White Paper

Zero carbon power system based primarily on renewable energy

Executive summary

The Intergovernmental Panel on Climate Change has stated that "it is unequivocal that human influence has warmed the atmosphere, ocean and land", and that "the stabilization of greenhouse gas concentrations…requires a fundamental transformation of the energy supply system". Decarbonizing, or reducing the carbon intensity of, the electricity sector is a key component of reducing these greenhouse gas emissions.

This white paper considers the challenge of decarbonizing the power system, the resulting required transition ahead, and what this may mean for the IEC, its members and the standards it produces, which guide the world's electrotechnology sector.

Exposure to a variety of pressures means power systems around the world are already changing and have been doing so for some years. Power system operators, users and other stakeholders are facing a once-in-a-lifetime level of profound challenges, ranging from the need to significantly increase capacity to support the global replacement of fossil fuels sources with electricity, to the uptake of new generation devices such as solar, wind and marine energy generation, to dramatically shifting generation and load profiles, and significant changes in the control and communications equipment used in the network itself.

Commitments towards net zero

Over 130 countries around the world have committed to a goal of carbon neutrality or net zero carbon emissions, and many more have committed to significant reductions in their energy intensity. These commitments, to be met over the coming decades, will only accelerate the changes already seen in power systems.

The challenge of net zero

Fundamentally, a commitment to net zero carbon emissions has profound implications for the electrical power system of a nation. The electricity sector is one of the highest sources of emissions in most nations and is also often considered the sector most readily decarbonized. Thus, a national country's net zero carbon goal can be taken to also mean a goal of net zero carbon for the electricity or power sector. Furthermore, the transition of other economic sectors such as transport, towards lower carbon goals will have a significant flow-on impact on the power sector.

Realization of a net zero carbon power system is an incredible challenge. At the time of writing, carbon-emitting generation sources make up over 60% of electricity supply around the world. The removal of these emissions, and the need to add carbon-free capacity to meet new electrical demands, will require an immense amount of work across a very broad range of topics. Effort will be required in policy and law, regulation, standardization, and technology development.

The implications of net zero

A net zero power system will look very different to the power system of today. A net zero power system will rely on large amounts of wind and solar generation, perhaps nuclear, hydro or marine generation, and will involve much more energy storage capacities, from pumped-hydro to batteries. Fossil fuel generators will either be phased out or converted to zero carbon operation.

The broader requirement of net zero carbon emissions will likely see many new loads appearing on the power system. Industries from transport to manufacturing will convert from fossil-fuelled equipment, such as boilers or combustion engines, to electrically-driven processes. Space heating for homes and buildings will transition away from fossil fuels to electrical heating including the use of heat pump technology. These new loads will dramatically increase demand on the power system – some estimates have countries such as Canada needing to more than double system capacity by 2050. If managed carefully, the increase in demand may also assist with power system operation and the integration of variable renewable energy generation.

Generation and load profiles in the power system will be much more dynamic, with significant swings from very low consumption to high consumption throughout a day, and seasonally. This will require generation to be much more flexible in order to match supply with rapidly changing demand, and it is likely some loads will be dynamically managed to match supply. A net zero power system will have far less rotating inertia than the traditional power system that relied on large rotating machines with significant mechanical inertia. In order to maintain system security and ensure the reliable operation of protection devices across the power system, generators and storage devices that rely on power electronic interconnection (such as solar and wind generators, or batteries) will need to emulate the operational characteristics of rotating machines. This will require new operational approaches and regulatory or other incentives to see these operational modes built into the machines and systems deployed.

These changes mean the transition to a net zero power system will require the power system to change in multiple dimensions. Generation will need to move to zero carbon operation. The control of electricity generation will be much more closely integrated with the control of loads and storage. Lastly, the power system control technologies will need to become more sophisticated, taking advantage of the latest digital technologies to manage a power system that is much more complex than those before it.

The technologies of a zero carbon power system

Multiple studies have shown that in many nations, hydro, wind and solar are the cheapest forms of carbon-free generation. These technologies are generally well understood. The key challenge ahead is not so much the operation of wind and solar generation, but rather their integration into the power system, and the reliable operation of a power system with very large portions of supply coming from wind and solar generators. Wind and solar generation need to be located where the wind and solar resource is available. In some cases, this will be at greater distances from electricity load centres, requiring significant transmission infrastructure to carry energy to where it is used. In other cases, solar and wind may be available close to load centres, and this will reduce the need for significant long distance transmission infrastructure. The electricity distribution system will need to absorb massive amounts of distributed renewable generation, electric vehicles, heat pumps and local energy storage. This has significant repercussions on the design of the power system, which will now need to enable significantly varying and bi-directional power flows. Meeting this challenge will require new sensing and control schemes and the provision of very large amounts (ranging from seconds to seasons) of energy storage.

A variety of other generation technologies have potential to assist in the transition to zero carbon. These include nuclear energy (including small modular nuclear reactors), and highly efficient and flexible coal or gas generators partnered with carbon capture utilization and storage. These technologies remain in their infancy, and many challenges still exist to their widespread uptake, not the least of which is the cost involved.

While much analysis of the path to zero carbon power systems focuses on the energy generation and storage technologies on the "supply side" of the system, consideration of the "demand" side of the power system will become increasingly important. In simply reducing the amount of energy needed to be generated, energy efficiency measures will have a key role in the transition to zero carbon and have been legislated by most countries around the world. Demand-side integration technologies, which seek to actively and dynamically manage the load on the power system, will also have an increasing role, helping to reduce emissions, avoid infrastructure upgrades, enable end customers to make choices in their energy usage and investment, and ensure power system reliability.

Power systems will become more "digitalized", with new information and communication technologies being introduced across all reaches of the power system. Similarly, this digitalization will impact all operational processes within the system. Technologies such as edge computing, data analytics and the industrial Internet of Things will allow for better monitoring and control, improved energy provisioning and faster response to faults. The benefits provided will help accelerate the transition to net zero carbon operation.

Standards implications of the transition to zero carbon

To ensure that energy systems, platforms, devices and markets can transition and work effectively in a zero carbon power system, standards have a critical role to play, ensuring interoperability, maintaining a minimum level of performance and safety, and helping guide the transition towards new technologies and operating regimes. While a range of standards exist today that are relevant to the zero carbon vision, a zero carbon power system will require a broad range of new standards to ensure reliable, efficient and resilient system operation. The standards required cover a broad spectrum, ranging from standards for new technologies, such as offshore wind generation, to standards for facilitating the much tighter integration between generation and demand that will occur in the power system of the future. These standards must not only support integration within the power system itself, but also interactions between the power system and both consumers of energy and external providers of energy services to the power system. Given the massive complexity of a zero carbon power system, a systems approach will need to be taken. System standards are likely to be needed considering requirements such as the environment, safety and health.

To meet climate targets, the transition to a zero carbon power system needs to happen very rapidly, much faster in fact than many of the changes seen in the power system over recent decades. If standards and regulation lag the rollout of new technologies in the power system, there is a significant risk of delayed implementation, inefficiency, misapplication, major outage, technical failures or other harm.

Standards and regulatory change often happen at a pace significantly slower than some of the changes occurring in the journey to zero carbon power systems. Thus, in this journey, as well as a need for new standards, there is also a need to consider the *processes* of creating new standards and regulation, so that these processes can (at the very least) keep up with the pace of change of technology and the short timeframes involved in the transition of the power system to net zero.

The abundance of new technologies in a zero carbon power system, and the convergence of distributed resources and non-power system technologies with large-scale power system infrastructure, will require a more top-down approach to standardization. This should be based on a systems approach that starts at the overall system architecture level, rather than the traditional bottom-up approach that focuses on individual components.

This white paper is structured as follows:

- Section 1 introduces the massive changes occurring in the world's power systems, the white paper and its aim.
- Section 2 considers the forces that are driving power systems to transition to net zero.
- Section 3 reviews what a zero carbon power system may look like.
- Section 4 considers the various pathways to a zero carbon power system.
- Section 5 introduces the technologies that will underpin the realization of a reliable, economic net zero power system.
- Section 6 considers what the changes discussed in the previous section mean for the IEC, its stakeholders and standards work.
- Section 7 concludes the paper and provides some key recommendations.

Net zero carbon power systems are no longer a remote possibility of some distant future. Many countries around the world have committed to net zero carbon emissions targets, and a variety of pressures mean that power systems around the world are changing dramatically. These changes have profound implications for all IEC stakeholders – from system operators to equipment manufacturers and service providers, or power system end-users. Understanding the changes detailed in this paper, the new technologies, operating principles and standards requirements involved, will ensure that the IEC remains at the forefront of the evolution now underway.

Acknowledgments

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List of abbreviations

Technical and scientific terms

6LoWPAN	IPv6 over Low-Power Wireless Personal Area Networks
AC	alternating current
AI	artificial intelligence
AMQP	Advanced Message Queuing Protocol
BLE	Bluetooth Low Energy
CCS	carbon capture and storage
CCUS	carbon capture, utilization and storage
CO_2	carbon dioxide
CoAP	Constrained Application Protocol
DC	direct current
DDS	data distribution service
DLMS	Device Language Messaging Specification
DSR	demand-side response
EES	electrical energy storage
EV	electric vehicle
GDP	gross domestic product
GHG	greenhouse gas
GW	gigawatt
GWh	gigawatt-hour
HIL	hardware-in-the-loop
HVDC	high voltage direct current
ICT	information and communication technology
IEV	international electrotechnical vocabulary (IEC)
IoT	Internet of Things
IPv6	Internet Protocol version 6
JTC	joint technical committee (ISO/IEC)
kW	kilowatt
kWh	kilowatt-hour

LCA	life cycle assessment
LCOE	levelized cost of electricity
LFAC	low frequency AC
LoRaWAN	Long Range Wide Area Network
LTE-M	Long-Term Evolution for Machine-Type Communications
LVDC	low voltage direct current
MW	megawatt
MWe	megawatt-electrical
MWh	megawatt-hour
NB-IoT	narrowband IoT
OneM2M	one machine-to-machine
P2G	power-to-gas
P2H	power-to-heat
PLC	Power Line Communication
PV	photovoltaic
RETL	renewable energy test laboratory
SC	subcommittee
SMR	small modular reactor
SRD	systems reference deliverable (IEC)
SyC	systems committee (IEC)
TC	technical committee
tce	tonne of coal equivalent
TS	technical specification (IEC)
TW	terawatt
TWh	terawatt-hour
UHV	ultra high voltage
V2G	vehicle-to-grid
V2H	vehicule-to-home
VPP	virtual power plant
VPS	virtual power station
WG	working group
WTE	waste-to-energy
ZB	zettabyte

Organizations, institutions and companies

AEMO	Australian Energy Market Operator
AREI	Africa Renewable Energy Initiative
BSI	British Standards Institute
BNEF	Bloomberg New Energy Finance
CEI	Italian Electrotechnical Committee
COP26	26^{th} United Nations Climate Change Conference of the Parties
ECOWAS	Economic Community of West African States
EDF	Électricité de France
EMEC	European Marine Energy Center
EU	European Union
EU-ETS	European Union Emission Trading Scheme
G7	Group of Seven
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
ISO	International Organization for Standardization
ITU	International Telecommunication Union
MSB	Market Strategy Board (IEC)
NDC	Nationally Determined Contribution (Republic of Korea)
NEM	National Energy Market (Australia)
OCCTO	Organization for Cross-regional Coordination of Transmission Operators (Japan)
PNIEC	National Integrated Energy and Climate Plan (Italy)
PNRR	National Recovery and Resilience Plan (Italy)
RETL	Renewable Energy Test Laboratory (United Kingdom)
RITE	Roosevelt Island Tidal Energy Project
UL	(formerly) Underwriters Laboratories
UNCTAD	United Nations Conference on Trade and Development
UNDP	United Nations Development Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change

Glossary

distributed generation

electricity generation, often relatively small, located close to the particular load to which it supplies power

duck curve

typically a pattern of net demand on a transmission or distribution system with very low demand in the middle of the day, and peaks in morning and late afternoon

intermittent

non-continuous

NOTE An intermittent generation source in and of itself cannot provide a constant non-zero power output over the long-term.

megawatt (MW)

a measurement unit of power equal to one million watts

megawatt electrical (MWe)

a measurement unit of power equal to one million watts referring specifically to the electrical power output capacity of a plant

megawatt hour (MWh)

a measurement unit of energy equal to 1 000 kilowatts of electricity used continuously for one hour

net zero carbon

refers to a system in which the total carbon emissions produced are balanced by the total carbon emissions taken out of the atmosphere

NOTE In this paper, "net zero carbon" is taken as synonymous with "net zero emissions".

net zero emissions

refers to a system where the greenhouse gas emissions produced are balanced by the total greenhouse gas emissions taken out of the atmosphere

power system

framework of electricity generation, transmission, distribution, storage and utilization, as well as associated efforts

synchronization

in the context of power system operations, the matching of phase or instantaneous voltage

tonne of coal equivalent (tce)

unit of energy comparable to the energy in one tonne of coal

transient

relating to a momentary event

NOTE Transient analysis looks at fine-grained temporary changes in state.

terawatt hour (TWh)

a measurement unit of energy equal to outputting one trillion watts for one hour

variable

changing significantly over time

NOTE The output of a variable generation source (such as wind or solar) changes over time and is not completely controllable.

zero carbon

a system that produces zero carbon emissions

NOTE In this paper, "zero carbon" is taken as synonymous with "net zero emissions".

Section 1

Introduction

1.1 Background

Around the world, electricity systems are undergoing incredible transition and upheaval. This shift is profound, affecting electricity generation, transmission, distribution, even business models. Gas, diesel or coal electricity generators that have been in place for decades are being replaced by technologies such as solar, wind, hydropower or marine generation and batteries, whose operating principles are very different. The way electricity systems are planned and laid out is also changing dramatically. Traditionally, electricity systems have operated under a relatively centralized structure, with a small number of larger generation stations sending electricity a long distance to where it is used. The arrival of renewable energies such as solar and wind generation means energy systems are being "decentralized": instead of relying on a few large generation plants, energy systems may be made up of large numbers of much smaller plants, geographically distributed and closer to loads. This changes the topology of the electricity distribution system significantly. As shown in Figure 1-1, traditional power systems were based on unidirectional power flow, and generators were all closely synchronized. The power system of the future is likely to look quite different than those of today. As shown in Figure 1-2, power flow is likely to be bidirectional in many parts of the power system; generators will be smaller and more distributed, and not inherently synchronized.

These changes can bring benefits – for example, a more decentralized power system is likely to be more resilient to natural disasters – but in many other ways they pose significant challenges to power system operation.

The transition from large fossil fuel-based electricity systems to more decentralized systems based on renewable generation and storage (such as batteries) is occurring worldwide, in nations large and small. While the transition is well recognized and considered profound in its impact, in many ways it is not happening fast enough.

The Intergovernmental Panel on Climate Change (IPCC) 2021 report states that "it is unequivocal that human influence has warmed the atmosphere, ocean and land", and that this is "...already affecting many weather and climate extremes in every region across the globe [1][1]". Referencing this report, United Nations Secretary General António Guterres said "This is a code red for humanity. If we combine forces now, we can avert climate catastrophe. But…there is no time for delay and no room for excuses…" [2].

1 Numbers in square brackets refer to the Bibliography.

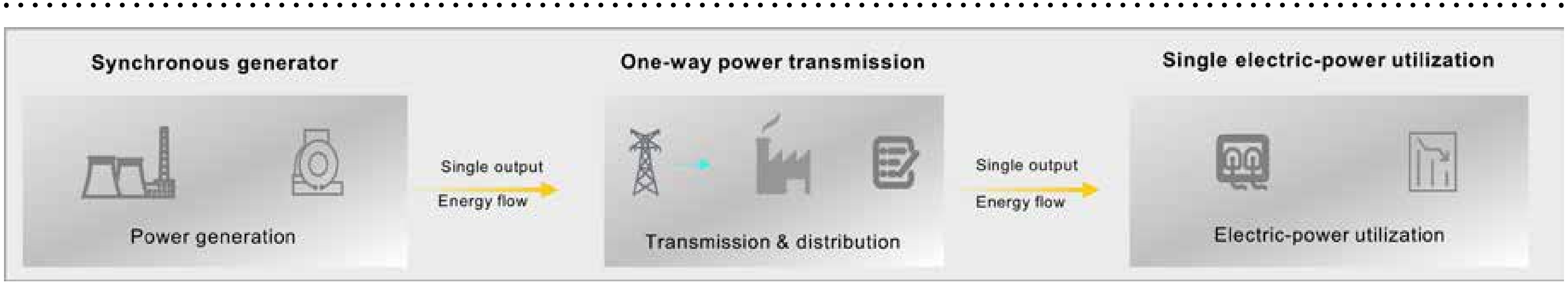

Figure 1-1 | A typical traditional power system topology

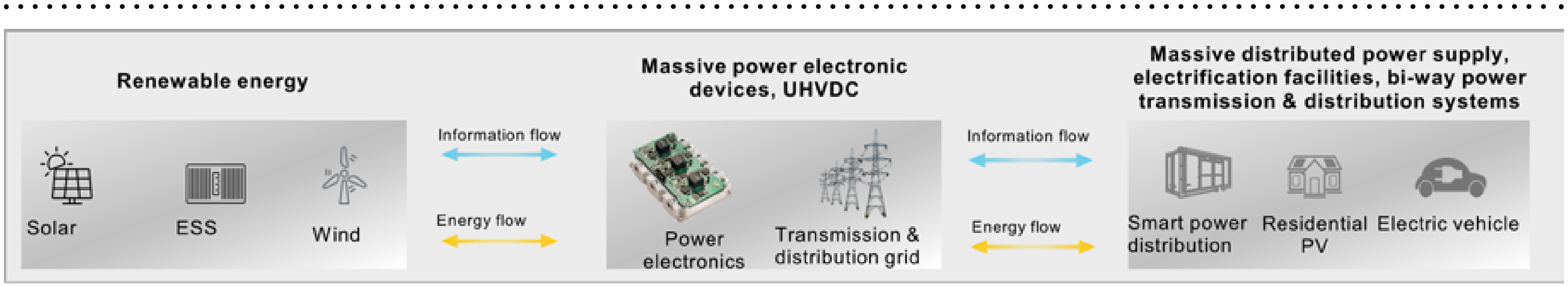

Figure 1-2 | A typical zero carbon power system topology

To avoid the worst effects of climate change, the world needs to reduce its greenhouse gas (GHG) emissions. The energy supply sector is the largest contributor to global GHG emissions, and the IPCC has said “The stabilization of GHG concentrations…requires a fundamental transformation of the energy supply system”. The electricity sector makes up approximately 40% of the world’s energy-related emissions [3], and thus decarbonizing, or reducing the carbon intensity of, the electricity sector is a key component of reducing greenhouse gas emissions [4].

The massive shifts already seen show that the world has started the journey of decarbonizing its power sector. Yet there is a long way to go. Today, approximately 60% of the world’s electricity generation comes from greenhouse-emitting fossil fuel generation [5]. The International Energy Agency (IEA), in considering the challenge of decarbonizing the energy sector, found that the entire global electricity system will need to produce net zero emissions by 2040, and that realizing this goal will involve “...nothing short of the complete transformation of the global energy system” [6].

As the transition of the energy system accelerates, it will have a significant impact on every facet of the power sector. This paper considers the transition ahead and what it may mean for the International Electrotechnical Commission (IEC), its members, and the standards it produces that guide the world’s electrotechnology sector.

1.2 Scope and definitions

This white paper is part of a series whose purpose is to ensure that the IEC can continue to contribute through its standards and conformity assessment services to solving global challenges in electrotechnology. The white papers are developed by the IEC Market Strategy Board (MSB), which is responsible for analyzing and understanding changes in the market in which the IEC operates, so as to help prepare the IEC strategy for the future.

The transition to a fully net zero power system is one of the most significant challenges facing the IEC and the electrical power industry. This paper is an initial step in the journey of understanding, adapting and addressing this challenge. The paper considers why a net zero carbon power system is needed, how such a system will be different than today’s power system, and how such a system could be realized.

Realization of a net zero carbon power system is an incredible challenge, requiring an immense amount of work across a very broad range of topics. Effort will be required in policy and law, regulation, standardization, finance and technology development, while ensuring that societal needs continue to be met. This paper pays particular attention to the technologies likely to be part of a net zero carbon power system, and what these might mean for the IEC and its standardization work. The project team included representatives from utilities (Électricité de France (EDF), State Grid Corporation of China, Tokyo Electric Power Company, United Energy), electrical equipment manufacturers (Haier, Huawei, Schneider, Tratos), consultancies (EnSTAR, ZeroEN), and standardization organizations (IEC, British Standards Institute (BSI), Italian Electrotechnical Committee (CEI), UL, Korean Agency for Technology and Standards).

