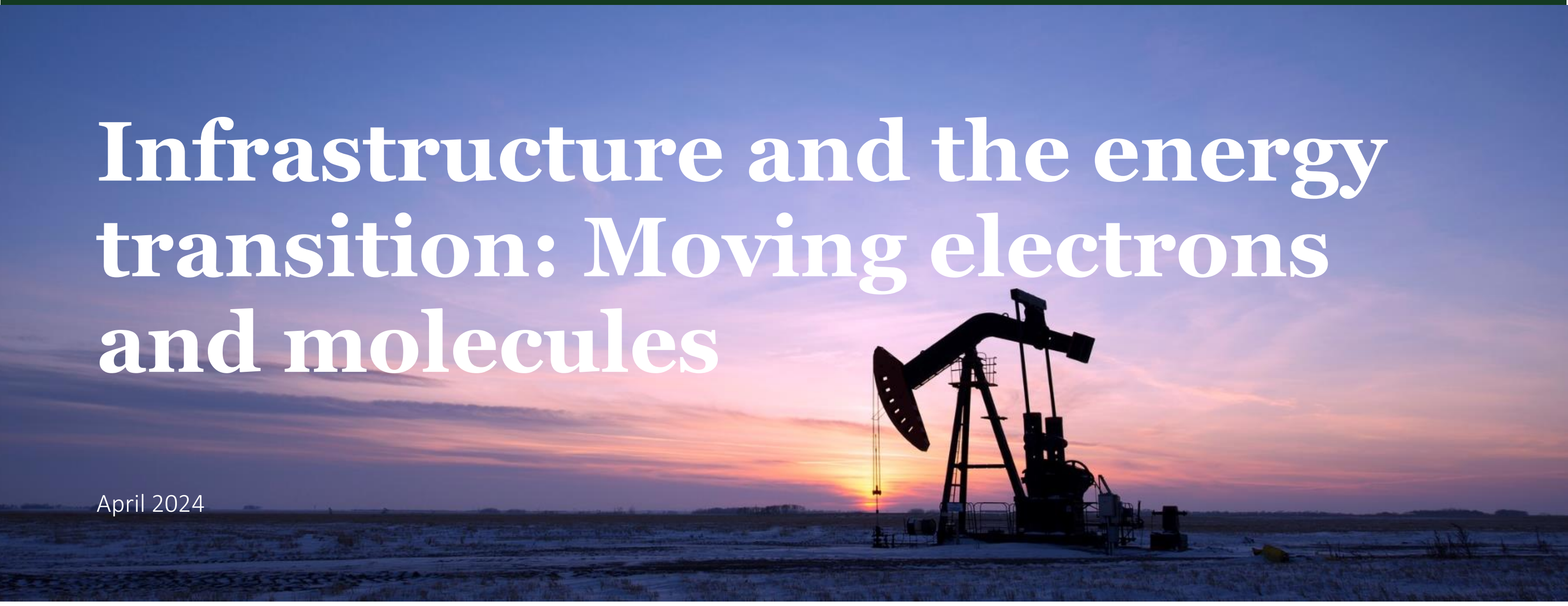

Infrastructure and the energy transition: Moving electrons and molecules

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Key points

- The energy transition is a massive endeavour - it can only be achieved via massive economic and societal changes and developing the right infrastructure, at the right pace
- A key challenge is to transport and distribute decarbonised electricity. Electric grids, storage mechanisms and access points already are and will be even more critical
- If carbon capture and storage is developed at a large scale, then transportation and storage infrastructure will be needed
- For hydrogen used in oil refineries, steel mills or fertiliser plants, nearby production with limited transportation will dominate. However, if its usage spreads to long-haul shipping, aviation, or heavy-duty trucking, large transportation and distribution infrastructure will be required
- The scale and the certainty of massive investment needed in electricity grids provides security and visibility for investors
- For hydrogen, we believe established players will be best positioned to capture growth while for CO_2, there are potential opportunities on a case-by-case basis

The transition to net zero goes far beyond just switching our energy supply and adapting a few consumption habits. It is much more complex. It demands a full transformation of our economic ecosystem – in terms of both supply and demand – alongside a significant behavioural and psychological reset.

Successfully transitioning means reaching net zero emissions – the moment when the concentration of greenhouse gases in the atmosphere stops increasing. This will not be easy to achieve, and this journey has not yet started as carbon dioxide (CO_2) emissions reached a record high in 2023.[1]

The speed at which emissions are reduced will determine future temperature increases: the faster we move, the lower it will be. Many reports, from the Intergovernmental Panel on Climate Change to the International Energy Agency (IEA) and the UN Environment Programme, have concluded the world is on track for an increase in temperatures of 2.5°C or more, far above the goal of the Paris Agreement which seeks to substantially cut global greenhouse gas emissions to limit global warming to “well below 2°C above pre-industrial levels”.[2]

While all transition relies on the same technological levers, they differ in how they stack up. Among those levers, electricity, carbon dioxide and hydrogen have a strong role to play. They all have a need for dedicated infrastructure to connect producers and consumers.

In this paper, we discuss the infrastructure required to electrify our society, enable carbon capture, create a hydrogen economy, and what it all means for investors.

Electricity networks: The nervous system of the transition

In its World Energy Outlook 2023[3], the IEA looks at three different scenarios to analyse future energy systems. In all cases, electricity gains in importance in the world's energy mix. The share of electricity in final energy consumption has already increased from 13% in 1990 to 22% in 2022 and is expected to increase further to between 30% and 53% and absolute electricity generation is expected to soar by 186% to 265% depending on the scenario.

The Network for Greening the Financial System[4], which comprises more than 100 central banks, has developed seven situations and uses three modelling tools, the so-called Integrated Assessment Models, to help central banks and financial regulators better assess what should be done to meet the Paris Agreement. Combining models creates 21 possible transition trajectories, where the consumption of electricity grows on average by 125%, with a range of +55% to +212%.

Réseau de Transport d'Electricité, or RTE, is the operator of the French electric transmission grid. In October 2021, it published the main results of a study assessing different energy transition scenarios for the French grid. Among its many observations and conclusions, RTE wrote that in all cases, electricity consumption increases – from 15% to 60% - and "the power grid must be quickly rescaled to enable the energy transition", and more so the higher the share of renewable electricity[5].

