs for typical utility-scale projects constructed in early 2015, without incentives, are estimated to vary from under USD 100/MWh to over USD 200/MWh. Within this range, China and India are at the low end of the spectrum and Japan is at the high end. However, the estimated global reference suggests that weighted average deployment can take place at around USD 125/MWh. Distributed PV (i.e. small and rooftop scale), while exhibiting higher costs of 220/MWh in 2015, is expected to reach USD 160/MWh by 2020.

In the case of solar PV, and in general with non-dispatchable power sources, cost trends do not represent a full picture of competitiveness. A fuller assessment of its competitiveness versus that of other power sources would need to take into account the system value of solar PV, i.e. where the PV is deployed, when its electricity is produced, and how well this aligns with system needs and capacities both on the demand and the transmission sides.

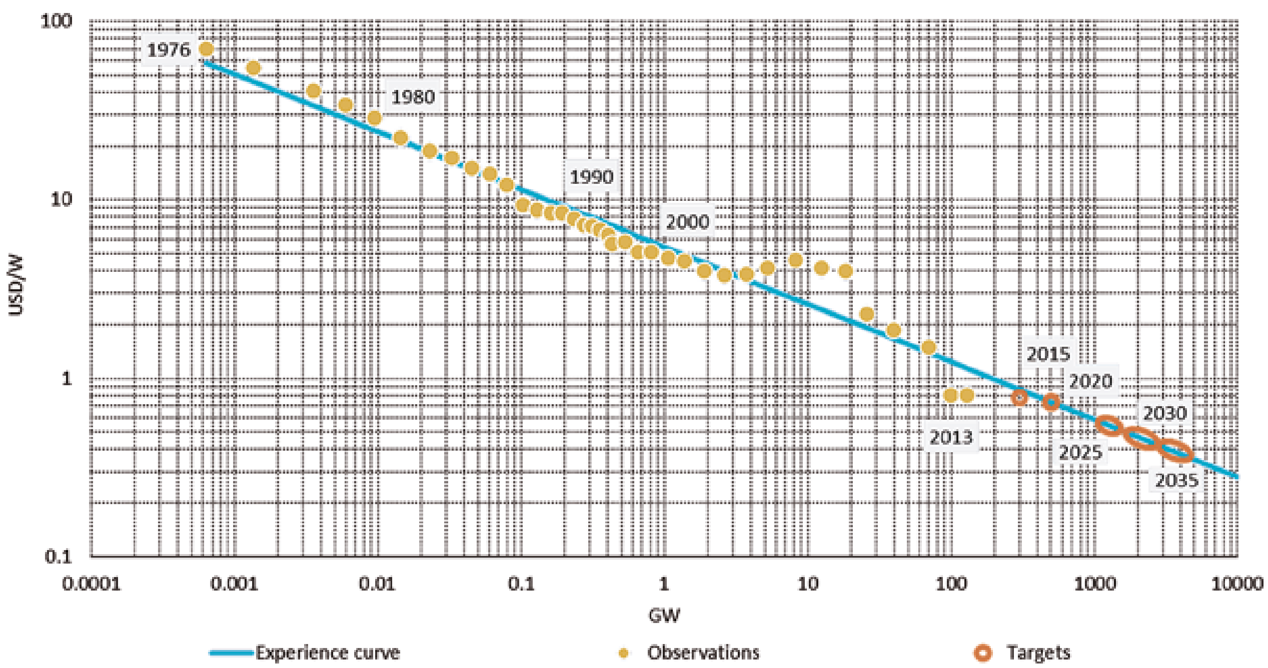


Figure 3-12 | Declining prices for crystalline modules (IEA)

3.2.2.2 Solar thermal power generation

Solar thermal energy (STE) from concentrated solar power (CSP) plants is a proven renewable technology that can provide firm peak, intermediate or base-load capacity thanks to thermal storage and/or a hybrid system (see Figure 3-13). By the end of 2015, total installed capacity in the world amounted to 4,94 GW. Of this, roughly 3,2 GW is without storage, while 1,8 GW includes thermal storage. Going forward, around 80% of the new capacity expected through 2020 should incorporate storage. However, a number of risks remain and the technology needs to move further down the cost curve to achieve a more rapid scale-up.

Storage and hybridization allow STE to have a generally higher value than PV for the system. Investment costs are characteristically high – for large plants (at least 50 MW) such costs amount to USD 4 000/kW to USD 9 000/kW. Over the medium term, the investment costs of STE plants are expected to decline with further deployment. For example, the solar field, whose size is linked to the amount of electric output, represents about half of the investment cost, and developers are looking to reduce its size by increasing electric conversion efficiencies. Costs could be further decreased by scaling up thermal storage using molten salts. The IEA expects that by 2020, STE investment costs in the US could decline to around USD 3 000-4 000/kW with 6 h of storage and USD 4 500-5 500/kW for 12 h of storage. Figure 3-14 shows the current and expected trend out to 2020 in LCOE for STE. The LCOE varies greatly plant to plant and does not provide the full picture of the economic attractiveness of STE, which also depends on the value of the electricity generated.

3.2.3 Market trends for other geographically-constrained RE technologies

3.2.3.1 Ocean energy

Ocean energy remains a small part of the global power mix. There is however a significant resource and the number of demonstration projects underway indicate there could be a commercial scale-up in the medium term. In 2014, total ocean capacity stood at an estimated 0,53 GW, equivalent to a single large natural gas power

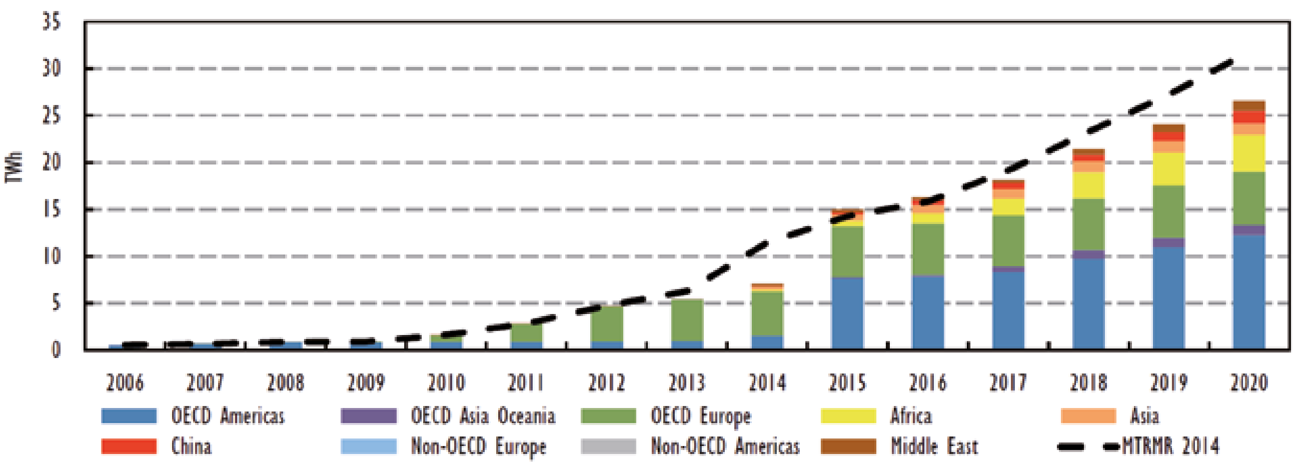


Figure 3-13 | Global total solar thermal power generation capacity and trend (IEA)

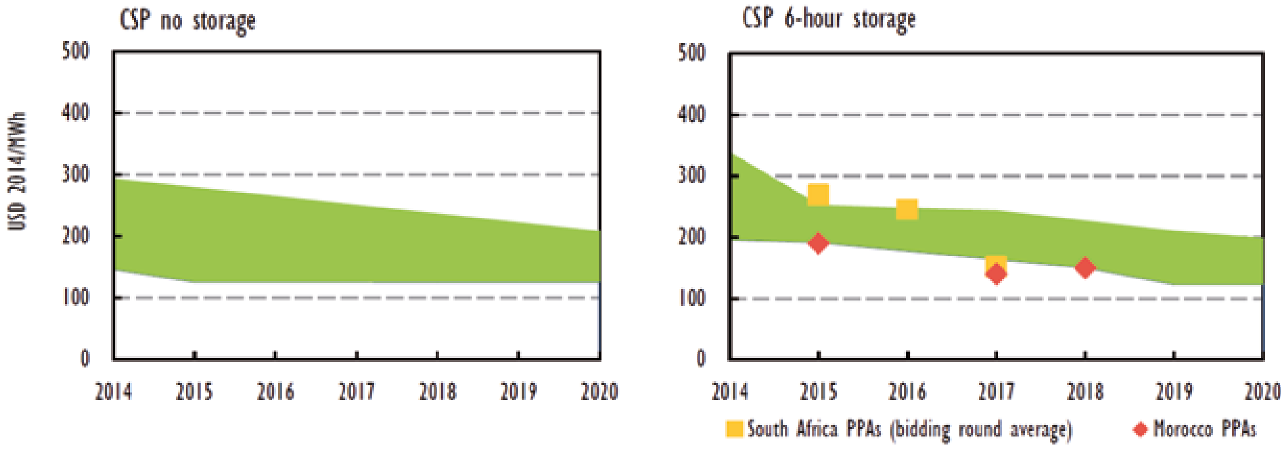


Figure 3-14 | Current and expected trend out to 2020 in LCOE for STE (IEA [2])

plant, including two large-scale tidal projects in France and Korea.

The IEA Technology Collaboration Programme on Ocean Energy Systems (IEA-OES) estimates total investment costs for a 3 MW wave energy plant at around USD 18 100/kW; however, costs could decrease by half to around USD 9 100/kW for a 75 MW plant. Investment costs for tidal projects of 10 MW are around USD 14 600/kW, but could decrease to USD 5 600/kW for larger projects of 90 MW.

3.2.3.2 Geothermal energy

The global geothermal resource is significant, and due to its dispatchability it is a highly attractive renewable generation technology option. Geothermal energy requires much exploration, extensive drilling and civil engineering works, which result in long lead times (i.e. 5-7 years).

Because of its characteristics, costs are very site-specific, with typical costs of a high-temperature plant at around USD 2 000/kW to USD 5 000/kW. Binary plants are slightly more costly at USD 2 400/kW to USD 5 600/kW. LCOEs for geothermal plants range from USD 35/MWh to USD 200/MWh, a result of the high capacity factors reached in geothermal generation.

3.3 Practical experiences of power system interconnection around the world

Following the three-stepped approach towards greater interconnection across the globe highlighted in Section 2.2.4, this section examines practical experiences relevant to each of the three phases outlined.

3.3.1 Experiences with large-scale national transmission interconnection

3.3.1.1 China

Over the past decades, the scale of interconnection in the Chinese power grid has increased substantially, accompanied by a constant increase in voltage levels. Since the 1950s, the Chinese national grid has evolved from hundreds of isolated grids to approximately 30 provincial grids, and finally to large-scale regional grids. Currently, there are six synchronous grids in mainland China,

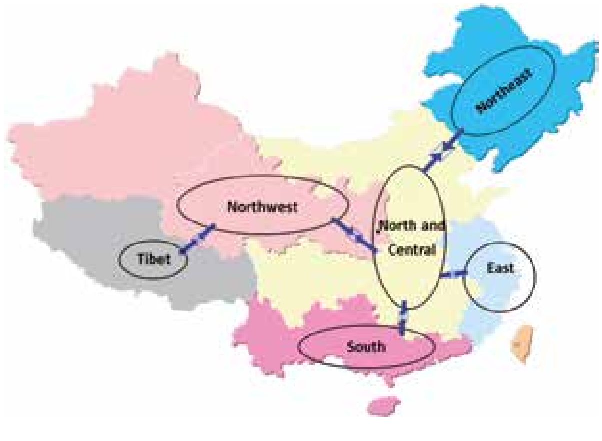


Figure 3-15 | Current status of grid interconnection in China (SGCC)

Figure 3-16 | Planned grid interconnection in China by 2020 (SGCC)

namely the North and Central grid – integrated into one synchronous grid in 2009 by the first 1 000 kV ultra-high-voltage alternating current (UHVAC) line –, the East grid, the Northeast grid, the Northwest grid, the Tibet grid, and the South grid. These grids are fully interconnected with HVDC links, as outlined in Figure 3-15.

With the number of planned and under construction UHV backbone transmission lines, these regional grids will be further consolidated in the future. In its new five-year grid development plan, State Grid Corporation of China (SGCC) proposed the formation of two synchronous grids by 2020, namely the East and West grids, as shown in Figure 3-16. The West grid will focus on the integration of a broad range of power bases, given Western China's rich resource endowment; the East grid will integrate major load centres. This clear two-region grid structure featuring a strong exporting region and a strong importing region is expected to support the cross-regional transmission of 88 GW of wind power, 20 GW of solar power and 60 GW of hydropower, helping the government to fulfil its decarbonization target.

3.3.1.2 Korea

Korea's electricity industry is dominated by the Korea Electric Power Corporation (KEPCO), which retains the nation-wide transmission and distribution grids (see Figure 3-17).

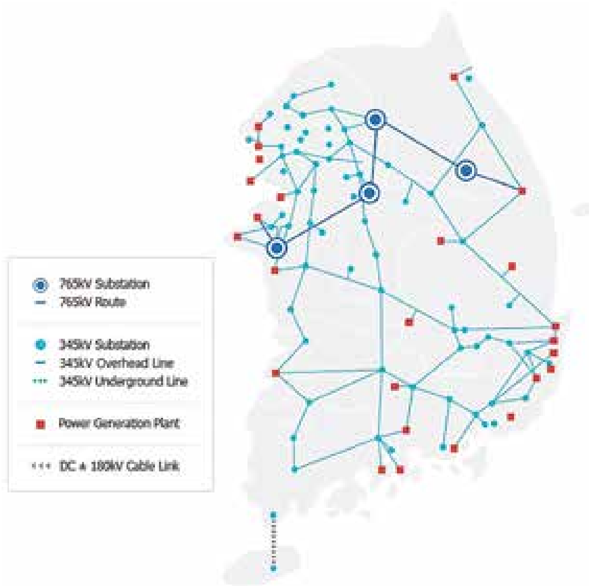


Figure 3-17 | National Power Grid of Korea (KEPCO)

KEPCO has pushed forward interconnection through UHV power transmission to address the serious supply imbalance between the high demand load centres in the Seoul metropolitan area and the power generation areas, concentrated in large-scale complexes. The commercial operation of the first UHV project in East Asia (a 765 kV transmission and substation project) began in 2002, using a range of advanced grid technologies with a low environmental footprint, including gas-insulated switchgear or steel towers with a low environmental impact. The Korean experience shows that upgrading and interconnecting the existing power grid with such UHV technologies allows for capacities 3,4 times greater than that of the prevailing transmission voltage of 345 kV. Land requirements are decreased by 22%, and transmission losses and construction costs are both reduced by a fifth (see Figure 3-18).

3.3.1.3 Japan

Figure 3-19 illustrates the domestic interconnected transmission network in Japan. As shown in the figure, excluding the Okinawa region there are nine regional networks, interconnected with each other via HVDC submarine cables, HVAC overhead lines, back-to-back systems and frequency converters.

There are two specific features in Japan's power system, relevant to the analysis of practical interconnection experiences worldwide.