Almost all of society is a stakeholder in the goal of a net zero carbon power system. The transition needed will affect energy consumers, generation and distribution organizations, energy service organizations, markets, governments and financiers. Consequently, this paper is targeted at a wide-ranging audience: from those with a simple interest in how the power system is going to change, to the organizations charged with developing and following the standards necessary to facilitate the move to a net zero carbon power system while maintaining the supply reliability and performance to which we are accustomed.

The paper is focused on the supply and utilization of electrical energy. Thus, "power system" is taken to refer to electricity generation, transmission, distribution, storage and utilization technologies and associated efforts. For the purposes of readability, this paper will use the terms "zero carbon", or "net zero" synonymously with "net zero carbon". Similarly, while the vast majority of GHG emissions associated with the power system are from the combustion of carbon-based fossil fuels, for the purposes of brevity, in this paper a "zero carbon" goal will be taken to refer also to the removal of non-carbon GHG emissions associated with the power system.

1.3 Structure

This white paper aims to review the background of the massive transition facing power systems around the world, introduce the changes that will take place, and then review what this means for the work of the IEC and its stakeholders. Following the introduction, Section 2 considers the forces that are driving power systems to transition towards net zero and reviews the different positions around the world on this topic. Section 3 reviews what a zero carbon power system may look like, and Section 4 considers the path to a zero carbon power system, and how to evaluate the carbon emissions of alternative paths. Section 5 introduces the technologies that will underpin the realization of a reliable, economic net zero power system. Having detailed what a zero carbon power system is expected to look like, and the changes this will involve, Section 6 considers what this may all mean for the IEC, its stakeholders and standards work. Section 7 presents conclusions and recommendations to IEC and broader stakeholders based on the reviews and research that underpin this paper.

Section 2

The zero carbon power system: driving factors and market needs

2.1 Climate change

Awareness of climate change and, subsequently, concern regarding its impact on humanity, has grown across the entire world over a number of decades. In 1992, the United Nations Framework Convention on Climate Change (UNFCCC) recognized for the first time that climate change and its adverse impacts are of common concern to mankind. In 1997, 37 developed countries set specific emission reduction targets for the first time, under the Kyoto Protocol. In 2005, the European Union established the European Union Emission Trading Scheme (EU-ETS) as the first in the world involving the engagement of multiple member states, and in 2008, the UK became the first country in the world to formulate a long-term legally binding framework on climate change. In 2015 the United Nations published its Sustainable Development Goals [7], which include specific goals on climate change and energy, and are strongly supported by the IEC standardization and conformity assessment efforts.

In 2015, 186 countries and regions signed up to the Paris Agreement, which specifies a "hard target" of temperature control, holding the increase in the global average temperature to no more than 2 degrees Celsius by the end of the century. At the time of writing, 124 countries have pledged to achieve net zero carbon emissions (or carbon neutrality) by 2050 [8]. The goal of "net zero" means that a country will balance the GHG emissions it releases into the atmosphere through its everyday activities with the amount it absorbs or removes from the atmosphere. In November 2021, the UN Climate Change Conference in Glasgow (COP26) brought together signatory countries to review and assess the current climate governance and make a further commitment to increase and accelerate emissions reduction.

In short, recognizing our climate change challenge, today net zero is a goal that has been committed to by many nations around the world.

2.2 Achieving net zero

The realization of net zero carbon emissions will have a far-reaching impact on countries' energy systems, financial systems and the development of enterprises. Emissions will need to be significantly reduced across all sectors, including energy, manufacturing, agriculture, transportation and construction, and key industries including steel, construction materials, non-ferrous metals and petrochemical. For many, the task of emission reduction is both daunting and urgent.

The energy industry, including fossil energy production and use, is the world's largest source of carbon emissions, accounting for 76% of the world's total GHG emissions in 2021 [9], and thus it is a key focus for nations striving towards net zero carbon emissions. Furthermore, the low carbon transition of a broad range of other industries is likely to depend on the transition of the energy industry. As an example, reduction of carbon emissions from the transport industry is likely to depend heavily on a move to electric vehicles, which will have a flow-on profound impact on all aspects of the electrical power system, from generation to transmission and distribution. The changes required here are immense: today, fossil fuel generation, which emits large amounts of GHG, makes up over 60% of worldwide electricity supply [10]. Ultimately, the faster the power system can achieve net zero emissions, or zero carbon, the sooner the entire world starts to meet its climate challenge.

2.3 Government policy

As mentioned previously, many countries and regions across the world have committed to a goal of net zero carbon emissions. A total of 124 countries have committed to reach net zero by 2050, with another 13 countries aiming to achieve this goal sometime after 2050 [8]. Countries including the United States, the European Union, the UK and Japan have made the commitment to reach net zero by 2050. Several countries have committed to a “predominantly” decarbonized electricity grid by 2035 [11]. With these goals in mind, governments around the world are considering how to meet their climate commitments, what this means for their incumbent industries and economies, and how a zero carbon power system may look given their particular domestic situation. Ultimately, government policy is a key enabler for the rapid transition to a zero carbon system. Government policy can also constitute a key barrier to the transition of the power system, with regulatory hurdles, organizational inertia or political forces delaying the rollout of already successful technologies.

Broadly, measures being adopted around the world to decarbonize the power system can be grouped into the following categories:

1) **Phasing out of carbon-intensive generation assets.** Countries around the world are phasing out carbon-intensive coal and gas generation assets and replacing these with low carbon assets. For example, the G7 countries have committed to a phaseout of all carbon-intensive generation by 2035 [11].

2) **Electrification of other sectors of the economy.** Replacing assets powered by fossil fuels with electricity-driven alternatives can reduce the emissions of a range of other sectors of the economy, providing that electricity comes from zero carbon sources. For example, the use of electric vehicles (EVs) can dramatically reduce the emissions associated with the transport sector, and nations around the world are looking to significant growth in the uptake of EVs. Similarly, replacing space and industrial heating with heat pump alternatives can help decarbonize the consumer, manufacturing and building sectors.

3) **Encouraging new zero carbon technologies.** A range of new technologies will be required to address the fundamental challenges of operating a reliable zero carbon power system or to decarbonize industries that can not rely on electrification for their carbon reduction. A wide range of new energy technologies are being developed and trialled around the world, from electricity generation or energy storage to energy efficiency and management technologies. As an example, further development of low-cost affordable energy storage (including but not limited to, batteries and pumped-hydro) will be needed for the operation of a zero carbon power system. Similarly, development of low-cost and safe hydrogen technologies can assist with the energy storage challenge as well as help reduce the carbon emissions of industries such as cement or steel manufacture. Lastly, some countries have made the choice to build new nuclear power plants and to invest in the development of innovative new nuclear technologies, as a source of zero carbon generation.

4) **Provision of financial assistance to encourage the uptake of zero carbon technologies.** Financial support through mandates, rebates and the issuance of

green bonds or loans can provide a financial advantage to zero carbon technologies as compared to their alternatives, and thus accelerate the transition. For example, in 2019, the energy sector witnessed the issuance of USD 190 billion worth of green bonds, and green loans have been issued by a wide range of companies, including companies from ExxonMobil to Tokyo Electric Power Company and Edison International [12].

With the aim of demonstrating the broad range of regulatory and policy mechanisms available for realizing a zero carbon power system, subsections 2.3.1 to 2.3.8 provide a few examples of government approaches to net zero from IEC member countries around the world. Further details can be found in Annex A.

2.3.1 Africa

African countries are especially vulnerable to the impacts of climate change due to the nature of their economies, which often depend primarily on rain-fed agriculture, and their geography [13]. Thus, countries across Africa are collectively, and unilaterally, devising policies and making economic changes towards a carbon-free future. One of the collective policy tools that is expected to play a critical role is the Africa Renewable Energy Initiative (AREI), which was established in 2015 [14]. The AREI shows how Africa intends to achieve low-to-zero carbon development through climate finance and implementation methods based on the principles of the UNFCCC [15]. The AREI initiative anticipates African countries will be able to generate more than 300 GW of zero carbon electricity by 2030. There are also subcontinental frameworks such as the Renewable Energy Policy adopted by the Economic Community of West African States (ECOWAS) in July 2013. The policy aims at ensuring increased use of renewable energy and the provision of access to energy services in rural areas. A target of increasing the share of renewable energy in the region's overall electricity mix to 19% (48% including large hydro) in 2030 has been set. Microgrids and stand-alone power systems are expected to be integral to Africa's plans going forward, as they are predicted to supply power to around 25% of the rural ECOWAS population by 2030 [16]. Sub-Saharan Africa is expected to implement policies that encourage renewable energy uptake, with the portion of renewable electricity generation in the region predicted by the IEA to increase by 76% during 2021-2026, doubling the capacity of the previous half-decade [17].

2.3.2 Australia

Australia is a world leader in the decentralization of the energy system, with one in three households having rooftop solar [18] and the expectation that the National Energy Market (NEM) will operate at 100% renewable energy for short periods of time by 2025 [19].

South Australia, a state with a peak load of approximately 3 GW is already operating at certain times with zero operational demand. That is, that the state's load is being met by generation on the distribution network that is not seen by the national system operator.

Over the years, uptake of renewable energy (particularly solar) in Australia has trended, or exceeded, the most aggressive forecasts of the Australian power system operator. While in part this has been driven by government policy, it has been largely led by consumers exercising their choice to purchase solar for either economic, social or energy independence reasons. This has led to Australia being one of the cheapest countries in the world to install rooftop solar [20]. Australia has not yet seen a high uptake of EVs, but this is expected to change rapidly as markets provide suitable products and infrastructure meets demand.

It is not just on rooftops that renewable energy is being produced in Australia. Australia is abundant with wind and solar resources. The challenge to the growth of centralized wind and solar generation in Australia is that the country's existing transmission infrastructure was built to support centralized coal generation, and this coal generation was often located in areas other than where the best wind and solar resources are found. Thus, new transmission and large-scale storage assets are required to support the large, centralized wind and solar generation being added to the Australian energy system. Providing the necessary investment signals and gaining social license for the construction of the new transmission assets are key enablers for this new storage and transmission to be realized.

The challenges that exist in Australia to meeting zero carbon goals include:

- A need to support market driven choices.
- Operating a power system with very low minimum system demand.
- The highly decentralized power system in Australia, with long distances between load centres.
- Gaining social license for some technologies.
- Federal government policy has changed regularly and has been unclear concerning the preferred path to take.

2.3.3 China

China has announced that it aims to reach peak carbon dioxide emissions before 2030 and to achieve net zero carbon emissions before 2060. By 2030, the proportion of non-fossil fuels used in primary energy consumption is expected to reach around 25%, and the total installed capacity of wind and solar power will exceed 1 200 GW [21].

By the end of 2020, China's total installed capacity of renewable energy generation reached 930 GW, accounting for 42% of the total installed capacity, an increase of 14,6% compared with 2012. Of this, hydropower represents approximately 40% of renewable generation capacity, wind power 30%, and solar photovoltaics 30% [22].

2.3.4 France

France's electricity system is already relatively low carbon, thanks to a generation mix mainly composed of nuclear power, together with wind, solar and hydro generation. France's energy-climate law includes the objective of net zero carbon emissions by 2050. The text sets the framework, ambitions and target for France's energy and climate policy [23]. Some of the more distinctive approaches incorporated in France's plan include:

- A gradual withdrawal from fossil fuels and the development of renewable energies, reducing fossil fuel consumption by 40% by 2030 and terminating coal-fired electricity generation by 2022. It introduces a cap on GHG emissions for existing fossil fuel-fired electricity generation facilities (0,55 tonnes of carbon dioxide equivalent per megawatt hour). The law also states solar panels or other renewable energy production or greening processes will have to be installed for new warehouses and commercial buildings containing over 1 000 square meters of floor space.
- Establishment of the concept of "renewable energy communities": this is a legal entity controlled by shareholders or members in the vicinity of the renewable energy projects it has subscribed to and developed. A renewable energy community is allowed to produce, consume, store and sell renewable energy, including through renewable electricity purchase agreements, and to share, within the community, the renewable energy produced by the generation units owned by the community, accessing all relevant energy markets directly or through an aggregator.

- Measures to assist low income consumers to improve the energy efficiency of their houses. The aim is to renovate houses currently served by technologies such as oil heaters within 10 years.
- A plan to revive nuclear power in France, with the construction of six new large nuclear reactors, the first by 2035, and to launch studies on the construction of eight additional large nuclear reactors, supported by small modular reactors [24]. The French government anticipates that by 2050, nuclear energy will be second to photovoltaics (PV) as the cheapest form of generation in France, and it has the ultimate goal of 25 GW of nuclear capacity by 2050 [24].

2.3.5 Italy

Italy's vision of decarbonization focuses not just on emissions, but also on the need to guarantee all citizens accessible energy of similar quality across the country. Italy is also considering the full breadth of environmental sustainability, including the principles of a circular economy, or dealing with waste. Italy's plans are encapsulated in the Italian Government's National Integrated Energy and Climate Plan (PNIEC) [25]. A related plan, the National Recovery and Resilience Plan (PNRR) [26] provides a package of investments and reforms, divided into six missions.

Mission #2 of the plan (approximately EUR 60 billion) focuses on the "Green revolution and ecological transition" and contains a strong emphasis on measures such as hydrogen and the circular economy. Additional goals include energy efficiency (particularly in metropolitan buildings) and recertification, which includes the structural recertification of buildings, with particular reference to schools and hospitals.

Mission #3 of Italy's PNRR (approximately EUR 25 billion) covers "Infrastructure for sustainable mobility" and aims to build a more modern, digital and sustainable infrastructure system by 2026. It includes the goal of decarbonization and reduction of emissions through the transfer of passenger and freight traffic from road to rail and the development of an integrated logistics chain.

2.3.6 Japan

Japan has announced an aim of net zero carbon emissions by 2050. Its Basic Energy Plan contains a goal that by 2030 the proportion of renewable energy generation will have increased to 36-38%, and nuclear power generation to 20-22%, making decarbonized power generation 60% of the total electricity output [27]. At present, Japan's total annual electricity consumption is approximately 987 TWh, where fossil fuel generation makes up approximately 70% of total capacity [28].

A unique challenge faced by Japan is that in recent years, the country has become more reliant on fossil fuel generation. Between 2010 and 2016, the proportion of nuclear power generation in total electricity output decreased from 26% to 1,7%, due to the public's concerns regarding nuclear power following the Fukushima Daiichi Nuclear Power Plant disaster in 2011. More recently, the carbon intensity of Japan's power industry dropped by 4,3% in 2019, which was the largest decline since 2009, as nuclear power has started to return and take a greater role in the power sector.

The transition of Japan's power sector is not just limited to the technologies in use. The sector is being completely disaggregated, new market mechanisms are being introduced, and mechanisms such as the Organization for Cross-regional Coordination of Transmission Operators (OCCTO) are being established to foster a free power market and competitive pricing mechanisms for generation and retail businesses [29].

2.3.7 Republic of Korea

The Republic of Korea's approach to a zero carbon power system has started with the design of detailed investment plans that include the prioritization needed in order to realize the transition. These investment plans are currently focused on strengthening the electricity system, considering the maximum demand in a geographical region, predicting available renewable energy capacity, and adding decentralized generation to meet any gaps. As such, the Korean approach is to strengthen and optimize the power network as soon as possible at province level, and then deploy additional zero carbon generation capacity on demand.

The Republic of Korea's 2030 Nationally Determined Contribution (NDC) Plan [30] includes over KRW 78 trillion of investment for strengthening of the power grid by 2030. Of this, KRW 30 trillion is dedicated to power system strengthening efforts associated with the expansion of renewable energy generation [31].

The Republic of Korea's approach to the power system transition focuses on a broad range of stakeholder impacts or benefits from the transition. Articles such as the *Electric Power Source Development Promotion Act* [32] include consideration of resident support projects in regions adjacent to new transmission infrastructures, and the provision of free space available to residents neighbouring new power system infrastructures. They seek resident and local government involvement in system planning, and construction design that particularly considers nearby residents.

The technologies being planned to strengthen the Republic of Korea's power system are similar to those of many other jurisdictions, with 1,4 GW of large-scale battery storage, and 1,8 GW of pumped-hydro planned [32]. New laws and incentive mechanisms to encourage various hydrogen power technologies have also been added. Supporting this new power system are measures such as existing pumped-hydro plants, district heating systems, and additional distributed battery storage uptake. The Republic of Korea is taking a "connect and manage" approach to the hardware rollout of its new power system and real-time control of these is expected by 2025.

The Republic of Korea's transition effort also includes regulation and standards changes. Multiple market mechanisms are being considered to incentivize dynamic participation of generators and storage. Standards for renewable energy equipment will be revised to improve the strength of the power system. The role and responsibility of power system organizations is also being revised, and local government has actively participated in power system planning activities. Empirical and trial projects on sector coupling technologies have been conducted including power-to-gas (P2G), power-to-heat (P2H), and vehicle-to-grid (V2G).

2.3.8 The United States

The US has set goals of a shift to zero carbon power generation by 2035 and realization of countrywide net zero carbon emissions by 2050. In 2020 fossil fuel made up 79% of energy production in the US [33].

In 2020, coal power generation in the US decreased by 20% compared to 2019, while renewable energy power generation, including small-scale solar farms, increased by 9% [33]. Wind power was the most common type of renewable energy power source in the US, an increase of 14% compared to 2019. Large solar farms (with an installed capacity of over 1 MW) increased by 26%, while distributed solar (such as grid-connected solar roofs) increased by 19% [34].

The US is unique in that much of the energy transition has been led by private companies, using options from power purchase agreements and purchase of renewable energy credits, to on-site solar or wind generation. Companies such as IBM, AT&T, Amazon and General Motors have announced carbon-neutrality goals, and these targets are having ripple effects across the economy. Utilities are following suit, with the five largest utilities in the US having pledged to realize zero carbon emissions.

2.4 Market changes

In many parts of the world today the cost of energy generated by renewable sources such as wind and solar is cheaper than the cost of energy from coal or gas generation. Bloomberg New Energy Finance (BNEF) found that in China, India and most of Europe, solar generation is cheaper than coal-based electricity [34]. It noted that the lowest "levelized cost of electricity" (LCOE) was USD 22/ MWh for wind in Brazil and Texas, USA, while a similar price was seen for utility-scale solar in Chile and India. BNEF also found that the cost of constructing and operating a solar plant in China now realizes an electricity price of USD 34/MWh, which they state is below the cost of running a typical coal-fired power plant at USD 35/MWh [35].

Critics of the levelized cost of energy approach state that it does not factor in the additional costs incurred to operate a reliable power system with large amounts of variable wind and solar generation, namely the costs of storage, additional transmission infrastructure, and devices to add rotating inertia. However, today, even when such additional costs are included, the final cost of wind and solar can be cheaper than coal or gas generation. Figure 2-1 is from the Australian Energy Market Operator (AEMO), and shows that even with 2-6 hours of storage added, based on AEMO's estimates, wind and solar PV generation are cheaper than new-build coal and gas generation in Australia.

