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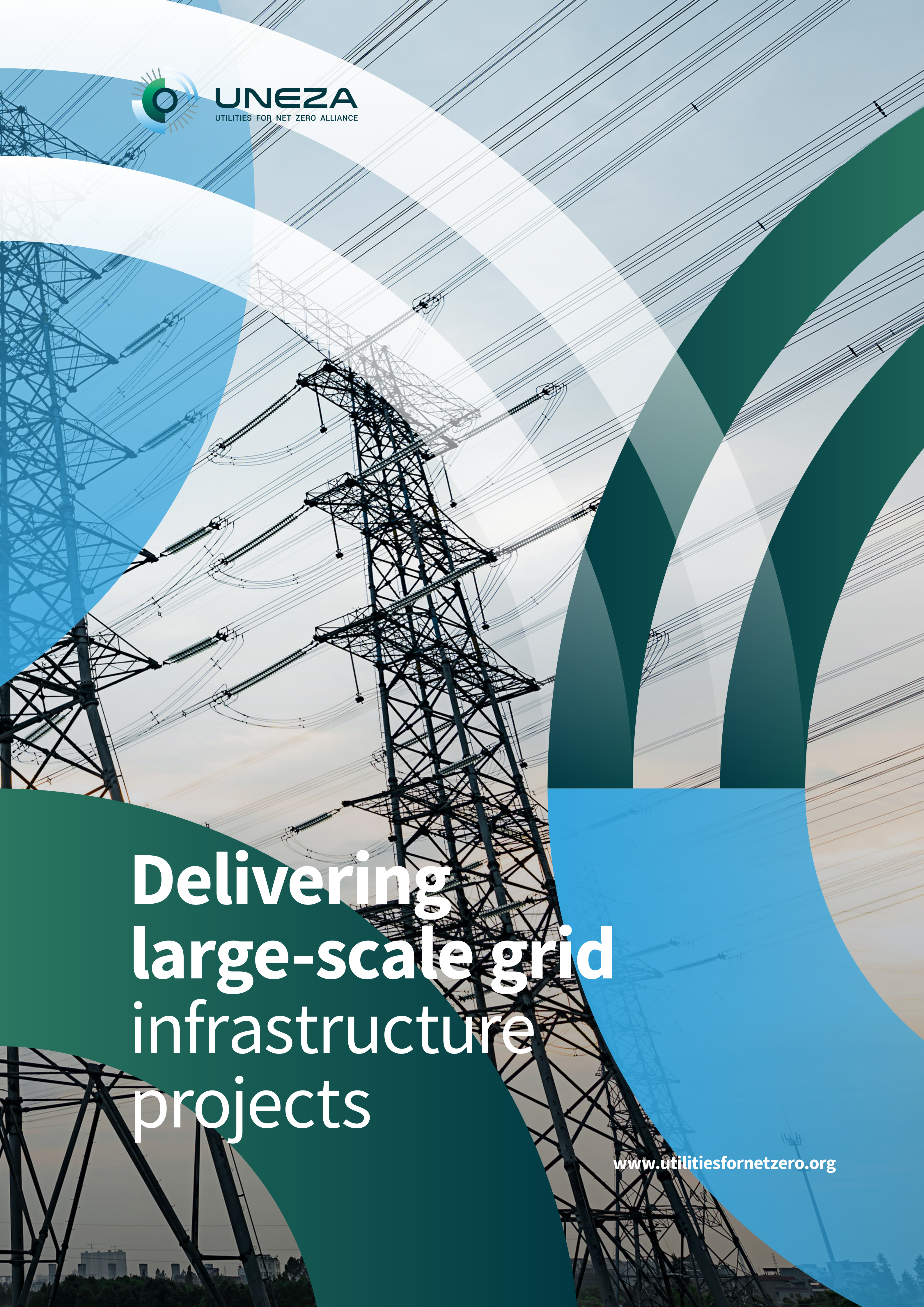

Delivering large-scale grid infrastructure projects

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About UNEZA

The Utilities for Net Zero Alliance (the “Alliance”) is the international platform for co-operation among entities operating within the power utilities ecosystem, to address and overcome common barriers to the realisation of net-zero ambitions and more near-term emissions reduction targets. The Alliance seeks to shape dynamic new partnerships and forge effective channels for dialogue with key public and private stakeholders. UNEZA’s members and partners recognise that the key to unlocking the utility sector’s global energy transition potential lies in the ability to deliberately target existing structural, regulatory and financial impediments and challenges that may stand in the way of progress. UNEZA operates under the guidance of the International Renewable Energy Agency (IRENA) and the UN Climate Change High-Level Champions, ensuring a focused and strategic approach to achieving a sustainable energy future.