First, power frequency differs between Eastern and Western Japan, set at 50 Hz and 60 Hz respectively. There are historic reasons for this difference: during the emergence of the electricity industry in Japan, the Tokyo area in the East adopted German-made generators, while Osaka in the West chose American-made ones. This

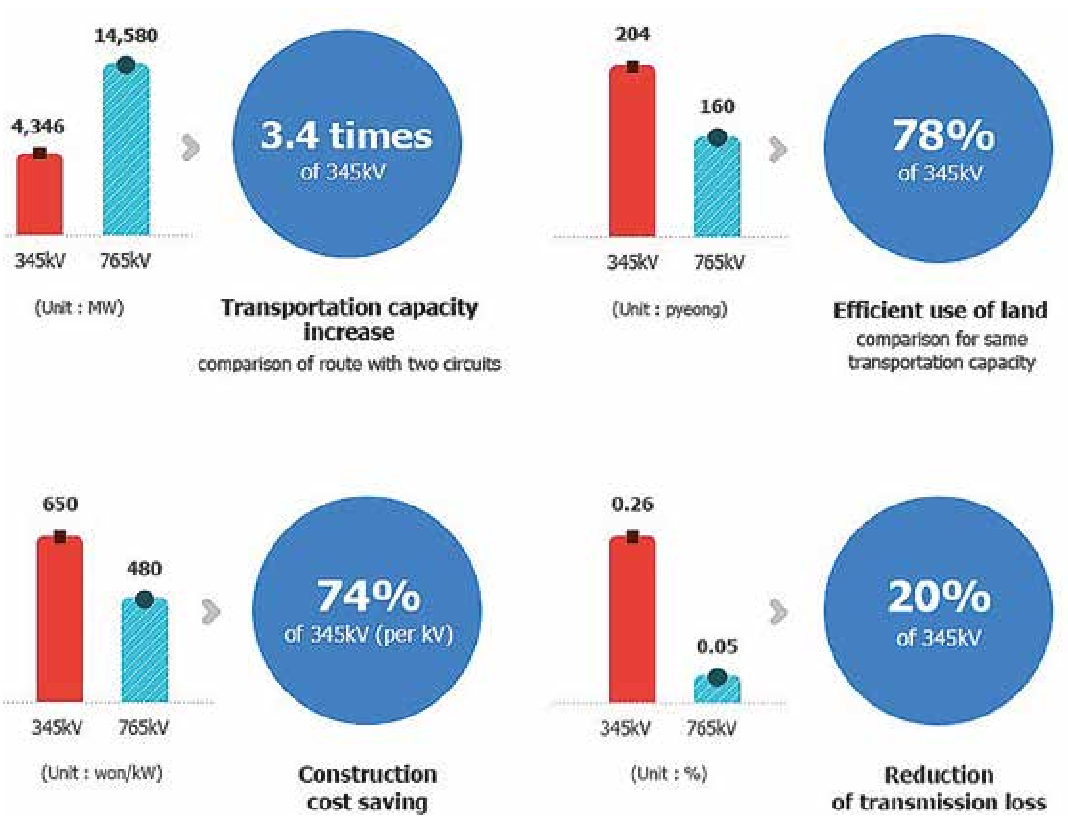


Figure 3-18 | Major benefits of the UHV transmission system in Korea (KEPCO)

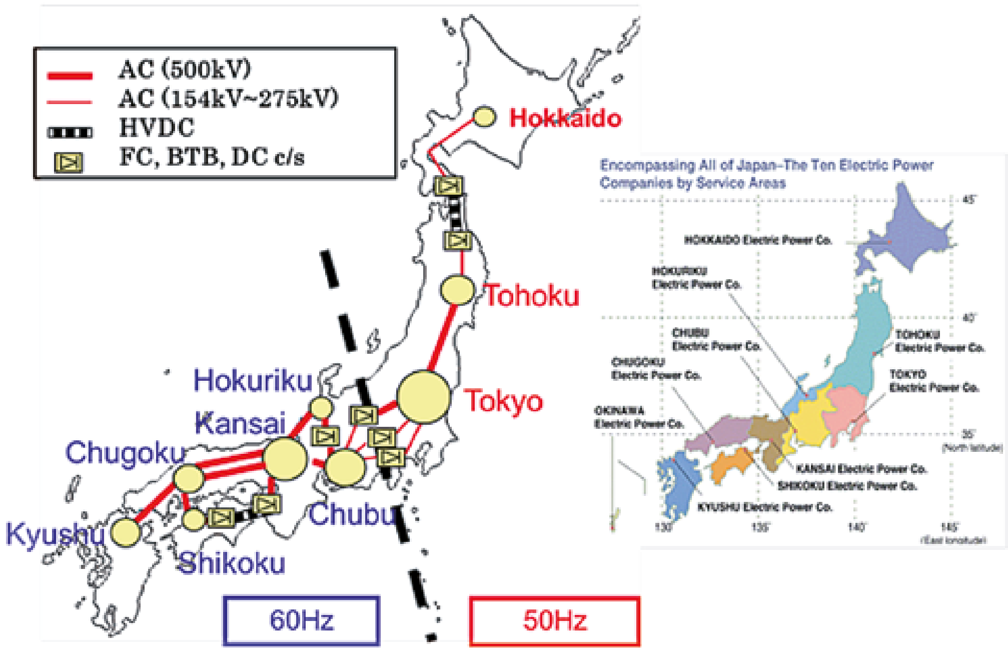


Figure 3-19 | Domestic interconnection of electricity transmission network in Japan (TEPCO)

frequency difference partitions Japan's national grid, requiring frequency converter facilities (FCFs) to exchange power between East and West. Three FCFs are currently in operation – with a total transmission capacity of 1,2 GW, the East-West Grid Connection is a bottleneck for power exchange.

Second, the nine individual utilities in operation in Japan have been individually responsible for securing adequate power sources for their own power demand and overseeing their own power system development and operation. In each region, supply and demand is strongly determined by the characteristics of local production and consumption. Interconnections have traditionally only been used for the purposes of transmitting electricity from distant power sources and emergency power system interventions. Therefore, almost all interconnection systems have only a minimum necessary minimum transmission capacity and have configurations suitable for those purposes.

In recent years however, Japan has been forced to rethink this conventional concept of network planning due to power supply deficiencies and imbalances in the Tohoku and Tokyo EPCO areas following the East Japan Earthquake in 2011, coupled to an increasing need for cross regional power exchange due to the full-scale liberalization of the electricity retail business in April 2016.

Figure 3-20 illustrates the enhancement plan for interconnections between Tokyo and Chubu EPCO via 900 MW HVDC transmission lines which will be commissioned in 2020.

3.3.1.4 India

The development of the Indian power grid can be divided into three stages:

- From 1947 to the 1960s, when state-level grids were progressively formed by interconnecting many isolated small grids

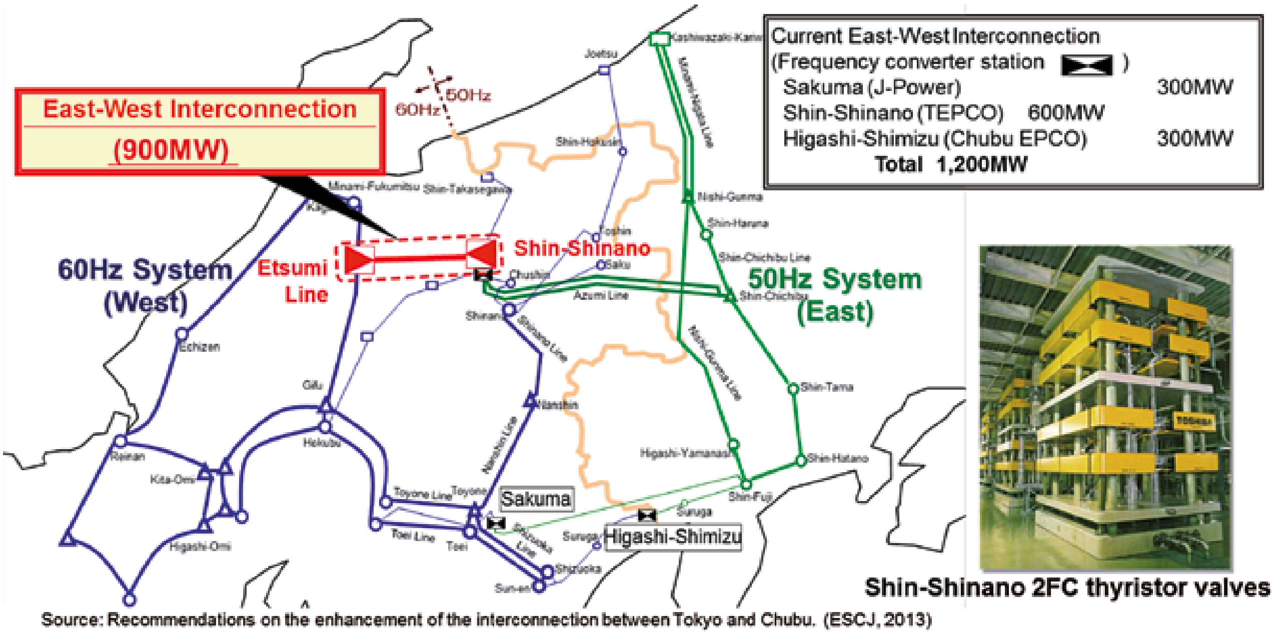


Figure 3-20 | Enhancement plan for east-west interconnection capacity by 900 MW HVDC

- From the 1960s to the end of the 1980s, during which five regional-level grids were formed by interconnecting state-level grids
- From the 1990s until the present time, when a national synchronous grid was created by interconnecting regional grids. The interconnection among the five regional grids in 2012 is shown in Figure 3-21

As in the Chinese case, the layout of the Indian power grid and its interconnections is driven by the uneven distribution of energy resources and load centres. The energy resources of India are mainly located in the North, Northeast and East of the country, while load centres are mainly located in the North, South and West. As a result, large amounts of power need to be transferred from East to West as well as from North to South. In the future, cross-regional grid interconnection in India will be improved through planned higher-voltage level transmission lines. India's 12th five-year grid plan contemplates at least two 400 kV AC or 765 kV AC or HVDC back-to-back links between regional grids by 2017. Also planned are ±800 kV UHVDC lines and 1 200 kV UHVAC lines to be built in the North and Northeast of the country. The first ±800 kV, 6 000 MW UHVDC line began operations on August 31, 2015, from Assam to Uttar Pradesh, and through West Bengal.

3.3.1.5 Brazil

Given its vast hydro resources, hydropower is the dominant form of generation in Brazil. Concurrent with the development of large-scale hydropower plants, cross-regional power grid interconnection in Brazil has accelerated. During the 1980s, four regional 500 kV backbone grids were formed, namely the North, Northeast, Southeast and South grids. At the end of the 1990s, a unified national synchronous grid was formed by interconnecting the four regional grids, through 765 kV, 500 kV and 345 kV links. There are also two ±600 kV HVDC lines in operation to transmit the power generated

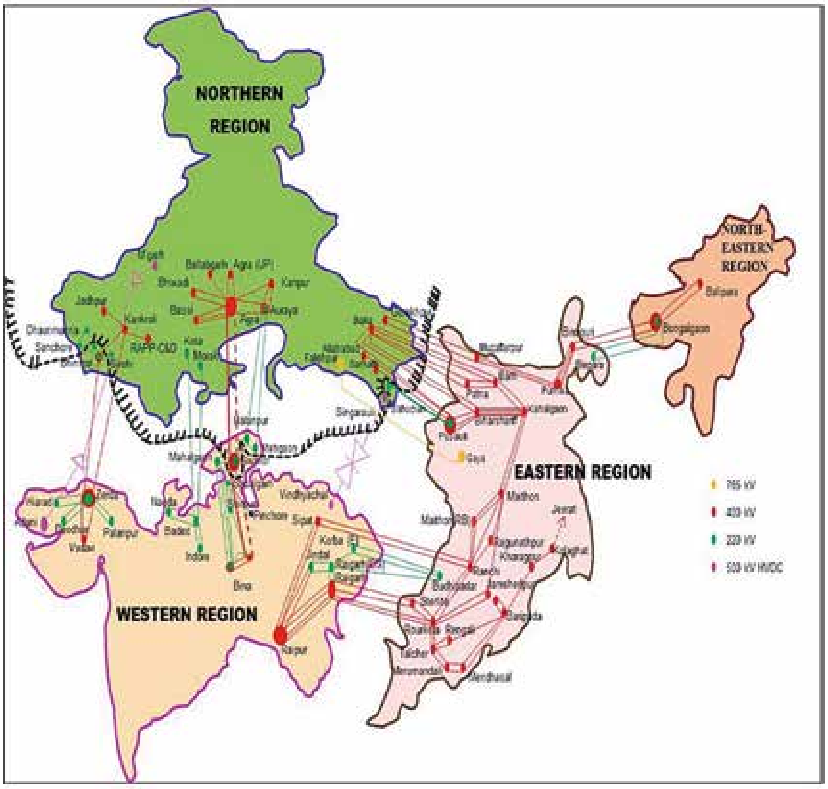


Figure 3-21 | Grid interconnection in India in 2012 (Government of India, Ministry of Power [3])

by the Itaipu hydropower plant. Brazil plans to continue to develop hydropower, especially in the Northwest and North of the country. Current plans would require further enhancement of cross-regional grid interconnection within Brazil. An illustration of the present and planned grid interconnection in Brazil is given by Figure 3-22. A ±800 kV UHVDC line is now under construction for transmission of the power generated by the 11 GW Belo Monte hydropower plant.

3.3.2 Practical experiences of regional interconnection

3.3.2.1 Asia

A number of interconnections exist in Asia which highlight potential pathways towards greater regional interconnection.

In Northeast Asia, the Chinese grid is now connected with the Russian grid by means of one 110 kV AC, two 220 kV AC and one ±500 kV back-to-back DC links. There are also two 220 kV AC lines delivering power from Inner Mongolia in China to Mongolia. Two further interconnections are planned before 2020: a ±800 kV/8 000 MW/ 1 830 km DC project delivering power between Russia and China, and a ±660 kV/ 4 000 MW/1 220 km DC project delivering power from Mongolia to China.

In Central Asia interconnections now exist between Kazakhstan and Russia through three 500 kV AC lines, one of them having been operated at the ultra-high voltage of 1 150 kV. A 500 kV AC loop has been formed between Kazakhstan, Kyrgyzstan, Tajikistan and Uzbekistan. Turkmenistan is also connected with Uzbekistan and Iran. A number of

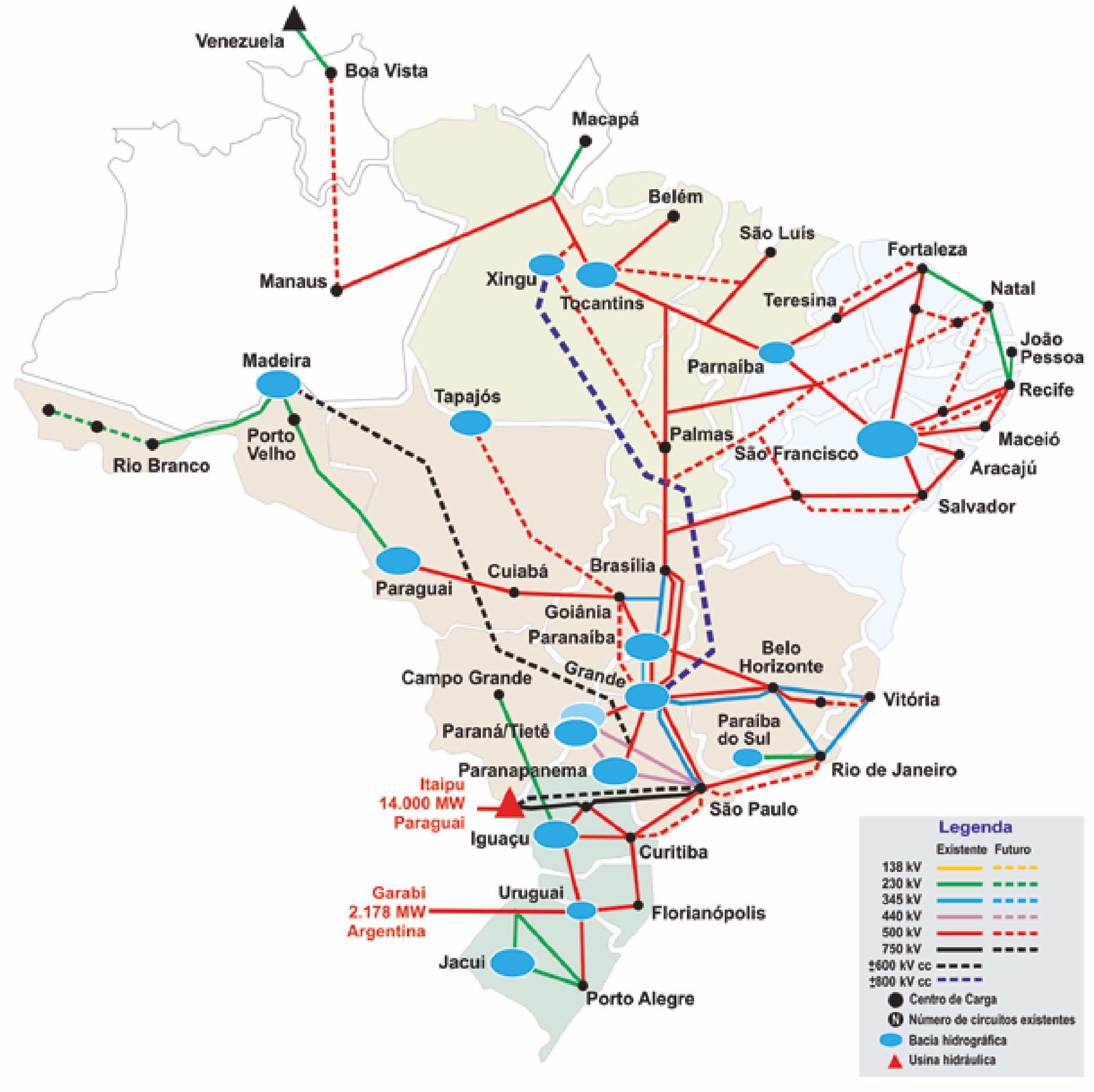


Figure 3-22 | Present and planned grid interconnection in Brazil (ONS [4])

500 kV links are under construction to enhance grid interconnection among the five Central Asian countries as well as Iran and Afghanistan. Figure 3-23 shows the existing and planned interconnection of Central Asian grids.