A Washington Post article[6] explains how faster-than-expected growth in electricity demand in the US is putting some stress on the power systems of certain regions and how an aging electric network is not helping.

These are complex and busy analyses coming from unrelated sources and touching both global and country cases, but they convey the same message: demand for electricity is already rising and will rise further, and infrastructure, i.e., the electric grid, is critical and will be even more so in the decades to come.

What is the electrical grid ?

The grid is a complex system of interconnected components that together bring electricity from power sources to customers - households, businesses, and industry. While electricity is essential to the functioning of our entire economy, it has become so ubiquitous in modern life that we do not really notice the sometimes hidden, sometime very visible, infrastructure on which it relies.

Electricity generation: There are several main electricity production technologies, each using different primary energy sources. Electricity can be generated from the combustion of fossil fuels in thermal power plants, which is still the most prevalent method today[7], from fission of atoms in nuclear power plants, or from harnessing renewable energy sources such as water, wind and the sun.

Transmission: Once electricity is produced, it must travel to centres of demand, in real time, through the transmission grid. The electricity is first sent to substations where transformers convert it into very high voltage levels[8] as it reduces losses. It then travels on large transmission lines to reach local substations or to directly power very large consumption sites such as aluminium smelters. Transmission grids are managed by Transmission System Operators.

Distribution: Distribution begins when transmission ends. Substations transform the electricity into lower voltages[9] that can be used by homes and businesses. The electricity travels from substations to end-consumers through the distribution grid which powers small businesses and industries through medium voltage lines, and then residential consumers through low voltage lines[10]. Distribution grids are managed by Distribution System Operators.

Transmission and distribution are often bundled together under the acronym T&D.

While electricity can be stored, it is challenging and costly to do so on a large scale. It means the amount of electricity produced and sent through the grid must always be equal to the amount of electricity consumed to maintain the system stability. However, the growing use of decentralised renewable power sources presents new challenges in maintaining this balance and the reliability of the power supply. The electrical grid must be able to meet these challenges.[11]

The grid today and in possible futures

Currently, there are approximately 80 million kilometres of overhead power lines and underground cables all around the world, 7% being high voltage transmission lines and 93% forming the distribution grid. In its Announced Pledges Scenario (APS)[12], the IEA estimates the total length of grids worldwide should more than double between 2021 and 2050, to 166 million kilometres. Each region has its own development path but most of the expansion is expected to take place in Emerging Markets and Developing Economies (EMDEs)[13].

Grids are therefore set to become increasingly important, and the question is not whether there will be a need to invest heavily in them, but rather how much and where. This is presented in Exhibit 1:

Exhibit 1: Expected development of electric grids in million kilometres

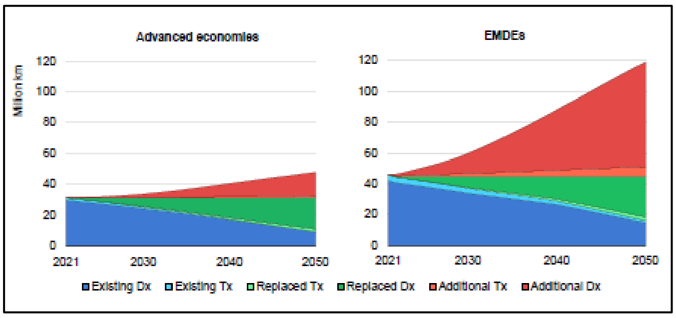
APS	2021	2030	Growth	2050	Growth
Advanced economies	31.2	33.7	7%	47.5	52%
EMDEs	45.9	59.7	23%	118.8	159%
Total	77.1	93.4	18%	166.4	116%

Source: Electricity Grid and Secure Energy Transitions, IEA, September 2023

In addition to expansion, according to the IEA, two-thirds of 2021's grid length is replaced in the APS by 2050. If EMDEs are the most affected by expansion, advanced economies are where renovation is most critical, with over 70% of transmission and distribution grids to be replaced by 2050. This is the direct result of older grid infrastructures built at the end of the 20th century and modest recent grid extension.

By contrast, China alone accounted for over one-third of the world's transmission grid expansion in the past decade, closely followed by India and Brazil. Renovating the electricity grid is one of the primary drivers of grid investment in all regions across scenarios. The grid is not only composed of lines and cables - the associated substations and equipment need to be added and/or replaced as well. [14]

Exhibit 2: Grid length development by region and nature in the APS



Source: Electricity Grid and Secure Energy Transitions, IEA, September 2023
Dx: distribution; Tx: transmission

Although both advanced economies and EMDEs' networks require significant development and investment, the challenges are different. For advanced economies, renovation and expansion needs mean mostly upgrading infrastructures, improving resilience and security and integrating new technologies, like advanced metering, to accommodate renewables. For EMDEs, the key objective is to ensure universal access to electricity, as well as to improve efficiency and to reduce energy losses.

Transmission grid development: The need for interconnections

The need for additional transmission lines is partially attributed to the development of new interconnections to strengthen grids and accelerate the integration of renewables. Interconnections across continents and countries or between regions within a country are becoming more common, for example in the US. Their construction often involves high-voltage direct current (HVDC) lines, used for long-distance transmission of electricity that can adapt to any rated voltage and frequency and that allow for more flexibility and low losses.[15]

Interconnections are crucial to the energy transition as they improve stability and security as well as enabling regions with excess clean energy to efficiently transfer it to areas with higher demand or less generation capacity. By allowing electricity to move across borders in real time, interconnections help to create a more flexible system that can balance geographic variations in wind and solar power generation, minimising output fluctuations and curtailment, reducing the need for power storage capacity.

However, they imply high investment costs, numerous regulatory challenges as well as delays and long lead times (an average of nine years in Europe). Proper deployment of interconnections then requires collaborative efforts in planning, coordination and regulatory harmonisation between countries and regions.[16]

The world's largest synchronised grid

The Continental Europe Synchronous Area (CESA) is the largest synchronised electrical grid in the world. It supplies electricity to over 400 million customers in 24 countries, including most of the European Union. This interconnected grid ensures efficient and reliable power transmission across the region, requiring a continuous production and consumption balance across the area and promoting cross-border energy trade and collaboration among participating countries. According to the European Network of Transmission System Operators, over 40 new interconnections are either under development or planned for completion by 2030.[17]

Why is the grid so important?