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2030 BREAKTHROUGHS

UNEZA UTILITIES FOR NET ZERO ALLIANCE

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Abbreviations

COP	Conference of the Parties to the United Nations Framework Convention on Climate Change
EMDE	emerging markets and developing economies
EUR	euro
GBP	British pound
GDP	gross domestic product
GEC	Green Energy Corridor
GGI	Green Grids Initiative
GW	gigawatt
HVDC	high-voltage direct current
IEA	International Energy Agency
IEC	International Electrotechnical Commission
INR	Indian rupee
InSTS	intra-state transmission system
IRENA	International Renewable Energy Agency
kVa	kilovolt
MVA	megavolt ampere
MW	megawatt
OIB	offshore investment bank
PGCIL	Power Grid Corporation of India Limited
REMC	Renewable energy management centre
RWE	Rheinisch-Westfälisches Elektrizitätswerk (German utility company)
TSO	transmission system operator
TWh	terawatt hour
UNEZA	Utilities for Net Zero Alliance
USD	United States dollar
VSC	voltage source converter
ckm	circuit-kilometre

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Executive summary

Global citizens and businesses want secure, affordable and clean energy. Accelerating the integration of renewable energy across global energy systems to meet an increasingly electrified demand can simultaneously offer markets more energy security and reduced environmental impacts, while also stimulating economic growth by creating new jobs, attracting investment and reducing long-term energy costs.

However, reports of increasing curtailment of renewable energy sources, combined with more than 3 000 gigawatts (GW) of generation projects currently in connection queues globally (GGI, 2024), highlight the structural challenges grids are facing. In 2023 alone, nearly 30 terawatt hours (TWh) of generation was curtailed across only six countries in Europe, representing a cost to the economy of almost EUR 9 billion (c. USD 11 billion) (Face, 2024).

The grids that transport power from where it is produced to where it is consumed now require urgent investment. This is driven by factors including accelerating demand, increasing complexity and aging equipment. Expansion, refurbishment and modernisation of our power grids is essential. To do this, the electricity community must develop and deliver an unprecedented number of large-scale grid infrastructure projects in the coming decades.

Large-scale grid infrastructure projects are complex undertakings that typically involve significant financial investment, extensive planning and the co-ordination of multiple stakeholders. Such projects regularly face unexpected issues, including cost overruns, delays and scope changes, throughout the planning, financing, design, construction and commissioning phases. Based on a representative sample of more than 500 large-scale infrastructure projects globally, McKinsey reported in 2022 that almost 80% of projects encounter budget overruns and over 50% experience delays (McKinsey, 2023).

Nonetheless, it is still possible to deliver large-scale grid infrastructure projects on time, within budget and according to scope. One example is the NordLink Interconnector completed in 2020, which connects the electricity grids of Norway and Germany, enhancing energy security and the integration of renewable energy in both countries. Another example is the Caithness-Moray-Shetland link, Europe's first multiterminal voltage source converter (VSC) high-voltage direct current (HVDC) link, completed in August 2024.

This report aims to highlight the message that delivering large-scale grid infrastructure projects according to plan is feasible and provides key learnings to be considered from the outset of project development to support delivery. The findings are not exhaustive, but address the key topics of planning, financing, overcoming supply chain challenges and ensuring the availability of a skilled workforce. They are based on the experiences of organisations delivering large-scale infrastructure projects. Together, they reflect pressing actions stakeholders should prioritise to accelerate delivery and reduce the risk of delays and budget overruns. This executive summary synthesises the report's key insights and serves as a direct call for action, highlighting where progress is possible and necessary.

Planning

Road transport decarbonisation requires systemic and holistic transformation through different measures, including among others, improved urban planning, as without proper co-ordination between utilities and charging operators, EV charging could stress power systems (IRENA, 2025). The planning phase of a large-scale grid infrastructure project should take about 20-30% of the overall time required to complete the project (Serrador, 2012).

Table S1 Planning recommendations and stakeholders involved

	Recommendation	Stakeholders
1	**Ensure long-term, holistic, co-ordinated planning.** Any large-scale grid infrastructure project should be part of a broader, forward-looking, holistic and co-ordinated national or regional plan, considering new generation and demand, as well as cross-border development. Such long-term planning should facilitate a shift from a project-by-project approach towards a programmatic approach.	Policy makers, regulators, developers, local communities, authorities
2	**Undertake continuous stakeholder engagement.** Stakeholder engagement is essential and should start early in the planning process and continue at regular frequencies throughout the build, operation and decommissioning phases of the project. Project developers, policy makers and local communities should communicate transparently on all viable options for the location of grid infrastructure, particularly existing and planned motorways, railways and other existing rights of way.	Policy makers, developers, local communities
3	**Ensure the planning and permitting approach is appropriate for delivery of large-scale infrastructure.** Unnecessarily onerous processes for permitting and other regulatory approvals can slow down the development of projects. Identifying and addressing permitting or approval challenges early, before significant resources are committed, will also be key.	Policy makers, regulators, local authorities, developers

Finance

Each country's power sector is unique and will embrace the energy transition across different time horizons with different technologies. Financing tools (including for cross-border projects) must recognise and accommodate these differences.

Table S2 Finance recommendations and stakeholders involved

	Recommendation	Stakeholders
1	**Ensure business case proposals are based on a clear and unique market need, are linked to long-term plans for the region, and offer adequate returns.** Long-term, holistic and co-ordinated plans should be the basis of feasibility studies and business case proposals, ensuring large-scale grid infrastructure projects can secure investor support and financing. For regulated businesses, regulators need to ensure there is an adequate return on capital to incentivise continued investment in regulated projects.	Policy makers, regulators, investors, financiers, developers
2	**Reduce the cost of capital.** Exploring all options to reduce the cost of capital is essential when securing financing. Options to explore could include public-private partnerships, green bonds and innovative project finance structures. For projects in emerging markets and developing economies (EMDEs) that meet development objectives, both blended finance and leveraging concessional finance in local currency to attract private capital will be important.	Policy makers, multilateral development banks, investors, financiers

Supply chains

Supply chains face two major challenges when catering to rapidly growing demand: availability of both critical materials and manufacturing capacity. These challenges are further influenced by socio-economic and geopolitical factors, often leading to cost increases and time delays for projects.