In West Asia, two synchronous grids have been formed through transnational grid interconnections. The first is the North Middle East Peninsula and Iran grid, which consists of the Iraq, Syria, Jordan, Lebanon and Iran grids, connected by 400 kV and/or 220 kV AC lines. This grid is also interconnected to the North with grids of Turkey, Armenia and Azerbaijan, and to the West with the grid of Egypt. The second is the Gulf Grid, an interconnection between Saudi Arabia, Kuwait, Bahrain, Qatar, the United Arab Emirates and Oman (see Figure 3-24). In 2015, the Gulf Cooperation Council proposed to enlarge the Gulf

Figure 3-23 | Grid interconnection in Central Asia (GENI [5])

Figure 3-24 | The Gulf Grid (Gulf Cooperation Council Interconnection Authority)

Grid through interconnection with surrounding Middle Eastern and Northern Africa grids.

In South Asia, the Indian grid is now connected with Bangladesh by a ±400 kV back-to-back DC link, with Nepal by a 132 kV AC link and with Bhutan by three links. The Asian Development Bank has proposed an India-centred grid interconnection enhancement plan for South Asia, connecting India to Bhutan, Nepal, Sri Lanka, Bangladesh and Pakistan, as well as India to Central Asia, as shown in Figure 3-25.

In Southeast Asia, the Chinese grid is now connected with the Vietnamese grid by three 220 kV and two 110 kV AC lines. One 500 kV and one 220 kV AC point-to-grid connection from China to Burma have also been established. The grids of countries in the Indochinese Peninsula have already been interconnected by a dozen 500 kV, 220 kV, 110 kV AC links and by one ±330 kV DC link. According to the Association of Southeast Asian Nations (ASEAN) power grid development plan proposed by the Heads of ASEAN Power Utilities/Authorities (HAPUA), 16 AC and DC projects will be built by 2025 to enhance grid interconnection among ASEAN countries (see Figure 3-26).

Figure 3-25 | Grid interconnection plan in South Asia (Nepal Energy Forum [6])

3.3.2.2 Europe, Russia and beyond

In Europe, interconnectors between countries have created a large synchronous frequency area extending into the eastern parts of the continent at a frequency of 50 Hz (see Figure 3-27). Interconnections of power grids among European countries started in the 1950s. The Western European interconnection first took shape and was then synchronously interconnected with Central European grids in 1996 [7]. Current interconnector capacity amounts to 11% of installed generation capacity across European countries. Today, as shown in Figure 3-27, the European power system mainly comprises five transnationally-interconnected synchronous grids in continental Europe, Northern Europe, the Baltic Sea countries, the UK and Ireland, as well as two independent power systems in Iceland and Cyprus. Grid interconnection and electricity market integration has enabled a high level of power exchange among the member states. In 2013, a total of 387,3 TWh was exchanged, representing 12% of total power consumption.

However, regional differences continue to exist. In the Baltic States, for example, there is a significant need for interconnectors to increase security of supply and reduce the market power of generators. In order to promote more cooperation among TSOs, the European Network of Transmission System Operators for Electricity (ENTSO-E) was founded in 2008 through integration of the former European Transmission System Operators association (ETSO) and five TSO organizations (ATSOI, BALTSO, Nordel, UCTE, and UKTSOA), covering 41 TSOs from 34 European countries [8].

Figure 3-26 | ASEAN Grid interconnection enhancement plan (EPRI)

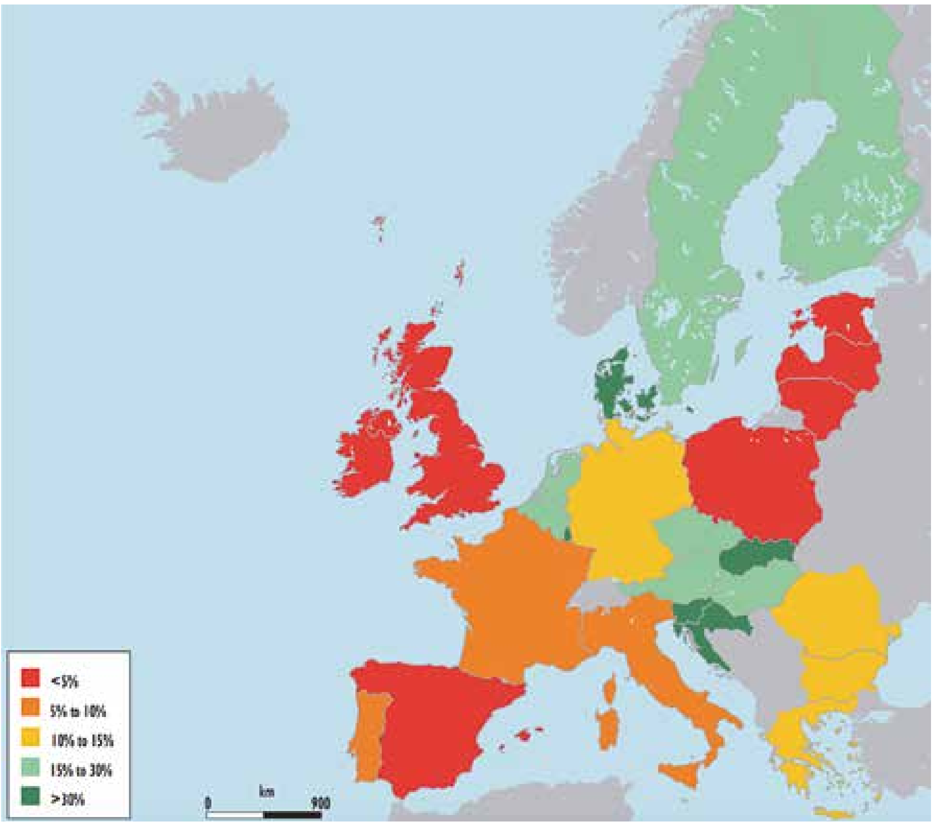


Figure 3-27 | Power exchange in Europe by 2020 (IEA)

A better interconnected European energy grid would bring notable market benefits to European citizens, as consumers could save between an estimated EUR 12 billion and EUR 40 billion annually by 2030. Such a grid is also crucial for accommodating the high level of RE required by the European Union's (EU) decarbonization policy. In 2014, the European Council discussed implementing a 15% goal for interconnection between member states in the EU. While this goal would bring visibility to the issue, the costs and benefits of interconnectors need to be thoroughly assessed, not only from an investment perspective, but also for public acceptability and understanding, which are required for transmission lines to be actually built. Public acceptance necessitates a thorough cost benefit analysis to demonstrate the positives of a project.

Russia and the EU are seeking to integrate the Integrated Power System/Unified Power System (IPS/UPS) and ENTSO-E grids, creating a synchronous super grid that would span 13 time zones. The formation of the IPS/UPS interconnection is now the world's largest synchronous grid in terms of geographical coverage, spanning eight time zones, and linking the grids in Russia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Moldova, Mongolia and Ukraine, among other countries. It is asynchronously connected with the Finnish power grid through back-to-back DC links, and is synchronously connected with the Baltic grid via AC links.

3.3.2.3 America

In North America, the greatest growth in interconnection was triggered by the development of large-scale hydropower as early as during the 1930s and was further advanced in the period of the 1950s-1980s with voltage level upgrades to meet the rapidly growing power demand. The North American grid has evolved into four major synchronous systems, namely the Western Interconnection, the Eastern Interconnection, the Texas (ERCOT) Interconnection and the Quebec Interconnection, together spanning Canada, the US and North Mexico, as shown in Figure 3-28 [7]. These interconnections are generally back-to-back DC links designed mainly for emergency backup purposes. Their power exchange capacity is limited and the power exchanged under normal operation conditions is negligible [9]. The different interconnections are not synchronized, precluding the use of AC interconnectors and limiting the level of physical interconnector capacity to DC lines. To date, only a few DC lines of about 2 GW of interconnector capacity exist between the Western and Eastern Interconnections, and one interconnector of 2,6 GW exists between the Eastern and Texas Interconnections.

The mutual isolation of these various transmission regions and the lack of transmission capacity have been identified as potential barriers for the US in its attempt to achieve its aggressive renewable energy goals as well as to improve the reliability and efficiency of the entire US power system. Vast amounts of rich wind energy resources are located in the Midwest, the Great Plains and Texas, and are open for development on a large scale and for transmission to load centres located in both the East and West Coasts. The Tres Amigas SuperStation was proposed in 2008 to integrate the Western, Eastern and Texas Interconnections through a single nexus and to act as a renewable energy hub, and initial steps towards implementation have begun in 2016 (see Figure 3-29) [10].

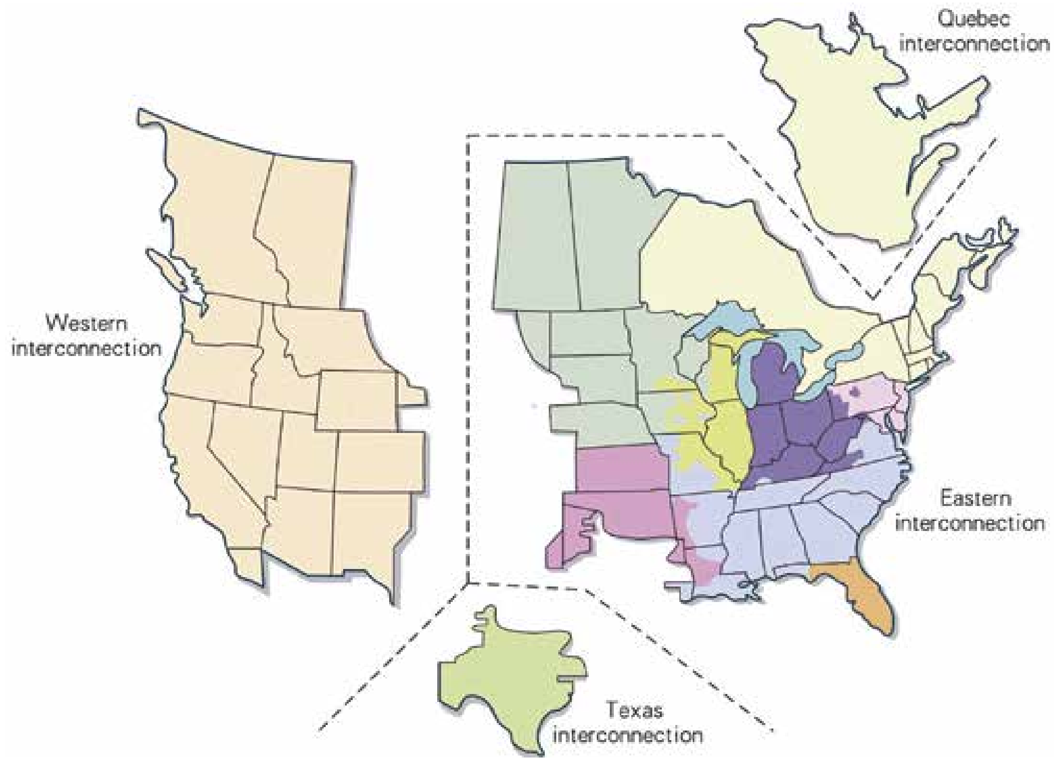


Figure 3-28 | Current North American interconnections [7]

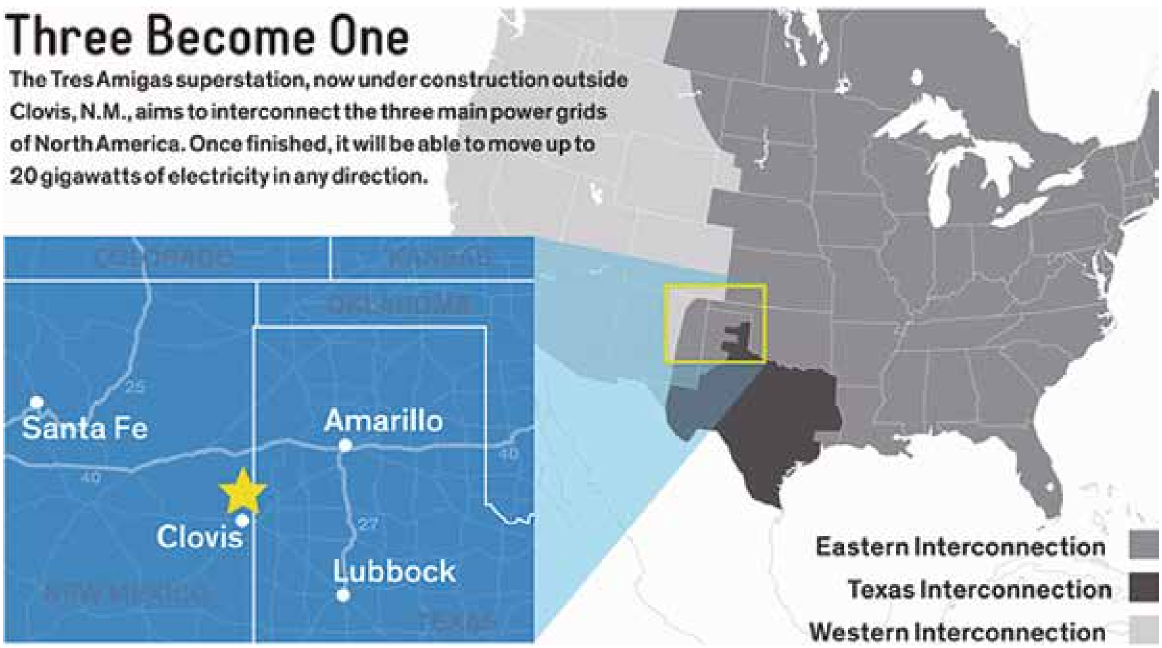


Figure 3-29 | Location of the Tres Amigas SuperStation (NERC, [10])

In South America, the existing, under construction or planned grid interconnections are mainly concentrated in two geographical areas, as shown in Figure 3-30. The northern section includes Colombia, Ecuador and Venezuela and the southern section Argentina, Brazil, Paraguay, and Uruguay. A grid interconnection between Columbia, Ecuador, and Peru is projected to be completed in 2017. The interconnection is planned then to be extended southward to reach Bolivia and Chile, as part of a larger programme to integrate the electric systems of the five Andean Community nations by 2020 [7].

In Central America, the grids of Costa Rica, Guatemala, Honduras, Nicaragua, Panama and Salvador, are interconnected through a chain of transmission lines, as shown in Figure 3-31, composed of 15 substations and 1 800 km long, 230 kV transnational lines [7].

Figure 3-30 | South America Interconnection [7]

Figure 3-31 | Central America Interconnection [7]

3.3.2.4 Africa

Since its inception in 1995, the Southern African Power Pool (SAPP) has been actively promoting transnational grid interconnections. The alliance comprises 12 members, including Angola, Botswana, the Democratic Republic of Congo, Lesotho, Malawi, Mozambique, Namibia, South Africa, Swaziland, Tanzania, Zambia, and Zimbabwe. Nine of these countries, not including Angola, Malawi and Tanzania, have developed grid interconnections through 400 kV, 275 kV, 220 kV, and 132 kV AC links. Planned grid interconnection projects in South Africa fall into two main classes. One involves the interconnection among Angola, Malawi, Tanzania and other member countries. The other involves central transmission channels, including a Zimbabwe–Zambia–Botswana–Namibia interconnection, a transmission corridor in central Zimbabwe, and transmission projects in Zambia [7].

African countries are also planning to form a pan-African power grid in 2020 by interconnecting the Southern, Western, Central and Northern African grids.

3.3.3 Transnational interconnection initiatives

Adopting a longer-term perspective, transnational power grid interconnection of larger areas has been studied, with several initiatives created, pre-feasibility studies carried out and specific plans proposed. These include the European Super Grid, the Desertec project, the Medgrid project, and the Gobitec and Asian Super Grid projects. Such projects would fall under the later stage of the GEI concept.

3.3.3.1 The European Super Grid

A range of European super grids have been assessed, generally including the interconnection of European countries with neighbouring North African and Middle Eastern countries and eventually with Caspian countries through UHVDC technology [11]. While a fully transparent cost-benefit analysis showing the attractiveness of such a grid relative to alternatives remains to be carried out, it would allow at a high level for the large-scale utilization of offshore wind power in the coastal regions of Northern Europe and rich amounts of solar resource in the South (where high direct normal irradiance (DNI) could also allow for the exploitation of CSP), as well as transmission of power from these bases to load centres around Europe using the rich hydro resources for system balancing (see Figure 3-32).

3.3.3.2 The Desertec project

The focus of the Desertec project is on harnessing solar power from the deserts of North Africa and the Middle East to provide these regions with both clean power and fresh water through sea water desalination, and to eventually export large volumes of electricity to Europe (see Figure 3-33). While renewed interest in the project has recently resurfaced, desert power remains in its infancy.