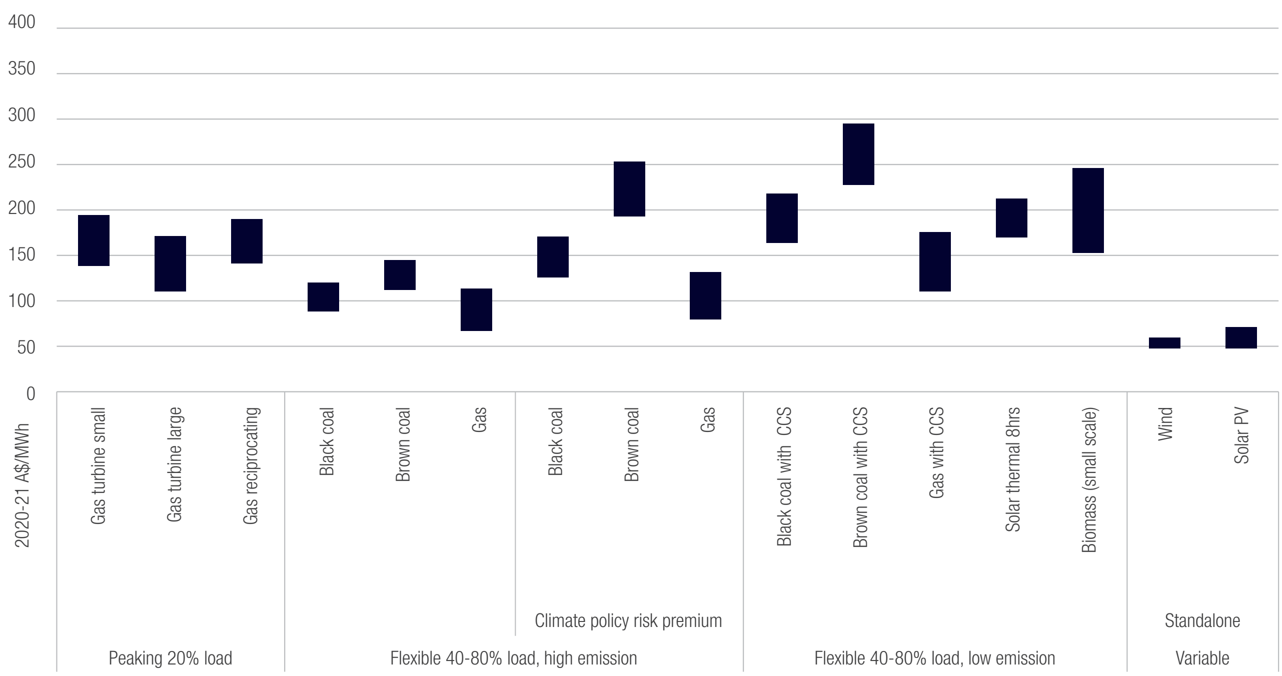

Figure 2-1 | Australian 2020 generation costs, with grid-firming included [36]

2.5 Reliable power supply

In a modern economy, a power system must not just provide electrical energy to end-users, it must also supply this power with very high reliability, be resilient to failure, and facilitate the rapid restoration of supply if there is an outage. As a critical service, any outage in the power system will cause significant impact and loss. Some selected examples of this include:

- On 14 August 2003, a tree touching a power line in Ohio, USA triggered the most widespread power outage in North American history, impacting 50 million people across many cities in the east of Canada and the US, and causing an economic loss of USD 25-30 billion [37].
- In 2011, several cities including Seoul in the Republic of Korea were hit by a sudden power outage, affecting 2,12 million households and plunging the whole country into chaos.
- A grid collapse in India in 2012 impacted 600 million people and induced traffic paralysis [38].
- In 2019, a power outage in Venezuela paralyzed the country, disrupting water and communication services and social order [39].

These outages were triggered by a variety of causes, from major equipment failures and human error to natural disasters, but in all of them, the failure of the power system resulted in further collapse of other systems, with wide-ranging impact and significant losses.

Even without the changes occurring during the transition towards zero carbon, the challenges to power system reliability and resilience are multiplying. Increasing extreme weather events due to climate change pose a significant risk to power system infrastructure. The growth of equipment automation and networked equipment bring the new risk of cyber attacks, in which remote actors can compromise system operation. These risks mean that, even without considering the move to zero carbon, power system resiliency needs to increase around the world.

As the transition towards zero carbon occurs in the world's power systems, it will bring a mixture of outcomes related to system stability and security. As detailed later in this paper, a move towards more distributed generation based on power-electronic converters will result in less system inertia, which is a challenge for traditional modes of power system operation. A more distributed power system is more difficult to control, and power quality can suffer. On the other hand, a move towards more distributed generation removes central-point-of-failure risks in the power system, may help avoid widespread outages after a local failure, and can be more resilient overall.

Ultimately, the key message here is that the path to a zero carbon power system is not one of simply replacing carbon-intense technologies with zero carbon technologies. The transition to zero carbon is enough of a challenge in itself, but this challenge is exacerbated by the overarching need to actually improve system resilience and reliability. In order to continue the reliability and affordability of system operation that modern economies are used to, the transition to a truly zero carbon power system will completely disrupt every aspect of system design, operation and maintenance. Ultimately, the power system of the future will be based on zero carbon technologies, with control systems that can sense the operation of the grid in a rapid and accurate manner, adapt to risks, coordinate internal and external resources, automatically reconfigure around outages, and do all this while adjusting to the rapid changes in output from renewable generation.

2.6 Affordable and economically competitive energy

The amount of investment in power system infrastructure and operations, and the costs to the end-user of electricity provided by the power system, have a profound impact around the world. Broadly, end-use electricity costs are a core element of the economic competitiveness of a particular country or jurisdiction. Electricity costs can also have a significant impact on the lifestyle, health and wellbeing of end-users. Thus, the amount of investment required in power system assets, and the price of electricity to the end-user, are key considerations during the transition of the power system towards net zero emissions.

Energy prices have been a particularly acute consideration in recent years. The soaring price of primary energy all over the world in 2021 led to a surge in electricity prices in major countries. For example, in September 2021, the wholesale price of electricity in the UK, Germany, and France was 4,3 times, 2,9 times and 2,9 times respectively that of the same period in 2020 [40]. Some provinces in China witnessed an increase of nearly 20% in wholesale electricity prices during the same timeframe, but government regulation meant end-user prices remained unchanged [41]. The war in Ukraine has significantly increased the price of fossil fuel in many countries.

The impact on electricity costs from the move to a zero carbon power system will vary depending on geography, regulatory arrangements, technology choices and market pressures. Thus, no simple statement can be made regarding the effect on costs from the move to net zero, except that this must remain an important consideration. Ultimately, though, as described earlier, as the price of renewable generation continues to decrease below the price of fossil fuel generation, this is likely to mean a move towards lower-cost electricity supply.

2.7 Changing energy consumption

Amidst all the other changes facing power systems, the loads they are built to supply are also changing significantly. The consumption profile of traditional loads is changing, and major new loads are also appearing. The changes outlined in subsections 2.7.1 to 2.7.2 have significant implications for the transition to a net zero power system.

2.7.1 Changing load profiles

In many developed nations, the profile of electricity consumption is changing very significantly, particularly in the electricity distribution network. There are multiple factors at play here:

- The consumption profiles of buildings are changing, with new appliances appearing or different living practices. For example, the uptake of air conditioning has increased significantly over recent years, and in some networks it is not uncommon for a single home to have multiple air conditioners that are only turned on a small percentage of the year. This results in very “peaky” load profiles, where the total demand from the building increases very significantly on the few occasions the air conditioner is active.
- The uptake of rooftop solar systems is changing the net load profile seen by the electricity network. As more and more buildings have solar panels installed on their roof, the total demand seen by the network changes. Today, there are many distribution systems in which the total load on a particular network segment may approach zero (or even be negative) in the middle of the day, as rooftop solar meets (or exceeds) the local demand in that segment.
- The arrival of major new electricity loads, as detailed in the following subsection.

Broadly, these changes mean that in many parts of the world, the net load profile seen by the electricity network is becoming very “peaky”, with total demand changing quite dramatically multiple times in a 24-hour period. An example of how load profiles have changed over time is shown in Figure 2-2, where the most recent load profile, with a significant drop in the middle of the day, is often referred to as the “duck curve”, due to the general shape presented.

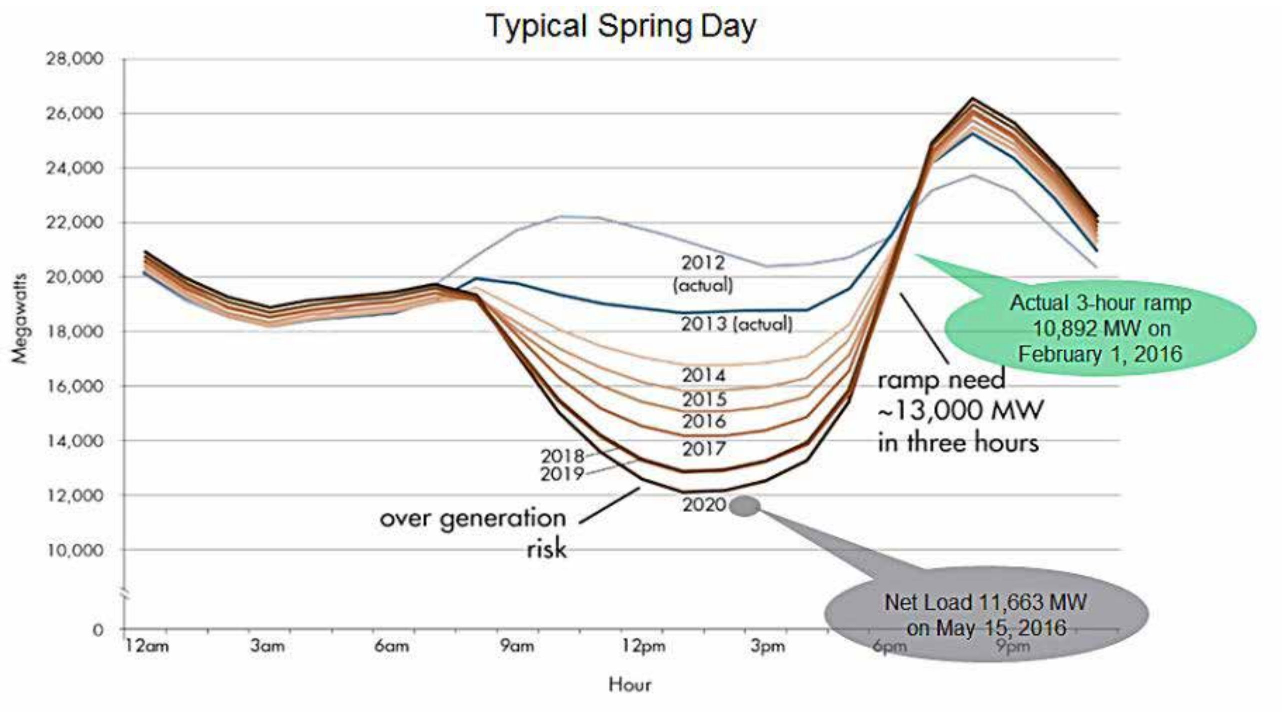

Figure 2-2 | Changing load profiles over an 8-year period, by California Independent System Operator [42]

In addition to seeing dramatic ramp-ups/ramp-downs in demand, power systems are starting to wrestle with "minimum demand" issues, where the net demand on the system is very low (approaching zero), and the bulk energy flow needed to meet this demand is thus also so low that system reliability is threatened. This minimum demand is typically caused by the growing uptake of solar systems: solar generation in the middle of the day may meet instantaneous demand but may be insufficient at a later time.

The changes in net load profile pose many challenges for power system operation. Generation needs to be highly flexible, able to adapt its output quickly to match the highly variable demand. Even with flexible generation, ensuring that supply matches demand at every instant, when both may be changing significantly, is difficult, suggesting a need for more energy storage on the system and more flexible load that is controlled, so load itself can be varied to match available generation. Additionally, sizing of infrastructure is difficult, given the trade-off between maximizing equipment utilization versus ensuring sufficient capacity to meet peak demand.

2.7.2 New loads

A growing trend in energy systems around the world is electrification of devices that may have traditionally used fossil fuels as their primary energy supply. By switching boilers, heating systems and similar loads to electricity as their primary source of energy, a facility may be able to reduce its GHG emissions or operating costs. Research has shown that the economic value of electric power is 3 times that of oil, and 17 times that of coal[2],

2 The overall benefit to society created by 1 tonne of coal equivalent (tce) of electricity is the same as the benefit created by 3,2 tce of oil or 17,27 tce of coal [43].

and every 1% increase of the proportion of electric power in end-user energy consumption will lead to a 2-4% reduction of per-capita GDP energy consumption [44]. Thus, electrification of loads that traditionally operated on fossil fuels has many benefits and is likely to be a trend that continues for many years.

Over the long term, another example of new-load for the electricity system may be the use of electricity to store energy in materials, produce new energy carriers or energy-intensive chemical products. Examples here may include the production of hydrogen, synthesis gas, or plastics. This “power-to-X” concept [45] has been proposed as a way of absorbing low-cost or excess renewable energy and helps add a large flexible load to the electricity system.

2.7.2.1 Heat pumps and induction cooking

In the residential sector, a significant change in load is the electrification of heating technologies that were traditionally fuelled by gas or liquid fuels. There is a rapid growth in heat pump-based air conditioning systems that provide both heating and cooling to a house. Similarly, domestic hot water units based on increasingly efficient heat pump technologies are growing rapidly around the world.

More broadly, a variety of jurisdictions are mandating "gas-free" buildings, where, on top of heating and hot water appliances, gas cooking appliances are being replaced by electric ones. Electric induction cooktops have similar cooking characteristics to their gas counterparts yet offer a number of emissions and cost benefits.

This change in electrical loads in a residential setting adds significant demand on the power system, but also adds “discretionary” load – electric storage hot water systems, and to some extent air conditioning systems, have some flexibility as to the exact time they consume energy from the grid.

2.7.2.2 Electric vehicles

The transport sector is another example where electrification will significantly reduce the GHG emissions associated with the sector. EVs are significantly more efficient than fossil fuelled vehicles, and if the electrical energy they use is sourced from zero carbon generation, they offer a means of zero carbon transport. However, such a move will add a significant extra load on the power system, potentially increasing peak demand and exacerbating the load profile challenges described in the previous subsection. The potential exists for this demand to be managed by technologies that control the time that an EV charges and the rate at which it draws energy from the power system.

If managed well, EVs could actually be considered an asset to the power system. Two examples of such behaviour are:

- EV charging being managed to match available renewable energy generation, and thus reduce the rapid swings in power system net demand.
- The energy stored in an EV battery being exported into the power system, supporting local demand. Such “vehicle-to-grid” (V2G) or “vehicle-to-home” (V2H) technologies are being trialled around the world.

Section 3

Characteristics of a zero carbon power system

A zero carbon power system is likely to look quite different than the power system seen in many developed nations today. Some features will certainly remain: gas turbine generators, as a flexible and reliable source of power generation are likely to remain in use for some time, potentially with technologies such as carbon capture used to turn them into a zero carbon generation source. Hydro power, a flexible and zero carbon generation source, will continue, as will fundamental approaches to electricity transmission and distribution. However, many other aspects of system operation will change. These differences are explored in the following subsections.

3.1 Large scale deployment of zero carbon energy generation

Any zero carbon power system will rely on the vast majority of electricity coming from zero carbon generation sources. As described earlier in this paper, today, in most regions, wind and solar-based generators are the cheapest form of new-build zero carbon generation. Thus, it follows that any zero carbon power system is likely to have a very significant amount of wind and solar generation, so long as sufficient wind and solar resources are available.

Wind and solar generators have quite different operating characteristics than traditional power system generators. Wind and solar generation can be found at a variety of scales, from less than a kW generation capacity to tens of GW. Large (tens of MW or greater) wind and solar generators typically connect to a high voltage transmission system, whereas smaller wind and solar generators connect at low voltage to the distribution network. When wind and solar generators connect "lower" in the power system, where the carrying capacity is more constrained, they can cause issues with voltage management, affecting the quality of supply of the power system.

A zero carbon power system may also use nuclear generation (which is typically considered carbon-free), hydropower or fossil fuel generators, in which the carbon emissions from the generator are absorbed and prevented from entering the atmosphere. Such generators can offer benefits to the power system, compensating for some of the challenges introduced by more variable generation. A zero carbon power system may also impose new operational requirements on traditional generators, such as more flexible operation or speed of response.

The focus of subsections 3.2 to 3.5 is on the significant differences between a traditional power system and a zero carbon system, which tend to follow from the extensive use of wind and solar generation and storage devices such as batteries.

3.2 High penetration power electronics and decreasing inertia

Today's power systems require significant "inertia" to cope with sudden shifts in generation or load. This inertia serves as temporary energy storage, providing time for supply and demand to be rebalanced. Traditionally, this inertia was provided by large, synchronized generators and, to a lesser extent, industrial motors, the significant rotating mass of these synchronous machines giving them the tendency to resist frequency changes when power imbalances occur. Furthermore, conventional synchronous machines are connected by electromagnetic forces, meaning their rotating masses are aggregated and contribute to grid inertia together. Traditional synchronous generators also provide very high short-circuit currents, which has been a fundamental principle of power system fault detection.

A zero carbon power system is likely to have far fewer large rotating synchronous machines. Wind turbines, solar photovoltaics and battery storage devices are "asynchronous" devices that connect to the power system through power electronics. As such generators proliferate, the total amount of inertia in the power system will decrease. This loss of inertia challenges the basic principles of traditional power system operation. Frequency swings are likely to become deeper and with a faster rate of change, fault detection will be more difficult, and there is a risk of reduced system strength.

With the amount of synchronous generation decreasing as power systems move towards net zero, some power system operators are installing technology not seen for many years, in an "old is new" approach to power system security. Synchronous condensers are a technology historically used to help manage reactive power flow in power systems, but they faded from operation as alternative ways of managing reactive power flow arrived that were cheaper and required less maintenance. An advantage of synchronous condensers is that they operate based on a large rotating mass, so their inclusion in a power system adds to system inertia. Thus, synchronous condensers are making a modern comeback in some power systems, with their primary purpose not being to manage reactive power, but to improve system inertia and strength. For example, the South Australian transmission system operator Electranet has recently installed four synchronous condensers, to improve power system security with the rapid uptake of renewable energy generation in South Australia. These synchronous condensers have allowed the minimum operational system demand to be lowered, and synchronous generators to be turned off [46].

One way of managing the loss of inertia in the power system would be to completely redesign the system and its operating principles, for example, to redesign the system to accept varying system frequency, and/or shift to much greater use of direct current (DC) energy transfer. Such changes would be profound and would affect almost all aspects of system operation and very many devices across the system. Given that the path to a zero carbon power system needs to be a managed *transition*, rather than a complete upheaval, such approaches are generally considered unviable by most system operators. Rather, the transition to a low-inertia zero carbon power system is being managed by requiring power-electronic based assets such as wind, solar and batteries to emulate the behaviour of more traditional rotating machines [47]. A variety of ways exist to provide this "synthetic inertia", including:

- Provision of frequency support through the kinetic energy in large wind turbines. This requires new control system approaches that mean the wind turbine blades (which have significant rotating inertia but are not directly coupled to the power system frequency) can provide frequency support, replicating the behaviour of a synchronous machine.
- Having inverter-based resources change their behaviour based on the local power supply frequency. While battery- and solar-based inverter systems do not have the rotating inertia of a large wind turbine blade, they can ramp up or down their output in response to system frequency. These output variations can occur much faster and over a larger range than conventional generators.

- The implementation of "grid forming" inverters that have the potential to function akin to a synchronous generator. Such inverters may operate on current-source principles, rather than on the voltage-source operation typically seen in a grid connected inverter, and are already available at the +100 kW scale.
- Regulation of load. Certain loads, such as EVs, some industrial processes, heat pumps, pool pumps and electric boilers, can vary their energy consumption over time, with little effect to end-user amenity or productivity. In doing so, these loads have the potential to respond to power system events, and thus support grid operations. Such loads could, for example, vary their consumption in response to the local frequency or voltage.

All behaviours listed above require changes in the control system of the devices mentioned. Often, new regulation or incentives are needed to realize such changes, to encourage device manufacturers to implement the new control approach and end-users to take up the new devices and enable their grid-interactive behaviour. Furthermore, the behaviours listed above are not a "natural" outcome of the physical properties of the power electronics, they derive entirely from the control system implemented by the equipment vendor. Given this, the dynamic behaviour of a large number of power-electronic based devices can be difficult to determine, which could result in interoperability or system stability issues. Standardized behaviour and (partially) open control structures set in grid codes can reduce these risks.

3.3 Digitalization of the power system

Power systems have relied on digital sensing and control technologies for decades, but typically such functionality was restricted to major power system assets. Even today, most power systems do not have much remote sensing or automatic control capability at the lower-voltage levels of the distribution network.

Managing the changes in power system operation described in the subsections above will require much finer-grained sensing and control at all levels of power system operation. This "digitalization" of the power system brings its own profound changes. The volume of data needing to be collected and acted upon by power system operators is increasing exponentially: power system controllers now need to consider tens of thousands of very small devices, and the issues to consider when making control decisions are dramatically more complicated. These issues are further considered in Section 5.

3.4 Decentralization of the power system

As they transition towards zero carbon, power systems are becoming more decentralized. Very large-scale generation plants are being replaced by greater numbers of smaller generators, geographically distributed.

There exists a range of "decentralization" of the power system that is possible. In some countries, the power system may be predominantly made up of relatively large (hundreds of MW or more) generation plants such as large solar or wind farms. In other countries, the power system will be more decentralized and will be made up of much larger numbers of smaller generation, such as rooftop solar, small wind generators, or diesel or gas generators located close to load. There are trade-offs involved in selecting fewer numbers of large plants over more distributed smaller plants. For example, larger plants may offer economies of scale, but smaller plants can reduce the load on the local distribution system and may be funded by the end-user directly.