Table S3 Supply chain recommendations and stakeholders involved

	Recommendation	Stakeholders
1	**Reshape the relationship between suppliers and developers.** Given the cost increases and delays being experienced across supply chains, strengthening traditional customer-supplier relationships through more strategic, trust-based partnerships can support more efficient solutions and help mitigate potential supply chain risks that could delay a project.	Developers, suppliers
2	**Explore new business models and approaches.** Innovation is not only applicable to technologies. Developers can work with suppliers to find new and innovative business models and approaches that could help avoid or reduce the impact of supply chain delays on the project's critical path. Examples include framework agreements, capacity reservation contracts, detached civil approaches and standardised programmatic approaches.	Developers, suppliers, regulators
3	**Leverage standards to promote safety and competitiveness.** The use of global standards (*e.g.* International Electrotechnical Commission [IEC] standards) and common technical specifications can help ensure the safety, security and interoperability of grid infrastructure, while also speeding up project delivery. Combined with streamlining and simplifying tendering processes, these could help drive the modularisation and reduction of design variations necessary to achieve economies of scale and reduce the strain on both component supply chains and manufacturers' engineering capacities. The benefits of standards can only be leveraged if they are implemented and their proper use is verified through testing and certification.	Policy makers, developers

Skills

One of the most complex and enduring power sector disruptors is the talent challenge. The skills needed to develop and operate large-scale grid infrastructure projects are evolving, along with demographics and employee expectations. It is becoming more difficult to fill positions for skilled workers, from tradespeople to engineers, especially since the skills needed for the energy transition are also needed by industry more broadly.

Table S4 Skills recommendations and stakeholders involved

	Recommendation	Stakeholders
1	**Promote cross-industry transitions and reskilling and upskilling initiatives.** Developers, system operators, suppliers and their trade associations could collaborate with policy makers to identify the quantity and types of skills that will be required in the short to medium term (as well as the longer term), such as planning, building and operating more complex, digital systems. Partnerships and initiatives between industry and the public sector could focus on reskilling and upskilling employees to ensure that the labour market can deliver when called upon.	Developers, system operators, suppliers, trade associations, policy makers
2	**Ensure adequate social infrastructure for employees.** Developing large-scale grid infrastructure projects requires people. These projects can be situated in rural areas. For mid-term and long-term projects, working with policy makers to ensure adequate social infrastructure, such as accommodation, transport links and other facilities, can be important to both find and retain skilled workers.	Policy makers, local authorities, developers
3	**Leverage available labour markets.** Developers can work with local universities, academies and schools to ensure that school leavers and graduates are available with the skills required to take entry-level roles in infrastructure projects. Where the workforce is not available, developers can work with policy makers to offer opportunities to external markets or to those requiring working visas.	Policy makers, academic community, local authorities, investors, developers

Introduction

Electricity is rapidly emerging as the core of the entire energy system. The electrification of heating, transport and industry, combined with new loads such as data centres, led to an increase in global electricity consumption of almost 1 100 terawatt hours (TWh) in 2024, more than double the annual average increase over the past decade (IEA, 2025). According to the International Renewable Energy Agency's (IRENA's) 1.5°C Scenario, electrification must expand rapidly to meet climate targets, with electricity projected to account for 52% of final energy consumption by 2050, up from 23% in 2022. Simultaneously, renewable energy will continue its rapid growth, with an estimated 91% of global electricity coming from renewables by 2050, primarily from solar photovoltaic and wind energy (IRENA, 2024).

Grids continue to be at the heart of the energy system, enabling the integration of large-scale renewables projects and the connection of large consumer loads. However, urgent and significant investment is now needed. More than 80 million kilometres (km) of grids will need to be built or refurbished by 2040 to align with climate and energy targets. This requirement matches the total global grid currently in operation (IEA, 2023).

National governments increasingly recognise the scale of the challenge. The 29th Conference of the Parties to the United Nations Framework Convention on Climate Change (COP29) Global Energy Storage and Grids Pledge commits to a collective goal of adding or refurbishing 25 million km of grids by 2030, which has been endorsed by 65 countries and over 100 non-state actors (COP29, 2024). Likewise, during the Summit on the Future of Energy Security in April 2025, governments from across the globe emphasised the importance of proactive investment in grid infrastructure in an "Age of Electricity" (IEA and UK Government, 2025).

Now more than ever, delivering large-scale grid infrastructure projects on time and within budget will be critical to driving the energy transition forward at pace. From high-voltage grid development projects to interconnectors, from offshore energy islands and wind parks to cable tunnels, these projects are critical for ensuring a secure, sustainable and affordable electricity supply today and into the future.

Large-scale grid infrastructure projects are complex and take time to develop. The right permitting and regulatory approvals processes, as well as access to adequate project financing, global supply chains, and skilled persons – across value chains and from conception to construction, operation and decommissioning – can help ensure on-time and within-budget delivery.