3.3.3.3 The Medgrid project

The Medgrid project was launched in 2010 by a Consortium of more than 20 utilities, manufacturers and investors, largely from European and North African countries circling the Mediterranean Sea. Medgrid's objective is the development of 20 GW of renewable energy, largely from solar power, with 5 GW dedicated to exporting power to Europe. Although the Medgrid Consortium ceased operation in January 2016, a number of grid interconnection planning studies had been conducted, including the design of three transmission corridors between North Africa

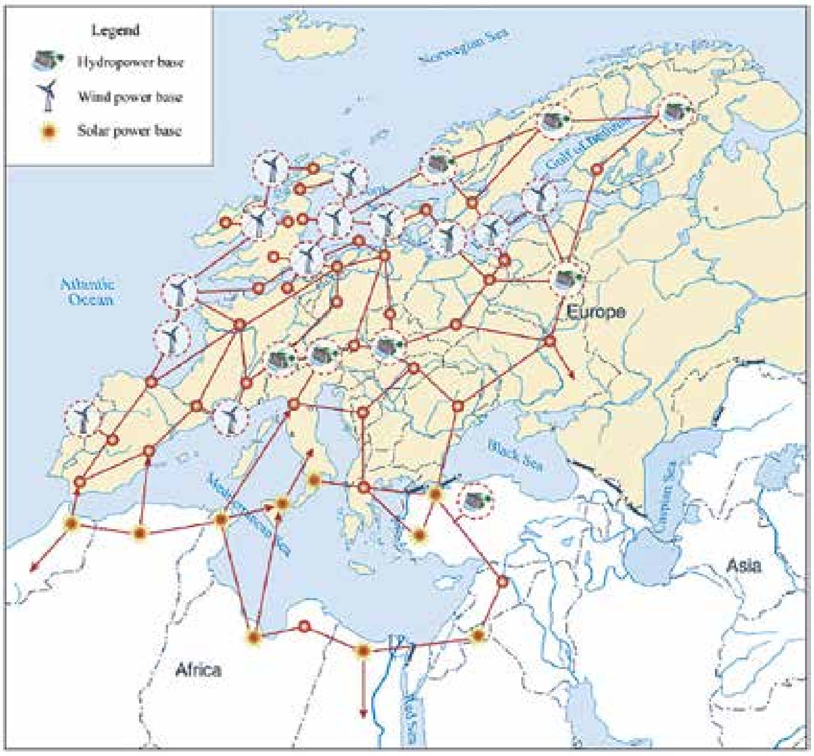


Figure 3-32 | llustration of the European Super Grid concept (Friends of the Supergrid)

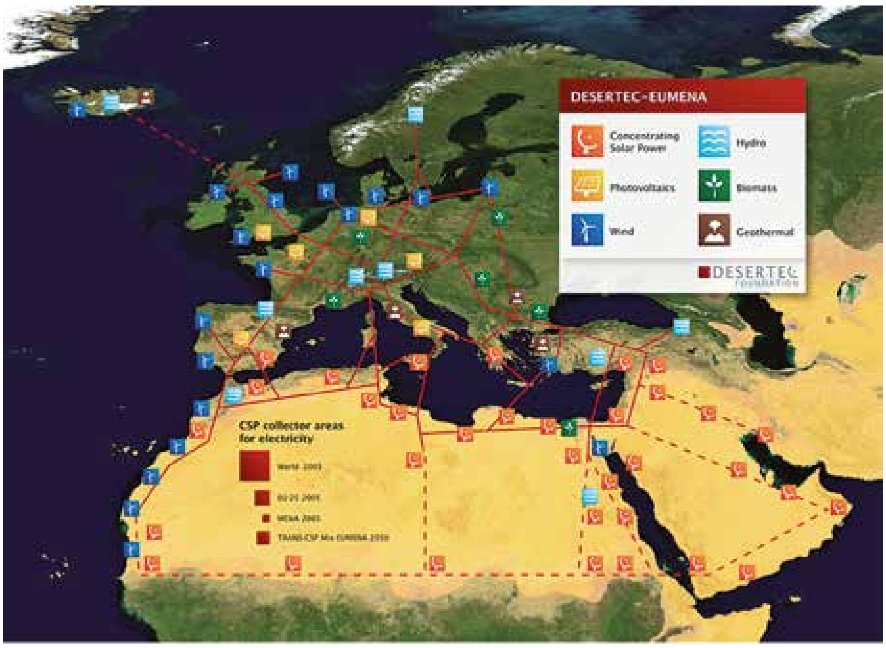


Figure 3-33 | An illustration of the Desertec concept (Desertec Foundation)

and Europe (see Figure 3-34) and completion of pre-feasibility studies on the western and central corridors.

3.3.3.4 The Gobitec and the Asian Super Grid projects

First proposed in 1998, the Gobitec project and the Asian Super Grid (ASG) project aim to exploit the vast renewable energy resources of the Gobi and Taklamakan deserts and of the Russian Far East, for the purpose of transmitting large volumes of power to Northeast Asian load centres in China, South Korea and Japan. These projects have been discussed and studied since 1998. A vision of the ASG was provided in a 2014 report [12] authored by research and government institutions from Mongolia, Japan, Russia and South Korea (see Figure 3-35) [12].

Using UHVDC transmission as a backbone, the ASG would interconnect wind and solar power bases in the Gobi desert and hydropower plants in Irkutsk, Russia with load centres in Beijing, Shanghai, Seoul and Tokyo. Despite the significant political, legal, institutional and financial challenges involved, organizations such as the Asian Development Bank and the SGCC are now supporting further studies.

3.4 Economic feasibility of GEI

As stated earlier in this White Paper, generally speaking, power system interconnection between

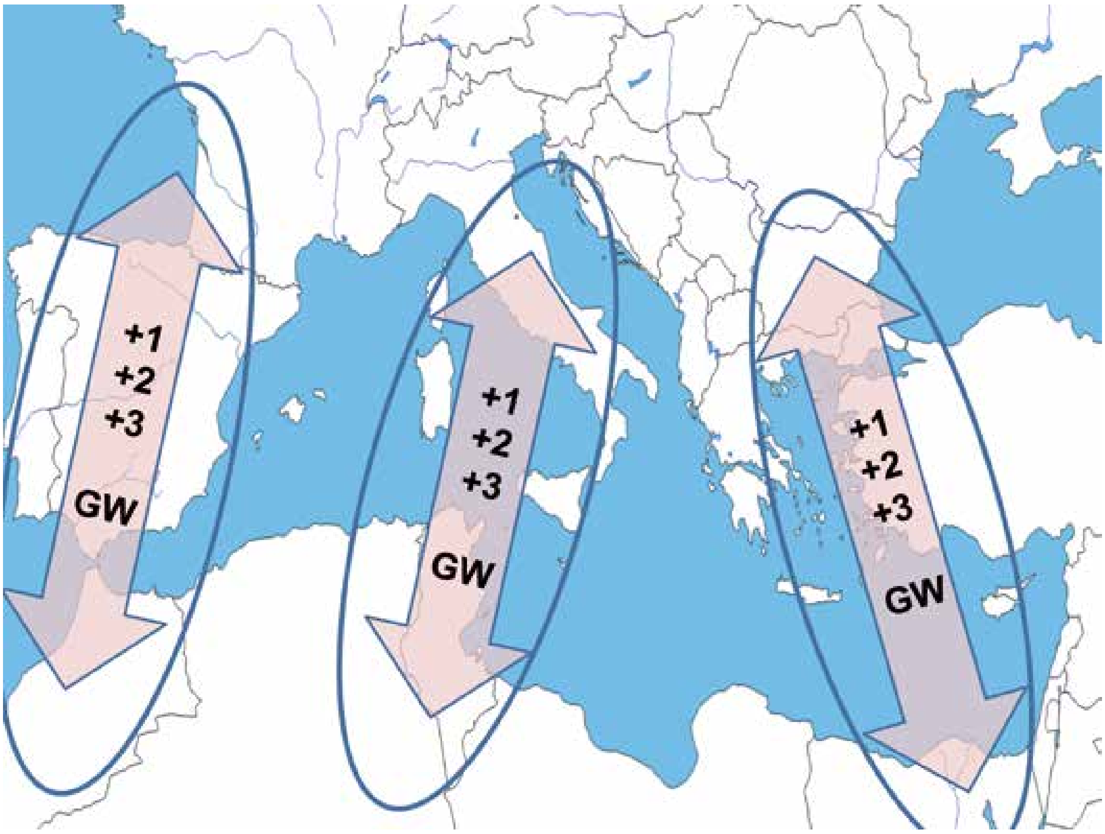


Figure 3-34 | Potential transmission corridors between North Africa and Europe (Medgrid)

Figure 3-35 | A vision of the Asian Super Grid [12]

countries can be an attractive proposition to enhance system security and reliability, aid in balancing and ensuring resource adequacy, increase asset utilization and reduce costs, and facilitate the decarbonization of power systems. The need for careful assessment of the costs and benefits associated with new transmission lines requires the application of a rigorous approach to cost-benefit analysis (CBA). With the interconnection of larger areas, as envisaged in GEI, proposals have become more complex from a regulatory, political and economic standpoint.

The economic benefits targeted in an interconnection proposal may include, among others, shared reserves, higher reliability and supply security, enhanced competition, production and operational cost savings, capacity savings due to capacity requirements, recovery of (partly) stranded investments, environmental impact reductions, such as lower carbon emissions, and lower congestion costs.

Balancing the benefits referred to above are the direct costs of the proposal, including investment costs related to the assets injected, and indirect costs, including the social and environmental costs generated by the transmission investment. An important change that interconnection brings relates to the price differentials between two regions, which might have differing benefits and cost sharing issues. The interconnection might bring benefits to generators in a region with a lower price, as the larger interconnected region will command higher electricity prices. This might in turn crowd some generators in the region with a higher electricity price. Provided there is sufficient network capacity, this supply change will lead to the alignment of prices between the regions. Consumers will benefit or be penalized accordingly, in the opposite direction. Ultimately, only when the benefits accrued by realizing the interconnection outweigh the costs will the undertaking be economically justified.

Two principles are fundamental for new network investments:

- Net benefit assessments, comprising both benefits and costs, should generally recognize full-scale market impacts of new investments
- *Ex ante* investment cost allocation commensurate with identified beneficiaries can mitigate financing uncertainties and enhance project acceptance

The inclusion of CBA in the planning framework can facilitate transparency and consultation among all market players, which is likely to result in mutually acceptable assumptions on important factors that trigger future costs and benefits. The coordinated development of such assumptions on future conditions is essential, as any investment planning can only be based upon expected developments. Such assumptions should also be accompanied by risk assessments, as uncertainties in the assumptions can alter benefits. Risks can generally be regarded as price risks and/or quantity risks for all relevant assumptions such as demand, fuel sources or supply capacities. The projection of benefits into the distant future increases the level of uncertainty, as is the case with GEI. Applying such a long-term planning time frame over such large areas will inevitably increase planning uncertainties, creating the risk of under- or overestimated benefits. The inclusion of adequate measures to assess long-term benefits and risks in economic planning principles is necessary.

Section 4

Enabling technologies for GEI

A series of enabling technologies are required for the levels of electricity interconnection envisaged in the GEI concept. These technologies are examined in this section. The description of enabling grid technologies sets the stage for the discussion of standardization needs in Section 5.

4.1 Transmission technologies

4.1.1 UHV transmission technologies

4.1.1.1 UHVAC transmission

UHVAC is one of two key options for transmitting power over vast distances, and refers to AC transmission technologies with rated voltage of 1 000 kV and above. UHVAC is already a mature technology today, having begun development as early as the 1960s in parallel in the former Soviet Union, the US, Japan and Italy [7]. The world's first UHVAC project, the 495 km-long Ekibastuz to Kokchetav line, began trial operations in 1985. In China, research into UHVAC started in 1986. In 2006, SGCC began implementation of a 1 000 kV UHVAC pilot project, a 640 km-long single-circuit line linking the North China grid with the Central China grid, commissioned in 2009 and re-inforced in 2011 to reach a power transmission capacity of 5 GW [13]. Lessons learned from the pilot led to the commissioning of two other 1 000 kV UHVAC projects in East China, with four others under construction.

Relative to lower voltage level AC transmission technology, UHVAC can transmit higher volumes of power over much longer distances at lower unit losses, footprint and costs. A brief comparison between the technical and economic features of 1 000 kV and 500 kV AC transmission is provided in Figure 4-1 [14].

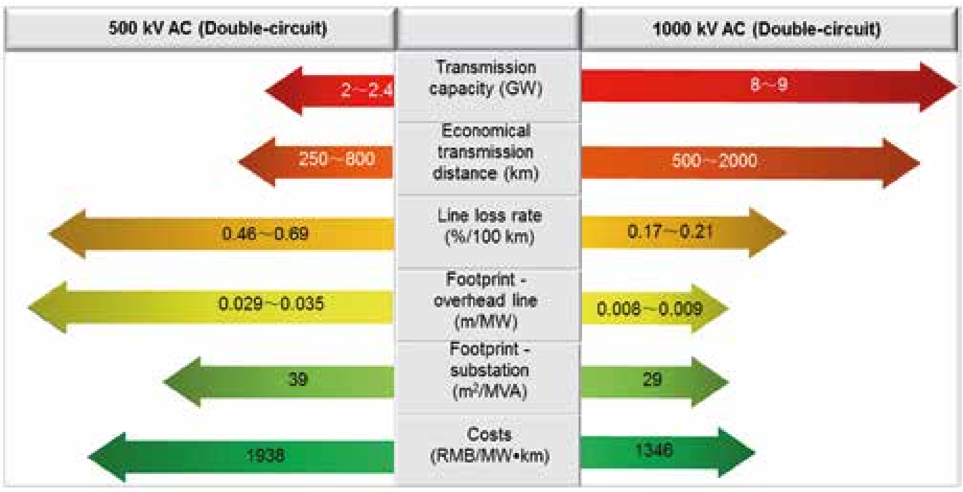


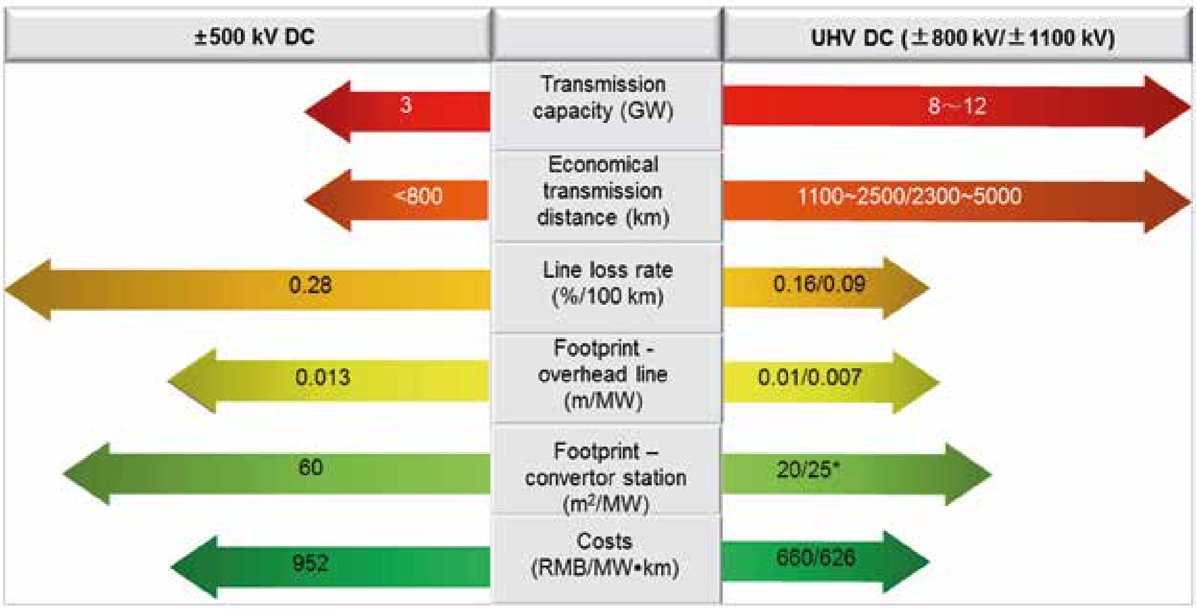
Figure 4-1 | Feature comparison between 500 kV and 1 000 kV AC transmission (SGCC)

4.1.1.2 UHVDC transmission

UHVDC is the second option for shifting large volumes of electrical energy over long distances, and refers to DC transmission technologies with a rated voltage of ±800 kV and above. Currently one variety of the technology, line-commutated converter-based high-voltage DC (LCC-HVDC), also known as current-source converter based HVDC (CSC-HVDC) can reach ultra-high voltage levels. LCC-HVDC technology is a mature technology, having been deployed commercially for the first time in 1954. It is currently the option for long-distance, large-capacity, point-to-point power transmission as well as for connecting AC grids with different system frequencies. Relative to classical AC transmission, it affords advantages such as reduced losses, lower costs, smaller footprint, or better controllability. In large emerging countries such as Brazil, China, India, and South Africa, where much power infrastructure remains to be built and there is a need for very large-capacity power transmission over very long distances, UHVDC transmission has been planned or deployed to a high degree in recent years.