A different version of decentralization is the microgrid, which is a combination of distributed energy devices, linked to provide reliable power in a network that resembles a smaller version of the electricity grid. A microgrid may be installed to supply a village, a university or commercial campus, or an outlying island. It may operate connected to the main power system, or be completely separate, “islanded” from the broader grid.

A more decentralized power system represents a significant change in business practices, regulatory approach and technical operation for the traditional power system operator. It can also represent a significant threat to their business model. For example utilities whose revenue depends on selling power, or maintaining a regulated asset base, may face the threat of less revenue if customers start supplying themselves locally from rooftop solar or similar technologies.

3.5 Bulk power transfer

Renewable energy, such as solar and wind generation, has significant geographical diversity. In one place, at a particular instant, it may not be sunny or windy, but in some other place at that same instant it may be very windy. In large areas, the variable nature of wind and solar generation can be at least partly managed by increasing the amount of bulk power transfer, or energy transmission, to enable the transfer of renewable energy from the places it is available to the places it is needed. Thus, the move to a net zero power system is likely to see a significant increase in transmission capacity in many areas around the world. This trend is already visible in Europe and China, where significant long distance transmission capacity has been added over the last decade. This increase is likely to include additional long-distance transmission, as well as more “intermeshing” of electricity transmission networks, to allow greater diversity in how and where electrical energy can be transferred across a particular area.

Section 4

Alternative pathways to a zero carbon power system

It is clear that any zero carbon power system will rely heavily on zero carbon energy generation and energy storage, will involve the electrification of services, and will have quite different net load profiles to many power systems operating today. These changes alone mean significant modifications to standards and regulation associated with all aspects of the power system.

Many different options remain that can be taken in realizing a zero carbon power system. What choices are made will depend on a very wide range of factors: regulatory and political preferences, the wind, solar, or other natural resources available in a geographical area, whether the challenge is to build a new power system in a relatively undeveloped area or transition an already-built mature power system, and so on. Subsections 4.1 to 4.6 review the key power system characteristics that will vary depending on the transition path chosen.

4.1 Centralized vs decentralized

As described earlier, traditional power systems tended to have a relatively "centralized" nature, where energy flowed in one direction, from a relatively small number of very large generators. Very large transmission and distribution systems were constructed to transfer that energy from the large generation plant to the loads where the energy was consumed. While it is likely that all zero carbon power systems will be more decentralized than their forebears, *how much* to centralize the power system remains a choice. For countries that already have large, mature centralized power systems, the transition to a net zero future is likely to continue to rely on relatively centralized approaches. Such power systems will continue to feature relatively large zero carbon generation plants and take advantage of their existing transmission and distribution systems for the carriage of energy. This is not to say that such countries will not feature distributed energy solutions. Rooftop solar, battery storage and similar technologies will certainly feature, but bulk energy is likely to come from centralized generators and transmission and distribution infrastructure.

In places where there is not already a mature, extensive power system, the path to net zero may be based on much more decentralized approaches. Such approaches may replace centralized generation plants with large numbers of smaller net zero generators, located much closer to load centres, and thus reduce the need for costly high-voltage transmission infrastructure. Similarly, large energy storage infrastructures such as pumped-hydro plants may be replaced with much smaller distributed storage technologies, again located close to load centres. Such approaches may also improve system reliability, reducing the number of failure points in the network.

4.2 Energy efficiency

A key decision in the path to net zero is how much to include the demand or load side of the system in transition plans. In a fossil fuel-based power system, one seemingly straightforward way to reduce emissions is simply to use less energy. Energy efficiency efforts aim to use less energy, but without a reduction in output or amenity. Another way of framing energy efficiency is to "waste less". As such, energy efficiency is a relatively easy political choice, and is thus high on many zero carbon plans across the globe. Moreover, while over 130 countries around the world have committed to net zero targets, many more, in fact *most* countries worldwide have the goal of being less energy-intensive [48].

Broadly, energy efficiency can be considered a "no regrets" option to realizing the net zero goal, as it offers many benefits:

- Energy efficiency helps to reduce costs. As just one example, the UK government found savings of 39% were achievable through energy efficiency improvements across all non-domestic buildings in England and Wales in 2014. This is equivalent to GBP 3,7 billion that businesses could have saved on their energy bills [49].
- Reducing energy usage reduces emissions. Currently a large part of the world's energy comes from fossil fuel, and so reducing energy use means emitting less GHG and other pollutants into the atmosphere, soil, and water.
- Energy efficiency provides other system benefits. By reducing consumption, power system operators are able to manage peak loads in a reliable, predictable, and measurable way. This optimizes the grid and delays, reduces, or eliminates the need for new infrastructure investments, which can contribute to a more reliable and resilient grid.

4.2.1 Electrification makes energy efficiency easier

The electrification of loads traditionally supplied by gas, oil, or other fossil fuels, as described in Section 2, generally makes energy efficiency easier. It also adds more controllable load to the electricity system, which can bring benefits as described in subsection 4.3. The IEA expects the electrification of other fuel sources to contribute to electricity generation rising 40% by 2030 in the Net Zero Emissions by 2050 Scenario [50]. However, while generation output rises, this is amidst increased efficiency and lower total emissions. Equipment driven by electricity is often much more efficient than the equivalents powered directly by fossil fuels, with electric heat pumps, for example, being three to four times more efficient than burning fossil fuels for heat. How much to electrify loads traditionally outside the electricity sector will remain a choice for regulators, operators and end-users.

4.2.2 Standards are essential to help realize energy efficiency outcomes

The UK government recognized that the built environment massively contributes to the carbon emissions produced by a country, and that if the country's housing stock is more energy-efficient it will better be able to reach its carbon reduction targets. The UK recognized that while building regulations ensured that new properties met minimum energy efficiency standards, there was a gap when considering existing buildings. As such, the government set minimum energy efficiency standards for domestic privately rented properties, ensuring that such properties will become more energy-efficient, and reducing their energy use.

In addition to buildings, standards have helped halve the energy consumption of key electrical appliances [50]. Over 120 countries have implemented or are developing mandatory standards and labels for electrical appliances. Typical appliances that have minimum efficiency standards applied to them include air conditioners, refrigerators, lighting, televisions, washing machines and cooking appliances [50].

4.3 Load/demand integration

In considering how much the "demand side" of the power system should feature in the path to net zero, in addition to energy efficiency measures, load integration or demand-side management is another option available. Traditionally, power system operators considered the demand side of the system relatively uncontrolled, and so supply had to be managed in order to match the varying demand. As described in Section 5, today many technologies are available that facilitate careful control of loads in the power system. So the challenge of ensuring that supply and demand are carefully matched can be considered two-ended: one end involves matching generation to the current load, while the other involves matching the load to the available generation.

Power system operators have a choice regarding how much to rely on demand-side management. At one extreme, they can effectively ignore demand-side measures and simply focus on the supply side of the power system. This may result in lower asset utilization, but it is a well-known and understood method of power system operation. Alternatively, they may rely heavily on demand-side management, which can bring benefits such as improved utilization of infrastructure, but also brings added complexity to system operation.

Standards are key to enabling load integration or demand-side management. They are critical to the interoperability required when a power system operator seeks to manage individual loads located relatively low in the power system. Standards take time to be realized, so even if the choice is made to have a relatively small amount of demand-side integration in the short term, it is likely standards and interoperability efforts will need to start in earnest, to enable greater demand-side participation at a later date.

4.4 Electrical vs chemical energy transfer and storage

Electricity systems are fundamentally a way of transferring energy from where it is produced, to where it is needed. They also include a means of storing energy for use at a later time. While electricity-based energy storage and transfer mechanisms are pervasive, there is a growing interest in the use of alternative energy storage and transfer mechanisms that may provide advantages over electricity in certain situations.

Hydrogen is seen as one potential alternative to electricity for the transfer and storage of zero carbon energy. Hydrogen can be produced, stored, and then transferred close to loads. It may be used itself (for example, to provide heat) or be converted to electricity for end use. Hydrogen proponents suggest that hydrogen, or related chemical energy carriers, may be cheaper or more appropriate than electricity for very long-distance energy transfer, long-term energy storage or some uses such as aviation transport.

Hydrogen-based technologies are further described in Section 5. Ultimately, if hydrogen technologies meet the technical and commercial goals their proponents suggest, then in the future organizations may have a choice whether to follow an electrical- or a chemical-based approach to bulk energy transfer and storage.

4.5 Comparing technology options: evaluating emissions

In striving towards a zero carbon power system, it is important to be able to compare the greenhouse or carbon emissions associated with various technology options. Various ways exist to count the emissions of a particular technology. Generally, these are categorized into three scopes according to the World Resources Institute Greenhouse Gas Protocol [51]:

- Scope 1 includes emissions released into the atmosphere as a direct result of an activity at a facility level. Examples include emissions produced from the burning of fossil fuels or the fugitive emissions produced from leaking gas pipes in a gas generation facility.

- Scope 2 includes emissions released into the atmosphere from the indirect consumption of an energy commodity. Scope 2 emissions in one facility would usually be considered scope 1 emissions in a different facility. For example, the scope 2 emissions of a data centre would be the scope 1 emissions of the electricity generator that produces the electricity used by the data centre.
- Scope 3 includes all other indirect emissions and can be identified as the emissions from the "corporate value chain". Scope 3 emissions occur as a consequence of the activities of a facility, but from sources not owned or controlled by that facility's business. Thus, for an electricity generation facility, scope 3 emissions would include the emissions associated with the extraction, production and transport of fuels for the facility. They would also include the emissions associated with the manufacture of the equipment used in that facility, and the extraction and transport of raw materials used to produce that equipment. Scope 3 emissions also typically include emissions associated with waste from the facility, its inputs and outputs.

Electricity systems contain a variety of potential emissions, particularly the emissions associated with burning fossil fuels. But emissions can also be inherent to particular equipment or materials, for example, common electrical insulation materials such as sulphur hexafluoride can have a very significant greenhouse potential. Often, "zero carbon" is taken as referring solely to the scope 1 emissions associated with a technology or facility. However, ideally all emissions associated with the facility and produced over its lifetime would be measured. This is a very complex process. Among the methods of measurement available for this purpose, the life cycle assessment (LCA) methodology is most common. An LCA of the emissions from a technology or facility can assist in:

- Providing industry, government or other stakeholders a like-for-like comparison of the *total* emissions produced by various technologies, as defined by a comprehensive list of measurements.
- Identifying opportunities to improve the environmental performance of products at various points in their life cycle.
- Identifying the most important indicators of environmental performance for a particular technology or business approach. For example, while "distance travelled" has often been taken as a proxy for a product's carbon impact, an LCA might show that, if carried efficiently, a product that travels a long distance may actually have a relatively low carbon impact.
- Marketing a product, service or technology.

The LCA methodology is standardized in the ISO 14040, ISO 14041 and ISO 14044 standards. In the IEC, technical committee (TC) 111 on environmental standardization oversees work relevant to this topic. There is a significant opportunity to develop further standards for applying these general methods to the specific needs and features of the power sector.

4.6 Evaluating zero carbon systems

When considering the goal of a zero carbon energy system, it is critical to determine how to actually measure if the system is truly zero carbon. Two common goal-oriented approaches associated with renewable energy or zero carbon include:

- Goal of carbon neutral, in which a company, government or other organization offsets its emissions by purchasing carbon offsets that reduce or prevent future global emissions.

- Goal of 100% renewable energy, in which a company, government or other organization purchases enough renewable energy to match its annual energy use.

A more ambitious goal considered by the United Nations [52] and supported by a range of commercial organizations is the concept of 24/7 carbon-free energy, where rather than emitting and subsequently compensating for carbon emissions, organizations do not emit carbon in the first place. This requires every unit of electricity consumption to be supplied by zero carbon sources, at every instant in time. Such a goal is significantly more challenging than measurement approaches that operate based on averaging measurements over a long period of time and is considered a "… transformative approach to energy procurement, supply and policy design." [52].

Overall, whether a 24/7 carbon-free goal or more traditional time-averaged goals are adopted, further effort is needed to standardize the approaches taken to measuring the progress and success of such targets. Possible issues to be addressed include the specific geography a goal applies to, what types of data are measured and how, adequate means to ensure traceability, and so on.

Section 5

Key new technologies and their challenges

The transition to zero carbon operation brings many new technologies to power system stakeholders. While well-known technologies such as hydropower, gas, and other forms of generation will continue in the zero carbon power system, many other new technologies, or significant evolutions of older technologies, are appearing. From generators to end-users, the technologies that source, distribute and manage electrical energy are changing significantly. The following subsections introduce some of the new technologies that will feature in a zero carbon power system, their benefits, and the challenges to their operation.

5.1 New generation technologies

5.1.1 Efficient coal generation technology

Due to the variable nature of generation technologies such as solar and wind power, and the current limitations of storage technology, coal power will continue to feature in our power systems, albeit in a decreasing amount, for years to come. As a result, industry needs to find new ways to make the utilization of coal as efficient as possible.

Modern coal plants that will remain in the power system in the coming years are likely to have new features, such as:

- The highest thermal efficiency possible. A variety of programmes around the world are targeting net power generation efficiencies that approach 50% for a coal generator. The Huaneng RuiJin Power Plant in China achieved a supply efficiency of 49,25% in 2021, using 620°C ultra-supercritical double-reheat turbine technology [53]. The path to higher thermal efficiencies includes operation at higher temperatures. Plants today operate at up to 600°C, and system developers have a goal of 650°C-700°C, which will require new high-temperature materials. Another option is to move away from traditional steam turbine cycles for coal-based generation to new cycles such as integrated gasification combined cycles, integrated gasification fuel cells, supercritical CO_2 or chemical looping cycles.
- High thermal efficiency under low-load conditions. It is not sufficient to achieve high thermal efficiency at full-load operation. Given the variability in power system demand, a modern coal generator is likely to operate at low or partial load for significant periods of time, and thus needs to maintain its efficiency in these usage regimes. The Chinese Huaibei Pingshan project used technologies such as broad reheat, flexible reheat and concentrated frequency conversion to maintain efficiency at low loads [54].
- Flexible operation. Given the variability of demand in a net zero power system, a coal generator needs to be very flexible, changing its operation to match changing demand. Here, flexibility includes the ability to start and shut down the machine, the rate of change of output power, and having a wide safe load range. As an example of such performance, China has recently regulated in-service generators to have a range of operation of 20%-100% of rated load. This target presents

an enormous challenge to the operation of the coal generator.

- Fast cut back ability, which means the generator can swiftly cease output in case of a grid contingency, and then come online quickly thereafter.
- Biomass mixed combustion. Biomass is considered a low-carbon energy source. If biomass can be used in a coal generator, replacing some if not all of the coal, this provides a low-carbon path for coal generation assets. While trials have been run throughout the world for 20 years (for example, the Drax plant in the UK, with four units running purely on biomass in 2018), a key issue for such plants is the availability of biomass (for example, the Drax plant imports almost all its biomass from overseas [55]). Another challenge is that existing coal generators often require an upgrade of their furnaces, fuel transportation and storage systems in order to handle biomass. New units can have such changes already incorporated in their design, even if they start operation based on coal.

5.1.2 Carbon capture, utilization and storage

Carbon capture, utilization and storage (CCUS) technologies, although not a form of "generation" are relatively new technologies that can help with the transition to a zero carbon power system by reducing the emissions from fossil-fuelled generation, and/or compensating for the carbon emissions from other sectors of the economy. CCUS refers to a range of technologies that fundamentally are designed to capture carbon dioxide emissions, preventing them from going into the atmosphere and exacerbating the greenhouse effect.

Broadly, CCUS consists of the following stages:

1) Carbon capture. All CCUS approaches have carbon capture as their first step. Carbon dioxide must be captured from the source (for example, after combustion), or captured from the atmosphere. This carbon dioxide then needs to be concentrated for use in the latter stages of the CCUS system.
2) Transport. The carbon dioxide needs to be transported by pipeline, tanker, ship or other means to where it is subsequently handled.
3) Storage. In a carbon capture and storage system, captured carbon dioxide is stored, usually underground or in an aquifer, hopefully permanently, rather than allowing it to escape into the atmosphere.
4) Utilization. In a carbon capture and utilization system, captured carbon dioxide is used in a follow-on industrial process. Some examples of how the carbon dioxide could be used include:
   - Enhanced oil recovery, in which the carbon oxide is injected into an oil or gas reservoir, where hopefully it stays, but in doing so assists the extraction of oil or gas from the well.
   - Utilization in industrial processes. The carbon dioxide could be converted to fertilizer, gas, plastic or other carbon materials.

Many of the technologies that underpin the CCUS concept are well-proven. Enhanced oil recovery techniques have been used for some time, and carbon dioxide absorption methods trialled extensively around the world. The biggest challenge to CCUS is the cost: it is currently very expensive to first capture the carbon dioxide and then store or utilize it.

CCUS is a feature of many plans for net zero power systems. The US, Canada, China, Australia and Germany all have significant plans for CCUS deployments, and as of early 2020 there were 65 integrated CCUS projects around the world, 28 in operation, with the remainder in construction or development [56].

5.1.3 Nuclear power

Nuclear power is the second largest source of low-carbon electricity today, with 452 operating reactors providing 2700 TWh of electricity in 2018, or 10% of global electricity supply. Yet nuclear is losing ground compared to other technologies. While 11,2 GW of new nuclear capacity was connected to power grids globally in 2018 (the highest total since 1990) these additions were concentrated in China and Russia, and many other parts of the world have not seen a new nuclear power station built for decades [57].

The key issues that have limited the uptake of nuclear power in recent decades are:

- The cost and time required to build the technology: traditional nuclear power plants are very expensive to build, and may take 8-10 years to construct.
- Nuclear waste, which is dangerous and needs to be stored for very long periods of time.
- Public concerns regarding the safety of nuclear power.

Amidst these issues, proponents argue that new nuclear technologies mean nuclear power has the potential of being a zero-emissions, reliable source of bulk electrical power. Thus, of late, the attention and investment targeted towards new nuclear technology has grown. Subsections 5.1.3.1 and 5.1.3.2 introduce the variety of new modern nuclear technologies.

5.1.3.1 Conventional nuclear power

The term “conventional” nuclear power refers to most of the fleet in operation today, which is based on pressurized water, pressurized heavy-water, boiling water and light water graphite-moderated reactors. As of early 2021, 443 of these nuclear power plants were in operation around the world, providing 393 TW of capacity [58]. Of particular importance to a low-carbon power system, the average life cycle emissions of these plants have been estimated at 5,5 g CO_2 equivalent per kWh [59]. As shown in Figure 5-1, this is very low compared to many other generation technologies.

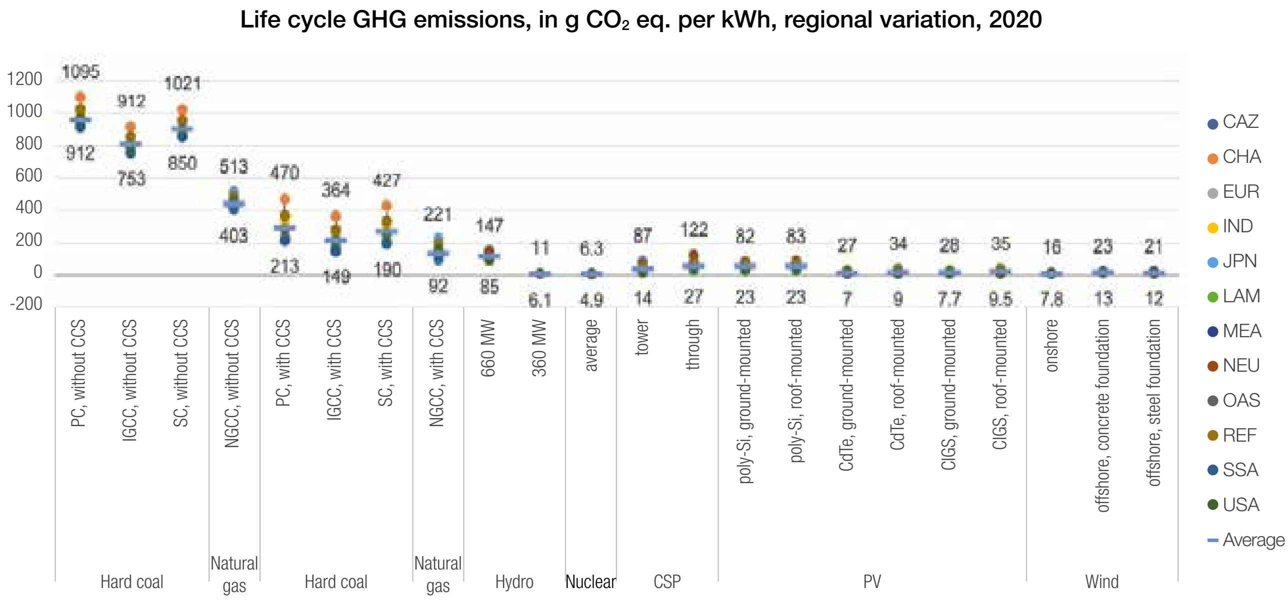

Figure 5-1 | Life cycle assessment of electricity generation options, UNECE, 2021 [59]

5.1.3.2 Small modular reactors

Small modular reactors (SMRs) are nuclear reactors with a power output between 10 MWe and 300 MWe. They integrate by design higher modularization, standardization and factory-based construction in order to maximize economies of scale, with the aim of reducing construction costs [60].