Grids have been the backbone of electricity systems for more than a century. Their expansion and upgrade are essential to meet the growing demand for electrification and the need to connect more decentralised powers sources. Yet, the grid currently receives too little attention and risks becoming the Achilles' heel of the clean energy transition. [18]

Rising electricity demand and rising electrification: Global final electricity consumption has nearly doubled since 2000, a trend that is expected to continue according to the IEA. The demand for electrification in sectors including transportation, buildings and industry presents a promising opportunity to reduce carbon emissions and improve efficiency, but also emphasises the importance of electricity grid security.

The IEA predicts that by 2050, electricity demand will increase between 179% and 206% depending on the scenario.[19] EMDEs are expected to account for two-thirds of global electricity demand by 2050, so most grid expansion should occur in those markets.[20]

Ensuring power systems security through a stable and reliable supply of electricity, which is always able to meet demand at an affordable price, will be more crucial than ever. Power generators will have to be more agile; consumers more responsive, and grid infrastructure will need to be re-enforced and digitised to handle a more dynamic flow of electricity and data. [21]

Renewables from decentralised sources: Traditional electricity grids were originally designed to support centralised fossil fuel power plants and were not equipped to handle distributed and intermittent renewable energy sources. If renewable energy sources, mainly solar and wind power, are to play a crucial role in achieving global decarbonisation goals, integrating them into the electricity grid poses several technical challenges. In contrast to centralised power plants, renewable energy sources can be connected to both transmission and distribution grids, although the bulk is directly connected to distribution, leading to higher power injections from distributed generation facilities and adding complexity to the overall system. With the rise of these decentralised energy sources, energy networks must adapt to manage bidirectional power flows.[22]

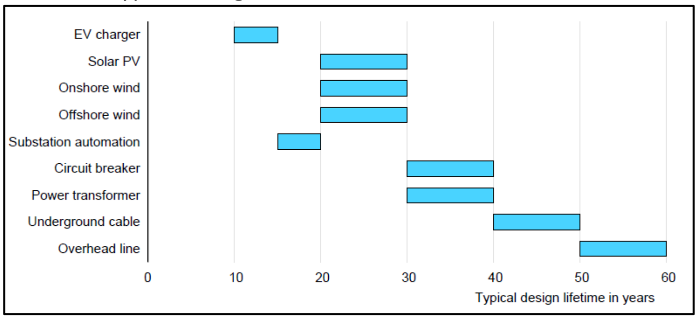
Renewable energy is not always available when the consumption is at its highest, which can cause imbalances between electricity supply and demand, resulting in lower quality and reliability of the electricity network. However, if countries' national energy and climate goals are met on time and in full, renewables are expected to account for over 80% of the total increase in global power capacity over the next 20 years, compared with less than 40% over the past two decades[23]. This acceleration calls for a grid expansion and renovation encompassing not only lines and cables, but also components such as substations, stability and load flow control devices, energy storage and digitalisation technologies to enhance the utilisation of grid assets.

Currently, there are already approximately 3,000 gigawatts (GW) of renewable projects waiting in grid connection queues. This shows that the grid is rapidly (and already) becoming a bottleneck as the list of renewable energy projects in need of connection keeps increasing. [24]

Aging grids and infrastructure: The age of electricity grids varies by country, influenced by historical development, investment, and modernisation efforts. Typically designed to last for 40 to 60 years, electricity grids are often in service much longer than the equipment they connect. These aging assets pose safety and reliability risks, leading to potential outages, equipment damage, and safety hazards.

Grid lifespans depend on overloading, maintenance practices, technological advancements and environmental factors. Climate change considerably increases the risk of outages due to extreme weather events, making electricity networks vulnerable. Around one-quarter of global electricity networks are exposed to severe storms, and close to half are exposed to fire-prone weather conditions for more than 50 days per year, highlighting the significant impact of climate change[25]. New technologies offer opportunities for preventive maintenance, extension of service life and cost savings, but also mean addressing issues such as software lifecycles and cybersecurity.

Exhibit 3: Typical design lifetimes



Source: Electricity Grid and Secure Energy Transitions, IEA, September 2023

The need for flexibility and modernisation

Modernising the electricity grid through smart grids, energy storage technologies, demand response systems and communication technologies is key to leveraging the benefits of distributed energy systems and efficiently integrate renewables. Digitalisation is a higher priority at the distribution level and plays a crucial role in coordinating the needs and capabilities of all the power systems actors, including generators, grid operators, but also end-users. Smart grids can enhance visibility of load flows while making customers more aware of their electricity consumption and enabling new tariff structures that makes it easier to anticipate and balance supply and demand variations and handle bidirectional flows. We believe that development of smart grid technologies will help minimise costs and environmental impacts while providing better visibility for monitoring and greater electricity demand flexibility.[26]

To meet national climate goals, system flexibility needs to double between 2022 and 2030 as the share of renewable energy sources continues to grow. Most of the current flexibility is provided by dispatchable thermal power plants – where output can be adjusted based on demand - and hydropower, which will likely continue to be the case for seasonal flexibility needs. However, digitalisation will become crucial for short-term flexibility through batteries, curtailment and demand response systems. Digitalisation also brings incremental challenges such as increasing vulnerability to cyberattacks, highlighting the need to develop efficient cybersecurity protocols and measures to protect the power system. [27]

New challenges in hardware, software and cybersecurity

Electric grids have integrated information technologies where complex software is helping run the supply demand balance and consumption data is collected and processed to better manage the load, among other uses and benefits. This is improving efficiency and productivity, but also creating challenges, for instance the life of physical assets – as seen in Exhibit 3 – is longer than the life of typical software and they have different upgrade cycles.

Another challenge is the risk of cyberattack. The grid is a strategic and critical infrastructure and disruptions have systemic impacts. Protecting it is essential, both physically and virtually. The war in Ukraine provides a real-life illustration[28]. In a recent report[29], the IEA highlights the increasing risk and what it deems the insufficient reactions of the power system, be it grid operators or electric utilities. Governments are aware that grids must be hardened against cyberattacks – as agreed recently by the European Union[30] and the US Senate[31] in a rare show of bipartisan support.

Storage: Electricity storage on a small scale has long been possible through batteries. However, at a grid scale, there are limited options. The energy transition will mean a greater need for electricity storage, partly as a solution to manage the intermittency of renewable energy.