The majority of UHVDC projects currently in operation and under construction around the world are being developed in China. Their main purpose is to transmit power generated in Northern and Western China to load centres in Central China and along the Chinese coast. SGCC currently operates four ±800 kV UHVDC projects, with five others under construction, while China Southern Power Grid (CSPG) manages two ±800 kV UHVDC projects already in operation, and one under construction. The transmission distance of these ±800 kV UHVDC projects ranges from 1 100 km to 2 400 km. In January 2016, SGCC began construction of the world's first ±1 100 kV UHVDC project, with a transmission distance of 3 324 km and a rated power of 12 GW.

A brief comparison of technical and economic features between UHVDC and ±500 kV HVDC transmission technology is provided in Figure 4-2 [14]. Over long distances, UHVDC can



* The convertor station is connected to the AC system in two voltage levels.

Figure 4-2 | Feature comparison between 500 kV and 1 000 kV AC transmission (SGCC)

transmit much larger amounts of power at lower transmission losses, with reduced footprint and costs, when compared to lower voltage HVDC. Crucially, with current ±800 kV and ±1 100 kV UHVDC technology, transmitting power can become economical at distances of 2 500 km and 5 000 km respectively.

4.1.1.3 UHV transmission for GEI

Current UHV transmission technology can already be deployed to build the backbone grids for large-scale interconnected regional and transnational power grids, and eventually for GEI. As portrayed in Table 4-1 [7], distances between some major global energy bases and load centres range from 2 000 km to ~5 000 km, within the transmission distance that can be economically feasible for UHV. UHVAC or UHVDC assets at different voltages could be deployed for different purposes and different transmission distances. For example, UHVAC grids would preferably be used to collect power on the supply side, or to deliver power on the demand side, while UHVDC could be used for point-to-point power transmission. Beyond the 5 000 km mark, power could potentially be transmitted using ±1 500 kV UHVDC technology, currently in the demonstration phase.

4.1.2 Flexible AC/DC transmission

4.1.2.1 Flexible AC transmission

Based on advanced, large-capacity power electronics components and innovative control strategies, various flexible AC transmission systems (FACTSs) have been developed since the 1990s. These have greatly improved the controllability, flexibility, stability and capacity of AC transmission. FACTS are also helpful in variable RE integration for voltage and power flow control.

4.1.2.2 VSC HVDC and HVDC grids

Voltage-source converter-based HVDC (VSC-HVDC) and HVDC grids are a fundamental component of modern power system interconnections, and would form a key pillar of future regional and transnational grids. Unlike conventional LCC-HVDC (CSC-HVDC), which uses semi-controllable valves, VSC-HVDC, a newer alternative first commercialized in 1997 [15], uses fully controllable valves. Compared to LCC-HVDC, these characteristics offer the following advantages:

- VSC-HVDC permits quick control of both active and reactive power independently, and even black starts. Therefore it does not rely on

Table 4-1 | Distance from selected major renewable resource bases to load centres [7]

From	To	Distance (km)
Arctic Kara Sea (wind power)	North China	4 400
Bering Strait (wind power)	N. China, Japan, S. Korea	5 000
Bering Strait (wind power)	West US	4 000
Arctic Greenland (wind power)	North UK	2 100
Arctic Greenland (wind power)	Quebec Canada	2 000
North Africa (solar power)	Europe	<2 000
Middle East (solar power)	West India	4 000

the strength of the AC system to which it is connected and can provide dynamic reactive power and voltage support for the AC system rather than consuming a large amount of reactive power. This feature is also desirable for integrating remote renewable generation, especially for offshore wind power integration.

- It simplifies the design of equipment on both sides of the connection, namely the converter transformers, and reduces the complexity and size of converter stations. See Figure 4-3 and Figure 4-4 for configurations of LCC- and VSC-HVDC converter stations.
- Power flows are easy to reverse, and they are not susceptible to commutation failures. This makes the technology suitable for forming multi-terminal HVDC (MTDC) and HVDC grids, which is difficult or impractical with conventional LCC-HVDC technologies.

Dozens of VSC-HVDC projects are in operation, in construction or in the planning stage, mainly in Europe, China and the US. They are implemented for different purposes, including grid interconnection, offshore wind power integration, as well as power supply to offshore oil or gas platforms and to large cities. Key examples include the ±320 kV/2 x 1 000 MW link between France and Spain, the ±500 kV/2 x 600 MW link between Italy and France, a number of links delivering North Sea offshore wind power to Northern Europe, the ±200 kV/400 MW Transbay project in the US, and the ±320 kV/1 000 MW real bi-polar project commissioned in Xiamen, China in 2015 [8],[16],[17],[18].

The voltage and power ratings of VSC-HVDC are still relatively low as compared to LCC-HVDC due to the limited availability and high cost of valves and cables. Currently available maximum voltage and power ratings for VSC-HVDC are 500 kV and 2 GW [19], but they are expected to increase steadily.

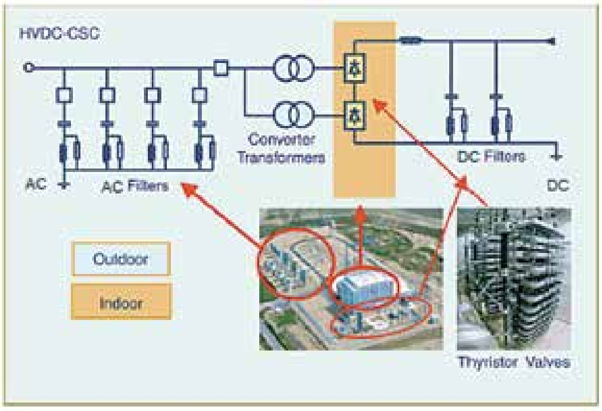


Figure 4-3 | Configuration of a conventional LCC-HVDC converter station [20]

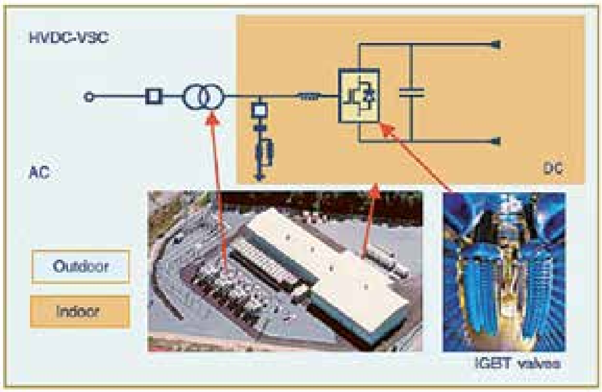


Figure 4-4 | Configuration of a VSC-HVDC converter station [20]

HVDC grids are a key element of large-scale, regional and eventually global energy interconnection. Building on the improvements of VSC-HVDC technologies, HVDC grids have been envisioned and intensively studied [21]. A HVDC grid consists of at least three converter stations and includes at least one mesh formed by transmission lines. It may also include a HVDC switching station to enable grid reconfiguration. The technical feasibility of HVDC grids has been established, although challenges remain, including adequate protection, control and grid simulation, and may be in many cases more cost-effective than point-to-point HVDC schemes for integrating disperse variable RE sources. In practice, HVDC grids can be formed by gradually expanding MTDC schemes, i.e. HVDC schemes with more than two converters connected together [17].

In Europe, the Super Grid, Desertec and Medgrid concepts and initiatives proposed for integrating North Sea offshore wind power and North African and Mediterranean solar power into the European grids, all rely on the implementation of HVDC grids. In the US, a submarine interconnector from New Jersey to Maryland and Delaware connecting multiple offshore wind farms has also been proposed [17]. Finally, in China the world's first and second VSC-MTDC projects have been commissioned, namely the three-terminal Nan'ao offshore wind power integration project commissioned in 2013 in the Southern coastal Guangdong Province [22], and the 5-terminal Zhoushan Islands interconnection project (see Figure 4-5) commissioned in 2014 in the Eastern coastal Zhejiang Province [23]. HVDC grids for

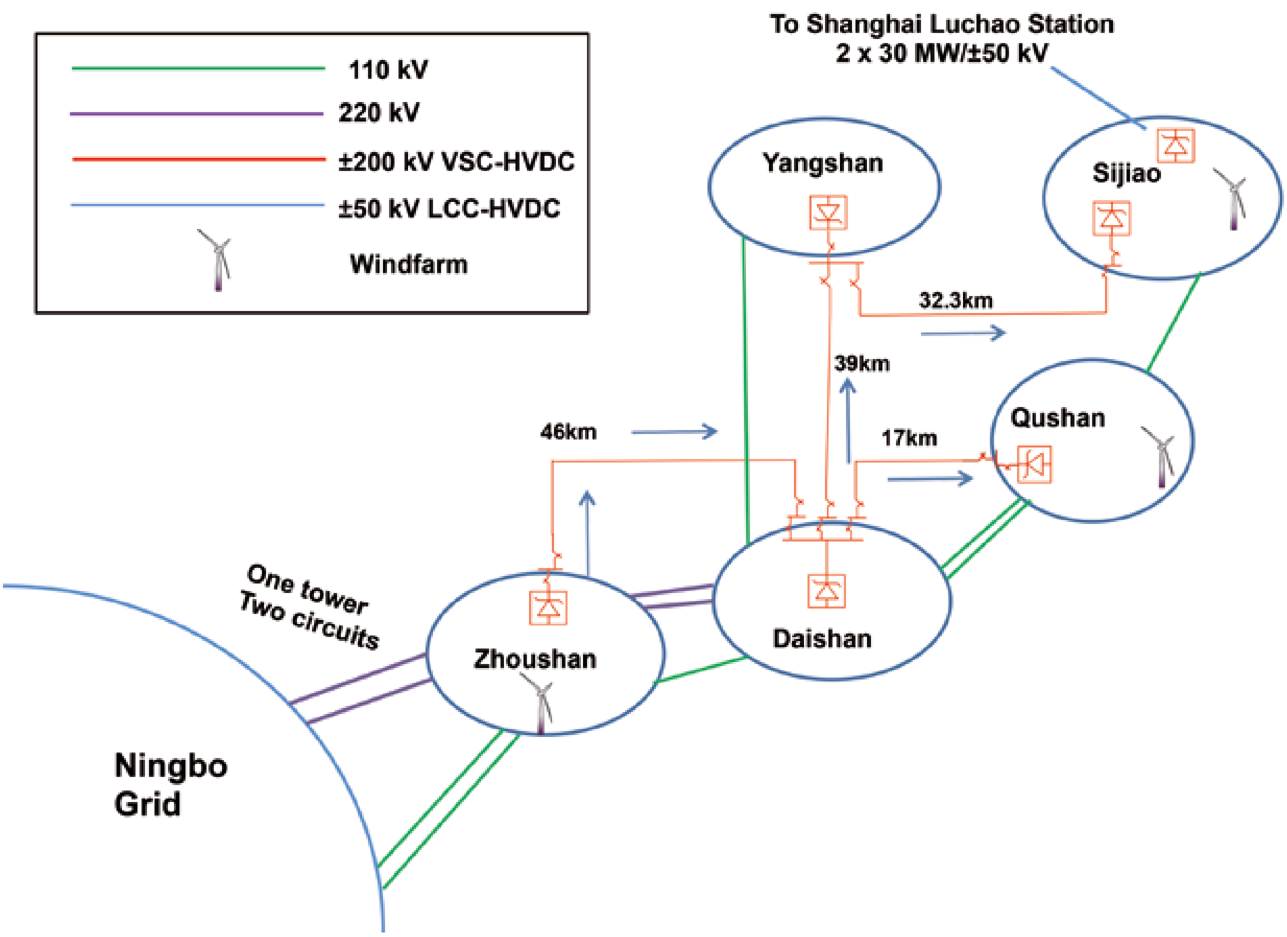


Figure 4-5 | Configuration of the Zhoushan MTDC [23]

integration of RE sources in wide areas of West and North China are also under study [24].

Continued development of VSC-HVDC and HVDC grid technologies will make large-scale grid interconnection and regional, transcontinental and global energy interconnection more feasible and efficient in integrating RE bases spanning large geographical areas.

4.1.3 Other emerging technologies

4.1.3.1 Half-wavelength AC transmission

Half-wavelength AC transmission (HWACT) is a promising technology under development for long-distance, high-capacity power transmission. Its name refers to three-phase AC transmission over a distance close to half of the length of a power frequency wave, which is 3 000 km for 50 Hz and 2 500 km for 60 Hz [25]. The concept of HWACT was first proposed in the 1940s by former Soviet Union scholars for transmitting thermal power in Kazakhstan and hydropower in Siberia to western load centres. During the first decade of the 21st Century interest in HWACT has been renewed and CIGRE working group A3.13 has been set up to carry out feasibility studies.

UHV-HWACT can be a practical and economical alternative to UHVDC for large-capacity power transmission over distances of 3 000 km or multiples of 3 000 km (in the case of 50 Hz system frequencies), and demonstrations of this technology are under way. Such technologies can play a key role in transnational, transcontinental grid interconnection and ultimately the realization of GEI [25].

4.1.3.2 High-temperature superconducting transmission

High-temperature superconducting (HTS) transmission refers to power transmission over high-temperature (defined as –180°C and above) superconducting cables. Theoretically, HTS transmission can offer vast advantages over classical power transmission, including the following features [26] that are very desirable for large-scale interconnection and GEI:

- Very large transmission capacity: a ±800 kV HTS UHVDC line can transmit 16 GW~80 GW, i.e. about 2~10 times that of a current conventional UHVDC
- Very low power losses: about 25%~50% of the loss of conventional cables
- Lower spatial footprint and lighter weight, as well as flexibility in changing transmission capacity by regulating temperature and limiting fault current through phase changing

Despite its technical advantages, progress in HTS physics and materials is required before HTS transmission can be used in practical power transmission projects and play a role in power system interconnection and GEI in the long term. Intensive research, development and demonstration of HTS cables, first focused on AC cables then shifting towards DC cables, have been carried out since the 1990s, mainly in the US, Europe, Japan, South Korea and China [26]. The length and voltage and power ratings of these cables are still very low. For AC cables, the length ranges from 30 m to 1 000 m, with voltage rating ranging from 10 kV to 138 kV. For DC cables, the length ranges from 200 m to 2 500 m and voltage rating ranges from ±1,3 kV to ±80 kV.

4.2 Smart Grid technologies

4.2.1 Large grid operation and control technologies

Beyond physical power system assets and technologies, transmitting power over regions and continents, in areas as large as those envisaged within the GEI concept requires advances in the operation, monitoring and control of large grids.

4.2.1.1 Control and protection of large-scale grids

Traditionally, power system monitoring and control has been mainly based on supervisory control and data acquisition/energy management system (SCADA/EMS) systems and protection has relied on local measurements to detect faults and abnormal states. SCADA/EMS systems allow measurements of voltage, frequency, power and status of circuit breakers/switches to be collected by field terminal units (FTUs) and sent to control centres, where the necessary technical properties can be calculated through state estimation. A major drawback of SCADA/EMS systems is that the gathered data is not time-synchronized, meaning that state estimations may differ between measurements.

Supported by satellite navigation systems, phasor measurement units (PMUs) can directly record timely synchronized voltage magnitudes and phase angle measurements of buses and send them to control centres, which enables the transition from "state estimation" to "state measurements" [27]. Many applications have been developed based on PMU networks, which are called wide area monitoring systems (WAMSs) [28], including wide-area visualization, oscillation detection and damping control, generator model and parameter validation, island detection, voltage instability monitoring, post-event analysis, or wide-area protection, among others applications, which have significantly improved the control and protection level of large grids. Future PMU/WAMS application trends include developing high-precision PMUs, switching from offline to online and from monitoring to control, and combining PMU/WAMS technology with big data technology [29]. In the context of GEI, PMU/WAMS technology is expected to play a fundamental role (see Figure 4-6).