Many SMR designs are being researched, and a few of these are getting close to being trialled. SMR technology is still relatively immature, and there are no SMR plants in operation. If SMR technology is proven to be commercially viable, it holds promise as a zero carbon generation technology that can closely follow load and thus integrate well into a zero carbon power system.

Some of the key challenges to the widespread uptake of SMR technology include:

- Cost. There is great uncertainty regarding the costs of SMR technology, and this cannot really be known until a number of operating plants have been constructed.
- Supply of the fuel and managing the entire fuel cycle.
- Public perception of nuclear power in general.
- A diversity of standards and regulatory codes.

5.1.4 Solar

Solar power includes solar photovoltaic (PV) and solar thermal technologies. Solar power is a clean primary source of energy that has grown incredibly rapidly over the last 20 years, and the technology continues to develop, with ongoing improvements in efficiency and reductions in price.

In the power sector, PV technologies that convert light to electricity using solar panels are by far the most common form of solar generation. By the end of 2020, the total installed capacity of solar systems worldwide had reached 714 GW [61] and this is expected to grow to 1 870 GW by 2025 [62].

As the penetration of solar power increases, and solar systems replace gas or coal generation, the uptake of greater amounts of solar power poses several challenges to the operation of the power system. These include:

- Disturbance ride-through. Solar inverters were traditionally configured to disconnect from the power system during voltage or frequency disturbances. While disturbance ride through has been a relatively common requirement for large-scale generators for some time, as the portion of generation made up of solar generators increases, even relatively small solar generators will need to be able to remain connected through a disturbance, providing critical system support.
- Predictability of supply. To ensure supply matches demand, system operators need to provide forecasts of the generation available from solar generators, ahead of time. Given the variable nature of the solar resource, such forecasts are challenging, yet getting them wrong can have significant impacts on reliability. This challenge is even more acute for solar when compared to wind; while large wind turbines have some rotating inertia, a small cloud can cause the output from a 100 MW solar farm to drop to zero almost immediately.
- Power quality. Voltage fluctuation and harmonic generation can be common power quality issues experienced on grid segments with a large penetration of solar generation.

5.1.5 Wind

At the time of writing, wind is second to large-scale hydro generation in terms of installed zero carbon generation capacity, with 733 GW of capacity available worldwide in 2020 [61] and this figure expected to grow to over 1 800 GW by 2025 [63].

Wind generation technology continues to evolve. While today it is typical to see a single wind turbine of 3-5 MW capacity, commercial units are available as large as 12 MW, and organizations are preparing for 20 MW wind turbines by the end of the decade [64]. The recent rollout of large offshore wind developments is another major breakthrough, opening significantly more wind resources, and assisting with concerns around the land footprint or visual impact of wind farms.

Distributed wind is also a significant part of the recent growth in wind power development. Small wind turbines installed at homes, farms, businesses, and public facilities can meet all or a portion of the local energy demand. Small wind turbine retrofits, with new turbines being installed on existing towers and foundations, have also become common.

As the penetration of wind power increases, and wind turbines replace gas or coal generation, the uptake of greater amounts of wind power poses several challenges to the operation of the power system. These include:

- Disturbance ride-through. As described earlier in this paper, wind turbines were traditionally configured to disconnect from the power system during voltage or frequency disturbances. As the portion of generation made up of wind turbines increases, the turbines will need to be able to remain connected through such events, providing critical system support.
- Predictability of supply. To ensure supply matches demand, wind turbine operators need to provide forecasts of the generation available from the wind generators, ahead of time. Given the variable nature of wind, such forecasts are challenging, yet getting them wrong can have significant impacts on power system reliability.
- Power quality. Voltage fluctuation and harmonic generation can be common power quality issues experienced on grid segments with a large penetration of wind generation.

Though wind generation is one of the most mature renewable technologies, a great deal of research is still occurring on topics such as:

- Addressing the impact of intermittency, uncertainty, and fluctuation of power generation.
- Forecasting the impact of very large amounts of distributed wind generation on power system reliability and power quality.
- Resource assessment and planning, particularly given new geographies of installation, or the impact of climate change.
- The development of offshore wind technologies and installation practices.
- How to reduce curtailment due to grid carrying capacity.
- Reducing capital costs through material selection and more efficient manufacturing.

5.1.6 Smart hydropower

While hydropower is a generation technology that has been used for many decades, a range of innovative new hydropower technologies are appearing which provide greater flexibility and resilience for electricity grid operation. Smart hydropower is a new power generation concept that combines hydropower generation with the sophisticated control available from cloud computing technology, Internet of Things (IoT), artificial intelligence (AI) and other emerging technologies, to operate the hydropower generation in close interaction with variable generation such as solar or wind. The smart hydropower concept enhances hydropower's traditional strengths of flexibility and ancillary services provision to provide even greater flexibility and inertia for grid operation and balancing of variable generation sources, thereby supporting the construction and operation of next generation power systems.

An example of the smart hydropower concept is the 850 MW Longyang Gorge Hydropower and Photovoltaic Complementary project recently built in China. This project uses hydropower to complement the operation of a large-scale solar farm, where the outputs of the hydropower and solar plants are coordinated to achieve a smooth and stable combined generation output, meaning the photovoltaic power generation is as high quality a generation source as hydropower. Furthermore, by coordinating the hydro and solar generation, the power grid can reduce the rotating reserve capacity required to absorb renewable energy into the grid operation.

While further large-scale smart hydropower projects are under consideration or planning, a number of scientific and technical challenges need to be solved in operation control, maintenance management and other aspects, before such projects will become widespread. These include:

- Determining the relative scale of hydropower versus variable generation capacity needed to assist power system operation.
- Complementary control methods for automatic generation control of hydropower, wind power and photovoltaic. This includes challenges around short-term scheduling models, how to combine individual generating units, and optimal load allocation.
- Stability analysis of combined hydropower, wind and photovoltaic generation systems.
- The social license, community or environmental challenges of installing new hydropower plants.

5.2 Energy storage

Considering all the challenges of operating a zero carbon power system described throughout this paper, the addition of energy storage will constitute one of the main approaches taken to address these challenges. Energy storage helps with the challenge of matching supply and demand in a power system where both vary dramatically. Energy storage adds flexibility to the power system, providing a reserve of additional energy, and has a key role to play in providing the synthetic inertia discussed earlier in this paper, which is critical to allowing the system to handle a variety of system transients.

Traditional power systems had a relatively low amount of energy storage. They relied on the inertia of large rotating machines for short-term energy storage, and as load and generation changes were relatively slow, generators such as gas and hydropower could adapt to demand or supply changes. For the reasons detailed throughout this section, a zero carbon power system will be much more dynamic, and thus very significant amounts of energy storage will appear over the years to come.

Around the world, all forecasts of energy storage uptake involve very significant levels of growth. In 2020, the European Investment Bank promised to provide financial support to the pan-European battery industry, with the total investment in battery-related projects in Europe to hit EUR 127 billion in 2022 [65]. In China, the installed capacity of pumped storage plants is predicted to grow from 40 GW at the end of 2020 to 90 GW by 2025 [66]. China expects battery storage to increase by 55% per year until 2024, with the installed capacity surpassing 15 GW. According to the National Renewable Energy Laboratory, the installed capacity of long-term (continuous discharge of power for over 12 hours) power storage in the US will surge by 2050 and will rise from 125 GW to 680 GW in the next three decades [67].

Globally, Wood Mackenzie forecasts the accumulated installed storage capacity to reach 1 TWh by 2030, over 17 times the current level [68]. Meanwhile, the annual investment in the industry will increase from USD 18 billion in 2019 to USD 100 billion in 2030.

5.2.1 Uses of energy storage

Energy storage brings a variety of services or benefits to the power system. These include:

- Helping match supply and demand on the bulk-power system. Large-scale energy storage systems can help buffer mismatches between available generation and the demand or load on the power system.
- Relieving peak demand constraints. Particularly on distribution networks, where net demand can sometimes exceed network capacity, energy storage can be used to help address capacity constraints, without requiring changes in the distribution network.
- Provision of power system services. Energy storage can be used to help with frequency regulation or voltage management on the power system.
- Provision backup power services. Energy storage can be used to provide a backup resource, avoiding outages or load shedding after a system event.

Energy storage can also bring benefits outside power system operation, for example, providing energy market or tariff services, helping to mitigate rapid swings in electricity price. A variety of technologies are available to provide the sorts of services described above, and these are addressed in the following subsection.

5.2.2 Energy storage technology

Given the variety of services described in 5.2.1, energy storage technologies for the power system can be loosely grouped into three categories:

- Short-term storage that provides energy for tens of minutes at most. Batteries are well suited to this service provision.
- Medium-term storage that provides energy for several hours at most. Batteries, pumped-hydro generation or compressed gas storage are classic examples.
- Long-term storage that provides energy for multiple days or more, even storing energy between seasons. Today, pumped-hydro generation is the only widespread example of long-term energy storage.

Some of the challenges to the growing uptake of energy storage in the power system include:

- Safety. Batteries and other forms of chemical energy storage present challenges around the risk of fire and explosion. Addressing these is going to require a range of new safety measures, from new materials to cooling and enclosure systems. IEC 62933-5 series of standards by IEC TC 120 specifically considers the safety of energy storage systems.
- Social license. Storage technologies from pumped-hydro to batteries can be challenged by the degree of a community's acceptance of such technologies, making it difficult for proponents to get permission to install. Batteries and chemical energy storage can be perceived as a safety risk. Large pumped-hydro plants may raise significant concerns among the community regarding environmental impacts.
- Life cycle. The lifetime of a typical battery system is expected to be 10 years or less, although some newer commercial battery systems are available with 20-year warranties. Even if the price of battery technology continues to drop, the relatively short asset life of current technologies poses longer problems for the sustainability of this technology.
- Price. If variable renewable generation is to replace traditional fossil generation, then the additional cost of the storage needed to ensure power system reliability needs to be such that end-user energy prices can be kept at levels similar to those of today.

- Duration. A zero carbon power system is likely to need long-duration energy storage, and as yet the only viable form of such storage is pumped-hydro storage. The number of places in which a pumped storage system can be constructed is quite constrained, and alternative long-term storage technologies will need to be found.
- Sustainability. Many storage technologies have a significant impact on the ecosystem, whether through the disruption of watercourses or due to a reliance on rare materials. Storage technologies need to be more easily recycled and to have a lower overall environmental footprint.

5.3 Transmission and distribution system technology

5.3.1 Control

A modern power system supplies thousands of devices that are individually managed or controlled by the system operator. This control is critical to reliable power system operation.

Control of a zero carbon power system will include the following main functions:

a) Energy management

In any power system, the available supply needs to match the energy demand at every instant. Managing supply and demand so that they match is a significant challenge in a zero carbon power system. In order to ensure supply and demand are balanced in a power system operating with large amounts of intermittent or variable generation, both generation and load need to be forecast with reasonable accuracy. These forecasts will then be used by the power system operator to dispatch additional generation, control load, or dispatch storage, each of which require sophisticated computing, communications and control technology.

b) Transient and dynamic stability control

Dynamic stability control refers to managing the very short term (sub-second) operation of the power system. This role is made harder with a reduction in system inertia, as described elsewhere in this paper. The growing challenge of dynamic stability control is likely to mean greater penetration of short-term energy storage in the power system and introduction of new operating regimes for the power electronics in solar or wind generation systems that focus on provision of grid stability services rather than, or in addition to, bulk energy supply.

c) Demand-side management and energy efficiency

It is highly unlikely a power system will achieve its zero carbon goal through changes restricted to the supply side of the system. As described earlier in this paper, demand-side measures will also need to be introduced. These are likely to include energy efficiency measures that aim to reduce the total energy consumption of an appliance or facility, through to demand-side-control schemes that focus on short-term changes to an appliance's consumption profile. In this way, by modifying the demand of a particular appliance, the challenge of matching supply and demand is not just met by supply changes but also by altering demand to match the available supply. Such schemes are becoming commonplace in many countries around the world [69, 70].

Some of the major challenges related to control of a zero carbon power system include:

- The greater deployment of variable, uncertain and fluctuating renewable generation.
- The use of DC links and power electronic-based generators that reduce system inertia [71].
- The possibility of unwanted behaviour emerging from large numbers of power electronic converters, where their individual detailed control strategies are unknown to

the system operator, and thus the interaction of large numbers of these devices may be unknown.

- Realizing the control techniques and communications systems needed to manage a very large number of diverse and distributed assets, from distributed generators to customer equipment.

The following technical developments could significantly assist with these challenges:

- Development of a flexible standard control and protection system architecture that is suitable for the rapid application of control and protection systems in power systems operating with a large amount of renewable energy.
- Adoption of a standardized approach to control system design to ease the development and rollout of coordination and management systems that connect to generation, loads and energy storage.
- Continued development of digital power grid technology, so that AI can solve the management, operation and maintenance problems of a large number of control and protection system devices, reducing the load on humans.

5.3.2 Congestion management

Some of the changes inherent in a zero carbon power system can also be used to upgrade or improve the performance of the transmission and distribution system. One example is energy storage; in cases where a transmission or distribution line is close to exceeding capacity, the traditional approach would be to install additional line capacity, as shown in Figure 5-2.

Building additional line capacity can be very expensive, and energy storage systems can help avoid this. In such a case, energy storage systems can be placed at either end of the line, as shown in Figure 5-3.

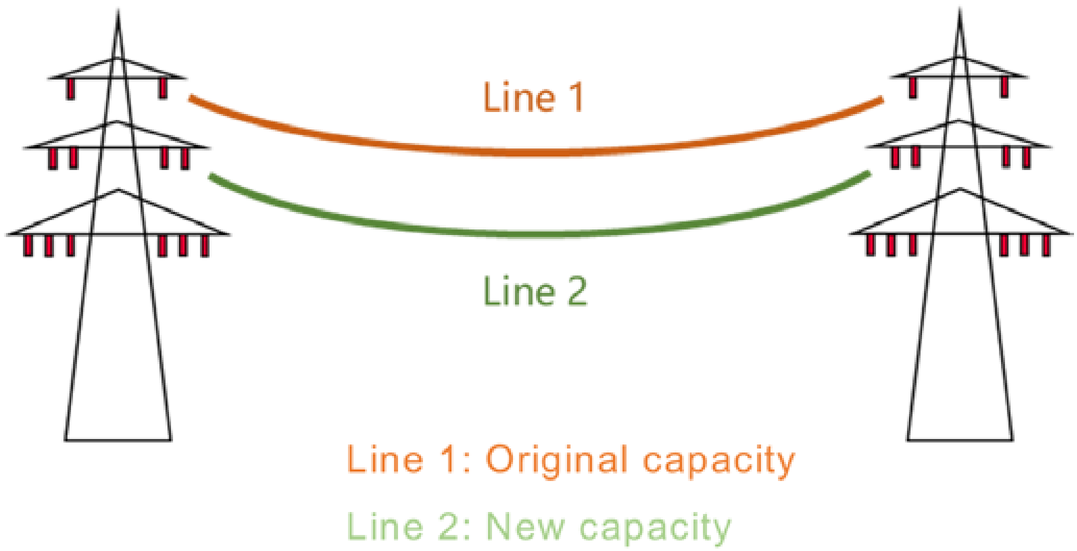

Figure 5-2 | Traditional approach to adding capacity: build a new line

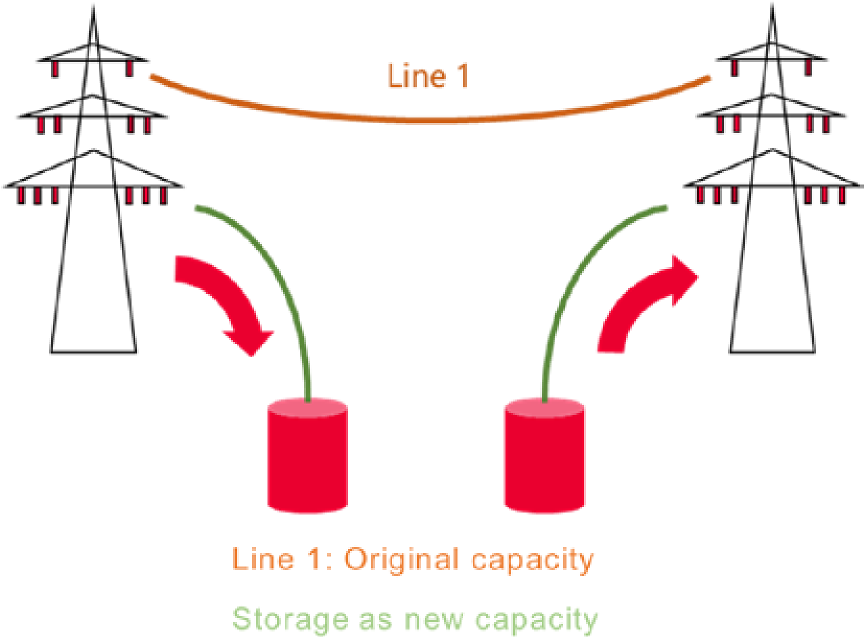

Figure 5-3 | Storage as a way to add new capacity

The storage connected at the *generation* side of the line in Figure 5-3 helps avoid the curtailment of generation due to insufficient line capacity, by charging from the renewable supply. When discharging, this storage delivers the renewable energy once sufficient line capacity is available. The storage connected at the *load* side of the line in Figure 5-3 charges when the load is lower than the renewable generation, and so there is spare line capacity. This storage discharges when the load exceeds the line capacity.

The application of dynamic line limits is another example of where the technology inherent in a zero carbon power system can assist with transmission or distribution line operation. Here, the additional instrumentation and sensing capabilities of the power system needed to manage variable renewable generation enable the line limits to be varied, adapting to changing environmental conditions, in particular the ambient temperature. By signalling the changing line limits, the power system can then enable generation or storage to adapt their output to the current line limit. Renewable generation may vary its output, or storage may be used to store excess renewable energy for a time when the line limits are higher, and the line can carry this additional energy. Such an approach helps to maximize the utilization of all elements of the power system.

5.3.3 High voltage direct current

New high voltage direct current (HVDC) connections are an enabler for the widespread deployment of renewable energy. HVDC converters transform alternating current (AC) into direct current (DC) and vice versa. HVDC technology has traditionally been used for bulk power transmission over long distances, for undersea connections and to connect different synchronous zones. Recent HVDC technologies such as voltage source converters allow HVDC to operate in a power system with low or zero rotating machinery. HVDC systems are now operating over very long distances and have been shown as the most cost-effective transmission technology at very high power ratings over long distances.

HVDC technology is quickly evolving from traditional point-to-point connections, to meshed DC grids. While research and development are still necessary, significant developments have been made and meshed DC technology has been demonstrated in the Zhangbei HVDC grid [72]. HVDC grids are expected to evolve into new backbone grids. In North America this concept is often referred to as the "macrogrid", while in Europe the term "supergrid" is more common.

5.3.4 Protection

Protection plays a key role in any power system and is required to detect and isolate faults, preventing equipment damage, human harm, or the fault spreading to other parts of the system.

As the power system changes in the transition towards zero carbon, this will have a significant impact on the design and operation of the protection aspects of the system. Some of the key challenges include:

- Relatively low fault currents. Protection systems have traditionally operated based on the high fault current produced by large rotating machines. In a power system that consists of power electronic-based devices, fault currents are much lower, making it more difficult to detect a fault.
- Distinguishing a genuine fault from transient and dynamic disturbances is much more challenging, as detailed in IEC TS 62898-3-1.
- Design of the protection system to accommodate bidirectional power flow is challenging.

In light of these challenges, new techniques such as the design of adaptive protection methodologies [73], fault current injection, or use of artificial intelligence approaches to fault detection and isolation are being developed [74].

5.3.5 Demand-side response and energy management

Demand-side response and energy management are important tools in the transition to a zero carbon energy system.