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1. Overcoming challenges to deliver large-scale grid infrastructure projects

1.1. Planning

Effective grid infrastructure planning enables the timely and cost-efficient delivery of projects, while also ensuring alignment with local needs and regulatory requirements.

It is important that project developers aim to ensure that a potential project meets a unique gap in an existing long-term, holistic, co-ordinated grid development plan for the country or region. Planning should be comprehensive to enable a shift from a project-by-project approach to a more programmatic approach, *i.e.* looking out 20-25 years and incorporating expectations of new generation and demand, as well as cross-border developments. Policy makers and regulators should be working closely with project developers, often transmission system operators (TSOs), to ensure that these plans are reflective of data-based projections on energy from across all areas of the economy, as well as neighbouring countries. Such plans should be stable in nature, based on a broader goal, but also flexible enough to adapt to market evolutions. Long-term plans should be backed up by short- to medium-term action plans. With this holistic view in place, project developers can ensure that a potential project meets a gap in this plan.

As part of this programmatic approach, authorities can identify areas for development where permitting and approvals can be accelerated. Long-term planning also enables anticipatory investments that should deliver longer-term benefits to citizens and businesses.

Project developers must also ensure broad stakeholder engagement from the outset of the project. Large-scale grid infrastructure projects often face opposition from local communities linked to concerns such as environmental impact, land use and disruption during construction. Navigating these concerns requires careful planning, open communication and, often, compromises. Buy-in from various parties can be crucial. Policy makers and regulators can help by ensuring that stakeholders (particularly local stakeholders) already see the benefit, and were involved with the creation, of a longer-term development vision. Earlier engagement in the broader energy vision and associated socio-economic benefits can help pave the way for large-scale grid infrastructure projects. Employing skilled and unskilled workers in the affected areas will also be important.

1.2. Financing

Investment in large-scale grid infrastructure projects has recently increased, thanks to accelerating demand, increasing complexity and the need for grid modernisation. According to BloombergNEF (BNEF, 2025), global energy investment exceeded USD 2 trillion (United States dollar) for the first time in 2024, more than doubling since 2020.

Nonetheless, investors in large-scale grid infrastructure projects are still predominantly governments and state-owned companies. Public money is therefore funding a significant portion of these grid projects, and that can contribute to a rising debt-to-gross domestic product (GDP) ratio for governments, as well as higher electricity bills if regulators need to increase the allocations to the regulated bodies developing the projects. In the long term, however, investment in large-scale infrastructure can often offset the initial costs by lowering constraint costs, for example.

While the investment focus is now shifting to encouraging more private sector financing of large-scale grid infrastructure, this can be complex given the high upfront costs and long payback periods associated with these projects.

Regulators, in particular, need to ensure there is an adequate return on capital to incentivise continued interest from investors in regulated projects. Attracting investors with an appetite for the risks associated with large-scale infrastructure projects, such as construction or delivery risks, is essential to avoid investment delays.

This is particularly critical in emerging markets and developing economies (EMDEs), where energy demand is rising rapidly and infrastructure needs are most critical. Although financing is available in EMDEs, the challenge seems to be around bankable projects: very few projects can meet investors’ risk-return expectations (even when the investor is the public sector) and reach financial close. In fact, only 10% of infrastructure projects reach financial close, with the vast majority failing at the feasibility or business planning stage (NGFS, 2023). Challenges around higher interest rates, higher inflationary pressures and more uncertainty around geopolitical risks increase the cost of capital, thereby affecting the business case for many large-scale grid infrastructure project investments. Development finance can be leveraged by EMDEs but may not move fast enough, and non-concessional financing may be an additional burden on borrowers if not provided in local currencies.

There is a need for long-term, stable, consistent and reliable governance, from policies to regulatory frameworks. Industrial policies offering subsidies and incentives for localisation are attractive and can be helpful in the short-term. However, stable, reliable governance will offer far more value in the longer term, ensuring that assets are optimally utilised and maintained and contribute to broader national and regional climate and energy goals.

Box 1 Financing offshore grids

Onshore transmission grids are usually designed and developed as meshed grids, offering multiple paths for power to flow through. Until recently, the development of offshore grid infrastructure has been mostly based on point-to-point connections radiating out from the onshore grid towards an offshore wind farm. Now, with an aim of 2 000 gigawatts (GW) of installed offshore wind capacity globally by 2050 (UN Global Compact, n.d.), there is a need to evolve the approaches being used to transmit the power from offshore power generation sites to our industries, businesses and homes. This transformative evolution is advancing high-voltage direct current (HVDC) systems from basic point-to-point connections to sophisticated multi-terminal and multi-purpose networks and further towards meshed offshore grids, ushering in a new era of electricity transmission. However, the financing and business models of such innovative developments remain a challenge.

To address this, the establishment of an offshore investment bank (OIB) for each European sea basin has been proposed (Ørsted, 2024). Each OIB would co-ordinate a unified approach across its respective areas as well as co-ordinate investments in projects of regional importance within its sea basin. This structure could unlock capital, foster economic growth and reduce investment risks. Countries bordering a particular sea basin would be the primary participants in each OIB, while others, such as landlocked nations, could join on a voluntary basis to support offshore targets and contribute to the financing of renewable energy source projects that are more cost-effective than those within their own borders.