Based on technology innovations such as online fault monitoring and diagnosis, new types of relay protection and wide-area backup protection, fault recovery strategy optimization and smart reconfiguration, power grids of the future could possess a strong security, stability and self-recovery capability in the face of different operating

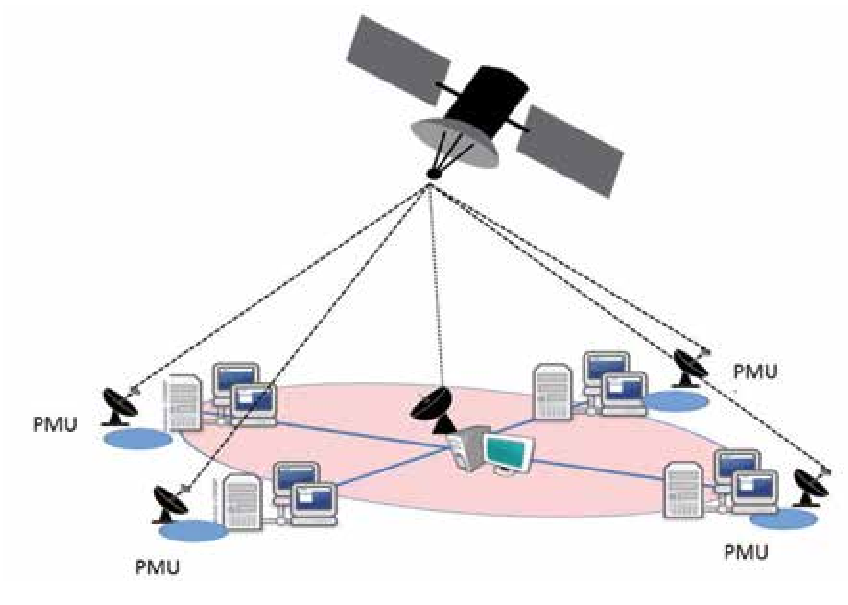


Figure 4-6 | Illustration of a PMU/WAMS system

environments and different types of faults. These technologies can greatly improve the defense capability of large grids against cascading faults, extreme weather conditions, and harmful external elements. With the development of ICT and control theory, grid operation and control is gradually moving in the direction of forecasting, pre-warning and automatic fault recovery. Highly automated operational control, expected to materialize in the medium-term, can support day-ahead forecasts for renewable power generation within a small (i.e. 5%) margin of error and help achieve a low cost integration of renewables, traditional energy and loads [7].

4.2.1.2 Large grid simulation and analysis

Since it is impossible to run experiments involving disturbances or faults on an actual running power grid, simulation and the analysis of simulation results are indispensable to explore the characteristics of a given power grid. With the continuous upgrade of algorithms, models and computer hardware and software, simulation has played a key role in guaranteeing the secure and stable operation of power grids as their technology has evolved over time.

The growth of the grid scale that comes with large-scale interconnection imposes ever-higher requirements on the timeliness of grid operation analysis and decision-making. In the early days, power system analysis was based on offline simulations due to the constraints of computer technology. However, with the progress of ICT technology, an increasing number of simulations can be performed online, which has enabled online dynamic security assessment and pre-warning. Through online transient stability analyses, one can not only assess the current level of grid security, but also help the power system dispatchers develop preventive control strategies to improve grid security. Real-time[1] and even faster-than-real-time simulations have also been achieved for grids of a certain scale, which will further improve the operation and control level of large grids.

In the context of large-scale interconnection and GEI, the complexity of power system operation would be tremendously increased, which imposes much higher requirements on the precision, speed and efficiency of simulation and analysis. There is a need to improve simulation capacities using super-computing and hybrid electromechanical and electromagnetic transients simulation technologies to support the analysis of power systems with millions of buses. Accurate models of high penetrations of renewable generation plants, DC transmission and new types of grid control and protection elements need to be established. Hybrid digital and analogue simulation is also required, so that physical control and protection devices can be connected to digitalized system models in a hardware-in-the-loop manner in cases where accurate modelling is difficult (see Figure 4-7). In addition, management and sharing of global equipment and network data is necessary to support both centralized and distributed simulation and analysis.

4.2.2 Information and communication technologies (ICT)

The ambitious vision of a GEI network – which would equate to a global super-smart high-voltage grid – requires the deployment of sophisticated next generation ICT technology based on the most modern standards.

The operation of such an intelligent, complex technical network would require the efficient convergence of operational and commercial data/

1 A "real-time" simulation means that the time used in simulating a system event equals the time that the physical event lasts in the real world.

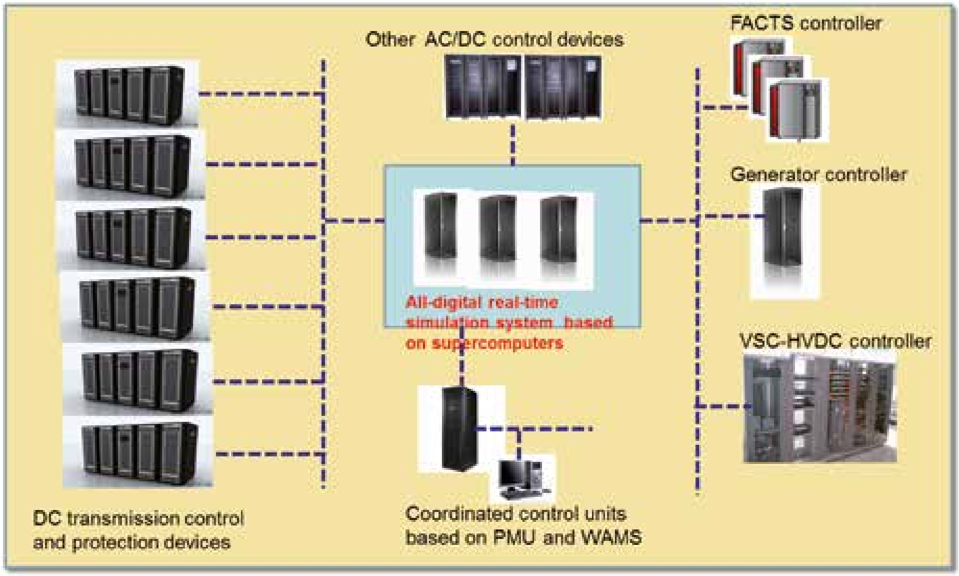


Figure 4-7 | Architecture of a hybrid digital and analogue simulation platform (SGCC)

processes to enable critical decisions and business transactions in real-time. This necessitates a new kind of technical platform that bridges the historic "Chinese Wall" between OT and IT systems in order to provide a platform adequate for transactions over such large areas.

This IT/OT integration platform will also be the technical application basis for comprehensive information systems that are necessary to manage the core processes of planning, operation and maintenance of the grid, metering, billing and settlement of energy flows and related services, and continuous process analysis in real-time to immediately identify technical and commercial issues such as technical losses, fraud, outage risks, etc.

This platform would also include automated data exchange between involved partner companies based on common market standards and processes, and orchestrating of an extended asset information and business network to optimize the collaboration with suppliers and market partners.

4.2.3 The need for an IT/OT integration platform

Existing IT landscapes are today made up of dozens if not hundreds of sometimes integrated, but in many cases also completely separated systems such as business and business intelligence (BI) systems, energy portfolio management and trading systems and operational systems such as SCADA, geographical information system (GIS), and network information systems and data historians. With the rapid increase in volume and granularity of data coming from the GEI Smart Grid, it is becoming more important for the affected TSOs to reduce the number of times this data is replicated in order to improve their analytical ability. It will not be economically feasible to continue replicating these big data volumes from one siloed system to another in a consistent way. In addition, most analytical and business processes will provide better results and deeper insights if they leverage an up-to-date, comprehensive and consistent data set.

In addition to the rising data volume, the time span between the moments when the data is measured and when it has to be made available to support business processes is growing shorter and shorter, and in many cases (near) real-time data will be required.

At a high level this leads to three important functions a TSO platform has to perform in the context of GEI:

- Handle both a steeply increasing volume of data and many different data types
- Combine data from various different sources and enable the integration of business and operational systems (IT/OT integration)
- Make the data available in (near) real-time

The following business processes represent examples of required functions for a TSO platform in the context of the GEI. These examples highlight some of the key requirements involved but by no means constitute an exhaustive list of all the business processes that have to be supported now.

- **Grid analytics** support near real-time analysis of the grid to improve grid stability and effectiveness and prevent outages. This requires correlation analysis, for example to understand under what circumstances specific equipment such as a transformer is overloaded, and forecasting capabilities to predict peak loads. The analytic results are required to trigger manual interactions or the intervention of other systems that actively control the grid assets.

  This process heavily relies on sensor and event data from the grid, however meter data is also required. The grid analytics solution provides most benefit if the data and analysis is available in near real-time, i.e. within a couple of minutes or even seconds after receiving the data, to enable rapid actions.

- **Predictive maintenance** estimates when a failure or decrease in efficiency of an asset is to be expected and triggers maintenance actions accordingly. This is based on meter and sensor data as well as on historic values. In general, predictive maintenance is of interest for grids and power plants, but especially for assets in remote locations such as offshore wind power plants and secluded transmission facilities.

  Data requirements are similar to those of the grid infrastructure analytics process, however data would not be required in real-time but rather on a daily basis. Unstructured data, for example texts from work orders or customer messages, can support this process as well.

- **Leakage management** supports processes such as fraud management and an early detection of technical losses. It contributes to determining where losses occur and whether fraud could be the cause and acts as a starting point for follow-up processes. It also has a safety aspect.

  In addition to meter, asset and GIS data, forecasted consumption data, event data and customer data from the customer relationship management (CRM) and billing system are required to support these processes. Unstructured data, for example from social media platforms, can also be leveraged to detect possible fraud. While a daily data upload would be sufficient for fraud management, detection of technical losses benefits from real-time data.

- **Energy settlement** aggregates metered data for a group of delivery points over a certain time period as a basis for the commercial settlement of transmission services. This information can then be sent via market messages to each of the participants in the operational area for further processing.

The above-mentioned business processes and the respective applications would benefit from a single platform that provides a unified data repository as well as generic tools and functions. The reason behind this is that business processes would then operate on comprehensive, consistent and actual data, thus reducing the need for data replication. Applications would benefit from generic functions that do not have to be redeveloped repeatedly in each siloed application. Moreover integration between different applications would be simplified, as less data exchange and fewer interfaces would be required.

The overall total costs of such a platform, including applications on top of it that reuse many generic functions, is expected to be much lower than the total costs of a system landscape involving several different products, each with its own data tables, tools and technology. Costs would be lower, for example due to the reduced effort needed to replicate data, cleanse it and keep data consistent.

To fulfil all these requirements, a TSO platform would need to support the business processes outlined above and to provide functions in support of heterogeneous applications.

Such a platform therefore would need to be able to:

- rapidly upload different types of data in high volumes;
- process different kind of data from various sources, including data from meters and sensors, event data and geographical data, as well as prices, weather data and more;
- enable data uploads at different frequencies, from monthly to sub-daily (down to real-time);
- handle data that comes in any granularity from monthly values down to minutes or even seconds;
- handle equidistant time intervals and non-equidistant (discrete) values;
- handle unstructured data.

Beyond uploading and storing the data, the platform would also need to be able to:

- validate, estimate and edit data;
- store versions of the data if it is changed;
- support auditability, for example when reports have to be delivered due to regulatory rules;
- store data for periods longer than one year and support data aging.

In addition the platform would need to support generic functions that can then be used by all applications residing on the platform. These include:

- Calculation tools, for example to calculate consumptions out of raw data, replacement values, or energy consumption or generation costs
- An aggregation engine to aggregate data from several points of the network, for example all delivery points, that belong to one holding company, or all meters linked to one transformer. The data would be used for analysis and pattern recognition in business processes such as grid infrastructure analytics or fraud management
- Forecasting algorithms for maintenance and replacement strategies for assets
- Data mining tools to support data analysis, for example in predictive maintenance
- Complex event processing, as required in many business processes, for example outage management; the platform does not need to support the entire business process, but rather make analytic results available for respective systems
- Interfaces to external systems and data gathering from external data suppliers or from other GEI participants

To cope with those requirements, operators of large-scale energy networks and GEI would require an IT/OT integration platform, including a portfolio of products tightly optimized to work together to solve today's data management challenges. Such management elements include data processing across massive volumes of data storage, high velocity streaming data, automated data movement, and data visualization and further processing. These challenges include the ability to handle master data, information governance and information modelling. Today's requirements also involve supporting the vast variety of data types, including structured data, semi-structured (or text-based) data, as well as unstructured big-data such as image, audio and video. The combination of Hadoop® Distributed File System and Hadoop® MapReduce framework is emerging as a standard for very large unstructured data-pre-processing and processing.

The IT/OT platform will need to address all these data management challenges from the ground up, with proven ability to scale. It has to include capabilities that provide organizations with a robust, yet flexible environment for managing their data needs, including online transactional processing, data processing and analysis, data modelling and movement, information governance as well as a unified administration and monitoring tools. Among other elements, the portfolio or products inside the IT/OT platform need to include:

- An in-memory computing platform that provides in-memory online transaction processing (OLTP) and analytical capabilities with the ability to embed code libraries and advanced and statistical algorithms close to the data
- Classical database technology to augment and complement in-memory requirements for better economics and price/performance requirements, especially critical as more customers scale into Petabyte class data volumes. It features a native MapReduce framework and provides integration techniques with Hadoop® for big-data analytics
- Event streaming processing capabilities for high speed streaming data analysis and filtering for ultra-low latency applications enabling continuous intelligence
- Extended data security components with most progressive security protocols and data encryption capabilities to safeguard mission-critical technical data and to avoid any intrusion

In addition to that, the IT/OT integration platform will need to provide tools for data modelling and data movement and a development framework for partners and customers who can build their own applications on the same platform.

All components of the IT/OT integration platform will have to be open for integration with third party tools, for example to support business intelligence, information management, or infrastructure management.

The realization of such a platform requires the merging of commercial enterprise resource planning (ERP) systems with technical applications such as meter data management (MDM), SCADA and document management system (DMS). Figure 4-8 illustrates the conceptual architecture of such an IT/OT platform as envisioned by SAP. The data integration of SAP's commercial MDM application with the technical head-end system (HES) from a partner on a common, cloud-ready in-memory capable platform (the SAP HANA Cloud Platform) connects business transactions with technical mass data in real-time and enables the introduction of fundamentally new processes, such as real-time forecasting of transmission loads, etc.

4.2.4 Advanced planning, operation and maintenance of the grid with Asset Intelligence Networks

The effective and secure management of technical assets has been a core requirement of the energy

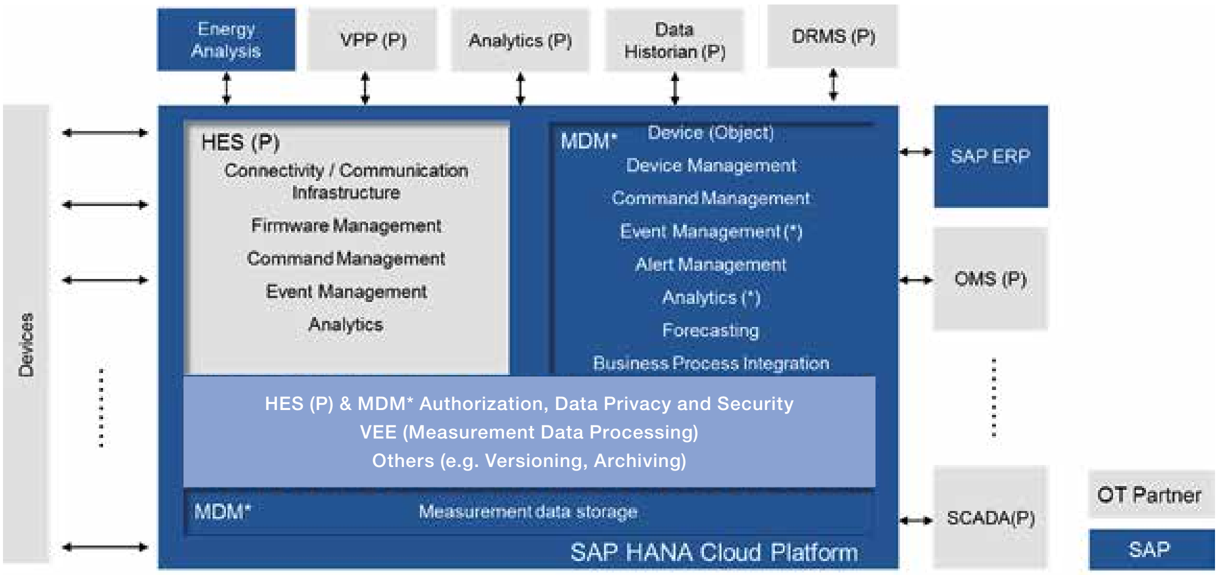


Figure 4-8 | The concept of an integrated IT/OT Platform (SAP)

industry since the beginning. Hence there are various proven IT solutions on the market which very effectively support the planning, operation and maintenance of power grids.

However, some of the specific needs of a TSO who would operate within a complex GEI framework require more intelligent and interconnected asset management processes. A key requirement for a sustainable GEI will be the standardization of asset management processes around the world to leverage best practices and to enable the international collaboration of TSOs ensuring the reliable transmission of energy across country borders. The importance of those Standards has already been described comprehensively in the IEC Whitepaper *Strategic asset management of power networks*.

Today, the industry has not yet fully integrated the asset management chain. There is little consistent definition of model information, and every original equipment manufacturer (OEM) and operator typically uploads the same data manually – possibly introducing errors and delays that make the data incorrect. Lack of complete, consistent, consumable equipment data hampers future purchasing and maintenance decisions. Business processes for asset management are rarely integrated across enterprise boundaries, a deficiency which helps keep everyone in the dark. But the realization of a GEI will only succeed with a collaborative, efficient management of technical assets and processes based on common Standards. This requires the introduction of an integrated Asset Intelligence Network (AIN).