The main storage option available today is pumped storage hydropower. Hydropower, beyond being the largest source of renewable electricity[32], is also a way to store energy in a latent form as water in reservoirs. According to the IEA[33], there was 160GW of pumped storage hydropower capacity in 2021, accounting for more than 90% of total electricity storage capacity. There is potential to increase this in certain regions, but it often faces local community issues - as flooding a valley is often not popular - and raises biodiversity concerns. There are also question marks linked to the impact of climate change on precipitation patterns and what it means for future hydropower production.

Battery storage is the other option and is growing fast, albeit from a very low base – from an annual deployment of less than 1GW in 2016 to more than 10GW in 2022, to reach a total capacity of 45GW that same year. The IEA forecasts extremely fast deployment this decade and beyond, with capacity multiplying from a minimum of 12-fold by 2030 and by a maximum of 93 times by 2050. Battery storage consists mostly of lithium-ion battery farms and means renewable electricity can be produced while demand is weak then stored for later use - for instance storing solar-based power at noon and releasing it at night.

Electric Vehicles: Challenge or opportunity?

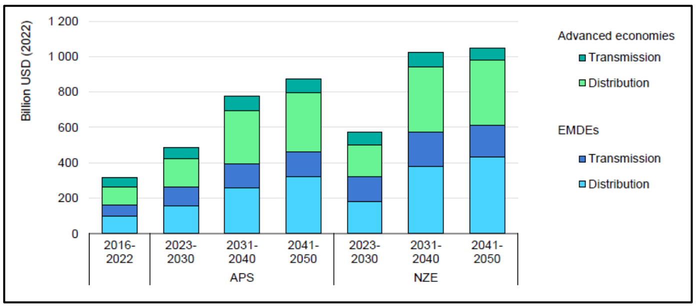
Road transport electrification is one of the key pillars of the energy transition and electric vehicles (EV) will play a key role. In its Announced Pledges Scenario, the IEA expects electricity to represent 40% of transportation energy demand by 2050, becoming a key driver of total electricity demand growth and calling for adapted infrastructure development. [34] EV charging could potentially aggravate the hard-to-manage peak electricity periods during evening and daytime and add pressure to the distribution grid.

However, electric transport can be beneficial for energy security and flexibility due to its storage capabilities. To unlock this potential, investments in the right technological solutions will be required, with a strong emphasis on active control charging. [35] Correctly managing EV charging presents an opportunity to develop synergies with renewables and increase the hosting capacity of the grid. [36]

Investment and planning needs

Investments in electricity grids stood at $320bn per annum in average over 2015-2022 according to the IEA. Under its Announced Pledges Scenario (APS), they must breach the $600bn mark by 2030 and $800bn a decade later. But based on a pathway to achieve net zero emissions (NZE) by 2050, the ramp is sharper, and investments must reach $1trn per year by 2035. The vast majority of this investment applies to the distribution grids. [37]

Exhibit 4: Average annual T&D investments over 2016-2050 under two IEA scenarios



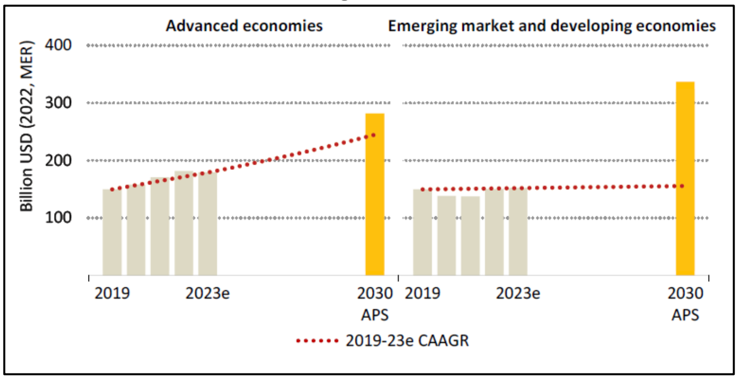
Source: Electricity Grid and Secure Energy Transitions, IEA, September 2023

While investment in renewables has nearly doubled since 2010, global investment in grids has remained relatively stagnant at around $300bn per year, showing an important gap between current trends and the investment required to reach climate goals, especially in EMDEs. In EMDEs ex-China, investment in the grid has declined from more than $100bn per year to less than $70bn per year between 2015 and 2022, while energy demand and reliability improvements have continued to rise sharply. [38]

This is notably due to insufficient financial resources, regulatory barriers and the political instability of many of these countries. Based on these recent trends, 2030 investment in the electricity grid in EMDEs would be less than half that needed in the APS scenario ($335bn), while the gap in advanced economies is far smaller.[39]

As a practical illustration, the European Commission estimates[40] that €584bn needs to be invested in the EU's electric grid in the current decade to implement the REPowerEU strategy.

Exhibit 5: Investment trends in grids relative to the APS

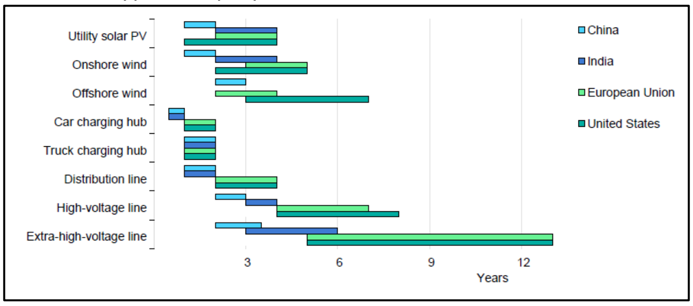


Source: World Energy Outlook 2023, IEA, October 2023

Anticipatory investments take into consideration the expected future growth and development of the electricity grid and its integration with renewable energy sources. If they are considered, the IEA estimates that for every dollar spent on renewable energy, one to three dollars needs to be spent on grids. By making these investments ahead of time and strategically upgrading the grid infrastructure in advance, the grid system can proactively adapt to the rising demand and to changing supply patterns. It will reduce connection delays, enable faster integration of renewable assets, and ensure a smooth transition toward a more sustainable energy system, avoiding costs associated with deploying more infrastructure at a later point in time. [41]