Box 2 How UNEZA is supporting grid financing

The Utilities for Net Zero Alliance (UNEZA) is advancing a set of delivery mechanisms under its **Global Infrastructure Programme** to mobilise capital and accelerate investment in grid infrastructure. These include unlocking stranded GWs of renewable energy capacity that cannot be delivered to the grid due to inadequate infrastructure, pooled procurement to reduce capital costs and co-ordinated fund mobilisation. The UNEZA Secretariat is carrying out ongoing technical consultations with relevant partners, and high-level consultation is expected to occur during the IRENA Assembly in January 2026.

In 2024, UNEZA and the Green Grids Initiative (GGI) identified the lack of a unified criteria for defining "green grids," limiting access to climate finance. At the IRENA 15th Assembly in January 2025, a joint session with UNEZA, GGI and other partners highlighted that over 60% of grid investments are excluded from climate finance due to inconsistent definitions (Fuselli et al., 2024).

Following consultations, UNEZA supported the **Climate Finance Principles** under GGI at COP29. These principles provide a clear framework to identify grid projects as "green," aiming to align climate finance with essential transmission investments. A joint open letter to multilateral development banks will call for their adoption and greater investment in grid infrastructure (GGI, 2024).

1.3. Supply chains

The availability of critical materials and adequate manufacturing capacity are two significant and structural challenges for supply chains that can lead to cost increases and time delays for large-scale grid infrastructure project developers.

UNEZA released a high-level statement (UNEZA, 2024) during New York Climate Week in September 2024 highlighting supply chain priorities for policy makers across the electricity ecosystem. This report builds on that statement.

Traditional customer-supplier relationships are no longer adequate in a time when multiple large and complex infrastructure projects are being built simultaneously in a market. These transactional relationships must evolve into strategic partnerships where developers and suppliers collaborate to design and develop projects, as well as to overcome supply chain challenges encountered along the way.

Such strategic partnerships can also contribute to the new and innovative business models that are required to manage the current turbocharged demand for everything from transformers and switchgears to high-voltage transmission cables.

Examples include framework agreements, which are agreements between one or more businesses or organisations establishing the terms governing contracts to be awarded during a given period, including price and quantity. Framework agreements require a shift away from project-by-project approaches towards programmatic approaches, which will often need to be supported by national regulators.

Framework agreements for multiple projects as a part of a programme can be further complemented by leveraging standardisation and common technical specifications across the projects. For example, TenneT's 2GW Program (TenneT, n.d.) aims to build 14 HVDC offshore grid connection systems with a transmission capacity of 2 GW each in the Dutch and German North Sea by 2031. The programme's standardised, one-size-fits-all 2 GW HVDC offshore platform is an innovation in the offshore space.

More broadly, standards play an important role in ensuring safety, as well as greater interoperability and accelerating project delivery. From a manufacturers' perspective, a reduction of design variations will ease pressure on component supply chains and on manufacturers' engineering capacities, particularly at a time when it is challenging to hire the skilled people required.

Box 3. Shifting from projects to programmes

In 2023, TenneT, the TSO for Germany and the Netherlands, announced plans to develop 14 offshore HVDC grid connections in the North Sea – seven in Germany and seven in the Netherlands – each with a 2 GW transmission capacity, by 2032. Also known as TenneT's 2GW Program, this announcement was a game changer for the industry and the largest energy transition infrastructure tender ever awarded in Europe.

TenneT collaborated with partners to co-design a blueprint for future offshore grid connection systems: a standardised, one-size-fits-all 2 GW HVDC offshore platform and a new 525 kilovolt (kV) bipolar cable system. In addition, instead of tendering each offshore grid connection system individually in a project-by-project approach, TenneT formed framework agreements for a whole series of systems and awarded these to consortiums with different partners responsible for the technological components and for the engineering, procurement, construction and installation.

In 2024, following suit, German utility company Rheinisch-Westfälisches Elektrizitätswerk (RWE) signed agreements for the supply of three offshore HVDC systems and constructing offshore platforms to deliver on RWE's offshore wind development portfolio (RWE, 2024).

RTE, the French TSO, also awarded multi-billion-euro framework agreements in 2024 and 2025. The 2024 agreements were awarded to a consortium for the engineering, procurement, construction, installation, commissioning and turnkey delivery of three integrated HVDC grid connection systems for three offshore wind projects (Memija, 2024). In 2025, RTE awarded an additional large-scale framework agreement for the design, production and delivery of HVDC cables to link offshore wind farms to the French transmission network. The contract includes 450 km of high-voltage subsea cables and 280 km of high-voltage onshore cable.

1.4. Skills

The energy transition, combined with advances in the digital economy and artificial intelligence, is spurring a jobs transformation. New types of jobs, new skills and even whole new professions are emerging as we evolve towards a complex "system of systems". It is essential that these new jobs offer fair wages and maintain high standards of workplace safety and health.

More than 16.2 million individuals were working in the renewable energy sector in 2023 (IRENA and ILO, 2024); however, this will increase to around 30 million by 2030 under the IRENA 1.5C Scenario (IRENA, 2024). With the rapid expansion of renewable energy and the transition away from fossil fuels, skills demand is outpacing supply. IRENA finds that educational misalignments, and persistent labour and skills shortages, pose an increasing challenge, and that the skills gap will continue to widen in the absence of proactive measures (IRENA et al., 2024).[1] This will take time: for example, an electrician in the United Kingdom or the United States typically trains in an apprenticeship for at least four years (Financial Times, n.d.).