The transition to the digital economy and the increasing adoption of new technologies such as IoT and cloud-based networks provide an opportunity to automate data exchange and enable a simplified collaboration model among involved stakeholders via asset management networks. An AIN, as conceptualized in Figure 4-9, could answer the above described challenges by providing a secure cloud platform that serves as a central clearing house and communications hub for all stakeholders in GEI asset management.

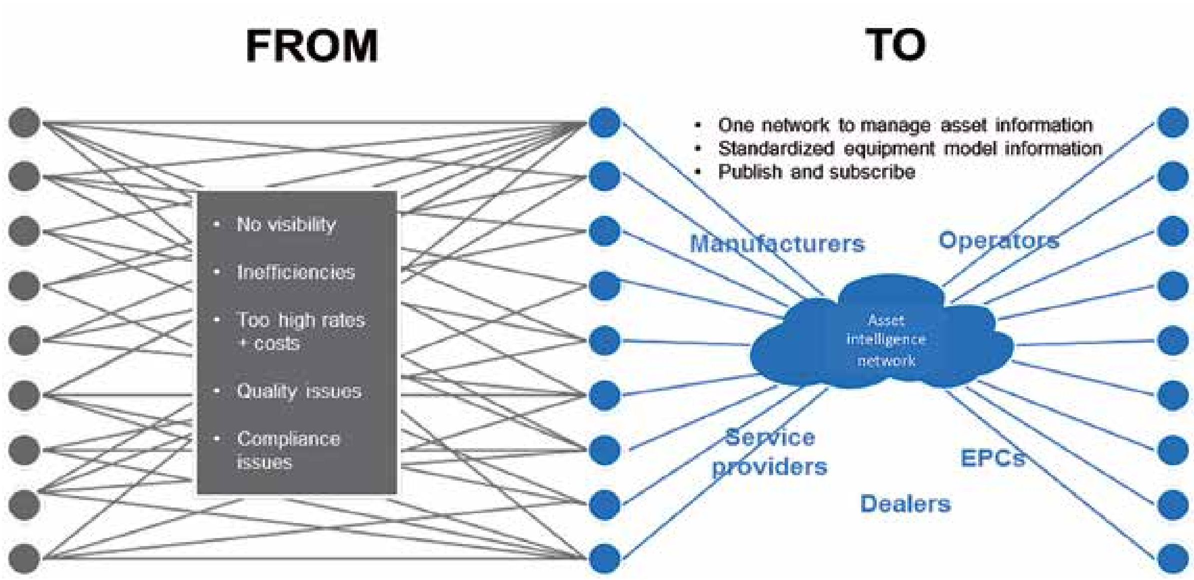


Figure 4-9 | The concept of an AIN connects assets and businesses everywhere in one seamless network (SAP)

Such an AIN will bring business partners together in a common environment to facilitate the next wave of collaboration among organizations within the asset management ecosystem, i.e. operators, OEMs, EPCs, and service providers. It is a single cloud-based IoT linking all the equipment in an ecosystem. A host of applications runs on this collaborative platform to simplify maintenance and enhance cooperation for complex tasks. Built-in analysis inspires innovation for managing assets as a service or redesigning them based on performance (see Table 4-2).

The equipment in the AIN should be based on standardized models (e.g. on API 610 datasheet for pumps) furnished by OEMs or third-party content providers. These datasheets for models will provide technical attributes about equipment and content, such as recommended maintenance strategies, standard job instructions, bills of materials, spare parts lists, drawings, etc. Manufacturers will only have to provide the datasheet once, and it will then be available for consumption by all approved business partners. Moreover, operators will have a single site from which to retrieve consistent datasheets from multiple manufacturers ready for use in their environmental assessment and management (EAM) environments.

The AIN could provide a number of benefits to all involved GEI stakeholders (see Figure 4-10):

4.2.4.1 Global job catalogue, visual work instructions, and task lists

The AIN enables operators to build a global library of recommended maintenance strategies, maintenance plans, standard jobs and safety instructions for use in their work management system. OEMs will publish recommended maintenance strategies, maintenance plans and standard jobs as part of the model information.

4.2.4.2 Business context for predictive maintenance

The AIN provides the business context for predictive maintenance and service, whether

Table 4-2 | The vast potential of an AIN

Category	Value	Capability	Arena
Effective asset management processes	Increased revenues from faster project commissioning	Operators and contractors can source and validate missing asset information from the network	Standardized equipment management
	Reduced capital expenditure	Engineering teams can investigate alternatives and tighten production expenses	Collaborative network services
	Improved asset availability	Stakeholders can reduce asset downtime collaborating with OEMs and using updated information and predictive maintenance	Maintenance process execution Collaborative network services
	Reduced spare-parts inventory	Warehouses can reduce obsolete and excess inventory for B- and C-class spares per network updates	Maintenance process execution Standardized equipment management
	Lower maintenance costs	Operators can optimize maintenance activities through closer collaboration with OEMs and service providers	Maintenance process execution Collaborative network services
User productivity	Reduced effort locating and updating asset information	All members have access to updated information already integrated with enterprise systems	Standardized equipment management Collaborative network services
	Shorter maintenance wrench time	Field workers always have up-to-date task-time instructions and spare part details	Maintenance process execution Collaborative network services

an operator, manufacturer or service provider is monitoring and maintaining equipment. This will significantly improve the interaction between TSO and manufacturer by alerting the operator and manufacturer about imminent failure.

4.2.4.3 Performance improvements

The AIN provides the platform for OEMs, service providers and operators to increase collaboration on improving machine design to reduce failures, lower operating costs, improve ease of maintenance and ultimately increase profits. This is enabled by the flow of information about how the machine is being used, where it is installed, what failures have occurred, what service bulletins have applied, etc. and failure mode and effects analysis (FMEA) from the operator.

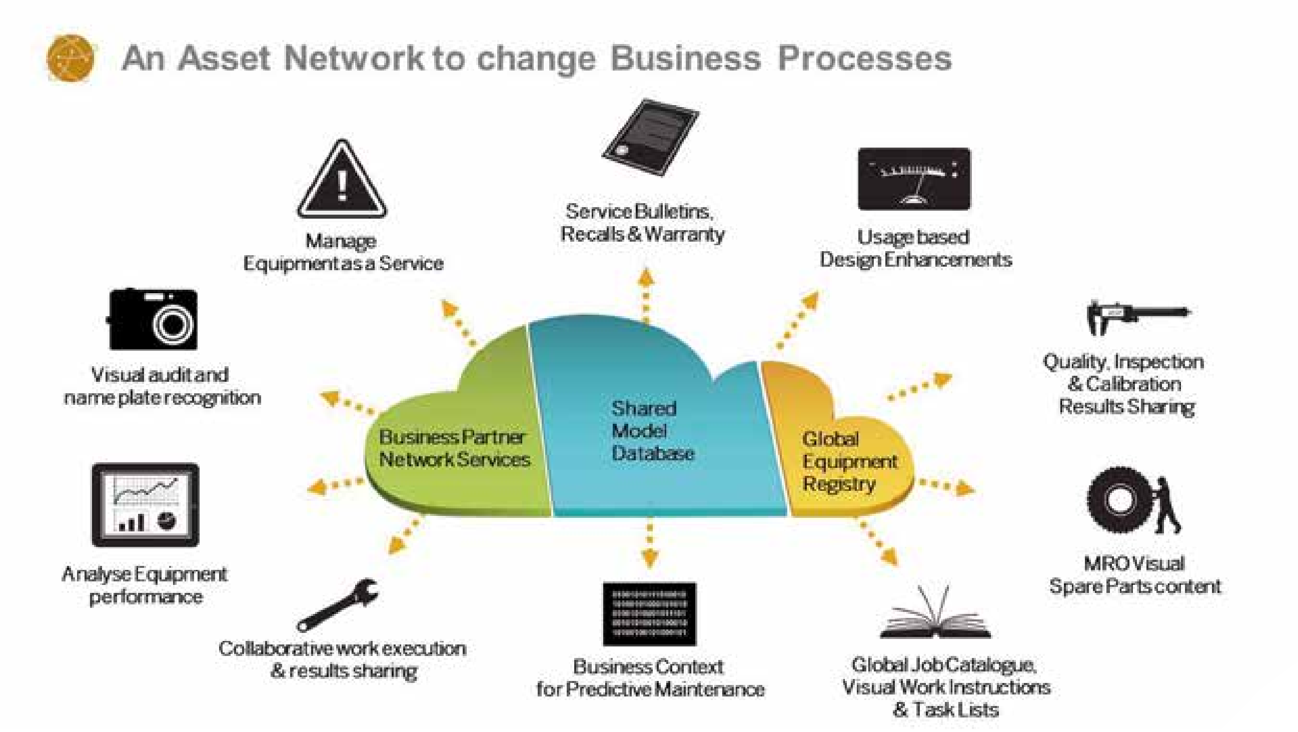


Figure 4-10 | Benefits of an AIN (SAP)

4.2.4.4 Integrated work planning and execution

The AIN facilitates collaborative maintenance activity between operators and service providers. Certain complex activities might need to be broken down into sequential steps, of which some are carried out by asset operators and more specialized ones by the service provider.

4.2.4.5 Manage equipment as a service

Operators want to minimize their capital expenditure and risks, whereas OEMs want to bundle value-added services with products. This convergence of requirements, along with new technologies such as the IoT and collaborative networks, is resulting in the new business model of managing equipment as a service.

4.2.4.6 Analyze equipment performance

The AIN helps operators drive asset improvement programmes by benchmarking reliability metrics from different operator sites that can be analyzed to identify best practice for operation and maintenance around the world. Depending on the requirements of the different parties supplying and consuming information, the information could be anonymized.

4.2.4.7 Marketplace of intelligence

Companies are capturing more and more information about their machines. And more advanced algorithms are possible to analyze data and make predictions and prognoses to improve machine performance. Is it still feasible or desirable that operators do all of this data processing themselves? Can manufacturers, service providers or even individuals provide more of this “intelligence” in a competitive marketplace where the best provider wins? An AIN could provide a marketplace where business partners can connect with other third parties to competitively source the best intelligence for their machines. With a solid foundation of asset information in the network, a new class of potential enterprise scale solutions becomes possible.

4.2.4.8 Quality, inspection, and calibration results sharing

The AIN facilitates sharing of quality, inspection, certification, and calibration results. Statutory authorities and independent assurance companies, e.g. Lloyds Register, DNV GL, and TüV, will have access (provided they are given the necessary authorization) to view up-to-date information on whether statutory inspections have been performed on time with the relevant inspection results. Another example is obtaining the results and reports of condition-based maintenance tasks, such as oil analysis of engines, which are typically sent to an external laboratory for analysis.

4.2.5 Metering, billing and settlement of energy flows and related services

Like any other transmission grid, a GEI would operate in a commercial framework that bills the recipient and/or the remitter of the transmitted energy for the transmission service. This requires the availability of specific customer information systems, which are able to manage typical industry-specific processes, including orchestration of meter data reading processes, acquisition and management of large amounts of meter reading data in time series (load profiles), performant and reliable charging of transmission services, etc.

There are several solutions on the market which can satisfactorily fulfil those business requirements. However, due to the increasing importance of settlement rules based on most granular data (e.g. prices based on minute intervals) and the related data growth, the ideal solution should be able to process information in real-time. This requires the usage of modern, in-memory-based applications, which allow much faster processing times for complex calculations with mass data. Such systems combine the transactional and analytical data processing in one database and eliminate typical time-consuming batch processes. Moreover, they allow sophisticated operation reporting activities in real-time based on most recent data.

4.2.6 GEI market communication platform

The GEI will operate as a network with many national TSOs. In order to ensure the reliable and sustainable transmission process across country or even continental borders, a highly automated data exchange process based on internationally agreed communication formats is mandatory. Typical data exchange processes include nomination of transmission capacities, transmission forecasts and schedules, exchange of technical data to support cross-border ancillary services, exchange of asset and operational data to optimize collaborative asset management processes, measurements as input for settlement of transmission services, or billing of transmission charges.

Various market communication standards are already available for TSOs that should be considered as a basis for the extended GEI market communication.

For example, the European Network of Transmission System Operators for Electricity (ENTSOE-E) maintains an Electronic Data Interchange (EDI) Library which contains all the documents and definitions approved by ENTSO-E for the harmonization and implementation of standardized electronic data interchanges.

In the context of a potential GEI market model, it should be discussed whether a centrally operated GEI market communication hub could help to increase the efficiency of the GEI processes. This could be a cloud-based service provided by an “IEC-like” organization, which centrally orchestrates the communication flows and the intercompany data exchange between all GEI participants. The necessary IT technologies for such platform are available and are already productive in various clearinghouse projects.

Section 5

Standardization for GEI

Standardization is of central importance and, at the same time, represents one of the biggest challenges for the success of GEI, which demands an unprecedented degree of system integration across sovereign borders, technical domain borders, hierarchical borders and equipment life cycle phases. To achieve this success, consensus-based Standards and Specifications will form an indispensable basis upon which to build.

Existing but also future consensus-based Standards will create a firm basis for technical procurement, support communication through standardized terminology and concepts, ensure interoperability, certify fitness for use, and determine market relevance. Drawing up GEI concepts at an early stage by a consensus-based standardization process and through close cooperation between researchers, industry, regulators and the standardization bodies is one of the central requirements for success of the multi-phased implementation of GEI.

To succeed, these principles should be consistent with existing standards that support the core GEI technologies, i.e. UHV, clean energy, and Smart Grids. Not only will this facilitate subsequent promotion and application of equipment, interfaces and technology, but it will also create conditions for building international-level interconnections among energy grids and related equipment.

5.1 Present situation

Standards currently exist that cover the foundational technical domains of GEI, representing UHV, clean energy and Smart Grid. These Standards are required for incorporating multiple technologies into parts of a very complicated, large-scale power and energy system that will interconnect not only physical infrastructures across large areas but also the supporting ICT systems. The Standards involved are related to many technical committees inside IEC and to other coordinating organizations outside IEC. The following is a list of current IEC technical committees (TCs) and subcommittees (SCs) handling specific activities that support GEI:

5.1.1 Transmission

- TC 7: Overhead electrical conductors
- TC 14: Power transformers
- SC 17A: Switching devices
- TC 20: Electric cables
- TC 28: Insulation co-ordination
- TC 36: Insulators
- TC 115: High Voltage Direct Current (HVDC) transmission for DC voltages above 100 kV
- TC 122: UHV AC transmission systems
- ACTAD: Advisory Committee on Electricity Transmission and Distribution

5.1.2 Clean energy – renewable generation and energy storage

- TC 4: Hydraulic turbines
- SC 8A: Grid integration of Renewable Energy generation
- TC 21: Secondary cells and batteries
- TC 82: Solar photovoltaic energy systems

- TC 88: Wind energy generation systems
- TC 114: Marine energy – Wave, tidal and other water current converters
- TC 117: Solar thermal electric plants
- TC 120: Electrical Energy Storage (EES) Systems

5.1.3 Smart Grids

- TC 8: Systems aspects for electrical energy supply
- TC 13: Electrical energy measurement and control
- TC 22: Power electronic systems and equipment
- TC 57: Power systems management and associated information exchange
- TC 64: Electrical installations and protection against electric shock
- TC 77: Electromagnetic compatibility
- PC 118: Smart Grid user interface
- SyC Smart Energy
- ISO/IEC JTC 1: Information technology
- CISPR: International Special Committee on Radio Interference

5.2 Future standardization needs

Development of global energy systems for GEI will provide a worldwide platform that enables new technologies to be used optimally for maximum performance and reliability. For example, the prospects for wind power are very positive: the IEA forecasts that installed onshore and offshore capacity will exceed 1 300 GW in 2040, with onshore capacity making up 85% of the total, against 98% in 2011. This expansion will require additional International Standards to cover new areas. The very nature of the RE technologies means that standardization requires a dedicated effort to keep pace with developments in the various fields.

Also, Smart Grids and energy storage are more than ever to be unified with electricity generation and distribution systems, regional energy hubs and long-range ultra-high voltage lines.

The biggest market trend for UHVAC is towards long-distance bulk power transmission and interconnection with existing power systems. There is also a trend towards building strong power reception grids to receive more large-scale power feed-in. The grid changes are driven by rapidly growing power consumption in load centres of emerging countries and by structural changes from coal, gas and nuclear power generation towards full renewable power generation involving wind, solar, large hydro and other energies at distant generation locations. With increasing renewable power generation, mainly from wind, large hydro and solar, electrical energy will be competitive with oil, gas and coal sources, but it will need new AC transportation systems to cope with projected needs.