Operational challenges: Planning, lead time and coordination needs. The typical deployment time for electricity lines projects, especially high voltage ones, is much higher than for renewables and charging stations. Grid projects can take more than a decade in advanced economies, with significantly shorter lead times observed in China and India thanks to centralised decision-making and government prioritisation. Delays in the scoping, permitting, and construction phases further add to the already long lead times associated with these projects. Financial challenges, political instability, and complexities in the permitting procedure contribute to delays in emerging markets, while it is more a matter of societal support and politics, as well as long permitting procedures in advanced economies. Equipment delivery limitations and technical constraints can lead to project delays and budget blow-ups.[42]

Exhibit 6: Typical deployment times for electrical assets



Source: Electricity Grid and Secure Energy Transitions, IEA, September 2023

Managing these challenges requires planning coordination - between generation and grid, distribution and transmission, and between regions. The traditional approach of grid expansion, based on individual large generation projects, still has merits but does not integrate enough the multiplication of small renewable projects and lacks a systemwide angle. Planning processes must reflect the greater complexity of more renewable energy systems and more interconnection. In parallel, cooperation and communication to improve stakeholders' involvement in project planning is necessary to limit social opposition.[43]

Opportunities for investors

It appears clear – at least to us – that electric grids are strategic and critical assets that will grow in size and in complexity if the global economy is to transition. This will require massive amounts of investments as already indicated.
This will hence provide many opportunities for investors to allocate capital, through listed equity or bonds, as well as private and less liquid investment schemes. Those investments can be on the safe side – with regulated asset bases or toll-like structures – or riskier – where traditional competitive forces are at play.

There are many types and categories of companies and issuers that will benefit, and we would point at:

- Grid operators and integrated utilities
- Equipment suppliers, such as manufacturers of cables, high-voltage equipment or batteries
- Information technology suppliers, such as developers of smart grid management software or cybersecurity tools
- Civil engineering and construction companies, as the grid is a physical construct that requires lots of concrete and steel

Hydrogen: Infrastructure will be needed for hydrogen-based transportation fuels

To a certain extent, hydrogen is a magical lever for the energy transition as it theoretically can decarbonise many industrial processes and end uses. In a previous note[44], we explained that there is sadly little magic in the real world, that direct electrification is a better solution wherever it is possible, and that we believe hydrogen is the right decarbonisation solution for a limited number of end uses.

As such, the long-term outlook for hydrogen is very dependent on its penetration in the ecosystem and the nature of this penetration. This will determine the related need for infrastructure. Hydrogen is the lightest and smallest element in the periodic table, which makes its logistics challenging because it must be compressed or liquefied if it is to be consumed far from its production point. Doing so consumes energy and it is estimated[45] that the liquefaction process consumes 30% or more of the energy contained, while for compression it varies between 11% and 17% depending on the targeted pressure. Because of this, producing hydrogen close to the consumption, i.e., limiting the needs for logistics, will always be more efficient than sending it through long pipelines or liquefying it to move in a tank.

In 2022, according to the IEA's most recent hydrogen market review[46], production reached 95 million tonnes (MT), with 99.3% coming from a carbon intensive process. Some 84MT came from only four end-markets – crude oil refining, production of ammonia, methanol and steel – and 90% was produced on-site. Because hydrogen is such a local business, there is today a limited infrastructure with only 5,000km of pipelines, largely in Western Europe and along the US Gulf Coast.

In its recent reports[47], the IEA expects global demand to grow from 95MT in 2022 to more than 400MT – at 90% green hydrogen, i.e., made through the electrolysis of water with renewable electricity - by 2050 in its net zero emissions (NZE) scenario. In this case, 45% of hydrogen demand comes from transport, including hydrogen-based fuels such as ammonia and methanol. The IEA estimates this would require 209,000km of pipelines. In its two other scenarios - Stated Policies Scenario (STEPS) and Announced Pledges Scenario, demand also increases but by less.

Hydrogen and investments

In its review of the hydrogen market[48], the IEA estimates that investments in low-carbon hydrogen infrastructure are barely registering, at $0.2bn, and that by 2030 they should increase to $5.5bn in STEPS and to $36bn in NZE.

The Hydrogen Council, a think tank arguably very promotional of hydrogen, published a report[49] in December 2023, estimating there is a $570bn hydrogen project pipeline, of which only 10% is dedicated to infrastructure. However, more than half of those infrastructure projects have only been announced and are not even in their planning phase. For instance, the final investment decisions have been taken for barely more than 600km of pipelines.

The European Hydrogen Backbone (EHB) initiative, a consortium of mostly natural gas network operators, has published several studies about building a hydrogen network in Europe. In a recent report[50], it provides useful pipeline cost data. This is the result of bottom-up work by the EHB members, and reflects differences amongst rules, local challenges and specific geographies. The cost components are categorised in four groups: materials costs, labour costs, miscellaneous costs, and right-of-way. The result is presented in Exhibit 7. In addition, the same study indicates that a typical hydrogen compressor station carries a bill of €4m.

Exhibit 7: Median hydrogen pipeline costs, in million euros per kilometre of pipeline

M€ / km	New Pipeline	Repurposed Pipeline
20'' onshore pipes	1.80	0.54
36'' onshore pipes	3.20	0.64
48'' onshore pipes	4.40	0.88
36'' offshore pipes	5.44	1.09
48'' offshore pipes	7.48	1.50

Source: European Hydrogen Backbone

This analysis provides several insights:

- Repurposed pipelines require 70% to 80% less cost to build. The European natural gas network has the advantage of being made of pipes of a steel grade that is of sufficient quality to handle hydrogen (while this is not the case in the US). Existing natural gas pipelines can hence be switched to hydrogen, although this nonetheless requires investments in physical integrity, notably seals and valves, because hydrogen is a smaller molecule than methane, and in more powerful compressors, because the density of hydrogen is lower
- Offshore pipelines cost unsurprisingly more, to the tune of 70%. There are projects in the Mediterranean Sea and in the North Sea
- Those are median costs. The study also indicates that, depending on the factors listed above, costs can be 20% to 35% lower or higher
- As 70% to 80% of total cost is made of materials and labour, variation in those components, up or down, can strongly impact the final tally

Gasunie, the operator of the Dutch natural gas network, will control the planned hydrogen network. Construction started in October 2023[51], with the goal to build 1,200km of hydrogen pipelines - of which 85% is retrofitting of existing natural gas pipelines[52]- for a total investment of €1.5bn. In line with the EHB work - Gasunie is a member of EHB - reused gas pipelines are said to be 75% cheaper than greenfield pipelines.