There is an urgent need for greater collaboration among policy makers, project developers and academia. Such collaboration must focus on what skills will be needed to plan, build, operate and maintain our evolving power systems. Reskilling and upskilling initiatives must then focus on the development of these new and combined skills. Project developers must be part of these initiatives, contributing time and money, to secure the skilled workforce they will need to deliver their projects.

1 See, also, IRENA's *Leveraging local capacity* series of reports.

Developing large-scale grid infrastructure projects requires people, often in less populated areas. For longer-term projects, working with policy makers and local authorities to ensure adequate social infrastructure – such as quality accommodation, transport links and other facilities such as childcare – can be important to both find and retain skilled workers. Project developers must also engage with the local community to ensure that the influx and exodus of workers does not overwhelm the area or leave it suffering in the aftermath.

As industries continue to evolve in an increasingly digital era, the skills gap in the workforce persists and even widens. Developers must work with policy makers, local authorities and schools to leverage available labour markets, for example by increasing the integration of under-represented groups into the workforce, particularly when it comes to large-scale grid infrastructure projects where roles are traditionally dominated by men. Where the workforce is not available, developers can work with policy makers to offer opportunities to external markets or to those requiring working visas.

In parallel, developers should encourage policy makers to run focused campaigns to raise the profile of the energy sector in general, making it stand out as an attractive area for students.

Box 4. Addressing an unprecedented engineering skills gap

Around 230 000 people are currently employed in the Australian engineering workforce. A recent report (The Insight Center, 2023) forecasted a skills gap in Australia's engineering workforce amounting to 200 000 by 2040 if measures are not taken immediately. The report highlighted that, in the absence of strong engineering capabilities and proper oversight, government spending on major infrastructure projects may not achieve high quality and cost efficiency. Many countries, including Germany, Japan and the United States, are facing similar challenges (Deo, 2025).

Japan is addressing the skills gap in several ways. The Japan International Cooperation Agency provides training programmes for engineers from developing countries, covering areas like renewable energy, infrastructure development and environmental engineering. Meanwhile, institutions like Kyoto University of Advanced Science offer specialised engineering programmes that integrate practical learning experiences, such as capstone projects.

The Netherlands has launched an initiative known as the Technology Attack Plan, under which government and industry will each invest EUR 0.5 billion (equivalent to USD 0.6 billion) over the next ten years on measures aimed to fill an expected 60 000 technical vacancies. The plan involves science, technology, engineering and maths-focused educational programmes to ensure a steady pipeline of skilled graduates, vocational training programmes, and more partnerships between institutions and industries. The challenge facing companies is multi-faceted. It is not only about recruiting and retaining enough skilled staff, but also about making efficient use of their capabilities (Deo, 2025).

2. Case studies

The following case studies exemplify and highlight the results of large infrastructure projects that circumstances allowed companies to deliver efficiently. Each case study highlights particular elements that supported or accelerated project delivery.

2.1. London Power Tunnels

Phase 1 of the London Power Tunnels project, initiated in 2011 and completed by 2018, was a significant GBP 1 billion (equivalent to c. USD 1.35 billion) infrastructure undertaking aimed at modernising the electricity transmission system in London, United Kingdom by the National Grid (National Grid, n.d.).

Planning – Long-term, holistic and co-ordinated: This project marked the first major investment in the capital's electricity transmission since the 1960s and was aligned with the government's expectation of increasing electricity demand. Spanning a period of seven years, the project involved the construction of 32 km of underground tunnels across the city. These tunnels now accommodate ten transmission circuits, capable of meeting approximately 20% of London's electricity demand.

Figure 1 Route of London Power Tunnels Phase 1

Source: (National Grid, n.d.).

Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply the expression of any opinion on the part of IRENA concerning the status of any region, country, territory, city or area or of its authorities, or concerning the delimitation of frontiers or boundaries.

Planning – Permitting and approvals: This was an extremely complex undertaking requiring significant permitting and regulatory approvals. During Phase 1 of the London Power Tunnels project, the depth of the tunnels varied between 20 metres (m) and 60 m, and they passed beneath tube lines, canals and rivers. The construction process involved the installation of 192 km of 400 kV cable and 30 km of 132 kV cable within the tunnels. To support the tunnelling work, 14 access shafts were excavated. The entire construction phase was successfully completed in 2015, requiring over 6 million work hours. The project demonstrated a commitment to sustainability by recycling 99% of the excavated material.

Skills – Leverage available labour market: At its busiest period, the project employed over 700 individuals, and it created 40 apprenticeship tunnelling roles throughout its duration. The skills developed the first phase of this project are being leveraged as part of the second phase.

Planning – Stakeholder engagement: Phase 1 of the London Power Tunnels project left a positive legacy by engaging with over 30 000 students. Moving forward, there is an aspiration to build on this success and continue the engagement in Phase 2 of the project, which is currently underway.

2.2. Caithness-Moray-Shetland multi-terminal HVDC project

In August 2024, clean energy from Shetland Island, off Scotland's coast, could power hundreds of thousands of homes and businesses for the first time – part of a project led by SSEN Transmission and its partners.