As described previously in this paper, to decarbonize the energy supply, grids across the globe will need to incorporate more renewable assets. These assets are largely intermittent, meaning that excess generation might be generated when consumption is low, for example, solar farms generating energy in the middle of the day, or wind farms generating excess energy on windy days. At the same time, during times of high energy demand, renewables might not be able to generate the needed energy for peak demand at that specific time. Demand-side response (DSR) provides the ability to coordinate when electrical devices take, or give back, energy and thus balance the difference between supply and demand. This process is often automated but may also require manual intervention from a user. DSR programmes usually include an incentive (often financial) to encourage energy users to participate in an automated control scheme, or to take manual action themselves to turn non-essential functions down or off at times of peak demand, helping the grid balance supply and demand without the need for additional generation.

A classic example of DSR is the participation of electric storage hot water systems, or pool filtration pumps, in automated load management programmes. In these programmes, the hot water system or pool pump is turned on or off remotely, matching conditions on the local electricity infrastructure. Pool pumps and hot water systems have an inherent "discretionary" component to their consumption: as long as they operate for a minimum number of hours per day, exactly when they operate can vary, without affecting end-user amenity. A more recent example of DSR is the remote control of EV charging, or dispatch of the energy stored in the EV's battery to help supply a household load during peak times, after which the EV is recharged late at night, when demand (and, typically, prices) are low.

5.3.5.1 The importance of demand-side measures

Demand-side measures will take on a critical role in the evolution of the power system. They help with many of the challenges described previously in this paper, from the intermittency of renewable generation and more dynamic nature of net loads on the grid, to the electrification of energy consumption. Some of the key benefits of demand-side measures include:

- Carbon reduction. The easiest emissions to reduce are those that are not generated. As described earlier in this paper, basic energy efficiency measures on the demand side reduce the total amount of generation needed. DSR measures may further reduce emissions by lowering peak demand and the need to operate more carbon-intensive generators, or managing demand to operate when zero carbon generation supply is greatest.
- Better utilization of assets. Demand-side measures can help smooth out net demand profiles, reducing peak demand. This directly impacts the sizing of network infrastructure and improves the utilization of network assets.
- Cost reduction. The UK's Smart Systems and Flexibility Plan 2021 [75] shows that increased flexibility reduces system cost in all modelled scenarios, with flexibility providing savings of between GBP 6-10 billion, depending on the scenario.

5.3.5.2 Challenges to the adoption of demand-side response

Many existing players in the electricity market have recognized the potential benefits of DSR technologies. However, for DSR technologies to be fully integrated into grids around the world, several barriers need to be addressed. These include:

- Lack of knowledge and awareness. DSR technologies, and particularly the potential benefits to an end-user from participating in DSR schemes, remains a fairly new area.
- Uncertainty of financial return. Typically, end-users require a financial incentive to change their electricity consumption patterns. How to determine the financial returns from DSR measures, or how to analyze the trade-offs between the disruption caused by DSR and the financial returns from participating, is challenging for many.
- Complexity of integration. Integrating DSR technologies into a changing grid will result in increased complexity of the electric power system. More complexity requires greater interoperability between all the parts. Among other things, protocols and standards will be critical to enable the seamless integration and automation of DSR technologies.
- Market structure/regulation. As well as end-users, power system operators and other stakeholders need an incentive to incorporate DSR measures into their business practices. Such incentives may be financial, in which case markets that were designed around the bidding of generation need to be adapted to cope with DSR technologies. Alternatively, the incentives may be regulatory, for example, recognizing DSR as an equal "asset" to the transformers, poles and wires on which a distribution business has set its rates.

5.3.6 Virtual power stations

The virtual power station (VPS), also known as the virtual power plant (VPP), is a type of demand-side measure, in which large numbers of distributed energy devices are aggregated together, so that their power system behaviour replicates a single larger generator. Virtual power stations are typically made up of distributed solar PV systems, and/or distributed batteries, that are then controlled remotely to aggregate their behaviour.

VPPs are typically considered of benefit to the distribution network, where they can be used in a way similar to that of the DSR techniques described in subsection 5.3.5. Such plants can assist with peak demand reduction, can provide a bulk supply of zero carbon energy at a desired time, or can even (with advanced inverter hardware) provide grid services such as frequency or voltage support. VPPs may also help mitigate risks around rapidly changing electricity prices, whether from tariffs or market behaviour.

As in the case of DSR measures, a financial incentive is often provided to encourage end-users to allow participation of their solar or battery system in a VPP programme.

The VPP concept has been trialled or demonstrated in many places around the world, yet few examples exist of its widespread commercial use. Some of the challenges to an extensive uptake of VPP technologies include:

- Integrating or coordinating VPPs with the broader power system, its dispatch and market operations. VPPs are not yet considered a regular "asset" like traditional machinery, and thus their integration into the broader system can be challenging.
- Ensuring the VPP can be relied upon to deliver the services expected. Particularly when based on variable sources such as solar PV, knowing what capacity is able to be dispatched from a VPP can be challenging.
- Speed of response. Ideally, a VPP should respond quickly to power system dispatch signals, which can be challenging for a VPP that consists of thousands of devices spread across a large geography. This challenge is exacerbated if the VPP is expected to provide services such as frequency response, which require a response time in the millisecond range.
- Integration and coordination of assets from multiple vendors. Many of the VPP rollouts today have been based on inverter or battery hardware from a very small range of vendors. If the VPP is to incorporate solar, battery or other hardware from a large number of vendors, as would be seen in a typical power system, it becomes much harder to integrate the broad range of technical differences in the hardware available.

Case study: Zhangbei Internet and Smart Energy Demonstration Project in China

Centring around the Winter Olympics city of Zhangjiakou, and the Electricity-Based Heating Demonstration County of Shangyi, the Zhangjiakou Renewable Energy Demonstration Zone of State Grid Jibei Electric Power Company has aggregated dispatchable load, particularly based around electric boilers. Over 227 MW of load is able to be dispatched [76]. With the goal of building an auxiliary service market in Northern China, market means were used to encourage third parties such as customers and load aggregators to participate in the scheme and interact with the power system.

5.3.7 Vehicle-to-grid technology

The number of electric cars worldwide is increasing rapidly. This provides the carbon reduction benefits described earlier, representing a significant shift in the transport sector, away from fossil fuels and towards electrical energy supply. This growth is likely to accelerate. For example, China's Development Plan for the New Energy Vehicle Industry (2021-2035) has set a goal of ensuring that EVs will represent 25% of new car sales by 2025 and will constitute the majority of new vehicles sold by 2035.

Every EV contains a large battery, and with appropriate coordination, these batteries can be an asset to the grid. This broad concept, in which EVs are used to benefit the power system, is referred to as vehicle-to-grid (V2G). In a V2G system, the charging time and demand of an EV is managed, and the EV battery might also be discharged back into the grid, to match local demand or grid contingencies.

The size of the potential power system asset represented by EV batteries is very large. For example, it has been predicted that if China has 80 million EVs by 2030, this would represent over 5 000 GWh in storage capacity [77].

V2G remains a relatively early concept. Before it becomes widespread, some of the challenges that would need to be addressed include:

- Development of standards to facilitate interoperability between electricity system operators and/or load aggregators, vehicle charging stations and vehicles, so as to realize V2G across different control authorities, vehicles and chargers.
- Getting the right incentives so that car companies will provide the technology in the vehicle or charging system to enable V2G.
- Providing the right incentives to end-users, so they will allow their vehicle to participate in a V2G programme.
- Coordinating and controlling many thousands of EVs. A V2G programme needs to minimize disruption to end-users, who need their car to be available for when they travel. Ensuring this functionality across thousands of vehicles is a challenging control and optimization problem.

5.4 Hydrogen

Hydrogen is the most abundant element in the universe and is touted by many as a key solution to the world's energy transition challenge. Hydrogen provides an alternative to electricity for the transport of energy and can be used as a large-scale energy storage medium. Hydrogen can also be used to develop low-carbon processes for manufacturing materials such as steel or cement.

From the perspective of the power system, hydrogen is of most interest as:

- An energy storage or load-shifting medium. Hydrogen could provide an alternative to batteries or other electricity storage technologies.
- An energy transport medium. Long-distance hydrogen distribution (for example, by cargo shipping) could compete with long-distance electricity transmission.
- A major load. The production of zero carbon hydrogen is likely to occur using electrolyzers, which require a very large amount of electrical energy to operate.
- A form of "dispatchable" generation. Stored hydrogen can be converted to electricity, without the intermittency challenges of solar and wind generation.

Today, electricity generation capacity linked to hydrogen-based fuels currently accounts for less than 0,2% of global electricity generation, yet some expect worldwide hydrogen generation capacity to reach 140 GW by 2030 [78].

Many challenges will need to be met before hydrogen will have a significant role in the power system. These include:

- Cost. Hydrogen produced from fossil fuels is significantly more expensive than alternative gaseous fuels such as methane. If the hydrogen is produced from zero carbon sources, it is even more expensive.
- Transportation and storage. Hydrogen has a low density, and is typically stored at high pressures, thus requiring additional energy to compress the hydrogen for storage. The storage and transport of hydrogen requires specialized materials compared to other gases.
- Efficiency. Hydrogen electrolyzers are around 70%-80% efficient at converting input electrical energy to chemical energy stored in hydrogen, and thus require large amounts of primary energy supply.

Despite these challenges, hydrogen proponents have estimated hydrogen could contribute 20% of the total reduction in carbon emissions needed, and in doing so would make up 22% of the global final energy demand [79].

5.5 Digitalization of the power system

Digitalization is affecting every aspect of day-to-day life for most individuals. The evolution of the power system is following a similar trend, and the digital transformation of the power system is accelerating with developments in measurement, communication and data storage and analysis technologies.

The total amount of data produced and consumed in the world is forecasted to reach 180 ZB by 2025, from the 64,2 ZB in 2020 [80]. As with most other sectors, the power sector is also becoming more data-driven. This is significantly changing the generation, transportation and consumption of energy, with the incorporation of digital technologies set to make energy systems more connected, intelligent, efficient, reliable and sustainable [81]. New digital tools, such as satellites tracking GHG emissions at a high resolution can also bring about environmental benefits [81]. Digital technologies that are, or can be, applied across the energy value chain, and their respective impacts, are summarized in Figure 5-4. These are further explored in the following subsections.

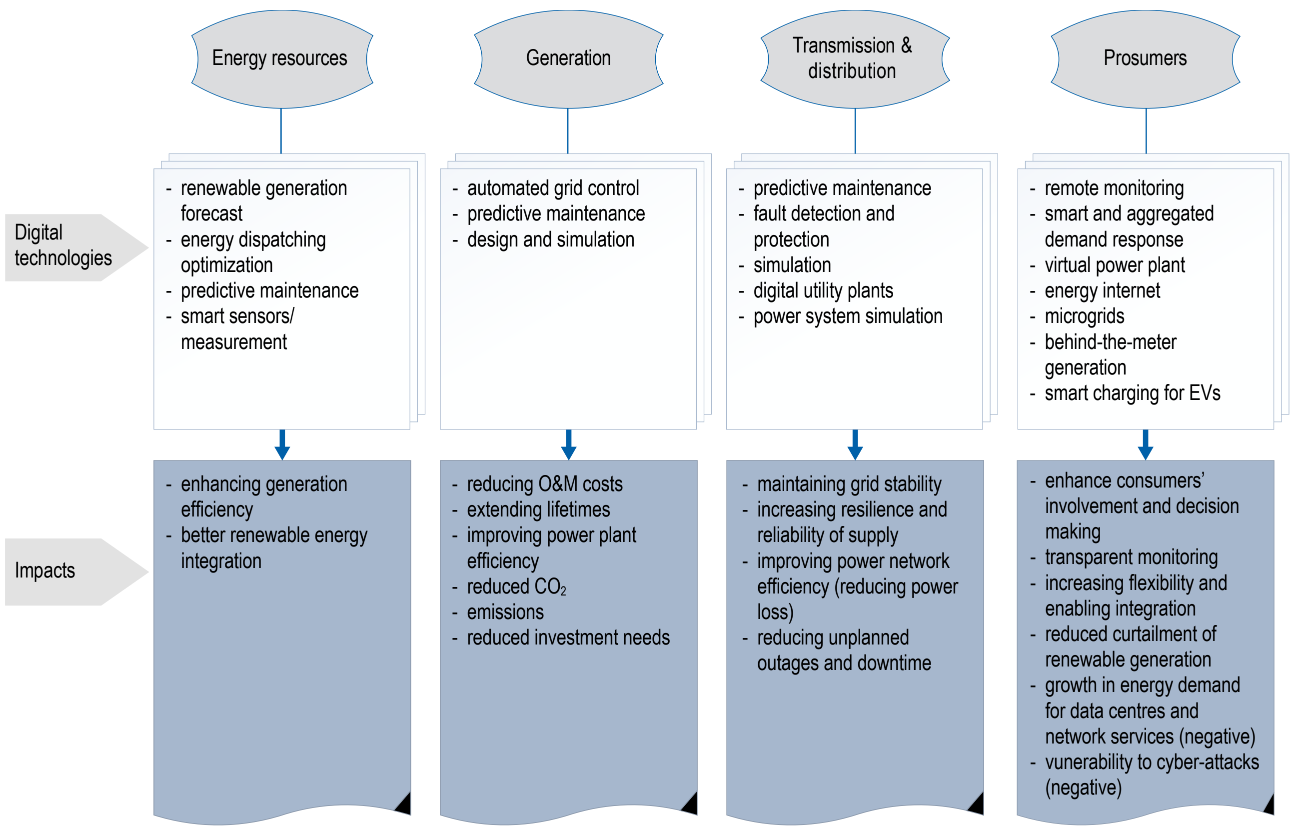

Figure 5-4 | Digital technologies and their impacts across the energy value chain

5.5.1 IoT/smart sensing

Internet of Things (IoT) is defined by the IEC as an "infrastructure of interconnected entities, people, systems and information resources together with services, which processes and reacts to information from the physical world and virtual world" (IEV 741-02-01:2020, ISO/IEC 20924:2018, 3.2.1). The IoT system includes IoT devices, IoT gateways, sensors, and actuators (IEV 741-02-07:2020, ISO/IEC 20924:2018, 3.2.7). IoT itself is a technology that is expected to reduce emissions, with one estimate claiming IoT technology could provide a 15% reduction in global emissions compared to the previous decade [82]. IoT technology also has a specific role to play in a zero carbon power system.

IoT is one of the great enablers in the drive towards a reliable zero carbon power system, bringing the availability of large and comprehensive data from the entire range of devices across the power system, which in turn allows for optimal and well-informed decision-making as well as remote and automated control [83].

Another term related to IoT in the power system is "smart sensing". Smart sensors can be seen as the evolution of the variety of sensors that have existed for years in power system operation, measuring quantities such as voltage and current, dissolved gases, temperature, and so on. A smart sensor performs functions additional to those of a traditional measurement device. As well as measuring a physical quantity, it may seek to evaluate the data measured, and for example, only report fault conditions to the broader control suite.

It is estimated that there were around 25 billion IoT devices in the power sector in 2018. This number is expected to grow to 75 billion by 2025 [84]. IoT and smart sensing technology can furnish a wide range of functions in the power system and provide benefits such as reducing the human costs of onsite inspection, identifying faults sooner, or improving system reliability. IoT and smart sensing technology can also help reduce energy consumption or facilitate greater operation of renewable energy generation. Some of the functions provided by IoT technology in the power system could include:

- Better monitoring and control of energy consumption. In the home, IoT technology is now enabling energy users to closely monitor what they use, and allowing better control of heating and cooling, the largest energy consumers in most homes. As another example, IoT technology enables improved control of street lighting, which can make up to 20% of municipal budgets [85]. Here the IoT technology, in the form of sensors and remote monitoring, control and management, is converting the streetlights into "smart streetlights" which can adjust their power consumption according to traffic and weather conditions.
- Smart meters are an example of IoT technology deployed by many power utilities. Smart meters allow system operators to better monitor energy flows in the network, assisting with infrastructure management and utilization, and the planning and forecasting of energy consumption and production. One forecast suggested that the use of smart meters can save utilities USD 157 billion by 2035 [86].
- Transmission or distribution system management and control. IoT technology can provide real-time feedback on the performance of a wide range of assets in the power system. This data enables detection of grid issues, improved outage recovery, and improved system stability.
- Demand-side services. IoT technology is a key enabler for many of the demand-side measures described earlier in this paper.
- Generation monitoring and control. IoT technology is particularly useful for monitoring and managing distributed generation (such as

rooftop solar) or storage assets. IoT technology also creates the opportunity for new market designs and business models [83].

The number of possible IoT devices in the power system is very large, from smart inverters to smart home controllers, weather monitoring and smart meters. An equally broad range of standards apply to these devices. These include:

- IPv6 over Low-Power Wireless Personal Area Networks (6LoWPAN)
- LiteOS (Unix-like operating system)
- OneM2M (one machine-to-machine)
- Data Distribution Service (DDS)
- Advanced Message Queuing Protocol (AMQP)
- Constrained Application Protocol (CoAP)
- Long Range Wide Area Network (LoRaWAN)
- Narrowband IoT (NB-IoT)
- Long-Term Evolution for Machine-Type Communications (LTE-M)
- Sigfox
- Power Line Communication (PLC)
- Bluetooth Low Energy (BLE).

Some of the challenges to the wider uptake of IoT technology in the power system include:

- Integrating IoT systems into legacy monitoring and control platforms
- Cyber security, safety (including functional safety) and privacy issues
- Cyber resilience: the ability of the system to resume operation after a breach of failure
- Scalability of the technology across millions of end points
- Data storage and management
- Energy consumption of IoT devices
- The immaturity of IoT standardization efforts

Case study: Smart meters and IoT in Italy

Italy has been overhauling its electricity metering systems, in order to allow both improved data collection and also integration with loads. Article 9, paragraph 3, of Legislative Decree 102/2014 provides that the Italian Regulatory Authority for Energy and Environmental resources shall define the specifications for the second-generation meters "taking into account the international standard IEC 62056”. Consequently, with Resolution 87/2016/R/EEL, the Italian Authority for Electricity, Gas and Water entrusted the Italian Electrotechnical Committee (CEI) [87] with the definition of a standard protocol for communication between 2G smart electricity meter and end-customer devices, in order to enable new opportunities and services related to consumption awareness and energy efficiency, such as new forms of supply, load modulation and home automation.

The efforts of the CEI resulted in technical specification Electricity metering systems – Communication with user devices, consisting of the following documents:

- CEI TS 13-82, *Electrical energy measurement systems – Communication with user devices - Part 1: Use cases*
- CEI TS 13-83, *Electrical energy measurement systems – Communication with user devices - Part 2: Data model and application layer*
- CEI TS 13-84, *Electrical energy measurement systems – Communication with user devices – Part 3-1: PLC protocol profile in the 125 kHz – 140 kHz band (C-band)*
- CEI TS 13-85, *Electrical energy measurement systems – Communication with user devices – Part 3-2: RF protocol profile in 169 MHz Band*
- CEI TS 13-90, *Electrical energy measurement systems – Communication with user devices – Part 3-3: Narrow band-IoT protocol profile*

To complete the set of standards, a new technical specification is currently being prepared on interoperability testing.

Building on this work, an agreement has been signed between the CEI and the Device Language Messaging Specification (DLMS) User Association [88], to initiate a collaboration for preparing equivalent documents at an international level, as well as for new applications such as the management of charging infrastructure for EVs (V2G) [89].

Case study: IoT in China's power system

China's State Grid company is exploring the convergence of traditional power system technologies with IoT technology, applying IoT cloud platforms, edge computing and short-range IoT communications technologies to distribution system operation [90]. As a result, the traditional power system information communications architecture of master stations and remote terminals is transforming into an IoT network architecture formed by cloud, edge and terminal devices.

The key features of State Grid's IoT network include:

- Intelligent terminals can automatically discover power distribution/consumption equipment, in a plug-and-play manner.
- The IoT communications are secured to prevent attack and eavesdropping.
- The IoT communications channels have backup (or redundancy) provision.

Such an IoT network has been deployed in the Shanxi and Shandong provinces of China, utilizing components that include edge computing IoT cards, internet protocol version 6 (IPv6) over high-bandwidth powerline carrier communications, and 5G communications modules. It is expected these systems will expand to 4 million intelligent terminals in 2022 [91].

In addition to management of State Grid assets, it is expected this IoT platform could extend to end-users or downstream equipment partners, where devices such as EV chargers are incorporated on the platform, bringing digitalization of the power system to a whole new level.

5.5.2 Big data and AI

Big data can, in simple terms, be defined as the collection and use of extremely large and complex data sets. The source of the big data in power systems is mainly the large number of IoT devices.