Focus: What about ammonia?

Ammonia is a molecule combining hydrogen and nitrogen – its chemical formula is NH_3 - and is already widely produced and traded, primarily to manufacture synthetic fertilisers, starting with urea. Current production is around 190MT, of which between 18MT and 20MT is traded, either overseas in dedicated vessels or inland through pipelines, trucks and trains[53].

Shipping hydrogen overseas requires liquefying it, through a cryogenic process that consumes large amounts of energy. NH_3 becomes liquid at *only* -33°C - compared to -253°C for pure hydrogen – and hence can be a more efficient way to transport hydrogen across oceans. NH_3 can then be cracked back into hydrogen at destination. Projects of this nature have already been announced[54].

However, NH_3 could be pursued on its own merits as a fuel, notably to decarbonise long-haul shipping. While NH_3 is a CO_2-free fuel it is toxic to humans – hence a need for careful handling and appropriate regulation – and it generates nitrous oxide while burning, a harmful gas for human health, which triggers the need for on-board exhaust gas cleaning systems, known as scrubbers.

If NH_3 is to take off, there will be a need for more vessels, the quantity of which will depend on the volumes. As an illustration of the possible amounts involved, Samsung Heavy Industry, a large Korean shipbuilder, announced in January 2024 an order for two large NH_3 ships for $235m[55].

Hydrogen storage. If hydrogen volumes grow in the future, it will be necessary to create storage infrastructure, as there is for oil and natural gas. The best solution appears to use underground salt caverns, as for natural gas. Today, according to the IEA[56], there are operational salt caverns only in the US (three) and UK (just one), with a capacity of 500 Gigawatt hours (GWh). There are several projects under development, notably in Germany and France. Given the lower density of hydrogen, salt caverns can store three to four times less energy for the same volume than they do for natural gas.
Depleted oil and gas fields could also be used but it is not clear yet whether what works for methane works for pure hydrogen. Different tests have been and are carried out to better understand the behaviour of hydrogen in such reservoirs, and notably how much of it dissipates through diffusion, dissolution, or consumption by bacteria.

Hydrogen and electricity. There is a close connection between hydrogen and renewable electricity, because green hydrogen is produced through electrolysis. There is hence a feedback mechanism between the growth of green hydrogen and the need for green power.

In the Announced Pledges Scenario, the IEA estimates that by 2050, 1% of power generation will be used to produce hydrogen and NH_4, and 1.5% in NZE, compared to zero today.

This will contribute to the growth in electricity production, but it is only one of many drivers. Large scale green hydrogen sites will most likely be close to large green power sites and this imply limited electricity infrastructure needs.

Opportunities for investors

Unlike for the electrical grid, there is limited visibility for hydrogen infrastructure developments. The future scale of the market and the nature of demand are two key variables that lead to a strong uncertainty.

There is also the risk of developing stranded assets if expected developments in hydrogen do not occur.

As such, we believe investors who want exposure should favour established hydrogen players – namely industrial gas companies, that already understand this market and are profitable – and possibly natural gas network operators which are natural developers of a hydrogen grid if it is to be built.

Carbon capture and CO_2 logistics: The tail wagging the dog

Carbon Capture and Storage (CCS) is about capturing CO_2 from exhaust fumes of industrial facilities, and then transporting it to underground storage sites. Capturing is a site-by-site task and does not need infrastructure, only dedicated equipment. Transportation means pipelines to storage sites and harbours and ships when storage is offshore. Storage means developing underground facilities and injection stations. The logistics of CO_2 can easily be seen as a common or collective infrastructure, like the electric grid or natural gas networks. The nature and role of CCS was covered in a previous note[57].

In almost all energy transition cases, CCS is part of the solution, sometimes a very large one. So, as for hydrogen, the question of sizing the necessary infrastructure can only be answered by looking at individual situations and at what scale CCS is developed. A key difference with hydrogen however is there is always a need for infrastructure as captured CO_2 must be transported and stored. And indeed, developing this infrastructure usually comes before capturing CO_2, as otherwise there is not an outlet for it.

In 2022, there were 45MT of CO_2 captured. In its World Energy Outlook 2023, the IEA indicates the expected changes depending on its three scenarios - see Exhibit 8.

Exhibit 8: IEA's scenario for carbon capture

GT of CO_2 captured	2022	2030	2050
STEPS		0.12	0.45
APS	45MT	0.50	3.80
NZE		1.02	6.04

Source: IEA World Energy Outlook 2023
MT: million tonnes. GT: giga tonne = one billion tonnes

From this table, we can conclude the infrastructure needs, and the pace at which they must be developed, range from 'a little and slowly' to 'significant and fast'.

If we contrast the data in the scenarios to what is happening on the ground, the picture is somewhat clearer, and the real world appears to align to a sub-APS level of CCS development:

- In its latest annual review of CCS[58], the Global CCS Institute, a think tank, estimates that as of July 2023, there were 32MT of capacity under construction and 279MT at various development stages

- BloombergNEF, a research organisation, estimates that CCS capacity could exceed 400MT per annum in the early 2030s
- The IEA itself estimates that, if all announced projects are built, around 400MT of CO_2 could be captured by 2030[59]
- In its recent energy transition strategy[60] calling for a 90% reduction in emission by 2040, the EU clearly included CCS in its toolbox, stating that "carbon capture, use and storage is a solution in hard-to-abate sectors in the absence of other solutions". The quantified targets are 50MT by 2030 and 450MT by 2050

According to the IEA, there are 9,500km of existing CO_2 pipeline today (with most of it in the Southern US) and, in the net zero scenario, there would be a need to add 20,000km to 40,000km by 2030 and 90,000km to 590,000km[61] by 2050. The agency does not provide data for its other scenarios, so we took out our ruler to make our own calculations. Exhibit 9 presents the result.

Exhibit 9: Length of CO_2 pipelines in thousand kilometres

	2022	2030	2050
STEPS		10-15	15-25
APS	9.5	15-30	60-380
NZE		30-50	100-600

Source: IEA World Energy Outlook 2023; AXA IM

The range is strikingly wide and reflects the strong uncertainty in both the scale and nature of CCS development. For instance, in geographies where storage sites are onshore and nearby industrial hubs, the pipeline infrastructure will be of limited scale, unlike places where there are long distances. Similarly, if storage is offshore, as will largely be the case in Europe, then land pipelines may be shorter – *just* going to the coasts - but harbour facilities will have to be built and either CO_2 ships ordered or offshore pipelines built (or repurposed).