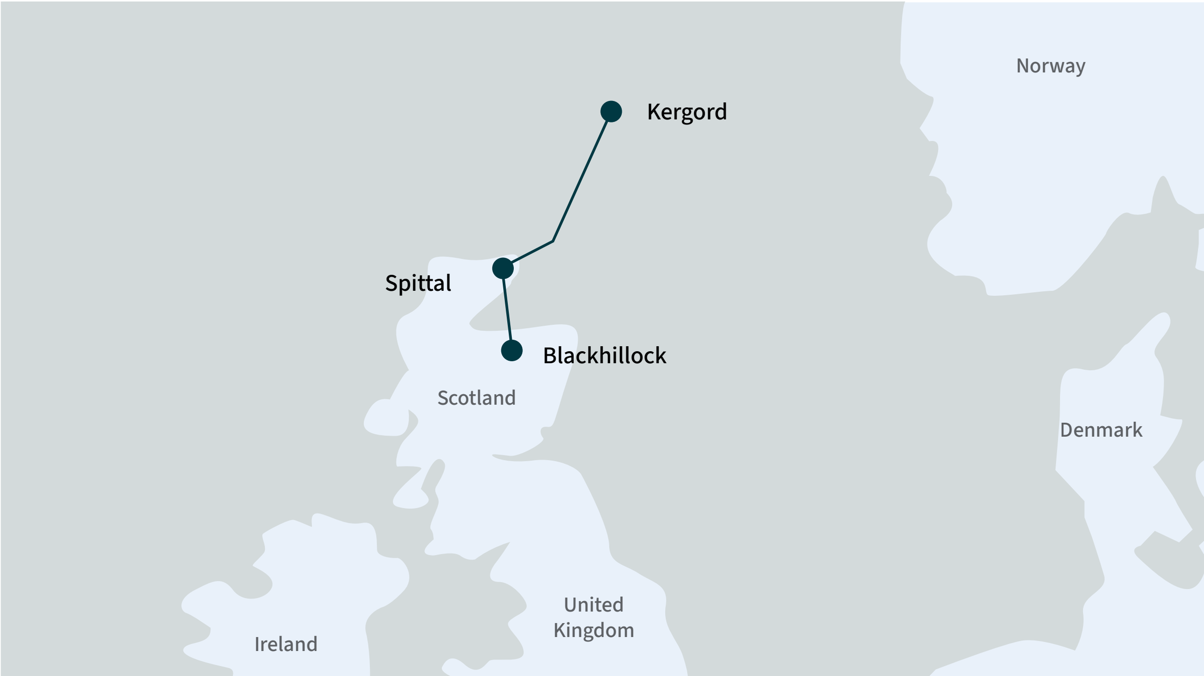
This was due to the commissioning of two major clean energy projects: the energisation of SSEN Transmission's 260 km subsea HVDC link to transport electricity between Shetland and the British mainland, and the construction of the 443 megawatt (MW) Viking Wind Farm, expected to become the United Kingdom's most productive onshore wind farm based on yearly electricity output (HITACHI Energy, n.d.a).

Planning – Long-term, holistic and co-ordinated: This project aligned with the United Kingdom's long-term focus on reducing carbon emissions and achieving net zero by leveraging renewables, including clear offshore wind targets since 2020. Additionally, forward grid planning ensured that the output from the offshore wind farm could be integrated by the existing grid.

A particularly interesting aspect of this project is the 260 km Shetland HVDC Connection link to the existing 320 kV CaithnessMoray Link to form Europe's first multi-terminal HVDC network. Converter stations are located at Spittal in Caithness, Blackhillock Substation in Moray and Upper Kergord on Shetland.

Supply chains – Reshape the relationship between suppliers and developers: The project developers moved away from the traditional transactional relationships with their suppliers and developed strategic partnerships. Such partnerships enabled stakeholders to work together to overcome challenges and deliver this world-leading multi-terminal HVDC link on time and within budget.

Figure 2 Route of the Caithness-Moray-Shetland project



Source: HITACHI Energy (n.d.a).

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Skills – Ensure adequate social infrastructure for employees: At peak construction, the Viking Wind Farm generated approximately 400 jobs, with an additional 35 full-time local roles in operations and maintenance expected over its lifespan. The project developers ensured adequate accommodation and transport for these workers, as well as delivering full-time local jobs once the workers moved to the next project.

Over 70 local companies have benefited from the project, with approximately GBP 80 million (equivalent to around USD 108 million) spent within the local supply chain.

2.3. Itaipú Dam

With an installed capacity of 14 GW, the Itaipú Dam ranks as the world's third-largest operational hydroelectric facility, following the Three Gorges and Baihetan dams in China. Construction began in 1975, and the first turbine became operational in 1984. The HVDC Itaipú is a high-voltage transmission link that connects the dam to the São Paulo region. With a capacity of 6.3 GW, it was commissioned in phases between 1984 and 1987 and remains one of the most significant HVDC systems globally (HITACHI Energy, n.d.b).

Figure 3 Route of the Itaipú HVDC link

Source: HITACHI Energy (n.d.b).

Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply the expression of any opinion on the part of IRENA concerning the status of any region, country, territory, city or area or of its authorities, or concerning the delimitation of frontiers or boundaries.