With the growth of load demand and the imbalance between energy demand and supply, power plants are needed which will be located far from load centres (e.g. large hydropower and pit-mouth fossil-fired power stations), and clean and renewable distributed generation (e.g. wind power and solar power) will be introduced extensively. The former are characterized by large capacity and long distance and will enjoy remarkable advantages when employing HVDC transmission technology.

Construction of HVDC transmission systems in severe environmental conditions, such as building converter stations and DC transmission lines at a very high altitude (3 000 m 5 300 m), are posing higher requirements for the HVDC transmission technology.

Smart Grid implementation has already started and will continue to be implemented in the form of an “evolution” of successive projects over several decades.

It is now necessary to manage the integration of new equipment that has a lower life span than traditional network assets: three to five years for consumer electronics and telecommunications, compared to 40 plus years for lines, cables, and transformers.

The Smart Grid represents a technical challenge that goes far beyond the simple addition of an information technology infrastructure on top of an electrotechnical infrastructure. Each device that is connected to a Smart Grid is simultaneously an electrotechnical device and an intelligent node. Today’s “connection” standards need to address both aspects concurrently.

Adopting advanced monitoring and control technologies is a key objective for future Smart Grids.

In order to support these future standardization needs for GEI, some important general considerations for standards are given below.

5.2.1 Systems standards

While smart energy activities will confront new issues and questions for GEI, new tools between standards developing organizations (SDOs) and stakeholders, such as creating use case repositories and system level standards, must be launched to bridge gaps between organizations working in totally different areas. Drafting of systems level standards will require understanding the interrelationship between other components from a physical/electrical point of view, as well as the flow of information with the grid network and changes in system behaviour.

From a conformity assessment perspective, understanding is also required of how the life of a standard evolves as changes occur at the component surroundings levels. Most importantly, system level standardization thinking for GEI is the understanding of the interrelation between the many systems-of-systems and the growing equipment assets that make up the GEI system.

In the IEC, a Systems Committee (SyC) Smart Energy has been set up to provide systems level standardization, coordination and guidance in the areas of Smart Grid and Smart Energy, including interactions with heat and gas. Key International Standards such as IEC 61850 have been introduced to ensure device and communication compatibility in substations, while IEC 61970 has been developed to define application programme interfaces for energy management systems. SyC Smart Energy has just begun its outreach to various internal and external stakeholders, but much work remains to be coordinated.

5.2.2 Management standards

Open data and data sharing facilitate data analytics and simulation, which provide the basis for planning, scheduling, operation and control. The large efficiency gains from integration and interoperability, however, are only realized if all the stakeholders collaborate effectively and agree to share data or information. Data aspects shall become a key issue in GEI, including data analytics, data utilization, data privacy and cyber security. The lack of exchange of fundamental data on customers, infrastructures and operations is one of the most important barriers highlighted by stakeholders. Specifications for data sharing and standards on data format are both needed. On the other hand, a series of management specifications or guidelines are also needed to guarantee the coordination in planning, trading and operation among all the participants.

Although many regional and national organizations, such as NERC, Nordel, UCTE, ENTSO-E and NGET, have their own reliability criteria, it is necessary to coordinate such criteria for the GEI.

For example, specifications are necessary for coordinating the control and protection strategy of interconnecting links and grid connection codes.

5.2.3 Standards for information exchange

Control, protection and scheduling for GEI depends upon effective information exchange based on appropriate ICT architectures. Therefore the Smart Grid core International Standards, IEC 61850, IEC 61968 and IEC 61970, are also very important but must be studied further to see if they can accommodate GEI, or whether it will be necessary to develop new Standards and to revise current ones. Cyber security is another major challenge for GEI, for which corresponding standards are required, and many consortia as well as ISO/IEC JTC 1 will need to re-evaluate this aspect.

5.2.4 Standards for new materials and equipment

As presented throughout this White Paper, for the implementation of GEI, energy would be globally interconnected via the Smart Grid, with UHV networks constituting the backbone and clean energy the main resource. Consideration should be given to new areas of standardization based on new material discoveries or environmental challenges that will further enable a GEI network to be installed.

For example, huge energy bases in the North Pole region and the equatorial belt area will deliver RE such as wind, solar and marine energy to customers worldwide. Higher voltage level UHV technologies will be a prerequisite for transmitting this large capacity power across long distances and to remote sites. Since the UHV transmission systems must adapt to such extreme environmental operating conditions, new energy conducting materials may need to be engineered and new reliability guidelines developed for this purpose.

Furthermore, with the rollout of the Smart Grid and microgrids, a development which implies that electrical storage will be installed at customer sites, extra RE is expected to be transferred to gas or stored in the form of hydrogen gas, thereby necessitating standards for energy transfer and energy storage technologies. The market for small and dispersed EES is also expected to grow substantially. EES will be used not only for single applications but for several objectives simultaneously by integrating the multiple dispersed storage sites that will be required by GEI.

In most cases, standardization plays a stabilizing role by pursuing research activities on which real market opportunities are built.

Section 6

Conclusion and recommendations

The GEI is an ambitious concept, integrating a large-scale deployment of clean energy led by variable renewables: a Smart Grid with various levels of interoperability and with IT and OT integration capabilities currently not deployed on an adequate scale, the large-scale deployment of advanced technologies for transmitting power over vast distances and forming high-capacity and high-voltage networks, and electrification of a large number of energy services involving new equipment.

Many of the building blocks of large-scale energy networks and an eventual GEI are available today. Large-scale RE is a reality, and achievements in UHV power transmission are redrawing the boundaries of how much power can be cost-effectively transmitted and across what distances. Technologies on the horizon, described in Section 4, will only expand this frontier further. Meanwhile, the vast potential for ICT and smart technologies in power systems has only begun to be tapped.

While the required technologies themselves are largely available or are in the pipeline, the challenge for large-scale, transcontinental or global energy interconnection is one of implementation, in which barriers and challenges will need to be overcome as the process unfolds. As such, the analysis in this White Paper provides a number of key recommendations for both evaluating and implementing large-scale interconnection and GEI.

6.1 Recommendations addressed to policy-makers and regulators

- **Policy-makers and regulators should consider the need to develop tools and methodologies to assess the costs and benefits of large-scale, regional, transcontinental and eventually global energy interconnections.** Interconnections are generally assessed on a case-by-case basis by the countries involved. Even under the relatively long planning time frames of TSOs, projects as ambitious as large-scale regional and transcontinental networks might fall below the planning horizon necessary to encourage assessment of the full range of benefits. Section 3 has presented practical experiences of regional energy interconnection, which provide confidence concerning the benefits that can be accrued when a longer-term system perspective is adopted between a large number of actors.

- **While large-scale deployment of renewables should continue to be encouraged, emphasis needs to shift to the joint planning of transmission and generation assets.** Regulators and governments should recognize the need to plan all power system elements jointly. Assessments of this aspect can reveal the advantages, for example of building long links to distant resources, reinforcing grids to pave the way for an accelerated deployment of energy generation in a given area or better designing incentives for deployment of new capacities.

- **Policy-makers and regulators should establish fora for discussion of large-scale grid interconnection initiatives.** While a large number of convening groups for industry stakeholders, governments or regulators already exist, organizations for discussing large-scale planning of grids are highly regional. Local TSO organizations have progressively coalesced into fora spanning larger geographical areas. A next natural step would be the establishment of international fora to share interconnection experiences around the world and establish dialogue concerning new opportunities.

6.2 Recommendations addressed toward meeting industrial needs

- **Studies should be carried out concerning the market readiness and economic feasibility of establishing remote bases for renewable energy, namely in far northern latitudes, in the arctic or along the equator.** While technologies have been deployed in extreme conditions, the human and implementation challenges involved in deploying generation and transmission assets on a large scale in these intense climatic conditions remain to be determined.

- **Scaling of equipment will pose challenges to industry so there will be a need for prior coordination and joint participation in demonstration efforts (e.g. development of technology), in order to avoid the first missteps on the Smart Grid.** It is clear that Smart Grid technology is a good investment but deploying the new technology is relatively expensive. The lesson learned will be to avoid the "big bang" approach in favour of a pilot demonstration-based approach. This suggests that full-scale deployment of GEI will be phased and allow further occasions for industry to generate investment.

- **Joint planning by relevant agencies, regional bodies and TSOs should be promoted and encouraged.** Taking advantage of each country's achievements in energy technologies, strategic planning, market establishment, policy innovation and cooperative research, and making good use of these best practices throughout the world, could significantly enhance the "know-how" of all stakeholders.

- **A coordinated and collaborative approach to code drafting and code implementation is needed to ensure that the activity of systems operators is compliant with the network codes.** In the context of the GEI market model, it should be discussed whether a centrally operated GEI market communication hub could help to increase the efficiency of the GEI processes. This could involve a cloud-based service provided by an "IEC-like" organization, which centrally orchestrates the communication flows and intercompany data exchange between all GEI participants.

6.3 Recommendations addressed to the IEC and its committees

- **The IEC Market Strategy Board (MSB) should consider new internal avenues that will allow the IEC to provide faster responses to industry.** In light of the large number of stakeholders who would have an interest in GEI, the MSB should enhance its outreach to industry through the activity of its project teams. The latter should survey the needs surrounding revolutionary GEI-related technologies.

- **It is recommended that the IEC Standardization Management Board (SMB) form an Advisory Committee on GEI to help prioritize needs in this area and to coordinate development of standardization efforts in response to these needs.** Specifically the AC should consider internal coordination for development of an architectural framework clarifying the GEI concept and the rules of interoperability and integration. This would involve identifying the gaps between the requirements for GEI and the existing interoperability Standards developed in the affected technical committees.

- **The IEC should consider expanding opportunities to affiliate countries in the equatorial regions for full participation in the development of International Standards for GEI.** As the equatorial regions of the globe will generate and contribute significant amounts of solar and wind energy to the GEI network, the IEC should encourage IEC Affiliate National Electrotechnical Committees (NECs) with Affiliate Plus status to be actively engaged in the Standards process for solar and wind. It is recognized that the IEC Affiliate Country Programme has been a pioneer in bringing the benefits and advantages of involvement in the IEC to many countries throughout the world, not only through the benefits afforded by the Programme, but also via measures such as opening participation in its Conformity Assessment Systems to developing countries Such Affiliates will directly benefit from the investment necessary for bringing large-scale renewables online, thus helping to bring social benefits in the form of energy access to clean power and opportunities for local capacity building and employment.

Bibliography

[1] WISER, R., LANTZ, E., HAND, M., et al., *IEA Wind Task 26: The Past and Future Cost of Wind Energy*, IEA Wind, May, 2012.

[2] International Energy Agency, *Medium-Term Renewable Energy Market Report 2015*, [Online]. Available: www.iea.org/bookshop/708-Medium-Term_Renewable_Energy_Market_Report_2015. [Accessed 19 September 2016].

[3] *Report of the enquiry committee on grid disturbance in Northern Region on 30th July 2012 and in Northern, Eastern and North-Eastern Region on 31th July 2012*, [Online]. Available: powermin.nic.in/sites/default/files/uploads/GRID_ENQ_REP_16_8_12.pdf. [Accessed 19 September 2016].

[4] Operador nacional do Sistema Eléctrico (ONS), *Mapas do SIN*, [Online]. Available: www.ons.org.br/conheca_sistema/mapas_sin.aspx. [Accessed 19 September 2016].

[5] Global Energy Network Institute (GENI), *The Water-Energy Nexus in the Amu Darya River Basin: The Need for Sustainable Solutions to a Regional Problem*, [Online]. Available: www.geni.org/globalenergy/research/water-energy-nexus-amudarya-river/Water-Energy Nexus-AmuDarya-River-RD.pdf. [Accessed 19 September 2016].

[6] Nepal Energy Forum, *Pros and cons of regional electricity grid*, [Online]. Available: www.nepalenergyforum.com/pros-and-cons-of-regional-electricity-grid. [Accessed 19 September 2016].

[7] LIU, Z., *Global Energy Interconnection*, Elsevier, 2015.

[8] BONPARD, E., FULLI, G., ARDELEAN, M., MASERA, M., *Evolution, Opportunities, and Critical Issues for Pan-European Transmission*, IEEE Power and Energy Magazine, Vol. 12, no. 2, pp. 40-50, 2014.

[9] ZHANG, Yi, ZHANG, Yang, *Overview of the Practice of Renewable Generation Integration and Transmission Planning in North America*, Energy Technology and Economics, Vol. 23, no. 8, pp. 1-7, 23, 2011.

[10] KUMAGAI, J., *The U.S. may finally get a unified power grid*, IEEE Spectrum, Vol. 53, Issue 1, pp. 35-36, January 2016.

[11] ANDREWS, D., *Why Do We Need The Supergrid, What Is Its Scope And What Will It Achieve?*, A Claverton Energy Reseach Institute Presentation, 19 June 2009.

[12] MANO, S., OVGOR, B., SAMADOV, Z., et al., *Gobitec and Asian Super Grid for Renewable Energies in Northeast Asia*, Spotinov print Ltd., 2014.

[13] IEC, *Grid integration of large-capacity Renewable Energy sources and use of large-capacity Electrical Energy Storage*, White Paper, 2012.

[14] HUI, L., *Research on the Economics of Ultra-High Voltage and Global Energy Interconnection*, Presentation, Sino-Europe Workshop on Technology and Equipment of Global Energy Interconnection, Berlin, 10-11 December 2015.

[15] ADAPA, R., *HVDC Technology: The State of the Art*, IEEE Power and Energy Magazine, Vol. 10, no. 6, pp. 18-29, 2012.

[16] MAJUMDER R., BARTZSCH, C., KOHNSTAM, P., et al., *High-voltage DC on the New Power Transmission Highway*, IEEE Power and Energy Magazine, Vol. 10, no. 6, pp. 39-49, 2012.

[17] ANDERSEN, B. R., *HVDC Grids – Overview of CIGRE Activities and Personal Views*, CIGRE, 2014, [Online]. Available: www.e-cigre.org/.../ELT_275_2(2).pdf. [Accessed 19 September 2016].

[18] YUE, B., MEI, N., LIU, S.-Y., et al., *Overview of HVDC Flexible*, China Electric Power (Technology Edition), no. 5, pp. 43-47, 2014 [in Chinese].

[19] CHEN, G., HAO, M., XU Z., et al., *Review of High Voltage Direct Current Cables*, CSEE Journal of Power and Energy Systems, Vol. 1, no. 2, pp. 9-21, 2015.

[20] BAHRMAN, M. P., JOHNSON, B. K., *The ABCs of HVDC Transmission Technologies*, IEEE Power and Energy Magazine, Vol. 5, no. 2, pp. 32-44, 2007.

[21] LUNDBERG, P., CALLAVIK, M., BAHRMAN, M., SANDEBERG, P., *High-Voltage DC Converters and Cable Technologies for Offshore Renewable Integration and DC Grid Expansion*, IEEE Power and Energy Magazine, Vol. 10, no. 6, pp. 31-38, 2012.

[22] RAO, H., *Architecture of Nan'ao Multi-terminal VSC-HVDC System and Its Multifunctional Control*, CSEE Journal of Power and Energy Systems, Vol. 1, no. 1, pp. 9-18, 2015.

[23] TANG, G., HE, Z., HUI, P., et al., *Basic Topology and Key Devices of the Five-Terminal DC Grid*, CSEE Journal of Power and Energy Systems, Vol. 1, no. 2, pp. 22-35, 2015.

[24] YAO L., WU., J., WANG, Z., et al., *Pattern Analysis of Future HVDC Grid Development*, Proceedings of the CSEE, Vol. 34, no. 34, pp. 6007-6012, 2014.

[25] XUMING, L., *Technology Research and Application Prospect of Half-wavelength Alternating Current Transmission*, Smart Grid, Vol. 3, no. 12, pp. 1091-1096, 2015 [in Chinese].

[26] LIYE, X., LIANGZHEN, L., *Status Quo and Trends of Superconducting Power Transmission Technology*, Transactions Of China Electrotechnical Society, Vol. 30, no.7, pp. 1-9, 2015 [in Chinese].

[27] SOONEE, S. K., AGRAWAL, V. K., AGARWAL, P. K., et al., *The view from the wide side: wide-area monitoring systems in India*, IEEE Power and Energy Magazine, Vol. 13, no. 5, pp. 49-59, 2015.

[28] NUTHALAPATI, S., PHADKE, A. G., *Managing the grid using synchrophasor technology*, IEEE Power and Energy Magazine, Vol. 13, no. 5, pp. 10-12, 2015.

[29] LU, C., SHI, B., WU, X., SUN, H., *Advancing China's smart: phasor measurement units in wide-area management system*, IEEE Power and Energy Magazine, Vol. 13, no. 5, pp. 60-71, 2015.

International
Electrotechnical
Commission ®

3 rue de Varembé
PO Box 131
CH-1211 Geneva 20
Switzerland

T +41 22 919 02 11
info@iec.ch
www.iec.ch

ISBN 978-2-8322-3680-2

CHF 50.-

IEC WP GEI:2016-10(en)