This uncertainty translates into uncertainty estimating investment needs.

In the World Energy Outlook 2023, the IEA wrote that $3bn was invested in CCS projects in 2022 – a record high - but this covers the entire chain and not just the infrastructure component.

In 2020, the Norwegian government initiated the Longship project, which covers the entire value chain, from capture to shipping to offshore storage. The total cost was estimated at 25.1bn Norwegian krone (NOK) [62] (of which NOK17.1bn is investment costs and NOK8bn is operating costs over 10 years) for 1.5MT of CO_2. The total cost of the Northern Lights project – the transport and storage section of Longship – was deemed to be NOK14.2bn, of which 80% will be funded by the Norwegian state.

In October 2023, the final investment decision for the Porthos CCS project in Rotterdam was taken[63]. The project is billed at €1.3bn for a storage capacity of 2.5MT of CO_2 per year. It includes 30km of a collective onshore pipeline, a compressor station, a 22km offshore pipeline and an injection station into a depleted gas field. The project will receive funding support from both the Netherlands and the EU.

On 26 February 2024, Germany made a policy U-turn[64] and decided to facilitate CCS and especially the transport and storage phase. In line with EU strategy, Germany chose to make storing CO_2 on its soil legal (it was not before) but only offshore and not for CO_2 captured from coal power plants. Rules and support mechanisms still have to be drafted.

Beyond broad trends and specific cases, there is also the simple reality that different projects will face different conditions. For a given CO_2 pipeline, the length and diameter, the specific land layout, the density of population and the presence of existing infrastructure (that can provide a corridor to build in) will impact the overall cost. For a project with offshore storage, the cost of subsea facilities adds to the bill, whether it is an offshore pipeline or a fleet of CO_2 ships.

CCS and storage

There is a significant difference for hydrogen and carbon dioxide storage. For the former, it is about a temporary storage – from days to possibly quarters – while for the latter it is about permanent storage.
In addition, as we have seen, hydrogen storage will be built by humans in underground salt caverns. For carbon dioxide, storage will mostly consist of depleted oil and gas fields where the molecules will be pushed inside the pores of the rock and trapped underground, as were the hydrocarbons before them. This is the reason several oil and gas companies are active on the storage side of CCS, because they have the right geological and geophysical skillset.

Opportunities for investors

It is difficult to assess today the scale of CCS infrastructure needs and the related opportunities for investors. There is somewhat more visibility than for hydrogen, but building a broad dedicated strategy might be difficult. There may however be specific opportunities in specific locations if there is visibility for given projects and/or there are existing assets that can be leveraged, such as docking facilities that can be adapted to CO_2 or pipelines converted. This could be of interest for investors in listed securities but also for investors in infrastructure projects and/or private debt.

Biomethane: The infrastructure is already there

Biomethane is chemically equivalent to methane (it is the exact same CH_4 molecule) and as such can use the existing natural gas infrastructure.

According to the IEA[65], natural gas production was 4,138 billion cubic metres (bcm) in 2022 and the world's transmission pipeline network was longer than one million kilometres. By contrast, biomethane production was a meagre 9bcm.

In its energy scenarios, the agency expects biomethane to grow from fast to very fast, to 66bcm by 2030 and 235bcm by 2050 in APS, and to 126bcm and 283bcm respectively in the NZE scenario. Although this is a massive development, those volumes are small compared to today's total gas demand.

In addition, the IEA estimates 300bcm of potential biogas and biomethane production from agricultural waste and residues lies within 20km of existing gas pipelines. This means the infrastructure needed consists of small and short pipes to connect to the existing network. This is therefore not a large-scale investment opportunity.

Common challenges and issues

Funding: We have established the funding needs will be considerable for the electric grid and that they could be large for CCS and hydrogen infrastructure. There are already large established financial mechanisms, such as green bonds or sustainability-linked loans, to fund renewable generation and electric grids. They will have to be leveraged further given future needs. There will also more than likely be opportunities for equity investment, either in listed markets or directly into physical assets.

However, despite growth and visibility, the return prospects of those investments must be attractive enough. Sustainability and profitability must go together to fully tap the capital pool.

Industrial and installation capacity: There are no widespread issues here, but there is specific equipment that few companies can provide and where production capacity is easily stretched, for instance HVDC cables. As an illustration, Nexans, a cable manufacturer, announced[66] in July 2023 that it won a contract to lay a subsea HVDC cable between Greece and Cyprus and that the project would be completed in 2029, some six years later. Such lead times are common and reflect strong demand for a product that only a handful of companies can produce and that requires dedicated vessels (in this example, the water depth is up to 3,000 metres).

In the same logic, building overhead transmission lines is done by a limited number of crews with a specialised skillset. As such, it could create shortages and delays if training and planning are not properly managed.

Permits: A common challenge for most projects in many jurisdictions is getting the right permits in time. The complexity of the permit process can be baffling, and the lack of human resources can compound the challenge. In its World Energy Outlook 2023, the IEA estimates the electric grids face especially high risks related to permitting and certification. Exhibit 6 already presented the long deployment time for the grid.

To enable the transition without too much delay, faster permitting is required for energy infrastructure projects, but also for any project that can contribute. This can notably be done by streamlining the rules, centralising the work into a single entity or point of contact, or by prioritising strategic projects. Another consequence of delays is to increase financial costs and lower returns.

Many countries have plans to streamline the permitting process - such as the EU, where the RepowerEU plan includes recommendations to simplify permitting, or the US, where a permitting action plan has been proposed by the White House[67].

This must be done without being complacent on critical issues such as biodiversity and local communities' rights, but those same issues should not be used as a pretext to block worthwhile projects. A balance must be struck for the energy transition to move on its own sustainable path.

Regulation: Regulation is obviously connected to permitting, but here we want to touch on the appropriate regulation to incentivise investments. Electric Transmission System Operators and Distribution System Operators most often have regulated returns – principally though Regulated Asset Base mechanisms or negotiations with regulators - and it provides them with visibility on their investments. Finding the right balance between adequate returns for grid operators and costs

for customers will be important for the grid to be expanded and modernised.
For hydrogen and carbon dioxide, this is a different territory. There is already a hydrogen market, and most of the suppliers and customers work based on take-or-pay contracts, which provides visibility to both. This is a structure that should support further hydrogen developments. If, as we suspect, natural gas networks operators become the developers of hydrogen networks, then we would expect a structure like what exists for natural gas – and for the electric grid.