The Itaipú Dam, located on the border between Brazil and Paraguay, is owned and operated by the Itaipú Binational Entity, a binational public company co-owned by Paraguay and Brazil. Itaipú represents a unique model of cross-border energy co-operation and governance. It is credited with giving rise to the process of regional integration in Latin America. While there have been challenges over the last 50 years, it shows that two countries can come together for a common interest, a mutual vision to harness hydraulic potential *jointly.*

Planning – Long-term, holistic and co-ordinated: The Itaipú Treaty was signed in Brasília in 1973, by the governments of Brazil and Paraguay, after years of negotiations for the joint utilisation of the hydroelectric resources of the Paraná River. The signing of the treaty put an end to a border dispute that had lasted for more than two centuries.

Finance – Business case proposals must be based on a clear and unique market need, linked to long-term plans for the region. Given the uniqueness of the Itaipú Treaty, it is often said that Itaipú is the result not only of mechanical, civil and electrical engineering, essential for the construction of the dam, but also of diplomatic and financial engineering, allowing the dam to be financed from the energy it generates.

The construction of the dam cost almost USD 20 billion (Power Technology, 2020). To finance the project, Itaipú Binacional relied primarily on loans. This debt-driven model shaped the financial approach, which was structured around a cost-of-service tariff and a capacity purchase agreement.

In 2023, the last instalment of the loans taken for the construction of the Itaipú Hydroelectric Power Plant was paid.

Finance – A long-term, stable, consistent and reliable governance approach is more attractive than investment incentives, which can be short lived. Up until 2023, the annual budget of Itaipú Binacional was dominated by paying off the construction debt through charging the buyers (ANDE of Paraguay and Eletrobrás of Brazil) for the capacity they contracted. The agreement states that Paraguay's utility, ANDE, determines the share of capacity it will contract, while Eletrobrás is responsible for the remainder. In 2020, ANDE contracted 12% of the available capacity, and Eletrobrás covered the remaining 88% (Llamosas, 2023).

Skills – Ensure adequate social infrastructure for employees. Apart from the dam and the HVDC link, the Itaipú project included the construction of roads, highways, air strips and housing complexes across both Paraguay and Brazil. Approximately 31 000 employees (Llamosas, 2023) were connected with the project, and many were employed by a consortium of eight Brazilian and five Paraguayan companies that were awarded the main construction contract.

2.4. India's Green Energy Corridor

Following a 2013 study by Power Grid Corporation of India Limited (PGCIL), the Green Energy Corridor (GEC) plan was developed to build dedicated transmission infrastructure for large-scale solar and wind power plant projects.

Planning: Long term, holistic and co-ordinated: The GEC project is crucial for achieving India's renewable energy targets, in particular 500 GW of non-fossil fuel-based energy capacity by 2030.

The GEC comprises both an interstate transmission system and an intra-state transmission system (InSTS), as well as renewable energy management centres (REMCs) and supporting control infrastructure, including storage systems.

Finance – Business case proposals must be based on a clear and unique market need, linked to long-term plans for the region. The project was justified based on the need to transmit approximately 6 GW of renewable power around India.

Finance – Reduce the cost of capital. The project cost over INR 11 000 Crore (c. USD 1.25 billion) with funding coming from a 30% equity by PGCIL and 70% loan from KfW (KfW, 2025) (c. EUR 500 million or USD 580 million) and the Asian Development Bank (almost INR 3000 crore, equivalent to c. USD 340 million) (Government of India, 2025).

Planning – Permitting and approvals: Implementation work started in 2015 (Government of India, 2025), following the permitting and approvals process. While the GEC has been quite successful, there are nonetheless some delays associated with permitting and approvals, mainly around challenges with land acquisition, right of way issues and forest clearances.

By 2020, a total of 3 200 circuit-kilometre (ckm) of interstate transmission lines and substations with an installed power of 17 000 megavolt amperes (MVA) had been commissioned. In addition, REMCs have been installed in several locations, including Tamil Nadu (south), Maharastra (west) and Rajasthan (north).

The InSTS, with a total target of 9 700 ckm intra-state transmission lines and almost 23 000 MVA substation installed power, was also approved in 2015. As of end of October 2024, over 9 000 ckm of transmission lines have been constructed and over 21 000 MVA substations have been charged. Remaining projects are due for completion during 2025.

2.5. Republic of Korea's VSC HVDC project from Wando to DongJeju

Jeju Province, the largest island and one of the nine provinces of the Republic of Korea, is known for its natural beauty and volcanic sandy beaches. Home to 620 000 residents, it is also one of East Asia's leading holiday destinations, attracting approximately 15 million tourists annually (HITACHI Energy, n.d.c).

Planning – Long term, holistic and co-ordinated: In 2016, as part of its Paris Agreement pledge to cut carbon dioxide emissions by 37%, the Korean government selected Jeju Province to become carbon-free and fully powered by renewable energy by 2030.

Like many islands, Jeju relies heavily on power received from the mainland. Two HVDC links already transmit 700 MW from the peninsula, located 100 km away, but additional capacity was needed.

To address this challenge, Korea Electric Power Corporation, the country's largest electric utility, built a third HVDC interconnection, adding 200 MW to strengthen supply and stabilise the island's power grid (HITACHI Energy, n.d.c).

Figure 4 Route of the Jeju 3 link

Source: (HITACHI Energy, n.d.c).

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