Artificial intelligence (AI) is a form of computing behaviour, in which machines demonstrate behaviour that appears "intelligent". An intelligent system can be defined as "any system that perceives its environment and takes actions that maximize its chance of achieving its goals" [92]. Modern AI approaches usually rely on the huge amounts of information provided by big data sets.

AI and big data have the potential to improve the efficiency of planning, operating, controlling, monitoring, optimizing, protecting, inspecting, and maintaining the power energy system. They are core to realizing the "smart sensing" systems described previously. A smart sensing system includes front-end sensors that measure physical values, with AI and big data techniques then being used to add "intelligence" to the sensing system, so that it does not just measure a physical quantity, but also analyzes the data collected and reports value-added information.

Big data and AI techniques may be used to make predictions of energy use, or future energy generation from renewable resources. They may be used to help in detecting anomalies in, or improve the operation of, major system assets, or to manage energy consumption and improve efficiency.

Lastly, AI and big data approaches are bringing a new requirement of "edge" processing to the power system. With the amount of data to be collected from the increasing number of smart meters and sensors in the digital power system, it is going to be nearly impossible to collect and process all the data centrally. Thus, there is a growing need to analyze and act on data close to where it is collected, with only a small amount of data sent to central infrastructure. Such a mechanism can be implemented through "edge computing" approaches (also known as "fog computing"), which makes use of AI methods at the gateway or node level, to process data locally.

5.5.3 Blockchain

Blockchain is a distributed ledger technology that is recently seeing a wide range of application across different sectors. A blockchain is a digital, distributed, immutable, and oftentimes public ledger that stores encrypted blocks of data across a network.

Blockchain brings a number of potential advantages compared to traditional data storage/communications approaches. These include:

- Enhanced security
- Immutability
- Confidence among all participants
- Reduced transaction costs
- Innovative business models

The fact that blockchain shares the core features of decentralization and coordination with the future power system makes it an interesting potential fit for application in the power sector. Uses for blockchain in the sector could include:

- Coordination of distributed resources
- Innovative finance mechanisms based on co-ownership and sharing of assets
- Decentralized and peer-to-peer energy trading
- Payment/billing
- Demand response schemes based on smart contracts

Blockchain technologies are still in an early stage of development with only existing implementations being relatively few and small in scale. There are many challenges to the wider uptake of blockchain technologies in the power system, with concerns including security, scalability, speed, governance, energy costs, flexibility, and user-friendliness.

5.5.4 Cyber security

Given the growing digitalization of the power system, the security of the system against digital or cyber attack is critical. Already a number of power system outages around the world have been attributed to cyber attack. As the number of "online" components in the power system increases, whether through new control methods or IoT devices, the risk of malicious cyber attacks multiplies, thus making cyber security a critical consideration for any digital power system component's operation.

Case study: Intelligent zero carbon campus

Huawei has proposed the concept of an intelligent zero carbon campus that ties together power system operations on a given campus (such as a university, hospital, housing or corporate estate) with energy-efficient heating, cooling and lighting equipment, energy-efficient building design, EVs, public transport and vehicle charging facilities. An example of such a campus is shown in Figure 5-5. Bringing these components together requires three focus areas: zero carbon, integration of devices, and "smart" control.

Information and communication technology (ICT) technologies such as IoT, big data and AI are used to provide real-time awareness across the campus of the energy status and carbon emissions of all components, and then to control devices to reduce emissions and improve economic value. The complexity here is significant, and Huawei proposes the campus would be managed by an "intelligent operations centre" that oversees campus energy, carbon and daily operations. The intelligent operations centre is a cloud-based platform that unifies and aggregates access to individual services from building services to energy management, as shown in Figure 5-6. The intelligent zero carbon campus concept received a World Summit on the Information Society prize in 2022, co-organized by the ITU, UNESCO, UNDP and UNCTAD. [93].

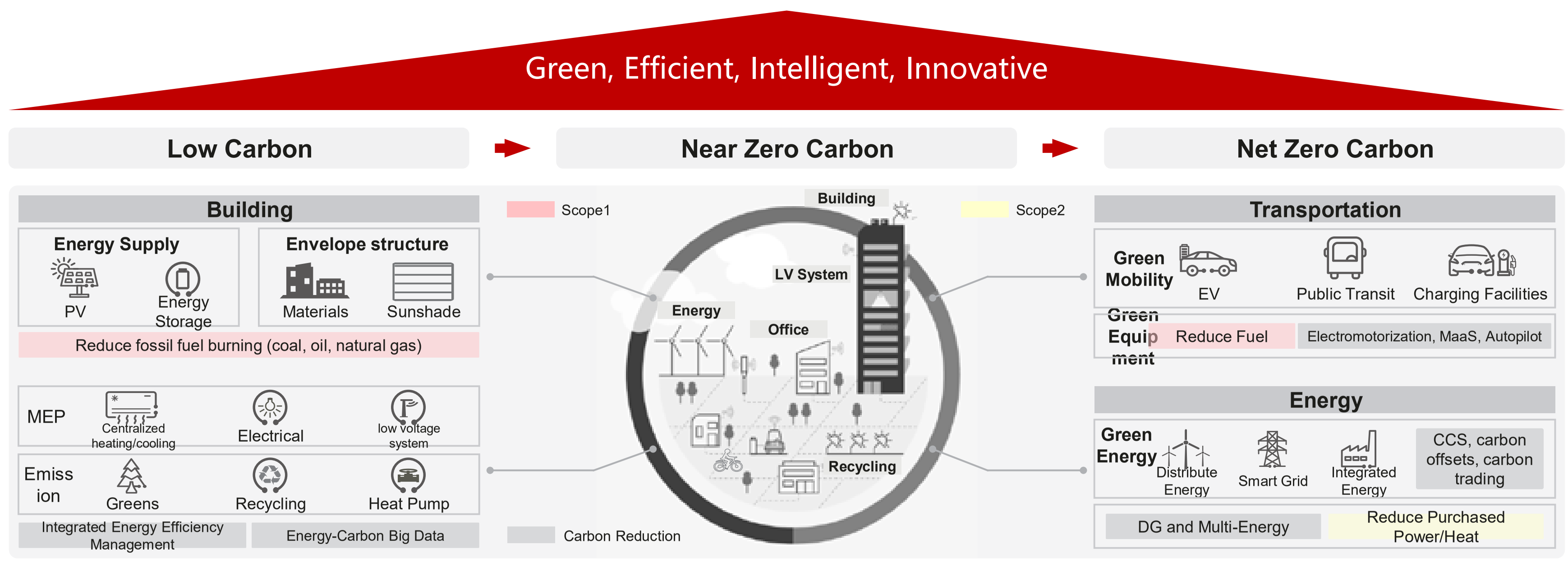

Figure 5-5 | An example intelligent zero carbon campus [courtesy of Huawei Electric Power]

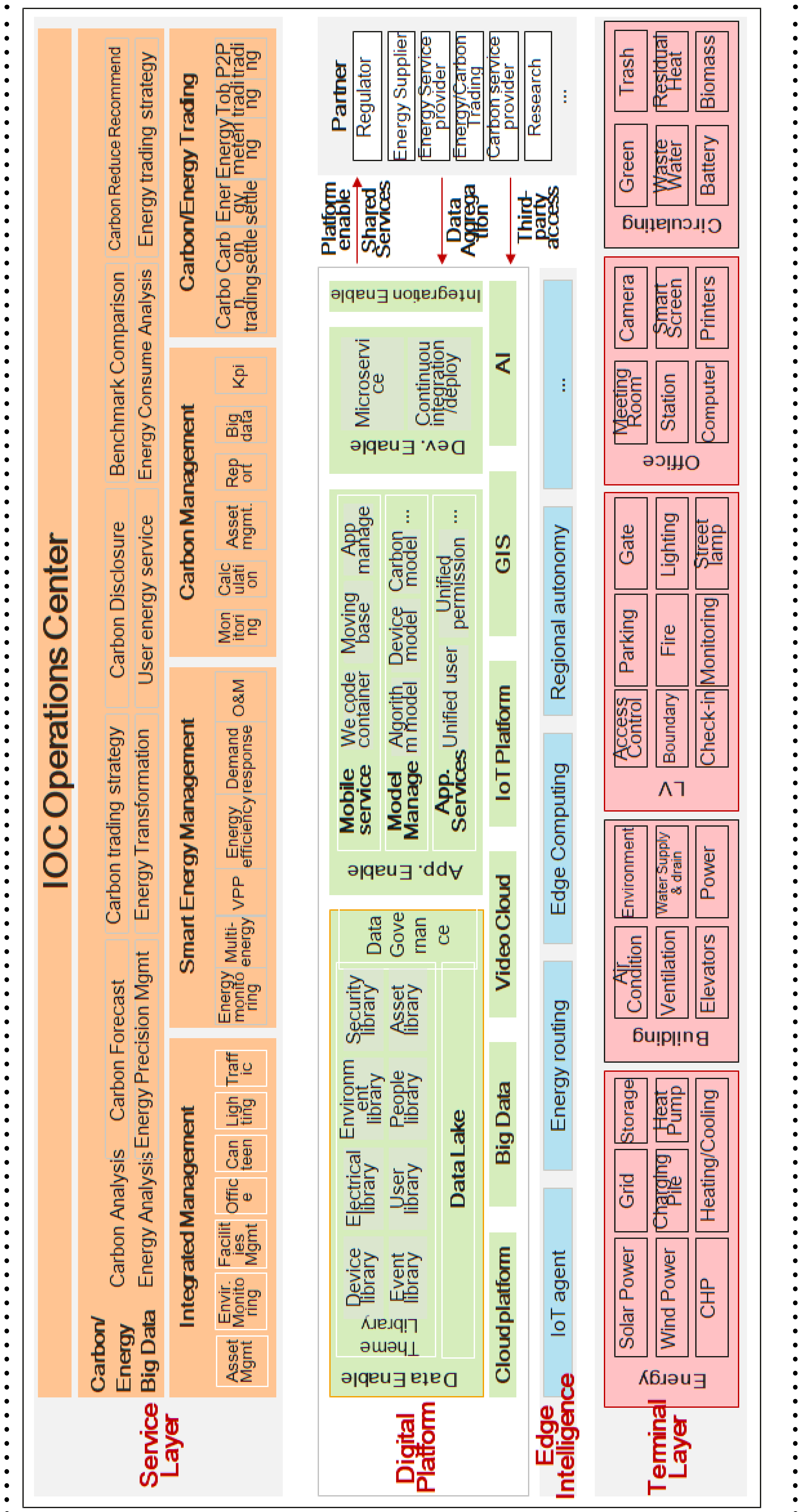

Figure 5-6 | Example system architecture for an intelligent zero carbon campus [courtesy of Huawei Technologies Company]

5.5.5 Simulation

The planning, design, and operation of zero carbon power systems require detailed engineering studies in order to understand the impacts of any change to system performance, reliability, safety, and economics. Properly conceived and conducted studies are a cost-effective way to prevent surprises during operation and to optimize equipment selection. These analytical exercises can be run at the planning stage, during operation, or after an event. A few examples of such studies are:

- Techno-economic analysis used to calculate the optimal size of individual components and a system arrangement that satisfies the technical requirements of the system.
- Unit commitment and energy management studies for reliability, economic or other objectives.
- Modelling the transient behaviour of the power system to identify reliability issues, understand the impacts of equipment failure and determine corrective measures.

A modern zero carbon power system is very complex, and the above engineering studies would be difficult, tedious, and time-consuming, if not impossible, to perform manually. The use of sophisticated power systems simulation software addresses this hurdle. Ultimately, simulation is a critical process in the development and operation of the new power system. Different simulation tools are used in the power system for different functions. These tools may be open-source or proprietary.

One recent type of simulation tool is hardware-in-the-loop (HIL) simulation, which aims to improve the reliability of a simulation by incorporating actual physical controllers (rather than a model) into the simulation. As such, HIL simulation aims to test how an actual controller behaves in real-time to realistic stimuli, with the broader power system represented by simulation.

Another recent phrase used regarding power system simulation is *digital twin*. A digital twin is a new concept of simulation that refers to the digital representation of a real-world entity or system. Whereas a traditional power system simulation would typically consider just one aspect of the power system, a digital twin is meant to replicate the entire operation of the system. Often, digital twin modelling will be extended to HIL tests, to understand how a particular piece of hardware interacts with the *entire* power system.

5.5.5.1 Simulation challenges

As described throughout this paper, the operation of a zero carbon power system will be significantly different, and more complex, than traditional fossil fuel-based power systems.

Ultimately, traditional simulation tools fail to thoroughly reflect the complex characteristics of a zero carbon power system. Traditional tools do not sufficiently consider the variation in generation, the application of very large amounts of power electronic devices, and the interaction of large numbers of distributed energy assets. Further, many time domain-based simulation analysis methods and tools fail to accurately simulate the multi-timescale dynamics and massive switching control of power electronic devices in the zero carbon power system. Given these challenges, additional research and development work is needed to realize more accurate and comprehensive simulation methods that will include modelling and simulation of various renewable energy resources, DC transmission, and the new control and protection methods used in zero carbon power systems of the future.

5.6 Alternative technologies

Given the massive challenge posed by the goal of decarbonizing the power system, a huge range of new or alternative technologies have been claimed to be able to assist the transition. The previous subsections of this paper have focused on technologies that are widely accepted, are well understood, and have seen significant uptake already. The following technologies have yet to see significant uptake but hold promise for assisting the transition to net zero.

- Superconductors are materials that exhibit very low electrical resistance (very close to zero), and thus very high electrical current-carrying capacity. If such materials could be made and deployed practically, they could reduce the size, cost and losses in electrical machines and transmission infrastructure. For example, a superconductor-based transmission line may have four to eight times the carrying capacity of a traditional cable, with less than half the losses. Unfortunately for almost any material to display superconductivity, it has to be cooled to very low temperatures, which significantly impacts their cost and practical usefulness. While so-called "high temperature" superconductors have been discovered in recent decades, they still require cooling to well below –100°C, and thus their practical application remains limited. Today, superconducting transmission lines have remained at the research demonstration stage, with the longest length of deployed superconducting cable being 1 km.
- Electrolyzers (to produce hydrogen from electricity) and fuel cells (to produce electricity from hydrogen) will take on a much greater role in the power system, and in the industries it supplies, if zero carbon hydrogen grows in usage.
- Waste-to-energy (WTE) is another technology that has seen a growing level of utilization in many countries during the last couple of decades. WTE plants convert waste streams that would typically have gone to landfill to useful electricity that is dispatched in the power system. Though the level to which WTE as a technology is carbon-free is debated, there are suggestions of employing WTE technology together with carbon capture and storage (CCS) to eliminate the carbon emissions. In such a scenario, WTE plants that operate on waste streams with a significant biogenic component could be converted to zero or negative CO_2 emission systems with CCS [94].

Section 6

Standardization and conformity assessment analysis

Given the challenges and technical changes described throughout this paper, standards will play a key role in easing the transition to a zero carbon power system. Furthermore, if standards fail to keep up with the massive changes occurring in the power system, there is a risk to system performance and reliability.

Case study: Wind power in Spain

Around the world, power system operators and regulators are challenged by having to adopt the new methods of operation outlined in the previous sections of this paper, amidst very rapid increases in renewable energy. At times, the arrival of renewable generation outpaces the changes in standards or regulation required to keep the power system reliable. One example of these challenges is the arrival of the first large-scale wind power plants into the Spanish power system in 2006. When a fault occurred in Spain's grid, several MWs of wind power generation was suddenly lost in a synchronized manner, due to the wind power plants disconnecting from under-voltage trips – Figure 6-1 shows a voltage map as the fault occurred. Consequently, there were widespread outages in the Spanish grid. These outages could have been avoided by the wind generators being required to "ride through" the voltage disturbances they saw. Such a requirement would have led the wind generators to continue generating through the voltage disturbance, ensuring the supply needed to match demand.

The behaviour of the wind generators in Spain in 2006 was not faulty. Disconnection after a voltage disturbance was common practice for distributed generation in 2006 and was required by most grid regulations around the world. This has now changed. It was realized that as distributed wind or solar generation becomes such a significant portion of power system generation, these units will need to ride through power system disturbances, and this fault ride- through practice is now required in many grid codes around the world. In Spain, two free national standards have been implemented related to grid connection at low and medium voltage respectively, which include specific considerations regarding protection and calibration to ensure faults in the generator do not cause grid issues, but also preventing generators from early disconnection in the event of grid disturbances. These standards specify a particular range of frequency and voltage through which a generator is expected to remain grid-connected [95, 96].

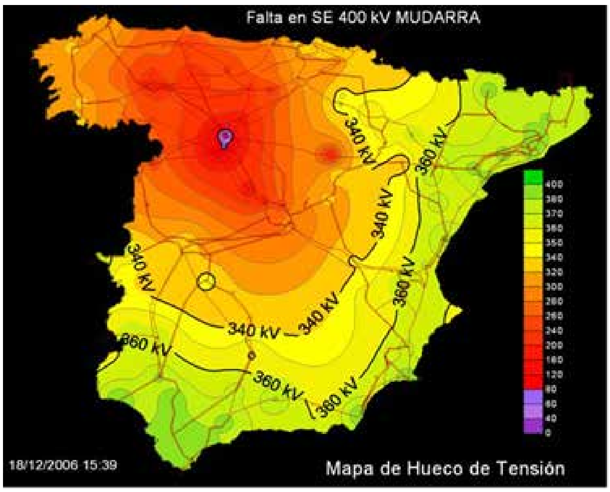

Figure 6-1 | Spanish voltage map when a fault occurred on a single bus [97]

As can be seen by this example, ensuring that regulation and standards keep pace with the transition to net zero and change along with the profound changes in technology and power system operating practices will be key to ensuring reliable power system operation in the future.

Given the sorts of issues shown in the case study above, whether standardizing business practices, ensuring interoperability between systems, or covering technology operation, the following subsections consider broad topics in which standardization efforts can make a significant impact. A number of existing standards, or standards efforts, are listed that are relevant to the transition to a zero carbon power system. Further, given the significant pace and scale of change involved, a number of new standards will be required. These range from standards on the performance or operation of particular technologies to standards guiding the interoperability of technologies.

6.1 Standards to facilitate interconnection, integration and interoperability

Interoperability and interconnection are key functions in any power system. Existing standards that are particularly relevant to a zero carbon power system include those maintained by the following IEC or ISO committees and subcommittees:

- IEC TC 8: System aspects of electrical energy supply
- IEC TC 8/SC 8A: Grid integration of renewable energy generation
- IEC TC 8/SC 8B: Decentralized electrical energy systems
- IEC TC 8/SC 8C: Network management in interconnected electric power systems
- IEC TC 13: Electrical energy measurement and control
- IEC TC 120: Electrical energy storage (EES) systems
- ISO/TC 301: Energy management and energy savings

To facilitate the demand integration and demand management discussed in earlier subsections, a range of new standards will be required:

- Standards that facilitate interoperability between individual components, for example, between power system operators and a particular load, such as a pool pump or air conditioner.
- Standards that facilitate interoperability at a system level. A variety of "systems" are of interest here. Examples could include a large commercial building, a zero carbon industrial park or microgrid, or a large industrial site or data centre. Standards have a role to play to facilitate the interoperability within each of these systems, and also to facilitate the interoperability between each of these systems and the power system.

Some specific examples are provided in subsections 6.1.1 and 6.1.2.

6.1.1 Bidirectional vehicle-to-grid interaction in the distribution network

As described earlier in this paper, EVs represent a very significant additional demand on the power system, and ideally their charging behaviour would be coordinated with power system operations. Such vehicles may even discharge into the power system during times of peak demand. As this represents a new type of (potentially) bidirectional controllable load, new standards will be required to implement this function, such as ISO 15118.

6.1.2 Interaction between natural gas and electricity systems

The significant increase in gas-fuelled power plants has intensified the interdependency between the electricity and gas systems. Both systems are complex to operate; an outage in one system can have significant impacts on the other. Thus, the integration and synergistic operation of these two systems will be key in any power system operating with a significant amount of natural gas.

The IEC Systems Committee (SyC) Smart energy has started work on this growing challenge, with IEC SRD 63200:2021 considering how to extend the smart grid architecture model to describe the interaction between the grid and heat/gas systems. Additional standards to coordinate the interaction and interdependencies of these systems would be helpful.