For carbon dioxide, nothing much exists today, and the market needs to be invented and business models designed. Regarding the transport and storage of carbon dioxide, it appears logical to us to think in terms of tolling agreement, where companies running pipelines, seashore facilities and storage sites charge a fee per ton of CO_2.

Social acceptance: Infrastructure, by its very nature, can be large and visible. Pipelines, if they are not buried, cannot be missed and overhead power lines are part of the landscape. Developing more of them is often accepted as a remote concept but can be challenged when it touches your neighbourhood.

For the electric grid, using existing transmission corridors is a way to avoid challenges. For the distribution grid, as it moves more into areas where people live, going underground is a clear – but more expensive – option.

As we highlighted, there is today a very limited network of CO_2 and hydrogen pipelines. Each region will be different, but we would expect resistance to the installation of such infrastructure – granted, perhaps more in Europe, than in say, Texas.

Safety: This topic is clearly related to the previous one and we believe is a key point for CO_2 and hydrogen.

Hydrogen burns very well, and as such it is easy – and reasonable – to be concerned by fire or explosion risks. This is the same situation for natural gas, but this molecule has been around for decades. CO_2 pipelines are not a common sight but when they burst it makes the news[68]. If long carbon dioxide and hydrogen pipelines are to be built, appropriate safety rules will have to be designed, that do not relax on safety while allowing the infrastructure to be built. For hydrogen specifically, we believe that, at least in the near term, policies will favour production close to demand points.

For electric power lines, safety is increasingly associated with forest fires and climate change. The bankruptcy of PG&E, a Californian utility, in 2019 (the company emerged from bankruptcy one year later) was deemed climate change-related because fires caused by falling transmission lines spread widely in lands touched by drought. This highlights the need for proper maintenance of the towers and electric lines and of the land they pass through, with a clear need of factoring in changing weather conditions. The subject is however broader and concerns everyone getting close to high voltage equipment, from operating staff to passers-by, and a larger grid will mean acute and smart safety measures in terms of work practices and signalling.

Basic materials bottlenecks: Unlike certain technologies, such as lithium-ion batteries or electrolysers, infrastructure mostly need old fashioned concrete, steel and aluminium. While costs can be a point of concern, availability is generally not a concern today, although demand will rise in the future and supply will have to follow suit, especially in low-temperature scenarios.

An investor's view: Q&A with Mark Gilligan, Head of Infrastructure, AXA IM Alts

Why is the energy transition relevant to investing in infrastructure?

We hold the conviction that climate change is the great issue of this century and the central risk of tomorrow. Accordingly, you should only want to own infrastructure which is either fit or adaptable for a net zero world. It's relatively easy to determine those infrastructures already fit for that world: for example, wind and solar generation and fibre optic networks. The more complex question is determining those infrastructures which are adaptable.

Our approach in answering that question is to assess whether we can develop, as part of our pre-acquisition due diligence, a credible business plan including all capital expenditure to adapt the infrastructure to be net zero materially before 2050. That's a window of less than 25 years which may seem long but given our long-term investment horizon and the challenges of decarbonisation, we think it's prudent.

By way of example, we are owners of Stockholm Exergi which is one of the world's largest district heating utilities. Exergi has already made great advances in decarbonisation over the last 20 years – reducing its CO_2 emissions per square metre heated by 80% - but it will take bio-energy carbon capture and storage (BECCS) to reach net zero. We are working with our co-shareholders and management to develop and fund such a BECCS project which, if executed as currently intended, would make Exergi net zero by 2032.
So, in summary, we don't think you can be a credible custodian of investors' capital without placing the energy transition – and its challenges and opportunities – at the centre of an infrastructure investment strategy.

What do you like and not like?

We judge that infrastructure investing will be dominated by decarbonisation, electrification and digitalisation for the next 30 years and beyond. We invest across the full spectrum of digital, energy, social, transportation and utility infrastructure and we are increasingly seeing a degree of convergence between subsectors.

This means that our strategy includes, for example, a pan-European fleet of electric locomotives which is a transportation business that generates vast amounts of data and, with ongoing investment in digitalisation, is allowing us to improve operational performance.

What do we like? For digital, we like hyperscale datacentre networks, defensive optical fibre networks and cellular tower networks – the three core elements of the internet. Our experience is that you can couple datacentres and renewable energy supply to deliver net zero solutions. For energy, we focus on vertically integrated independent power producers and avoid 'fruit salad' portfolios of wind and solar managed by external parties.

The reason is that renewable energy generation is about operational excellence and, over time, increasing exposure to merchant markets. We believe only vertically integrated independent power producers can really tackle those challenges. For transportation, we focus on electrification from electric trains and locomotives to electric vehicle charging. And utilities – we keep working hard for companies like Exergi which have a credible path to net zero.

What don't I like? That's simple, infrastructure businesses and management teams that cannot transition to a net zero world substantially before 2050. You won't find fossil-powered electricity generation, diesel-powered trains, oil terminals or coal ports in our strategy.

How risky can this be?

The energy transition is complex and inherently risky. There remain relatively conservative core infrastructure opportunities which align with the energy transition. For instance, we own the world's largest offshore wind farm, Hornsea Two, which is contracted for 100% of its output until around 2040 and that contract is indexed to inflation. It is 'core' infrastructure. Nevertheless, this is a complex utility-scale electricity generator operating in the hostile environment of the North Sea and it's exposed to wind variations over the short and long term.

It's certainly not a bond and its risks are there to be managed. From there, as you move up the risk curve through what is termed 'core-plus' and beyond, investors are exposed to development, construction, merchant, emerging technology and other risks. We think such risks can be managed through three key mechanisms: rigorous screening pre-acquisition to ensure that business plans are credible and deliverable; portfolio diversification; and an unrelenting year-on-year focus on portfolio value creation as the energy transition evolves and affects all infrastructure in new and unexpected ways.

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References to companies are for illustrative purposes only and should not be viewed as investment recommendations.

Image source: Getty Images