6.2 Standards for power generation technology

A broad range of very detailed standards exist covering generation technologies in the power system. These include standards maintained by IEC and ISO committees including:

- IEC TC 2: Rotating machinery
- IEC TC 4: Hydraulic turbines
- IEC TC 5: Steam turbines
- IEC TC 21: Secondary cells and batteries
- IEC TC 45 Nuclear instrumentation
- IEC TC 47/WG 7: Semiconductor devices for energy conversion and transfer
- IEC TC 69: Electrical power/energy transfer systems for electrically propelled road vehicles and industrial trucks
- IEC TC 82: Solar photovoltaic energy systems
- IEC TC 88: Wind energy generation systems
- IEC TC 105: Fuel cell technologies
- IEC TC 114: Marine energy – Wave, tidal and other water current converters
- IEC TC 117: Solar thermal electric plants
- IEC TC 120: Electrical energy storage (EES) systems
- ISO/TC 85: Nuclear energy, nuclear technologies, and radiological protection
- ISO/TC 180: Solar energy
- ISO/TC 238: Solid biofuels
- ISO/TC 255: Biogas

Subsections 6.2.1 to 6.2.3 cover generation topics or technologies requiring a new standards effort.

6.2.1 Offshore wind power

While the onshore wind industry is relatively mature, the offshore wind industry requires many different and new practices and technologies. Particularly relevant to the activities of the IEC are the following standards requirements:

- Online monitoring and communications technology for offshore wind, to facilitate communications by land-based maintenance and operations personnel with offshore infrastructures. This suite of standards could include online monitoring sensors, alarm and fault reporting approaches, and backend operations software.
- Communications and control technology for offshore wind. Offshore wind turbines can be located many tens of kilometres offshore and may be joined by DC or AC interconnectors to the power system on land. Standardized communications and control systems need to be realized to enable interaction with land-based power system operations, including frequency and voltage management and fault response.

Other new technologies such as low frequency power transmission and high voltage DC power systems with direct DC generator connection are particularly relevant to offshore wind farm operation, but as these can be applied in onshore applications also, they are listed separately below.

6.2.2 Fault ride-through

As discussed earlier in this paper, a key requirement for large renewable energy generators will be to remain connected to the power system during system transients or faults. While various countries have already standardized such behaviour, there exists a lack of common internationally accepted standards coordinating fault ride-through or related characteristics.

6.2.3 Case study: European Marine Energy Centre hydrogen testing

The European Marine Energy Centre (EMEC) is the world's first IEC renewable energy test laboratory (IEC RETL) focused on the marine energy sector. The laboratory has verified compliance to IEC TS 62600-200 at the Verdant Power Roosevelt Island Tidal Energy (RITE) Project. The EMEC is now producing hydrogen as a way of storing energy from its marine energy projects, which will require a whole new series of compliance assessment and testing, associated with the hydrogen aspects of the facility [98].

6.3 Standards for power transmission technology

Existing standards covering electrical power transmission are maintained by IEC committees including:

- IEC TC 20: Electric cables
- IEC TC 90: Superconductivity
- IEC TC 115: High voltage direct current (HVDC) transmission for DC voltages above 100 kV
- IEC TC 122: UHV AC transmission systems
- IEC SyC LVDC: Low voltage direct current and low voltage direct current for electricity access

New standardization efforts that should be pursued in order to keep up to date with the latest power transmission technologies are covered in subsections 6.3.1 to 6.3.3.

6.3.1 Low frequency power transmission

A relatively new area of interest in power system technology is low or fractional frequency AC (LFAC) transmission systems. These technologies operate at frequencies such as 16 Hz, instead of the 50 Hz or 60 Hz more typical of AC power transmission. Operating at such low frequencies can minimize frequency-related losses, which is particularly helpful for offshore wind farms located long distances (+180 km) offshore. Low-frequency power transmission equipment is still a work in progress, and the reliability of field applications has yet to be determined. As a result, relevant standards must be established as soon as possible to close the technological gap.

6.3.2 High voltage DC power systems with direct generator connection

With the increase in transmission distances to remote renewable energy generators, flexible DC transmission technology is of great interest as a way to reduce losses associated with AC transmission. High voltage DC transmission technology, in which the generator produces DC power and is directly connected to the DC power system (using technology such as voltage source converters) is particularly useful here, and yet standards for this area are lacking. It is thus necessary to formulate relevant standards covering the methods, test items and requirements of HVDC systems with direct connection of generators, from commissioning and testing to system operation.

6.3.3 Superconducting cable

The existing superconducting cable standard IEC 63075:2019 mainly deals with the testing of cables. Certain differences exist between superconducting cables and conventional cables in terms of traction force, side pressure, bending radius, etc. The laying process is more complicated than that of conventional cables, and a poor laying process will affect the cooling of the superconducting cable. Short circuit current characteristics of superconducting cables are quite different, which affects protection system design. Given these differences, as superconducting cable technology gradually enters the stage of experimental demonstration and commercial operation, relevant new standards need to be compiled.

6.4 Pervasive digitalization of power technology

The use of information (or "digital") technology is changing rapidly in power systems, with power systems now becoming "cyber-physical" systems, whose reliability depends as much on the information technology as it does on the large physical infrastructure. Existing relevant standardization activities include:

- IEC TC 13: Electrical energy measurement and control
- IEC TC 23/SC 23K: Electrical energy efficiency products
- IEC TC 57: Power systems management and associated information exchange
- IEC TC 118: Smart grid user interface
- IEC SyC Smart energy
- IEC SyC Smart cities: Electrotechnical aspects of smart cities
- ISO/IEC JTC 1/SC 41: Internet of Things and digital twin

Pervasive sensing will be a key enabler for the digitalization of the zero carbon power system. Better sensing will allow the grid to operate with greater flexibility and resilience and to accommodate a high penetration of variable generation sources. The sensors needed in a power system are different than those required in other markets, with unique reliability, coordination and communication requirements. With this in mind, a dedicated technical committee/ subcommittee is recommended to develop new standards for power grid sensor technologies.

6.5 Standards for cyber security

As with all other cyber physical systems, power systems are becoming increasingly exposed to cyber threats, and these threats are growing in intensity and frequency. To address these risks, the IEC has developed the following:

- IEC 62351 series of standards that addresses the security of the TC 57 series of protocols
- IEC 62443 series of standards that address cyber security issues for industrial automation and control systems
- IEC Technology Report Cyber security, *Cyber security and resilience guidelines for the smart energy operational environment*

The following IEC commitees continue to develop solutions to address cyber security risks:

- IEC ACSEC: Advisory committee on information security and data privacy
- IEC TC 57: Power systems management and associated information exchange
- IEC TC 65: Industrial process measurement, control and automation
- IEC SyC Smart energy JWG 3: Cyber security task force

6.6 Standards for hydrogen-based power systems

As described throughout this paper, hydrogen may play a significant role in the power systems of the future. The most relevant existing standards covering hydrogen are set by ISO/TC 197: Hydrogen technologies.

As described in Section 5, hydrogen technologies may offer a form of new flexible major load (in the electrolysis of water to produce hydrogen) or storage/generation (in the use of hydrogen in a fuel cell to produce electricity). Either of these functions can be tied closely to power system operation, and the fluctuations of variable generation. This will require new standardization efforts to link the systems and ensure safe reliable operation.

6.7 Power system carbon management/life cycle assessment

Operation of a "power system" is broader than managing electrical current flow and infrastructure. A zero carbon power system will require careful accounting and management of carbon emissions throughout the life of the power system and its components. Standards-related consideration of such activities are included in subsections 6.7.1 to 6.7.3.

6.7.1 Power system carbon footprint calculation

In working towards a zero carbon power system, it will be necessary to quantify carbon emissions associated with power system operations. These quantification methods need to be compatible, comparable and consistent across a large range of electrical technologies, different power system operating methodologies and geographies. A series of standards on carbon measurement or carbon accounting will be key to this goal. While ISO TC 207: Environmental management, has an existing standard on life cycle carbon assessment, more focused standards that concentrate on electronic devices and the major components of a zero carbon power system are needed.

6.7.2 Green power markets

Trading of green or zero carbon products is likely to be a key feature of any zero carbon power system. While such trading schemes exist around the world, they are often bespoke and relatively unique to their country of operation. A unified series of standards for green power trading could accelerate the development of the zero carbon power industry.

6.7.3 Carbon capture, utilization and storage

As described in Section 5, carbon capture, utilization and storage technologies may have a critical role in preventing the carbon emissions from traditional fossil fuel generation entering the atmosphere, and/or in removing existing carbon emissions from the atmosphere, thus helping to avoid climate change. Existing standards that cover this area are prepared by ISO/TC 265: Carbon dioxide capture, transportation, and geological storage. Further standards are likely to be required as this technology matures.

6.8 Conformity assessment

Existing systems on conformity assessment include:

- IECRE (IEC System for Certification to Standards Relating to Equipment for Use in Renewable Energy Applications)
- IECEE (IEC System of Conformity Assessment Schemes for Electrotechnical Equipment and Components)
  - 23 product categories, including

    - Photovoltaics: www.iecee.org/about/photovoltaics
    - Batteries: www.iecee.org/about/batteries
    - Electrical efficiency: www.iecee.org/about/electrical-efficiency-e3
    - Motor energy efficiency: www.iecee.org/about/gmee
- IECEx (IEC System for Certification to Standards Relating to Equipment for Use in Explosive Atmospheres)
  - Relevant explosive equipment:
    - Renewable energy sources/fuels
    - Marine ships/vessels using gases or other low-flashpoint fuels

6.9 Simulation and testing procedures

As discussed in Section 5, the integration of large amounts of variable renewable generation while maintaining power system security will rely on simulation and modelling of the power system. Such simulation requires accurate models of individual generation assets that replicate the real-world behaviour of these devices. For those modelling the power system, obtaining such models from commercial generator vendors can be challenging. Standards have a role to play here and could specify the minimum performance of generator models.

Similarly, the testing of the integration of large amounts of variable generation, whether physical or simulation testing, is made more complex without standardized responses from assets, or agreed test procedures. Once again, standards have a role to play here, allowing comprehensive, repeatable test results across vendors and system topologies.

6.10 The standardization process

To ensure that energy systems, platforms, devices and markets can work effectively in a zero carbon system, standards have a critical role to play, ensuring interoperability, maintaining a minimum level of performance, and helping guide the transition towards new technologies and operating regimes. Ideally, regulations and standards would be coordinated around the world.

A coordinated approach to standards is paramount, but challenged by:

- Different market models across the world
- Different grid architectures around the world
- The fast pace of change in the power system
- The need to have some amount of regulation, but also to ensure the opportunity for new innovation

One way to meet these challenges is to publish and update standards roadmaps and architectures, ensuring a unified approach and strategy to power system transition. The IEC SyC Smart energy is developing, maintaining and operating a collaborative standards roadmap. The first edition of this roadmap, IEC TR 63097:2017 provides standards users with guidelines to select the most appropriate set of standards and specifications for their needs. These standards and specifications are either existing or planned, provided by IEC or other bodies. The roadmap also aims at creating a common set of guiding principles that can be referenced by end-users and integrators who are responsible for the specification, design, or implementation of smart energy systems. As a living document, this roadmap evolves to serve the highest priority needs as identified by stakeholders. These needs are then written into the SyC Smart energy development plan. Current topics identified for future work include distributed energy management systems, management of distributed energy storage systems based on EVs, and coordination of cyber security. Further topics specific to zero carbon power systems could certainly be suggested to, or considered by, the IEC SyC Smart energy.

As well as roadmaps identifying future standards needs, it is necessary to consider *how* standards are developed, to enable innovation, and facilitate an environment in which standards can evolve together with rapidly changing technologies and technical approaches.

6.11 A systems approach

The very broad range of technologies involved in a zero carbon power system, together with the convergence of operating relatively small devices in close interaction with large-scale infrastructure, will require a more top-down approach to standardization. This should be based on a systems approach that starts at the overall system architecture, rather than the traditional bottom-up approach that focuses on individual components.

IEC systems committees could be the basis of the systems approach needed for the huge amount of standardization work required for zero carbon power systems. IEC systems committees develop high-level interfaces and functional requirements that span the work of several technical committees and subcommittees, to support those committees, increase interaction between them, and enhance overall consistency. Through collaboration and consensus, the systems committees develop an IEC work plan that involves all relevant technical committees and subcommittees, with a secretariat provided by the IEC Secretariat in Geneva.

Given the breadth of zero carbon power system activities, there is also an increased need for co-operation with standards developing organizations other than the IEC, as well as with relevant non-standards bodies. The systems approach also has implications for the IEC Conformity Assessment Systems and processes.

Section 7

Conclusions and recommendations

Many nations around the world have started a journey towards decarbonizing their power system. This is a journey of great change and many challenges. It will impact all operations of the power system, from the end-users, regulators and business models to the technologies that generate, transmit, distribute, store and utilize electrical energy.

Given the breadth of change and technical challenges described throughout this paper, standards have a key role to play in the evolution of the power system, and in facilitating the transition to net zero.

There exists already a broad range of standards relevant to the transition to a net zero power system: from standards focused on sector integration or conformity assessment to technical standards that focus on the details of a particular technology; from solar photovoltaic systems to the control of a nuclear power plant. These standards will need to be augmented, with a range of new standards required for recently-arrived technologies or operational practices, as well as for those in the future.

Interoperability standards will have a key role to play in a zero carbon power system, and new standards will be required here. As shown in Section 5, a zero carbon power system is likely to have much closer ties between the supply and demand sides of the power system, which will need to be facilitated by standards. Generators will need to operate more dynamically, being managed to respond to rapidly changing net loads on the power system, and load will need to be managed to operate in response to rapidly changing available generation.

New standards will be required for new technologies in the power system. Examples are likely to include standards to support the offshore wind industry, new transmission technologies, or carbon capture and utilization plants. The transition of the power system with the latest information, control and communications approaches, and the raft of new digital technologies this entails, will require a range of new "digital"-related standards.

Lastly, standards will be required for new business practices, from the operation and integration of green power markets to life cycle carbon assessment for the various potential paths to net zero operations.

Ultimately, regulation and standards constitute key mechanisms that tie the power system together. As shown by a variety of case studies throughout this paper, having these mechanisms keep up with the rapid changes in technology is a significant challenge. However, it is a challenge that simply must be met: ensuring that regulation and standards keep pace with the transition to net zero is absolutely key to guaranteeing reliable power system operation into the future. This requirement may mean that it will be necessary to consider *how* standards are developed, to enable innovation and a faster pace of change, and to facilitate an environment where standards can evolve together with rapidly changing technologies and technical approaches.

Based on the reviews and research that underpin this paper, a number of recommendations can be made for consideration by the IEC and broader stakeholders.

7.1 Recommendations to government, industry and broader stakeholders

Recognize that the transition to a zero carbon power system requires massive change, and that massive change requires time. If we are to meet zero carbon commitments, the transition of the power system needs to accelerate dramatically. This will require policy, regulatory and financial assistance.

Appreciate that from the perspective of an end-user, a zero carbon power system is likely to appear significantly more complex than what end-users have been used to. Zero carbon power systems may require more user involvement in demand-side management, or active participation in new market or trading mechanisms. This additional complexity is likely to require education and awareness campaigns, in order that end-users not be disadvantaged in the transition to a zero carbon power system.

7.2 Recommendations regarding new standards

A very large range of new standards will be required to support the transition to a zero carbon power system. It is recommended that the IEC and other standards developing organizations:

- Accelerate their efforts to create new standards for technologies *already* appearing in the power system, such as offshore wind generation, or vehicle-to-grid technology.
- Work to quickly address the disparate range of often incongruent interoperability approaches appearing in power systems. Standards are needed to harmonize the interoperability of (for example) loads, generation, and distribution system operators.
- Create new standards that enable the convergence of the latest information, sensing and communications technologies with power system operation practices, to facilitate a digitally-optimized power system.
- Increase their efforts on producing roadmaps or similar documents that identify standardization needs, and then plan and drive a harmonized approach to meeting these needs.

7.3 Recommendations regarding standardization practices and processes

Standards are already lagging behind changes appearing in the power system, and given the zero carbon commitments of power systems around the world, the transition of the power system needs to accelerate. Considering this, a new approach to standardization, to standards writing, organization and conformity assessment is needed. It is recommended that the IEC and other standards developing organizations:

- Seek to achieve more commonality in worldwide standards and regulation – the pace of change needed in the transition to zero carbon requires common, widely accepted and harmonious power system standards.
- Encourage the initiation of new standards and regulation by taking a top-down approach to the generation of roadmaps and standards architectures that quickly make clear the new standards and regulation required, and how these all tie together.
- Consider how to speed up the standards creation process, so that standards can (at the very least) keep up with the very rapid arrival of new technologies and the pace of change needed to meet zero carbon goals.
- Take a systems approach to the identification of standards requirements, and creation of new standards. Zero carbon power systems require standardization work across an incredible range and complexity of technologies and practices. A systems approach is needed to

ensure interoperability of these standards and technologies.

Net zero carbon power systems are no longer a remote possibility of some distant future. Many countries around the world have committed to net zero carbon emissions targets, and a variety of pressures mean that power systems around the world are changing dramatically. These changes have profound implications for all IEC stakeholders, from system operators to equipment manufacturers and service providers, or power system end-users. Understanding the changes detailed in this paper, the new technologies, operating principles and standards requirements, will ensure the IEC remains at the forefront of the evolution now underway.

Annex A
National roadmaps to net zero

While many nations around the world have committed to net zero carbon targets, their paths to achieving net zero vary quite significantly. The following links provide more information on how individual nations are planning to realize their net zero target.

Australia (NSW Electricity Infrastructure Roadmap):

- www.reuters.com/article/us-australia-renewables-idUSKBN27P03O

Brazil (Renewable Energy Law):

- www.dsneg.com/info/the-renewable-energy-law-review-brazil-64699696.html

Canada (Marine Renewable Energy Technology):

- www.canada.ca/en/services/environment/weather/climatechange/climate-plan/net-zero-emissions-2050.html

Caribbean (Sustainable Energy Roadmap and Strategy):

- https://c-serms.org

China (Renewable Energy Roadmap):

- www.reeep.org/projects/china-roadmap-30-renewable-energy-penetration-2030#:~:text=The%20Chinese%20government%20has%20issued,in%20the%20country%20has%20boomed

EU Commission (Offshore Renewables Roadmap):

- www.offshore-energy.biz/eu-commission-reveals-new-roadmap-for-offshore-renewables/?utm_source=marineenergy&utm_medium=email&utm_campaign=newsletter_2020-07-17

India (Renewable Electricity Roadmap):

- https://shaktifoundation.in/report/report-indias-renewable-electricity-roadmap-2030

Indonesia (Power Sector Roadmap):

- https://iesr.or.id/en/pustaka/summary-a-roadmap-for-indonesia-power-sector

Japan ("Beyond-Zero" Carbon Roadmap):

- www.meti.go.jp/english/policy/energy_environment/global_warming/roadmap

Maldives (Energy Sector Roadmap):

- www.adb.org/publications/renewables-roadmap-energy-sector-maldives

Netherlands (Floating Solar Energy Roadmap):

- www.offshore-energy.biz/dutch-government-releases-floating-solar-energy-roadmap/?branch=premiumarticle&utm_source=marineenergy&utm_medium=email&utm_campaign=newsletter_2021-02-10

Nigeria (Renewable Energy Master Plan):

- https://en.wikipedia.org/wiki/Nigeria_Renewable_Energy_Master_Plan

Pacific Islands (Renewable Energy Roadmap):

- https://irena.org/publications/2013/Sep/Pacific-Lighthouses-Renewable-Energy-Roadmapping-for-Islands

South Africa (Solar Energy technology Roadmap):

- www.energy.gov.za/files/SETR/SOLAR%20ENERGY%20TECHNOLOGY%20ROADMAPNew%20Folder/setr_overview.html

Spain (Offshore Wind and Marine Energy Roadmaps):

- www.evwind.es/2021/12/12/spain-approves-the-offshore-wind-energy-roadmap/83762
- www.plocan.eu/en/el-gobierno-fija-la-hoja-de-ruta-de-la-eolica-marina-y-las-energias-del-mar-para-espana-2

UK (Renewable Energy Roadmap):

- https://climate-laws.org/geographies/united-kingdom/policies/uk-renewable-energy-roadmap#:~:text=The%20Roadmap%20outlines%20how%20the,key%20actions%20for%20each%20technology.

US (Energy Efficiency and Renewable Energy Roadmap):

- www.epa.gov/energy-efficiency-and-renewable-energy-sips-and-tips/energy-efficiencyrenewable-energy-roadmap

International Renewable Energy Agency (IRENA)

- Renewable Energy Roadmaps: www.irena.org/remap
- Africa 2030 Roadmap: www.irena.org/publications/2015/Oct/Africa-2030-Roadmap-for-a-Renewable-Energy-Future

IEA (Net Zero by 2050):

- www.iea.org/reports/net-zero-by-2050

UN Group of Experts on Renewable Energy:

- https://unece.org/sustainable-energy/renewable-energy

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Notes

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